This is a post-peer-review, pre-copyedit version of an article published in Journal of Soils and Sediments. The final authenticated version is available online at:
http://dx.doi.org/10.1007/s11368-018-1989-0

Long-time 3D CFD modelling of sedimentation with dredging in a hydropower reservoir

Nils Reidar B. Olsen

Department of Civil and Environmental Engineering, The Norwegian University of Science and Technology, Norway

S. P. Andersens vei 5, 7491 Trondheim, Norway, Nils.R.Olsen@ntnu.no

Gudrun Hillebrand

Federal Institute of Hydrology, Department M3 - Groundwater, Geology, River Morphology

Am Mainzer Tor 1, 56068 Koblenz, Germany

Long time 3D CFD modelling of sedimentation with dredging in a hydropower reservoir

Abstract

The purpose of the current study was to present a 3D CFD model that can be used to predict long-term (11 years) bed changes in a reservoir due to sedimentation and dredging. And that this can be done with a reasonable computational time (18 hours) on a desktop computer.

The numerical model solved the Navier-Stokes equations on a 3D non-orthogonal unstructured grid to find the water velocities and turbulence. The convection-diffusion equation for suspended sediment transport was solved to find the sediment deposition pattern. Bed changes were computed and used to adjust the grid over time. Thereby, bed elevations over time were computed. The effect of dreding was also included in the model, and how this affected the bed elevation changes. The main feature of the numerical model enabling a reasonable computational time was implicit numerical methods giving the possibility to use long time steps.

The results were compared with annually measured bed elevation changes in the reservoir over 11 years, this gives 11 figures of bed elevation changes, due to sedimentation and dredging. Comparing the annually computed and measured bed changes, there was a fair agreement for most of the years. The match was not perfect, but the main deposition patterns were reproduced. The amount of sediments removed in three dredging campaigns were also computed numerically and compared with the measurements. Parameter tests were done for the grid size, fall velocity of the sediments, cohesion and sediment transport formula. The deviation was less than 16 % for all these four parameters.

The 3D CFD numerical model was able to compute water flow, sediment transport and bed elevation changes in a hydropower reservoir over a time period of 11 years. Field measurements showed reasonable agreement with the computed bed elevation changes. The results were most sensitive to the sediment particle fall velocity and cohesion of the bed material.

Keywords: sediment transport, reservoir, numerical modelling, Navier-Stokes equations, bed level changes, dredging.

1. Introduction

Sediment deposition can be a serious problem in many water reservoirs where the particle concentration in the inflowing river is high (Mahmood, 1987). The sediments can fill up the reservoir and reduce the storage volume. If the sediments reach the intake, abrasion on hydraulic machinery may result (Thapa et al, 2017). The sediments may therefore have to be removed. This is mainly done by either dredging or flushing (Brignoli et al, 2017; Haun and Olsen, 2012). The most cost-effective method is usually a flushing, where the water level in the reservoir is drawn down, allowing higher water velocities and erosion of the sediments. However, for some cases the sediments may be polluted (Vidmar et al, 2017), and a flushing will therefore release unacceptable levels of toxic concentrations in the river downstream of the dam. This is the case for the Iffezheim reservoir in the Rhine river on the border between Germany and France. The sediments in this reservoir are contaminated with hexachlorobenzene (HCB). The removal of these sediments is therefore done by mechanical dredging. This is a costly operation, which raises many questions regarding the sediment management of the reservoir:

- How much dredging is required?
- Where should the dredging be done?
- How long time does it take before the reservoir is filled up with sediments after a dredging?

These questions could be answered with a computational model that would calculate the sediment deposition in the reservoir and also the effect of the dredging operation. Such a model is presented in the current study. The model is applied to the Iffezheim reservoir, computing a time period of 11 years, from 2000 to 2011. Three larger dredging campaigns were carried out during these years and this is also included in the model.

A sketch of the Iffezheim reservoir is given in Fig. 1. The water is coming from the south and lead into a reservoir that has three outlets. The right (in the direction of flow) outlet is a ship lock, where relatively small amounts of water will flow. The center channel leads to the hydropower plant, which takes most of the water during low and middle discharges. The left channel leads to a spillway and is only used for high discharges. Most of the time, the water in this channel has close to zero velocity. In theory, sediments should therefore not enter this channel and be able to deposit. However, the flow field in the region just upstream of the spillway channel is fairly complex, and eddies still cause sediment to flow into this channel and deposit there. Fig. 2 shows the computed velocity field in this area. It is clear that a numerical model that is to predict the sediment deposition in the weir channel and its vincinity has to be multi-dimensional to capture the complex flow pattern. The current study therefore uses a fully 3D CFD model, solving the Navier-Stokes equation in all three directions.

Considerable research has previously been carried out on multi-dimensional modelling of reservoirs. Papanicolaou et al (2008) gives a summery of a number of different numerical models for sediment transport modelling in water hydraulics. Stamou and Gkesouli (2015) modelled the deposition of suspended solids in settling basins of a water treatment plant using a fully 3D approach. The CFD program CFX was used to compute the flow field in the tanks, which were subjected to wind stress on the surface. The study also investigated the use of baffles to improve the flow conditions in the tank, which is very useful for its design. Zinke et al (2011) computed sediment deposition in a delta of a natural lake using a fully 3D model.

Most of the deposition took place on the vegetated overbanks. The results were compared with field measurements. Mirbach and Lang (2017) used a 3D CFD model to compute density-driven currents in Lake Constance in Switzerland. They modelled density gradients due to the variations in sediment concentrations and temperature using the Navier-Stokes equations. The results were compared with time series of measurements of temperature and water velocity at one location in the lake. Ruether et al (2005) also investigated sediment flow in a water reservoir, but for an irrigation project. Two 3D CFD programs were used to find the sediment trap efficiency of the impoundment, and this was compared with measurements. However, no computations of bed elevation changes were carried out. This was done by Jia et al (2013), who modelled sediment deposition in the Three Gorges reservoir in China over a period of 3 1/2 years using a fully 3D model. The deposition rate was well predicted, although the deposition pattern was not. This was thought to be due to mass movements of muddy bottom sediments. Fang and Rodi (2003) also computed the water flow and sediment deposition in the Three Gorges reservoir and compared the results with data from a physical model study. Good agreement was found both for the velocity field and the sediment deposition. Haun et al (2013) computed sediment deposition in a hydropower reservoir in Costa Rica, and compared the resulting suspended concentrations with field measurements. A 3D numerical model was then also used. Faghihirad et al (2017) computed bed elevation changes over time in a water reservoir using a depth-averaged 2D model for the water flow field. The model was extended to 3D when computing suspended sediments and bed elevation changes. The model was tested and verified on a number of simpler cases where experimental data existed.

As seen in Fig. 2, the velocity field in the deposition zone of the Iffezheim reservoir is fairly complex with multiple recirculation zones. Such flow patterns may emerge when multiple channel branches are present (Đorđević, 2013). The recirculation zones will induce secondary currents that push the depositing sediments to the middle of the vortexes. This effect is similar to tea leaves collecting in the middle of a tea cup when it is rotated. The complex flow field will require a three-dimensional model. The main novelty of the current paper is to present a 3D CFD model that can compute sediment deposition in a reservoir with complex flow over a long time period (11 years), and include the effect of dredging. The model is also verified with extensive field data of bed elevation changes.

2. The Iffezheim reservoir

The Iffezheim reservoir is located in the Rhine river, at the border between Germany and France. The federal waterway of the Rhine river can be divided into three parts: the Upper Rhine, the Middle Rhine and the Lower Rhine. The Upper Rhine has 10 run-of-the-river hydropower plants, and the Iffezheim reservoir is the most downstream. It is the last dam in the Rhine, as Middle and Lower Rhine are completely free-flowing without any barrages. The German Waterways and Shipping Administration and the Federal Institute of Hydrology have carried out detailed measurements of suspended sediments in the Rhine for many years. They also measured bed level changes in the reservoir on a regular basis using echo sounding. The current study models the years 2000-2011. The total sediment inflow to the Iffezheim reservoir in these years is given in Fig. 3. The values are based on daily suspended sediment concentrations measured as point samples at a location approx. 10 km downstream of the reservoir. Cross-sectional measurements at both the sample location and the model inflow boundary are used to transfer the point measurements to the upstream model boundary. The numerical model simulated the grain size distribution as 9 fractions of different sizes and fall velocities. The values are given in Table 1. The resulting annual sediment inflow of the different fractions is given in Fig. 4. The split was based on measured grain size distributions in the Rhine.

The actual observed time series of water discharge from 2000-2011 was used. The resolution was based on averages over 15 minute intervals, giving 385 440 points in a time series. Fig. 5 shows the inflowing water discharge, together with the discharge through the turbine and the spillway.

The capacity of the turbines is 1100 m^3/s. As shown in Fig. 5, all the inflowing water is assumed to be used in the turbines for discharges lower than 1100 m3/s. For discharges exceeding the capacity of the turbines, the water will flow through the spillway.

3. Numerical model

The numerical model computed the water flow and turbulence by solving the Navier-Stokes equations on a three-dimensional grid. Two grids were used: a fine grid and a coarse grid. The coarse grid is seen in Fig. 6, from above.

The grid has 40x100 cells in the two horizontal directions and 10 cells in the vertical direction. The fine grid has 80x200 cells in the horizontal directions. The k-epsilon model (Launder and Sharma, 1974) was used to compute the turbulence, eddy-viscosity and the diffusion coefficients for the suspended sediment transport. A second-order upwind method was used for the discretization of the convective terms in the Navier-Stokes equation. The pressure was found by the SIMPLE method (Patankar, 1980).

The numerical model had several options to compute the location of the free water surface (Olsen, 2015). However, the water level was fairly constant over time and the water surface in the reservoir was fairly flat, so an algorithm based on the computed pressure was used (Tritthart and Gutknecht, 2007). Wall laws for rough boundaries were used at the reservoir bed:

$$\frac{U}{u_*} = \frac{1}{\kappa}\ln\left(\frac{30y}{k_s}\right) \qquad (1)$$

U is the velocity in the cell close to the wall, *y* is the distance from the wall to the centre of the cell, κ is an empirical constant (0.4) and k_s is the roughness height of the bed. The wall laws connect the velocity in the bed cell with the bed shear stress, τ, given in the formula for the shear velocity, u_*:

$$u_* = \sqrt{\tau / \rho} \qquad (2)$$

The density of water is denoted ρ (1000 kg/m^3)

The numerical model computed the bed shear stress from the velocity and used this as a sink term in the Navier-Stokes equations to reduce the velocity close to the bed. Since the roughness is included in the formula, this parameter was taken into account when computing the shear stress and also the velocity profile.

The suspended sediment concentration, *c*, was computed from the transient convection-diffusion equation for each of the 9 sediment fractions, *i*:

$$\frac{\partial c_i}{\partial t} + U_j \frac{\partial c_i}{\partial x_j} + w_i \frac{\partial c_i}{\partial x_3} = \frac{\partial}{\partial x}\left(\Gamma \frac{\partial c_i}{\partial x_j}\right) + F_{R,i} \qquad (3)$$

The fall velocity is denoted w, and given in Table 1 for the different sediment fractions. Γ is the turbulent diffusion coefficient, computed from the k-epsilon turbulence model. The sediment pick-up rate is denoted F and computed from the following formula:

$$F_i = \min(c_{R,i}, \max(c_{c,i}, c_{R,i} f_i)) w_i \rho \quad (4)$$

The sediment fraction at the bed for size i is denoted f_i. The variable c_c is the concentration in the bed cell computed in the previous time step. The sediment concentration, c_{Ri}, is given by van Rijn (1984a). Additionally, the bed load was computed by the formula by van Rijn (1984b). The formula from Engelund-Hansen (1967) was also used in the current study, where the sediment discharge given from the formula was converted to concentration similar to c_{Ri}, in Eq. 4. Given the computed sediment concentrations, the bed elevation changes for each time step were computed from the continuity equation for each bed cell (Exner equation). The bed was then raised/lowered accordingly after each time step, and the grid regenerated. The new time step started with solving the Navier-Stokes equations before computing the sediment transport. This sequence was repeated for each time step. The result was a change in the bed elevations over time.

One of the main problems modelling long time series with a 3D model is computational time. The current study employed the same strategy as Hillebrand et al (2017) to reduce this problem. The numerical model used an implicit solver for the Navier-Stokes equations, avoiding the constraint of the Courant number. Since the free surface was fairly flat and did not move much, the free surface computation did not cause a stability problem. Thereby, very long time steps could be used. Ideally, the time step should be very long during low discharges, when little sediment enters the reservoir. During floods the inflowing sediment concentrations are higher, which requires a shorter time step to resolve the changes in the bed elevations properly. Hillebrand et al (2017) used a time step that varied according to the water discharge, as given in Eq. 5:

$$\Delta t = \Delta t_0 (Q_{ref}/Q)^n \quad (5)$$

The current study used a reference discharge, Q_{ref} of 1000 m3/s and a Δt_0 of 20 000 seconds. The parameter n was set to 3. These values were also used by Hillebrand et al (2017). The computational time for the time series of 11 years was 18 hours on a desktop PC from 2014 for the coarsest grid. The fine grid required a computational time of four days.

A complicating factor for modelling long time series of reservoir deposition is that dredging often occurs. The Iffezheim reservoir was dredged several times during the time period from 2000-2011. Three of these dredging operations were considered to be of importance for the current simulation:

1 Sept 2000 - Mar 2001
2 Nov 2003 - Mar 2004
3 Jan 2005 - Sept 2005

The Waterways and Shipping Administration had obtained bed scans after each dredging period, as this was used to document the sediment volume that was removed. The scans after the three dredging operations were interpolated to the computational grid giving a bed elevation level, z_b, after dredging. The numerical model then computed the bed level changes, Δz, from the dredging according to the following formula:

$$\Delta z = \frac{\Delta t}{T}(z - z_d) \quad (6)$$

The time step in the numerical model is denoted Δt and T is the time period of the dredging operation. This bed elevation change was used to change the grid after each time step. A continuous and gradual bed change was assumed during the dredging operation for lack of in-between data. The bed level changes were implemented in the numerical model with the same function as the sediment deposition/erosion.

4. Results

The numerical model was applied to the computational grid with the previously described input data of water discharge, sediment inflow and dredging. The bed load and suspended sediment boundary conditions by van Rijn (1984a,b) were used for the initial (default) computation. This resulted in the bed level changes as given in Fig. 7. They can be compared with the equivalent measured bed level changes in Fig. 8. The two figures show that the numerical model gave very similar deposition/dredging patterns as the measurements. The amount of dredged volume exceeded the sediment deposition in the years 2000-2001, 2003-2004 and 2004-2005 both for the measured and computed results. The computed sediment deposition in most of the other years shows a similar pattern as the field measurements. Only some of the years, especially 2009-2010 shows a much lower computed sediment deposition than the measurements. However, the numerical model is able to predict a major deposition in the spillway channel. The sediment inflow into this channel is caused by a complex flow pattern as shown in Fig. 2. The reasonable replication of this pattern in many of the years shows that the numerical model is able to compute the complex flow field with recirculation zones, large scale vortexes and secondary currents. It is also able to compute the deposition of the suspended sediments in such a flow field.

The three dredging operations included bed scans both before and after the sediment removals. The scans were used to estimate the total sediment removal by dredging. The numerical model also computed this number as a difference between bed elevations at two points in time: before and after each dredging operation. A comparison of computed vs. measured dredged volume is given in Table 2.

The bed elevation after each dredging operation is given to the numerical model. The deviation between the measured and computed dredged volume does not reflect how accurate the numerical model can compute the bed elevation after the dredging. However, it is a computation on how much sediment has settled in the reservoir after the previous dredging to before the current dredging operation ends. This reflects how well the numerical model is able to calculate the correct amount of sediment deposition in the reservoir.

5. Discussion

The results of a CFD computation will always include errors and uncertainties. Input parameters, coefficients in empirical formulas, grid size, etc may have an effect on the results. One of the best methods to assess these uncertainties is by parameter sensitivity tests. Uncertain parameters are varied and the computations are redone. Comparing the results from the new and the original computation will give an estimate of how sensitive the result is for the parameter in question.

A very important parameter in a CFD computation is the grid. To obtain reasonable computational times, the current study uses a relatively coarse grid. A logical parameter test is therefore the grid size. The dimensions of the grid cells in Fig. 6 are around 1 meter in the vertical direction and 5-30 meters in the horizontal directions. The grid refinement was therefore done by doubling the number of cells in the two horizontal directions. This gave an erosion/deposition pattern as shown in Fig. 9.

Comparing Fig 9 with Fig. 7, the results are very similar. Also, it is difficult to see if there is an improvement compared with the measured bed elevations in Fig. 8. The main deviations between the deposition pattern in the years 2009-2010 are still present in the results from the fine grid.

The sediment deposition in the periods of dredging operations was also computed with the fine grid. This is shown in Table 3. The average deviation between the results from the two grids is 2 %. This a fairly low value. Hillebrand et al (2017) found a value of 10 % when computing the current case over a three month period in 2007 with a similar grid refinement. The study of Hillebrand et al (2017) was from a time period where the water discharge was higher than the average discharge in the Rhine from 2000 to 2011. Also, Hillebrand et al (2017) computed a shorter time period. Zhang (2017) showed that deviations usually decreased in computation of longer time periods because short-term fluctuations are averaged out. The inflowing sediment concentrations were therefore relatively higher and the spillway channel was more in use. This may explain the different results.

There are also other parameters that affect the results of a CFD computation, beside the grid. Hillebrand et al (2017) computed the sediment deposition for the current during three months of 2007. They found that the three most important parameters were the fall velocity of the sediments, the sediment transport formula and cohesion on the bed. Tests of these three parameters have therefore been included in the current study.

The study of Hillebrand et al (2017) showed that the fall velocity of the fine sediments was the most important parameter for the numerical model. The uncertainty in the fall velocity is due to the flocculation process of fine particles. The fine particles will form flocs that have higher fall velocities than each individual particle. The fall velocity will therefore increase. Modelling flocculation of particles is a fairly complex topic, so the current study has only investigated the process by increasing the fall velocity of the fine particles. The parameter test increased the fall velocity of the three finest particle sizes with a factor 2. The result is shown in Table 4. The average increase in the deposited volume was 9 %. Hillebrand et al obtained an increase of 48 %, but then the fall velocity was increased by a factor 3 instead of 2. Still, the increase in deposited volume is much larger for increased fall velocities than for the grid refinement.

Hillebrand et al (2017) also found that cohesion of the sediments was an important parameter for the sediment deposition. When fine sediments deposit on the bed and stay there for some time, the cohesion will increase. This means the particles will erode at a higher shear stress than for cohesionless sediments. In the current study, the cohesion was taken into account by increasing the critical shear stress on the bed according to the following formula given by Shields (1936):

$$\tau_c = \theta g(\rho_s - \rho_s)d + \tau_{cohesion} \qquad (7)$$

The Shields parameter is denoted θ, g is the acceleration of gravity, ρ_s is the density of the particles (2650 kg/m^3), ρ_w is the density of water and d is the particle diameter. The increased shear stress due to cohesion is given as $\tau_{cohesion}$. In the current study a value of 0.1 Pa was used. This gave an avarage increase of 10 % in the deposited sediments, as shown in Table 5.

Hillebrand et al (2017) found that the increase in the amount of deposited sediment was 24 %, with the same increase in the bed shear stress. Field measurements (Noack et al, 2016) show that the critical bed shear stress varies between from a low value at the top of the sediments to around 1 Pa one meter below the bed. The cohesion increases over time, and it may take weeks to reach a value of 0.1 Pa. When Eq. 7 is used for all the bed cells, the cohesion will be overpredicted for most of the reservoir. This leads to sediment deposits outside the vincinity of the weir channel, and this was not observed in the field data.

A third parameter found by Hillebrand et al (2017) to be important for the sediment deposition was the sediment transport formula, or the pick-up rate in Eq. 3. The default case in the current study was to use the formulas by van Rijn (1982). An alternative sediment transport formula was given by Engelund and Hansen (1967). Using this formula gave slightly different results, as shown in Table 6. The average deviation between the use of van Rijn's formulas and the Engelund-Hansen formula is 4 %. This is less than the deviation for the increase in the fall velocity, but larger than the deviation for the increased grid size.

Tables 2-6 also include the observed sediment deposition in the dredging periods. The difference between the observed values and the values computed by the default parameters is 10 %. This is more than the deviations in any of the parameter sensitivity tests. Although the measurements from the field have been done with considerable thoroughness and thought for detail, the field data will always have some uncertainty. The time series for sediment inflow in the current project were taken from values recorded downstream of the reservoir, and transferred to upstream values through a rating curve. This rating curve was based on measurements, but it also had some uncertainty. The authors believe the uncertainty in the inflowing sediment concentrations could easily be in the order of 20 %. This is therefore one of the main uncertainties of the current computation. The numerical model will never be able to predict the sediment deposition with a higher accuracy than the uncertainty in the sediment discharge flowing into the reservoir.

6. Conclusions

A numerical model is presented that has been used to compute the sediment deposition in 3D in a hydropower reservoir over an 11 year period with a reasonable computational time (18 hours on a PC for the coarse grid). The model is stable even though long time steps are used, that vary according to the water discharge. The effect of dredging is included in the model. Parameter tests show that the results are somewhat depending on the grid size and the fall velocity of the sediment particles (flocculation). The results are also dependent on the sediment transport formula. The good agreement with measurements and the reasonable computation time allow the model to be used for long-term projections of deposition and dredging volumes.

Acknowledgements

The authors would like to thank the German Waterways and Shipping Administration for providing the data for the current study.

References

Astor B, Gehres N, Hillebrand G (2014) From source to mouth, a sediment budget of the Rhine river: Grain size distribution of suspended sediment samples in the Rhine and its tributaries. BfG 1798. Bundesanstalt für Gewässerkunde, Koblenz. (In German)

Banhold K, Frings R, Schüttrumpf H (2017) Sediment budget of the High Rhine and Upper Rhine from Konstanz to Iffezheim. In: Hillebrand, G., & Frings, R. M. 2017. From source to mouth, the sediment budget of the Rhine river for the period 1991 – 2010. Report KHR/CHR

II-22. International Commission for the Hydrology of the Rhine basin, Lelystad. ISBN: 978-90-70980-39-9, DOI: 10.5675/KHR_22.2017, p. 42-67. (In German)

Brignoli M L, Espa P, Batalla R J (2017) Sediment transport below a small alpine reservoir desilted by controlled flushing: field assessment and one-dimensional numerical simulation. J Soil Sediment. doi:10.1007/s11368-017-1661-0.

Đordevic D (2013) Numerical study of 3D flow at right-angled confluences with and without upstream planform curvature. J Hydroinform. **15** (4) 1073-1088. DOI: 10.2166/hydro.2012.150.

Engelund F, Hansen E (1967) A monograph on sediment transport in alluvial streams. Teknisk Forlag, Copenhagen, Denmark.

Faghihirad S, Lin B, Falconer R A (2017) 3D Layer-Integrated Modelling of Morphodynamic Processes Near River Regulated Structures, Water Resources Management, 31**.** 443–460. doi:10.1007/s11269-016-1537-x.

Fang H-W, Rodi W (2003) Three-dimensional calculations of flow and suspended sediment transport in the neighborhood of the dam for the Three Gorges Project (TGP) reservoir in the Yangtze River, J Hydraul Res. 41(4), 379-394, doi:10.1080/00221680309499983.

Fenocchi A, Petaccia G, Sibilla S (2016) Modelling flows in shallow (fluvial) lakes with prevailing circulations in the horizontal plane: limits of 2D compared to 3D models, J. Hydroinform. 18 (6) 928-945; doi: 10.2166/hydro.2016.033.

Haun S, Kjærås H, Løvfall S, Olsen NRB (2013) Three-dimensional measurements and numerical modelling of suspended sediments in a hydropower reservoir. J Hydrol. 479, 180-188. doi: 10.1016/j.jhydrol.2012.11.060.

Haun S, Olsen NRB (2012) Three-dimensional numerical modelling of reservoir flushing in a prototype scale, Int J River Basin Management, 10(4) 341-349. DOI:10.1080/15715124.2012.736388.

Hillebrand G (2014) Sediment analysis of drill core samples from the IKSR investigation of the reservoirs in the Upper Rhine from the years 2000 to 2002. KLIWAS-Report series, KLIWAS-56/2014, pp. 63. Bundesanstalt für Gewässerkunde, Koblenz. (In German)

Hillebrand G, Otto W, Vollmer S (2012) Findings from ADCP-measured flow velocities and suspended sediment concentrations at the Upper Rhine. 2nd IAHR Europe Conference, Munich, Germany.

Hillebrand G, Klassen I, Olsen NRB (2017) 3D CFD modelling of velocities and sediment transport in the Iffezheim hydropower reservoir, Hydrol Res. 48(1), 147-159. doi: 10.2166/nh.2016.197.

Jia D-D, Shao X, Zhang X, Ye Y (2013) Sedimentation Patterns of Fine-Grained Particles in the Dam Area of the Three Gorges Project: 3D Numerical Simulation. J Hydraul Eng. 139(6), 669-674. doi: 10.1061/(ASCE)HY.1943-7900.0000709.

Launder BE, Sharma BI (1974) Application of the Energy Dissipation Model of Turbulence to the Calculation of Flow Near a Spinning Disc. Lett Heat Mass Trans. 1(2), 131-138. doi:10.1016/0094-4548(74)90150-7.

Mahmood K (1987) Reservoir Sedimentation: Impact, Extent and Mitigation. World Bank Technical Paper 71, Washington, DC.

Mirbach S, Lang U (2017) Density-driven underflows with suspended solids in Lake Constance, J Soil Sediment. doi:10.1007/s11368-017-1753-x.

Noack M, Hillebrand G, Seidenkranz U, Wieprecht S (2016) Investigation of erosion stability of cohesive sediment deposition in the spillway channel of the Iffezheim barrage at the Rhine river. Hydrologie und Wasserbewirtschaftung, 60.2016(3), 164-175. doi: 10.5675/HyWa_2016,3_1 (In German)

Olsen NRB (2015) Four free surface algorithms for the 3D Navier-Stokes equations, J Hydroinform. 17(6), 845-856. doi: 10.2166/hydro.2015.012.

Papanicolaou AN, Elhakeep M, Krallis G, Prakash S, Edinger J (2008) Sediment Transport Modeling Review—Current and Future Developments, J Hydraul Eng. 2008, 134(1): 1-14. doi:10.1061/(ASCE)0733-9429(2008)134:1(1).

Patankar SV (1980) Numerical Heat Transfer and Fluid Flow, McGraw-Hill Book Company, New York. ISBN 9780891165224.

Pohlert T, Hillebrand G, Breitung V (2011) Trends of persistent organic pollutants in the suspended matter of the River Rhine. Hydrol Process. 25, 3803–3817. doi:10.1002/hyp.8110.

van Rijn LC (1984a) Sediment transport. Part II: suspended load transport. J Hydraul Eng, 110(11), 1613–1641. doi:10.1061/(ASCE)0733-9429(1984)110:11(1613).

van Rijn LC (1984b) Sediment transport. Part I: bed load transport. J Hydraul Eng, 110(10), 1431–1456. doi: 10.1061/(ASCE)0733-9429(1984)110:10(1431)

Ruether N, Singh JM, Olsen NRB, Atkinson E (2005) Three-dimensional modelling of sediment transport at water intakes. Proceedings of the Institution of Civil Engineers, UK, Water Management, 158, 1-7. doi: 10.1680/wama.158.1.1.62452.

Shields A (1936) Use of dimensional analysis and turbulence research for sediment transport, Preussen Research Laboratory for Water and Marine Constructions, publication no. 26, Berlin (in German).

Schlichting H (1979) Boundary Layer Theory. McGraw-Hill Book Company, New York. ISBN 978-3-662-52919-5.

Stamou A, Gkesouli A (2015) Modeling settling tanks for water treatment using computational fluid dynamics, J Hydroinform, 17(5) 745-762; doi: 10.2166/hydro.2015.069

Thapa BS, Dahlhaug OG, Thapa B (2017) Sediment erosion induced leakage flow from guide vane clearance gap in a low specific speed Francis turbine, Renewable Energy, 107, 253-261. doi: 10.1016/j.renene.2017.01.045.

Tritthart M, Gutknecht D (2007) 3-D computation of flood processes in sharp river bends, Proceedings of the Institution of Civil Engineers – Water Management, 160(4), 233-247. doi:10.1680/wama.2007.160.4.233.

Vidmar J, Zuliani T, Novak P, Drinčić A, Ščančar J, Milačič R (2017) Elements in water, suspended particulate matter and sediments of the Sava River, J Soil Sediment. 17:1917–1927. DOI 10.1007/s11368-016-1512-4.

Winterwerp JC, van Kesteren WGM (2004) Introduction to the physics of cohesive sediment in the marine environment. Elsevier, ISBN 978-0-444-51553-7.

Zanke U (1977) Computation of fall velocities for sediments, Mitteilungen des Franzius-Instituts für Wasserbau und Küsteningenieurwesen der TU Hannover, Vol. 46. (In German)

Zhang Q, Hillebrand G, Hoffmann T, Hinkelmann R (2017) Estimating long-term evolution of fine sediment budget in the Iffezheim reservoir using a simplified method based on classification of boundary conditions, Geophysical Research Abstracts
Vol. 19, EGU2017-9039, EGU General Assembly 2017

Zinke P, Olsen NRB, Bogen J (2011) 3D numerical modeling of levee depositions in a Scandinavian freshwater delta, Geomorphology, 129, 320-333. doi: 10.1016/j.geomorph.2011.02.027.

Tables

Table 1: Sediment data by size fractions

Size number	Diameter (mm)	Fall velocity (m/s)
1	20	0.57
2	3	0.22
3	1.3	0.14
4	0.4	0.055
5	0.13	0.005
6	0.04	0.0011
7	0.02	0.00027
8	0.005	0.000017
9	0.002	0.0000027

Table 2. Measured and computed dredged sediment volume in m^3 for the three dredging operations.

Period	Measured	Computed
Sept 2000 - Mar 2001	354 000	334 000
Nov 2003 - Mar 2004	105 000	126 000
Jan 2005 - Sept 2005	290 000	294 000

Table 3. Computed and measured sediment depositions (m^3) in the dredging periods, using a fine and a coarse grid.

Period	Computed Coarse grid	Computed Fine grid	Deviation (%)
Sept 2000 - Mar 2001	334 000	328 000	2
Nov 2003 - Mar 2004	126 000	126 000	0
Jan 2005 - Sept 2005	294 000	307 000	4

Table 4. Computed and measured sediment depositions (m^3) in the dredging periods, using a normal and increased fall velocity of the finest particles.

Period	Computed default	Computed Increased fall velocity	Deviation (%)
Sept 2000 - Mar 2001	334 000	347 000	4
Nov 2003 - Mar 2004	126 000	143 000	13
Jan 2005 - Sept 2005	294 000	329 000	11

Table 5. Parameter test on increase in critical bed shear stress of 0.1 Pa

Period	Computed default	Computed Increased τ_c	Deviation (%)
Sept 2000 - Mar 2001	334 000	337 000	1
Nov 2003 - Mar 2004	126 000	146 000	15
Jan 2005 - Sept 2005	294 000	336 000	13

Table 6. Sediment deposition (m^3) in the dredged periods for different sediment transport formulas.

Period	Computed van Rijn	Computed Engelund-Hansen	Deviation (%)
Sept 2000 - Mar 2001	334 000	333 000	-0.3
Nov 2003 - Mar 2004	126 000	130 000	3
Jan 2005 – Sept 2005	294 000	280 000	-5

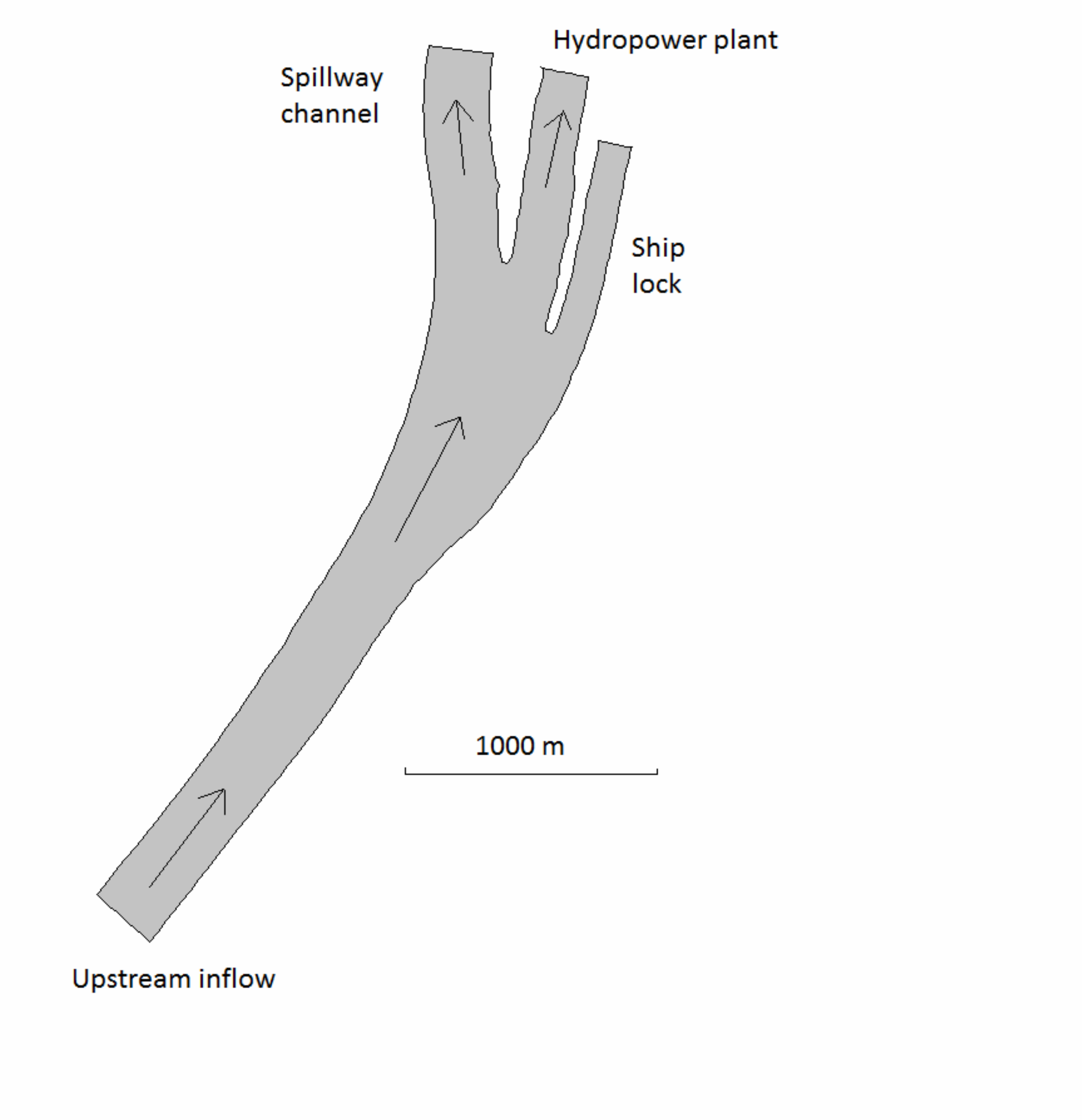

Figure 1. Plan view of the Iffezheim reservoir. The arrows show the flow direction.

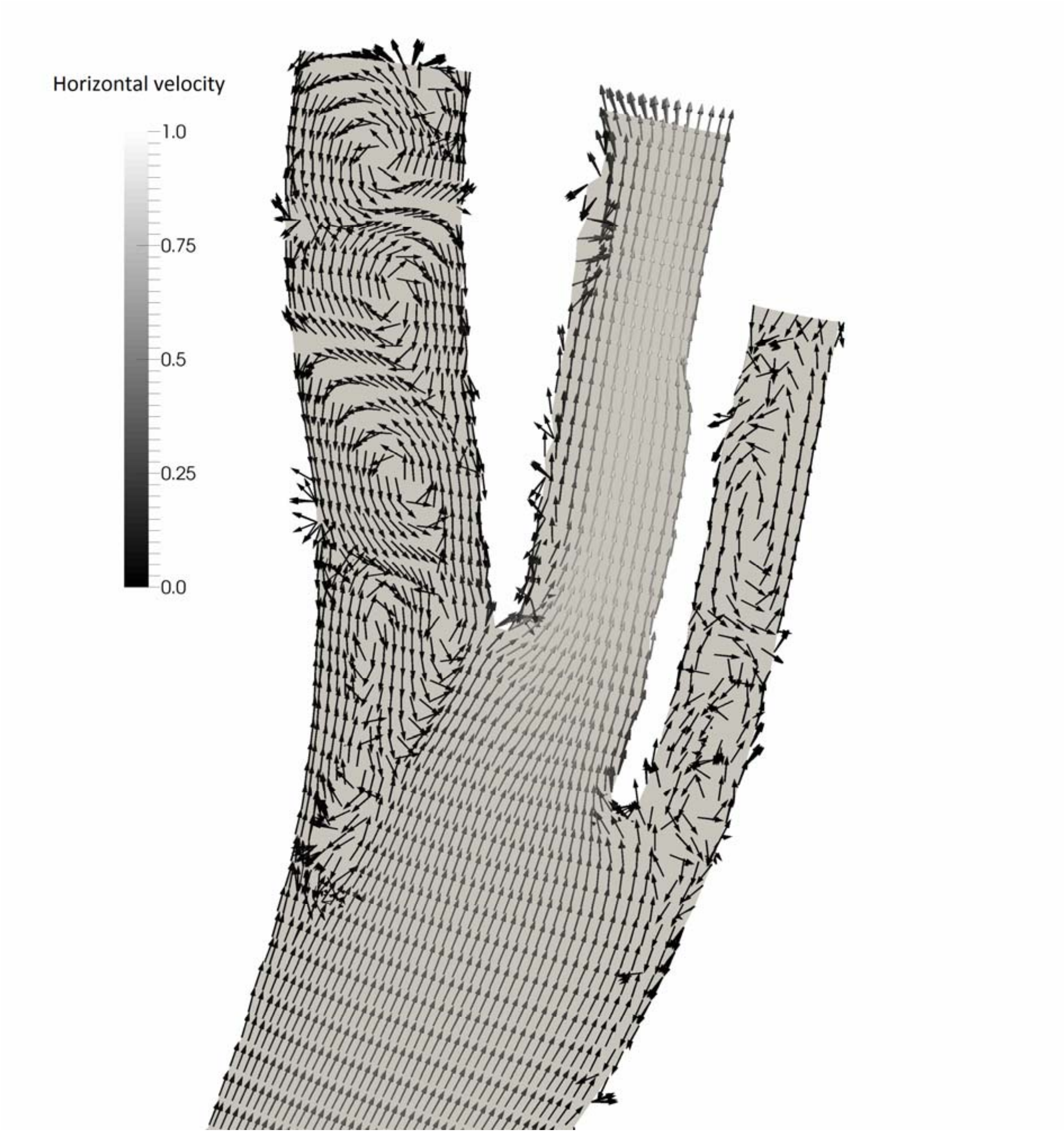

Figure 2. Velocity vectors close to the water surface in the area around the spillway channel during low discharge. Note that the velocity magnitude is given by the grayshading scale of the vectors, and not by their lengths.

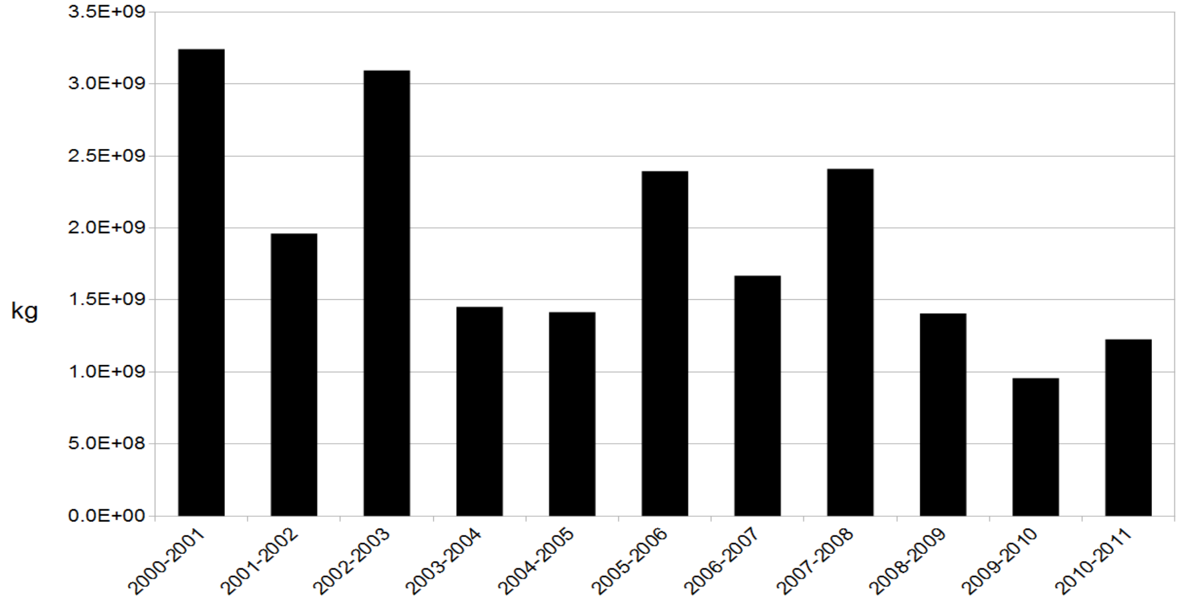

Figure 3 Annual sediment inflow into the Iffezheim reservoir during the computed time period, used as boundary condition for the numerical model.

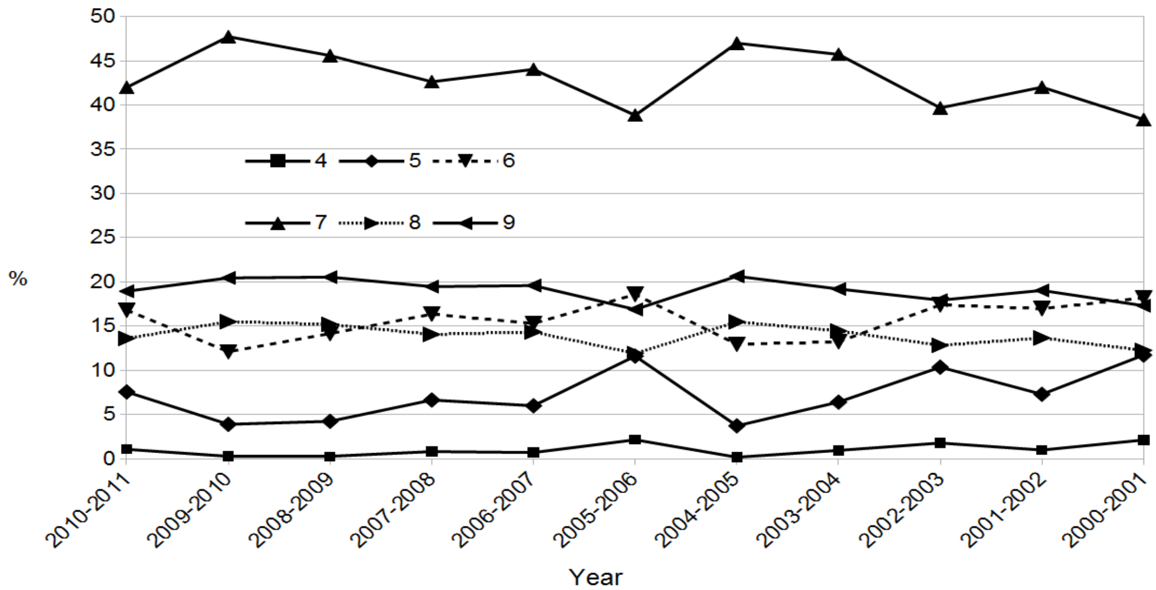

Figure 4. Annual variation of the percentage for each fraction (4-9) in the sediment inflow to the Iffezheim reservoir from 2000-2011. The information is used as upstream boundary condition for the numerical model.

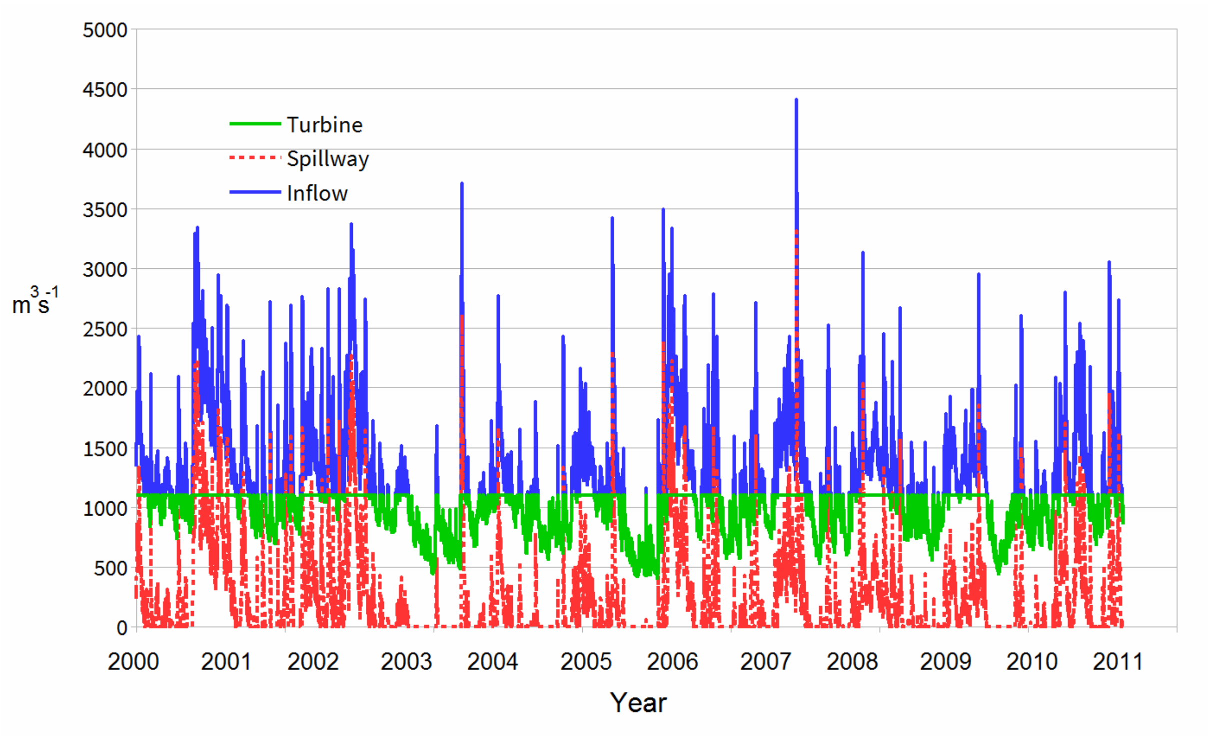

Figure 5. Time series of observed water discharges from the years 2000-2011.

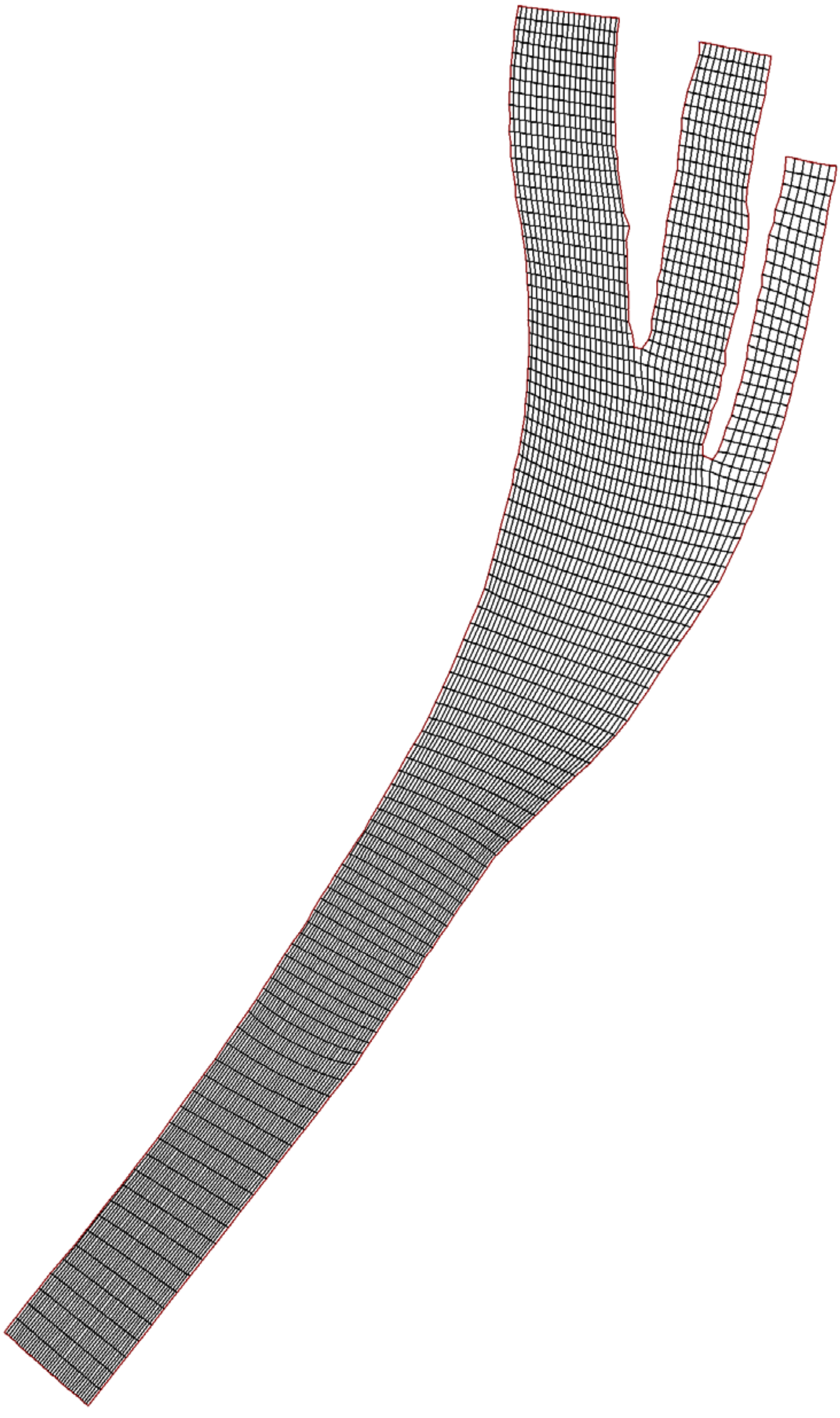

Figure 6. The coarse grid seen from above.

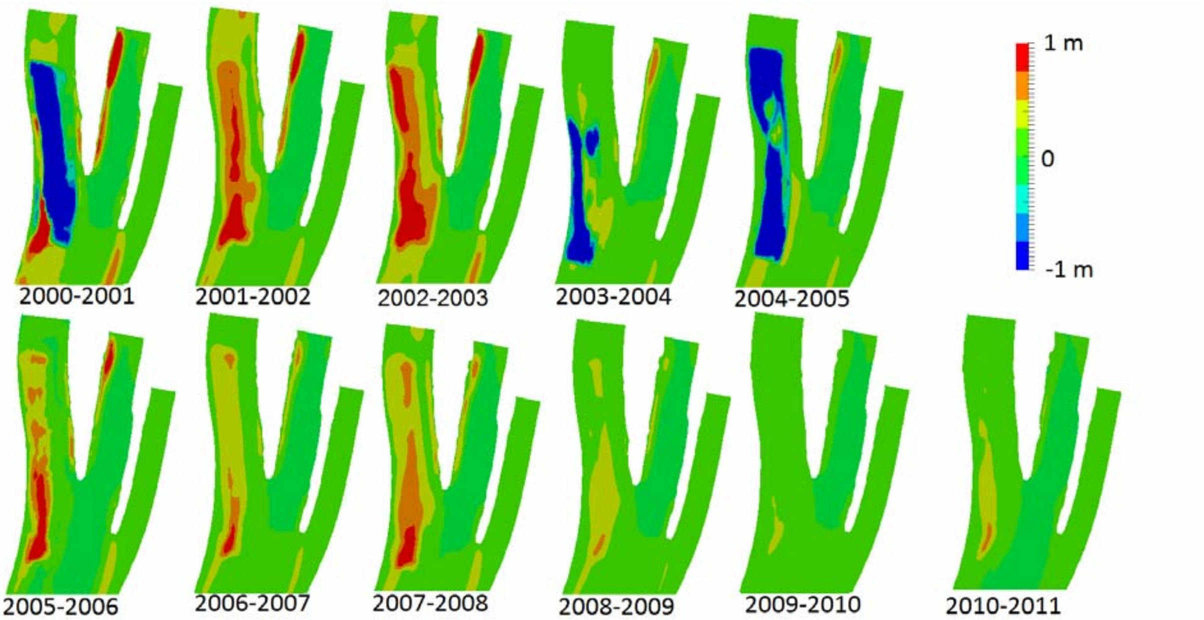

Figure 7. Computed sediment deposition in the Iffezheim reservoir for the years 2000-2011. The eroded areas (negative) are due to dredging.

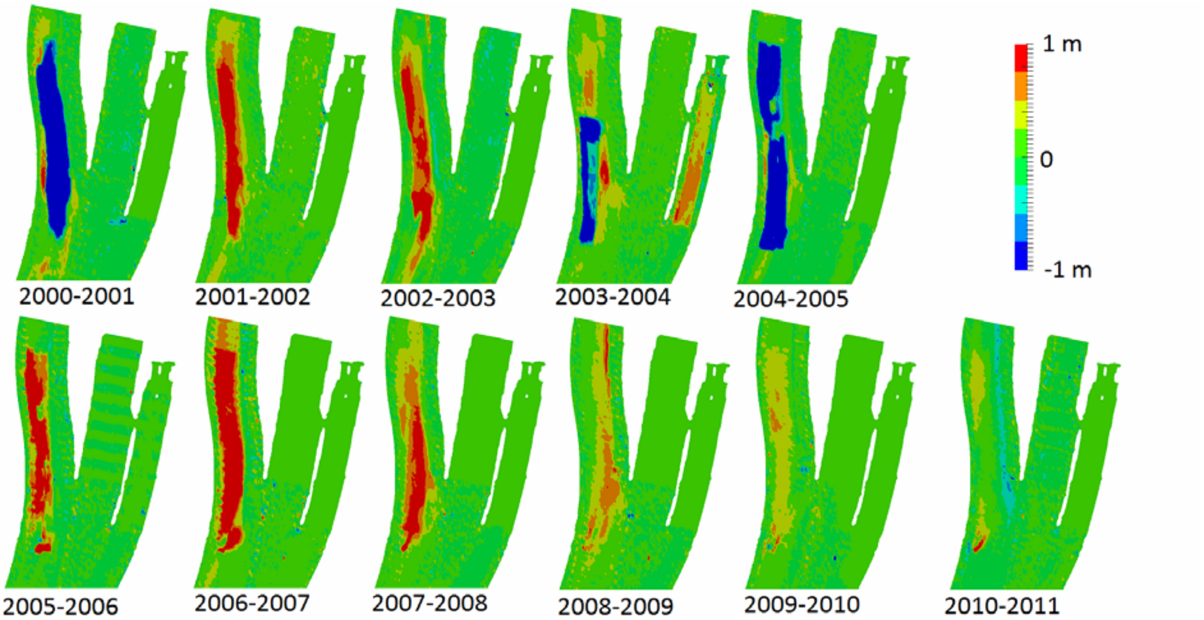

Figure 8. Measured sediment deposition in the Iffezheim reservoir for the years 2000-2011. The eroded areas (negative) are due to dredging.

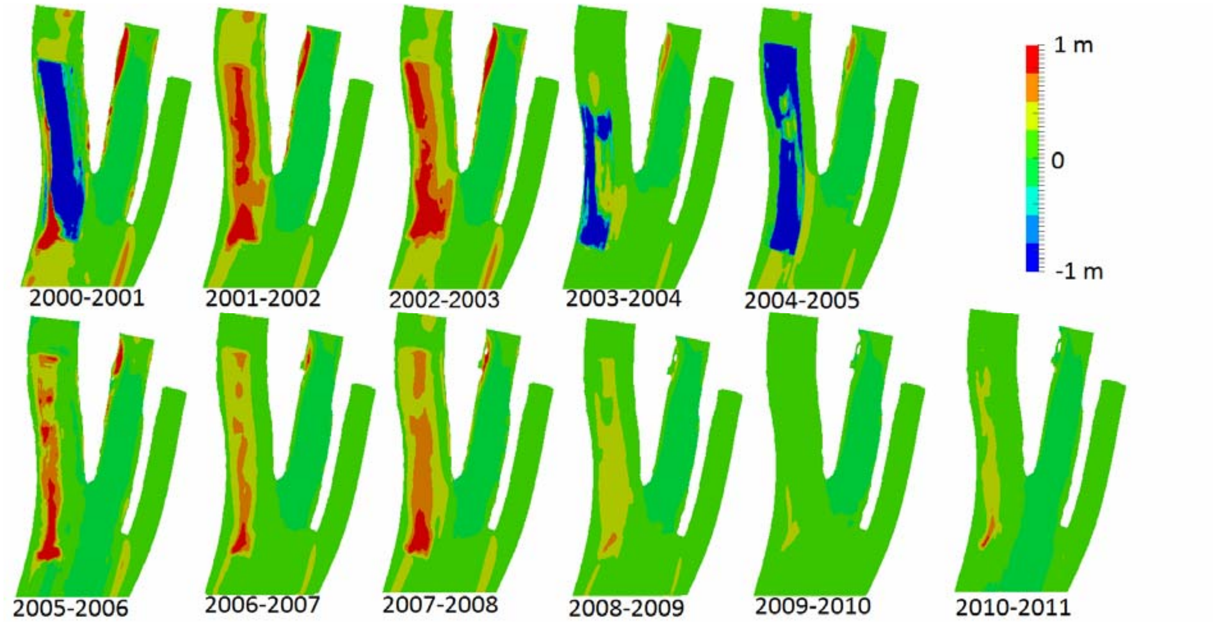

Figure 9. Computed sediment deposition in the Iffezheim reservoir for the years 2000-2011 using the fine grid. The eroded areas (negative) are due to dredging.