Conference Paper, Published Version

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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/104553

Vorgeschlagene Zitierweise/Suggested citation:
Seegers, Christina; Frings, Roy; Schüttrumpf, Holger; Kopmann, Rebekka; Wahrheit-Lensing, Andrea (2016): Suspended Sediment depositions in the impoundment of Iffezheim barrage effect of mesh resolution with Telemac3D. In: Bourban, Sébastien (Hg.): Proceedings of the XXIIIrd TELEMAC-MASCARET User Conference 2016, 11 to 13 October 2016, Paris, France. Oxfordshire: HR Wallingford. S. 41-48.

Suspended Sediment depositions in the impoundment of Iffezheim barrage effect of mesh resolution with Telemac3D

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Abstract—**Deposition of fine sediments (mainly silt) takes place in the weir channel of the Iffezheim barrage and makes dredging a necessity, due to flood risks that develop with higher water levels. The current pattern in this area is three dimensional and turbulent structures are believed to be one key factor for the deposition of the suspended fine sediments in the weir channel (influencing quantity and pattern of deposits). The aim of this study was to prove that a detailed representation of turbulent structures enables an improved simulation of deposits. Therefore a comparison between a coarse mesh model with ∼5 m resolution and a fine mesh model with ∼1 m resolution was made. With the fine mesh a turbulence model following Smagorinsky was used and with the coarse mesh a $k - \epsilon$ turbulence model was applied. Both meshes show the presence of a large recirculation zone in the weir channel. The fine mesh shows that superposed on this recirculation zone, time-varying eddies occur, which influence the sedimentation pattern. The better resolution of turbulent structures with the fine mesh leads to depositional patterns that fit better to the observed changes in bed level. This study shows that a good representation of the turbulent structures is essential for numerical investigations of suspended sediment deposits in impoundments with three dimensional current patterns.**

I. INTRODUCTION

Deposition of fine sediments (mainly silt) takes place in the weir channel of the Iffezheim barrage producing sediment volumes of on average 100 000 m^3/a between 2005 and 2010. Although most of the sediment that enters the barrage is not being deposited, the deposited sediments lead to a higher water level and have to be dredged due to flood protection requirements. The sediment is polluted with HCB (Hexachlorobenzene - a pesticide used until 1981) leading to high disposal costs, because the material has to be removed from the weir channel and then transported to a disposal area where it can be deposited. This results in a high interest in countering measures to reduce dredging costs by the responsible authorities. To find useful measures the processes influencing the deposition of sediments in this area were to be investigated with a 3D numerical model to further improve the understanding of the system.

Several investigations ([1]- [5] at different institutes) have been conducted in this region focusing on flood risks, a recirculation zone, possible measures [5] the amount of deposited sediments, sediment processes [1] and contaminants [4]. The current pattern in the depositional area (Figure 1) is three dimensional and for flows below 2 200 m^3/s a huge recirculation zone of ∼700 m length and with varying width (∼ 80 m to 280 m) can be observed. The presence of this recirculation zone and the associated time-varying eddies in the weir channel are believed to be one key factor for the deposition of the suspended fine sediments in the weir channel (influencing quantity and pattern of deposits). It should be known that although most of the time (∼85%) there is nearly no flow in the weir channel in most of the remaining time (∼12%) a recirculation zone is present in the weir channel.

The aim of this study was to show, that the reproduction of turbulent structures in the weir channel with the numerical model has a strong impact on the deposition patterns and quantities. Two numerical models with different resolutions and different turbulence models using Telemac 3D were used to achieve this. A fine mesh with a resolution of roughly 1 m in the weir channel was set up, to allow a good representation of the recirculation zone including eddies. A turbulence model following Smagorinsky was chosen for this mesh . The hydrodynamic situation and resulting sediment deposits produced with this fine model were compared to a model using a coarser mesh with a resolution of roughly 5 m that was operated with a $k - \epsilon$ model (to include small scale turbulence that would have been omitted using the Smagorinski model).

II. STUDY SITE

The study site is located at the upper Rhine at the border between Germany and France. This barrage is the last of a group of 10 barrages built for energy production between Basel and Iffezheim. Following this barrage, that was established in 1977, the Rhine is free flowing until it reaches the North Sea. The modelled region is of 3 kilometre length with the lower boundaries being located at the barrage constructions (lock, power station and weir). In the model area the Rhine splits up in three channels leading to these constructions (Figure 1). Since 2013 most of the water in mean discharge conditions and slightly above is used for power generation. The power station

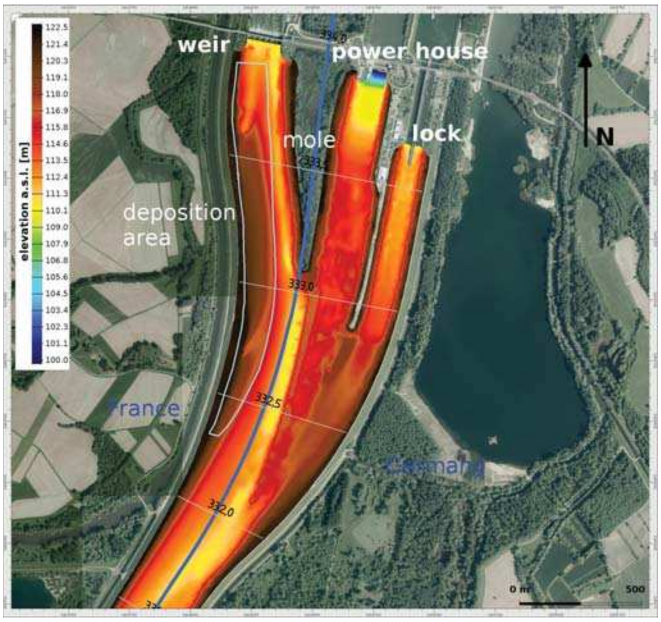

Fig. 1: The Iffezheim barrage in November 2014. Bed levels and the splitting of the Rhine into the three channels leading to lock, power house and weir. Photo images from BKG: Bundesamt fr Kartographie und Geodsie

can use up to 1 500 m^3/s of water per second, to generate 146 MW of peak power. Before 2013 1 100 m^3/s were used for power generation. Mean discharge flow means 1 250 m^3/s for the gauge at Maxau in Karlsruhe, which is roughly 30 kilometers downstream of Iffezheim. Mean low flow implies 581 m^3/s and mean high flow 3 060 m^3/s. The weir is made up of 6 weir fields, each giving the possibility to route water below or above the field. A torsion-rigid gate (fish-belly gate) is used for water flowing over the weir and allowing flow at the bottom a plain vertical rising gate is used. Each of these structures has a width of 20 m. Finding a good representation of this structure in the model proved to be challenging. Between the weir and the power station a mole was built resulting in a clear distinction of two channels, one to the power station and the other to the weir. A third channel leads to the lock, which is of no interest in this study.

The sediment deposited in the weir channel consists of a range of grain sizes from clay to sand, with most of the sediments being silt. The bed topography (Figure 1) shows two parts in the weir channel, a channel region with higher water depths (11-12 m) and a deposition area with water depths of 3-6 m.

III. MODEL SET UP AND CALIBRATION

The two models were set up with different meshes having a coarser grid resolution with mean node distances in the weir channel of about 5 m and a finer grid resolution with mean node distances in the weir channel of about 1 m. In both models the angles of the elements were in the range of 30°to 90°and both were consisting of 20 layers. As boundary condition for the inlet a flow was imposed. The boundary at the power station was steered the same way, while at the weir water levels were imposed. For simplicity there was no flow at the lock. For the sediment concentration C at the inlet a condition based on the discharge was implemented in bord3d subroutine: $C = C_0 * Q^{1.95}$, with Q the inflow and C_0 a basic concentration that was a function of the node n. The sediment was distributed along the nodes in a way that more sediment was close to the bed and to the left side of the inlet. Representing the sediment distributions found in measurements. For the fine mesh model (with higher computational costs) a Smagorinski turbulence model was used, while for the coarse mesh a $k-\epsilon$ model was used. Time steps were 1 s for the fine mesh model (FM) and 2 s for the coarse mesh model (CM). The sediment was calculated including flocculation using the default coefficients and without a consolidation model.

As implemented in Telemac (subroutine tfond) the friction velocity $v_{friction}$ was calculated via

$$v_{friction}^2 = (\frac{\kappa}{\log R})^2 * (u^2 + v^2) \tag{1}$$

with κ the karman constant, $R = \max\{1.001; \frac{30*d}{k_s}\}$, d is the distance between the first two levels of the mesh, k_s the Nikuradse roughness coefficient, u and v are the velocities in x and y direction at the first level of the mesh.

The shear stresses at the bottom τ_b (see Telemac manual [7] p. 52) were calculated via $\tau_b = \rho * v_{friction}^2$ with ρ the density. The shear stresses were only depending on the friction velocity and sediment content for these computations without salinity (and thus without a special density law).

For deposition of sediments the calculation of the deposition flux $F_{deposition}$ followed Krone (1962) using:

$$F_{deposition} = P_d W_C C \tag{2}$$

with P_d probability of deposition ($P_d = 1 - (\frac{\tau_b}{\tau_{cd}})$), τ_{cd} critical shear stress for deposition W_C settling velocity and C concentration of sediments in the water.

For erosion of sediment, following Partheniades (1965) the equation

$$F_{erosion} = M(\frac{\tau_b}{\tau_{ce}} - 1) \tag{3}$$

was applied with M, erosion coefficient, and τ_{ce} critical shear stresses for erosion.

The time period chosen for the calibration of the model was August 2006 to October 2006. The corresponding hydrograph is shown in Figure 2. This time period was chosen, due to the information available about the water levels at the weir and the discharges at the power house, as well as due to the typical time distance between two measurements with deposition occurring and discharges between 900 m^3/s and 2 900 m^3/s. The maximum discharge in the weir channel was thus 1 400 m^3/s. The measured differences in bed level, after the ~70 day period between August and October are shown in Figure 3. Both models with fine and coarse mesh have been calibrated with initial bed topography of august 2006 (based on echo soundings with distances of 20 m), the resulting parameter set is slightly different. Especially the critical shear stresses for deposition was different.

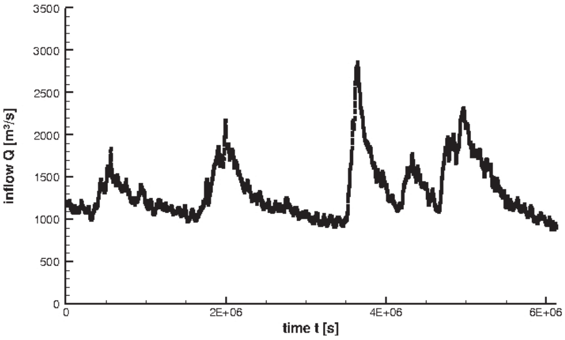

Fig. 2: The hydrograph of the calibration period August 2006 to October 2006.

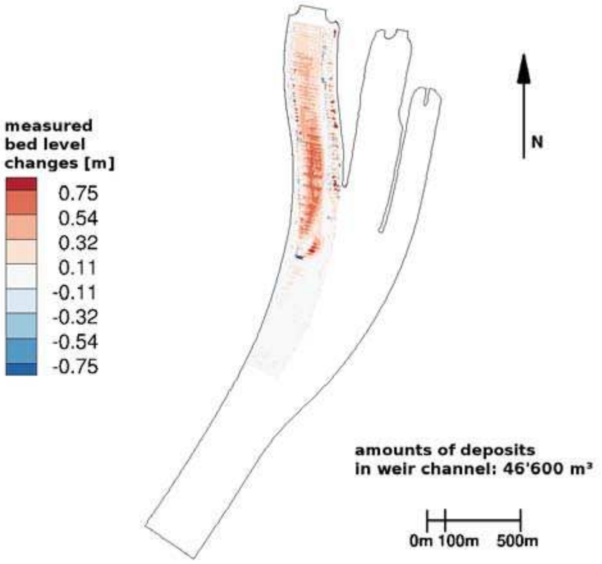

Fig. 3: The measured bed level changes between August 2006 and October 2006.

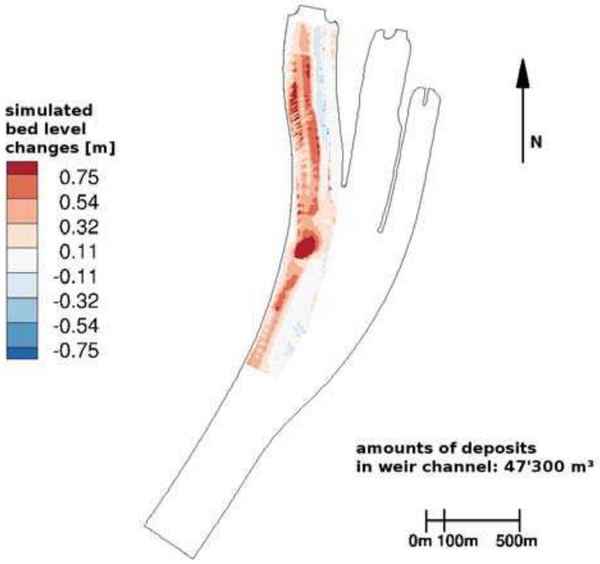

Fig. 4: The simulated bed level changes between August 2006 and October 2006, using the model with coarse mesh.

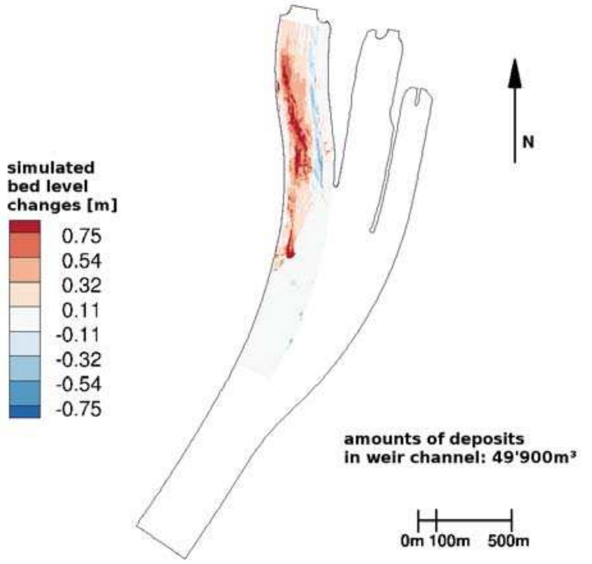

Fig. 5: The simulated bed level changes between August 2006 and October 2006, using the model with fine mesh.

A. *Coarse mesh model*

In the weir channel the coarse mesh had mean node distances of about 5 m length. The minimum value for the area ratio was 0.39. For the coarse mesh, the $k-\epsilon$ model was chosen as turbulence model. The calibration parameters were decided on the basis of sediment quantities deposited in the weir channel, to fit best with the following values: For the settling velocity a value of 0.0025 m/s, corresponding to a grain size of ~0.05 mm (coarse silt), following the equation of Soulsby [6], was chosen. The critical shear stress for deposition (Equation 2) was set to 0.135 N/m^2 and the critical shear stress for erosion (Equation 3) was 0.52 N/m^2, a value well within the range of measured critical shear stresses by Noack et al. [2]. The erosion constant (Equation 3) was set to 1.25×10^{-03} kg/m^2/s. The resulting bed level changes, calculated using the model with coarse mesh (Figure 4) fit reasonably well to the observed bed level changes, although for high discharges the erosion seemed to be somewhat to strong, resulting in too much bed level erosion (not shown here).

B. *Fine mesh model*

The fine mesh had mean node distances in the weir channel of about 1 m with a minimal area ratio of 0.34. For the fine mesh, the Smagorinski model was chosen as turbulence model and for the settling velocity a value of 0.0013 m/s, corresponding to a grain size of 0.04 mm (coarse silt), following the equation of Soulsby [6], was chosen. The critical shear stress for deposition was 0.004 N/m^2 and the critical shear stress for erosion was 0.59 N/m^2. The erosion constant was set to 0.80×10^{-03} kg/m^2/s. The resulting bed level changes, calculated using the model with fine mesh (Figure 5) fit well to the observed bed level changes. The erosion process during periods of peak discharges was not well reproduced by the model, which can be seen with different time periods (not shown here).

IV. COMPARISON OF FINE AND COARSE MESH MODEL

Both models, the one with the fine mesh and the one with the coarse mesh showed fairly good results after calibration. It is thus justified to compare these two models with fine and coarse mesh, to get more insight in the way the models simulate deposition. This comparison is divided in two parts. The first part deals with the hydrodynamics and illustrates the numerical representation of the recirculation zone and the forces acting on the bed. The second part will deal with the morphodynamics and compare the sediment in the weir channel and the resulting deposits. The sediment was strongly affected by the hydrodynamic situation.

1) Hydrodynamics: There was a big difference regarding the representation of the recirculation zone between the two models. In the model with the coarse grid, the recirculation zone was nearly stationary in time, while in the model with the fine mesh within the recirculation zone time-varying eddies occurred and more dynamic was observed in the flow pattern. The displacement of eddies was high, depending on inflow (about 20 m in 600 s for 400 m^3/s in the weir channel) and local hydrodynamic situations differed a lot with time. Therefore a comparison with the fine model was based on averaged quantities. Time averages were done over a period of 18 000 s (5 h). Three discharges were considered. One with 1 600 m^3/s as inflow and 100 m^3/s discharge in the weir channel termed as 'lower' inflow with a huge recirculation zone, a second one with 1 900 m^3/s inflow (leaving 400 m^3/s in the weir channel) called 'moderate' and a third one with 2 200 m^3/s inflow that allowed 700 m^3/s in the weir channel. The last 'higher' flow resulted in a recirculation zone of minor extent in the weir channel. The water levels in the weir channel were set to the same level to allow model comparison.

a) flow velocities: As shown in figures 6 and 7, the flow velocities for a moderate inflow situation gave maximum flow velocities in the coarse mesh of 0.5 m/s and average velocities of 0.20 m/s in the weir channel. The huge recirculation zone with an extent of ∼160 m in width and ∼800 m in length was more detailed in the fine mesh model and consisted of several eddies. The differences in flow velocities between coarse and fine mesh models were small 0.026 m/s in average and 0.25 m/s at most. They could be found in the region next to weir and mole and in the region with higher water depth. The most prominent difference consisted in more detailed, small scale flow structures in the fine mesh model with the Smagorinski turbulence model. For higher inflow (not shown here) the dimensions of the recirculation zone were reduced to 80 m and 700 m. The flow velocity differences were still small with 0.006 m/s in average and at most 0.35 m/s. Lower inflows (not shown here) lead to smaller flow velocities (with a maximum of 0.25 m/s) and the extend of the recirculation zone increased to 190 m width and 1 000 m length (differences were on average 0.0002 m/s).

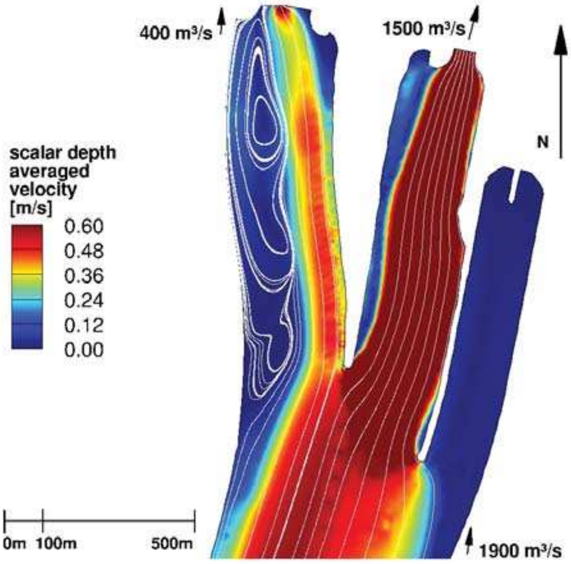

Fig. 6: Depth averaged scalar flow velocities in the weir channel. White lines represent the recirculation zone modelled with the coarse mesh model. An inflow of 1 900 m^3/s, a flow at the power house of 1 500 m^3/s and a flow at the weir of remaining 400 m^3/s, characterized as moderate flow situation, were applied.

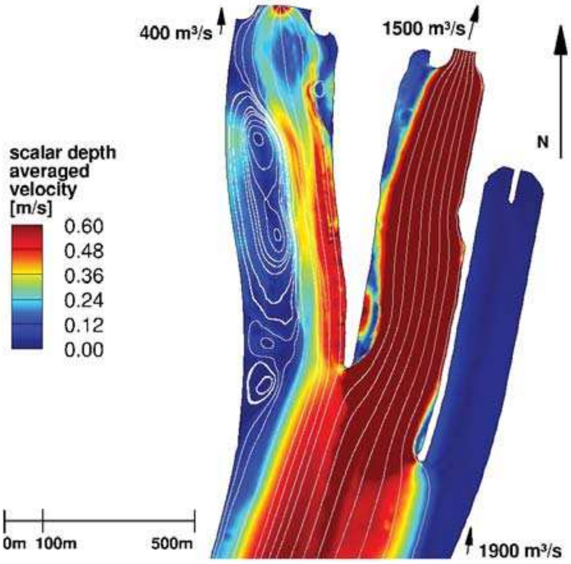

Fig. 7: Depth averaged scalar flow velocities in the weir channel. White lines represent the recirculation zone modelled with the fine mesh model for a moderate inflow situation.

b) friction velocities and shear stresses: The flow velocities led to the friction velocities, which were relevant for the sediment deposits, as can be deduced from the equations for sediment deposits (see section III). For the moderate inflow situation (leaving 400 m^3/s discharge in the weir channel) the average friction velocity with the coarse mesh model was 0.0085 m/s . With higher velocities in the deeper region with

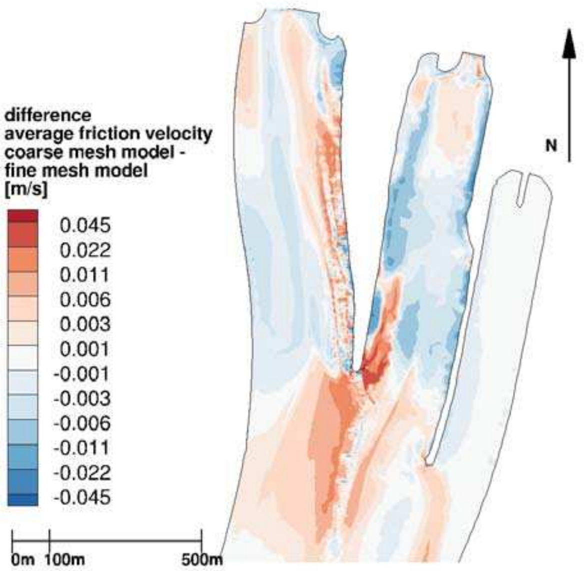

Fig. 8: The differences in the friction velocities (averaged in time) of the model with the fine mesh and the friction velocities of the model with the coarse mesh. For a moderate flow situation.

roughly 0.0177 m/s and lower velocities in the deposition area with roughly 0.0028 m/s. The fine mesh model gave an average friction velocity in the weir channel of 0.0084 m/s. It is obvious that the friction velocities mainly differ in the region close to the mole. While in the deposition region there were only small differences - see figure 8 for differences of averaged friction velocities. On average the differences were 0.0002 m/s. For higher inflow the region with higher velocities extended, while it decreased for smaller velocities so that average friction velocities in the weir channel changed to 0.0045 m/s for lower flows (0.0042 m/s FM) and to 0.0124 m/s for higher flows (0.0121 m/s FM) .

The pattern of the resulting shear stresses in the weir channel was the same as for the friction velocities with values up to 0.9 N/m^2 at the mole and lower values in the deposition area with 0.001 N/m^2 for the coarse mesh model. For higher flows the shear stresses increased. For lower flow situations they decreased to maximum values of 0.5 N/m^2 and average values of 0.06 N/m^2. The differences in shear stress were small with locally higher shear stresses, that changed positions along with the eddies in the fine mesh model.

c) vorticity: As a measure of turbulence the vorticity is shown in Figure 9 for the coarse mesh model and in Figure 10 for the fine mesh model. It is obvious that in the fine mesh model more vorticity could be observed, since more turbulence could be resolved with the fine mesh.

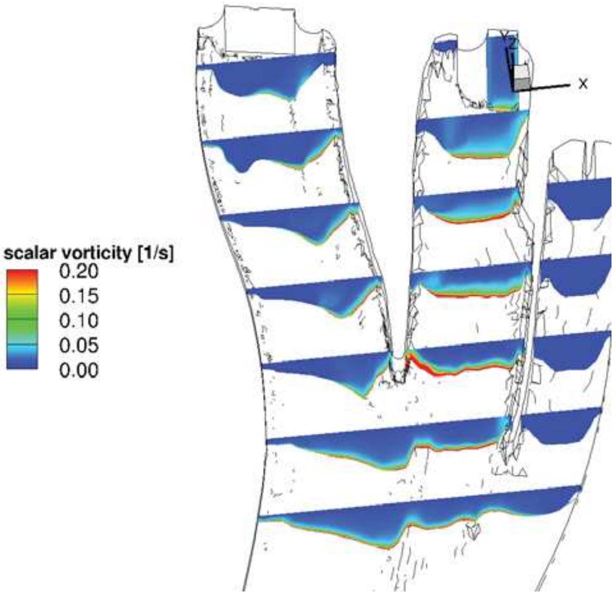

Fig. 9: The vorticity of the coarse mesh model for moderate flow situations in the weir channel.

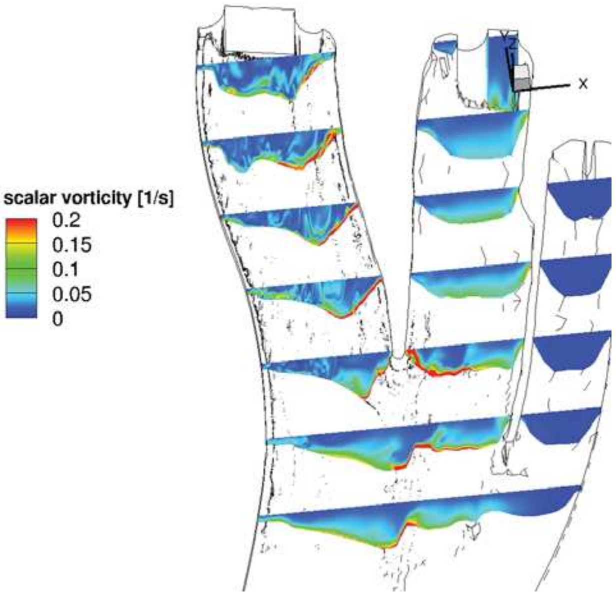

Fig. 10: The vorticity of the fine mesh model for moderate flow situations in the weir channel.

2) Morphodynamics:

a) sediment: The sediment in the water was given as concentrations. Figure 11 showed the sediment distribution in the model with the coarse mesh for moderate inflows. The corresponding Figure 12 with the fine mesh model illustrates the huge difference between the two models for the weir channel. The positions of the sediments in the weir channel were entirely different. For the coarse mesh model, the sediments were situated close to the mole. The sediment was held back at the boundary of the recirculation zone in case of the coarse mesh model and there the settling of the sediments took place. For higher flows the recirculation zone decreased and the sediment was distributed over a wider area in the coarse mesh model. It was the opposite for the model with the fine mesh. The sediment amounts (in the water in the weir channel) were 19 400 kg for the coarse mesh model and 55 700 kg for the fine mesh model (compared to CM: 58 000 kg and FM: 85 400 kg for the higher inflow). For lower

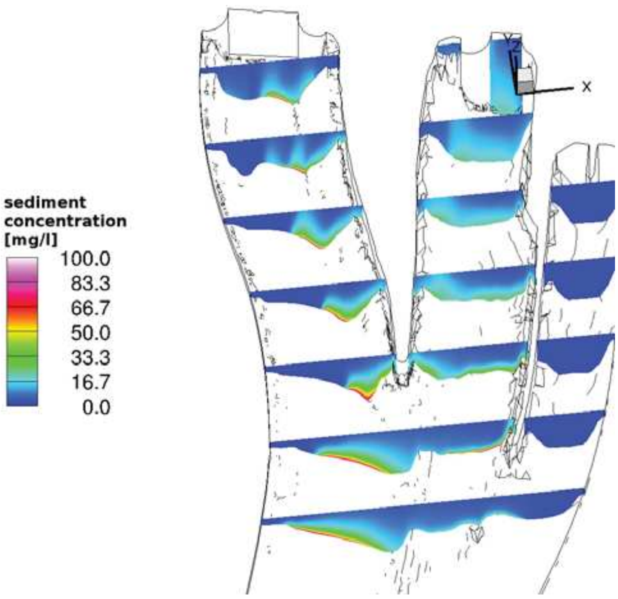

Fig. 11: The sediment concentrations using the model with the coarse mesh and a moderate flow situation.

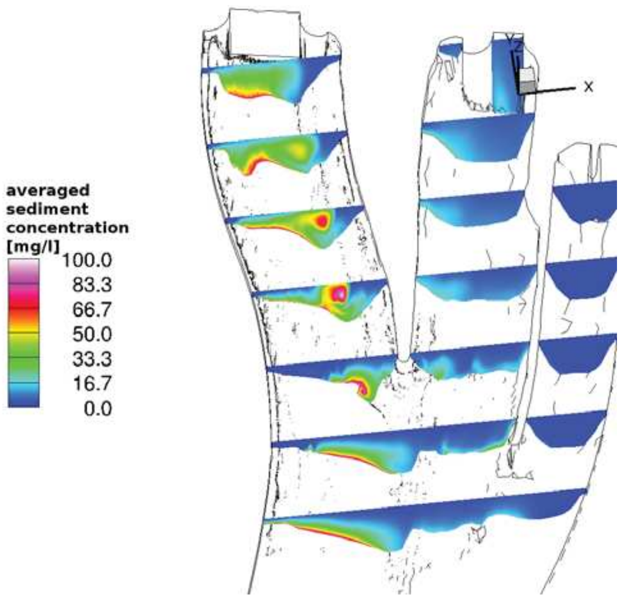

Fig. 12: The averaged sediment concentrations in the weir channel using the model with the fine mesh, for a moderate flow situation.

flows the recirculation zone increased and less sediment was present in the models (CM: 3 300 kg and FM: 12 000 kg). Not only the amounts of sediments in the weir channel changed also the position of the deposits. Sediment was present within the recirculation zone in the model with the fine mesh (see figure 12) and thus above the deposition area. While more sediment was in the deeper channel region, close to the bed in the coarse mesh model (see figure 11) and thus not above the deposition area. It is apparent that more sediment was routed along the weir channel in case of the fine mesh model compared to the coarse one.

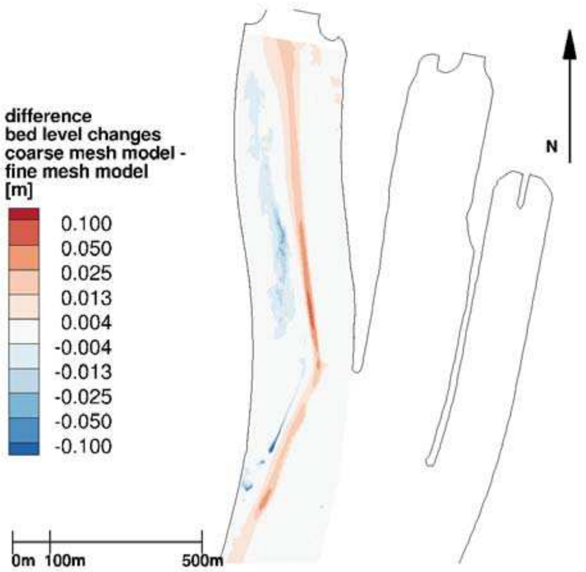

Fig. 13: The differences in bed level changes within 5 h between the models with coarse and fine mesh, for moderate inflows.

b) sediment deposition: The sediments present in the weir channel could possibly be deposited, if the hydrodynamic situation allowed this. The resulting depositional pattern was quite different for the two models. Figure 13 shows the differences between the bed levels. The areas where the sediments were deposited for moderate inflows were at the edge of the deposition area for the coarse mesh model (with 870 m^3 of deposits) and close to the french bank for the fine mesh model (with 410 m^3 of deposits). They did not even overlap, and could be described as at the border of the recirculation zone (CM) and within the recirculation zone (FM). For higher inflows, the region were deposition took place of the coarse mesh model (with 1 700 m^3 of deposits) moved closer to the bank. The region were deposition took place of the fine mesh model nearly stayed at the same position (with 500 m^3 of deposits). For lower inflows the region were deposition took place of the fine mesh model extended and covered most of the weir channel with 180 m^3 of deposits. The coarse mesh model deposited only in the deep channel region of the weir channel and close to the weir, but mostly before the weir channel begins with 230 m^3 of deposits. Although more sediment was present in the weir channel in the fine mesh model, more sediment was deposited in the coarse mesh model for the presented inflows. While for most flow situations the amounts of deposited sediments were of the same magnitude (with factors below 5) the most important result was that the positions were essentially different.

V. DISCUSSION

The differences in the depositional patterns during periods with the presence of the recirculation zone are to be dealt with. These patterns are governed by the description of the deposition (Equation 2). In a first step the differences between the models following this description are presented and the main causes are examined. As second step the relation to the turbulent structures is given. It will be explained why the fine mesh model is believed to better represent the deposition processes and what the effects of better representation of the turbulent structures were. The role of the eddies in this representation will be clarified.

The hydrodynamic situation was similar, but in detail there were a lot of differences between the models with coarse and fine mesh. These differences were associated with small scale flow structures and the time-varying eddies in the recirculation zone. The distribution of the sediment within the weir channel was in reaction to these small but essential hydrodynamic differences, totally different. To investigate the reasons for the different depositional patterns the underlying laws that influence the deposition are recalled here. The friction velocity was calculated via formula 1 and was thus depending on the local flow velocities and the local roughness. As described in the hydrodynamics part IV-1b, the average friction velocities were not too different between the two models. The shear stresses according $\tau_b = \rho * v_{friction}^2$ were directly depending on the friction velocities. These shear stresses were needed to calculate the deposition according to equation 2. The sediment content and settling velocity directly influenced the deposition of sediments and since the shear stresses were part of the equation to calculate the deposition of sediments also friction velocities had a control function. The sediment thus was in two ways present in the calculation of the deposits, directly as concentration and by means of density also via the shear stress calculation. The presence of sediments, that depended on the hydrodynamic situation, was the main factor for the differences between the models with coarse and fine mesh. This can be concluded since the differences in friction velocities were small in the weir channel, the differences in shear stress were also small while the differences in the sediment concentrations and position of the deposited sediments were huge with no or nearly no overlap. The positions of the deposits simulated with the fine mesh within the recirculation zone, were more plausible (Figure 13).

It is known from some measurements (done by the BfG: German Federal Institute of Hydrology) that within the recirculation zone sediments are present. Following the above process description these sediments were expected to be deposited. Although the calibration results (Figures 4 and 5) look similar the way they result from the simulations was different (not shown here). That within the recirculation zone in the coarse mesh model no sediment was being deposited was compensated by deposition at higher discharges in the weir channel at these positions. The higher sediment amount that was deposited in the deeper parts of the weir channel was compensated by higher erosion. The deposition behaviour is believed to be better captured with the fine mesh model, as indicated via sediment the mentioned concentration measurements and via application to different time periods (both not shown here).

The sediment was present in the water column due to advection and diffusion. Its distribution differed a lot between coarse and fine mesh model. The different sediment distribution in the weir channel led to a different availability of the sediment regarding the deposition. The different sediment distribution could be related to the turbulent structures and their representation in the weir channel. This can be seen by comparing Figure 14, showing the sediment concentrations in the weir channel calculated with the fine mesh model, with the vorticity of the fine mesh at the same time Figure 10. Regions of higher vorticity could be associated with regions of higher sediment concentrations.

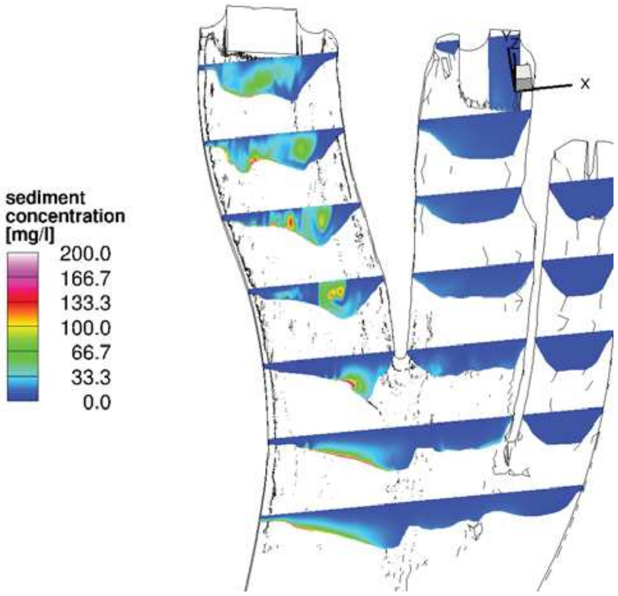

Fig. 14: The sediment distribution in the weir channel for moderate flow situations, with fine mesh model.

The vorticity could be associated with the time-varying eddies in the weir channel, as they moved around also the regions of high vorticity with more sediment content were moved along. This is the reason why time averages over 5 h were necessary for the comparison of coarse and fine mesh (Section IV-1). For short time intervals the sediment was deposited only at some parts within the recirculation zone, since the deposition flux (Figure 15) was high at the centre of an eddy.

Thus the representation of the sediment distribution and deposition was better in the fine mesh model. This could be associated with the turbulent structures, which were better represented in the fine mesh model.

In the model the amounts of sediments deposited in relation to the inflow can be gathered. Thus the influence of the representation of the recirculation zone on the overall sediment deposits for a given hydrograph can be specified. For the coarse mesh model of Iffezheim barrage and the calibration time period 105% of the sediment was estimated to be deposited in situations associated with the recirculation zone (and 21% in situations without recirculation zone). For the fine mesh model 118% of the sediment was estimated to be deposited in situations associated with the recirculation zone and 5% in situations without recirculation zone. Some of the deposited sediment amount was being eroded in higher flow situations with no recirculation zone.

This effect of better representation of the deposition area with higher mesh resolution was not depending on the bed level topography. Assuming that recirculation zones and 3D

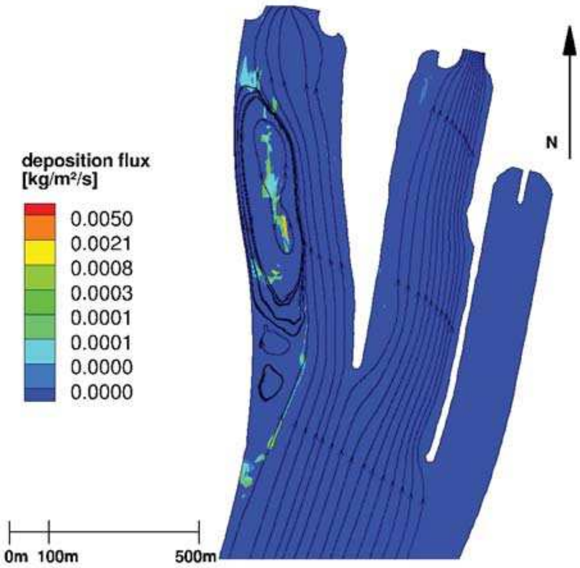

Fig. 15: The deposition flux in the weir channel for moderate flow situations, with fine mesh model. Black streamlines (of depth averaged velocities) show the recirculation zone.

turbulent structures are present in similar situations leads to the conclusion that for the numerical implementation of impoundments a good representation of turbulent structures improves the simulation of sediment deposition.

VI. CONCLUSION

The time-varying eddies observed in the model with the fine mesh and Smagorinski model influenced the depositional patterns in the Iffezheim barrage and led to more realistic deposition behaviour in the weir channel than the mainly static recirculation zone that could be modelled using the coarse mesh model. Leading to the conclusion that the effect of the turbulent structures, that introduces sediments into the recirculation zone, in the weir channel really is one key factor to model the sediment deposition. Yet there are still improvements regarding a realistic representation of the actual situation in the model to be achieved to gather more insight in the processes and their reactions to measures in the study site.

Generally a good representation of the turbulent structures associated with recirculation zones is essential for numerical investigations of sediment deposits in impoundments.

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