3D NUMERICAL MODELLING OF THE RESERVOIR FLUSHING OF THE BODENDORF RESERVOIR, AUSTRIA

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Abstract

The Bodendorf reservoir is located in the province of Styria in Austria. The high sedimentation rate of about 4 % per year decreased the reservoir volume from 900.000 m^3 to 300.000 m^3 in only 12 operation years. To reduce the high amount of deposited sediments, a first reservoir flushing was carried out in 1994. Since the first flushing a more or less frequently reservoir flushing was established. Through the Interreg IIIb project ALPRESERV a detailed study of the flushing event in 2004 was conducted. The recorded bathymetry data, water levels, discharge rates and the measured grain size distributions at the bed were used as boundary condition for a flushing simulation. The used numerical model solves the Reynolds-averaged Navier-Stokes equations in three-dimensions. The turbulence is simulated by the standard k-ε model and the pressure is computed accordingly to the SIMPLE method. The program uses an adaptive and unstructured grid which moves during the computation with changes in the bed and water levels. The suspended sediment transport is calculated by solving the convection-diffusion equation and the bed-load transport by the empirical formulas from Meyer-Peter Müller and van Rijn. Bed forms are taken into account in the study by an empirical formula from van Rijn. The presented results of the simulation show agreement in the amount of flushed out sediments. A comparison of the measured and simulated cross sections after the flushing is given in this study. This comparison also shows the sensitivity of the results in relation to different bed-load transport formulas.

Introduction

Reservoir sedimentation is one of the challenges in dam engineering today (Scheuerlein, 1990). Due to the construction of artificial barrages in rivers the alluvial balance is highly affected. Small flow velocities in reservoirs result in depositions and create a sedimentation problem. These accumulations decrease the reservoir volume and so also the available the amount of water for irrigation purposes or producing electricity (Morris and Fan, 1998). Also the lifetime of the reservoir may be reduced by sediment depositions, which represents an economic impact and should be taken into account in early design studies. The severity problem is not uniform distributed over the world. It depends on the hydrology, the geology and the land use in the basin (White and Bettness, 1984). Different approaches, like the use of soil control measure, are in use to minimize the sediment yield from the watershed (Shen, 1999). However, a sediment inflow into the reservoir could never be avoided completely (Scheuerlein, 1990). An often used method for reducing the sediment accumulations in reservoirs is reservoir flushing. During the flushing the water level is drawn down to a level so that free flow conditions occur. The high velocities and an increased bed shear stress initiate the erosion process in the reservoir. The effectiveness of a flushing depends on existing low level outlets and the possibility to ensure the excess runoff from the basin for a period with free flow conditions (White and Bettness, 1984). The performance depends also on the handling of ecological aspects. To avoid impacts on the downstream region, limitations of the minimum oxygen amount and the maximum suspended sediment concentration are most time specified for the flushing.

A special challenge is the flushing of mountain reservoirs, like the Bodendorf reservoir in Austria. This is because of the high amount of coarse material, which settles in the entrance area of the reservoir. During the flushing process this material can erode and settle further downstream in the reservoir (Scheuerlein, 1990).

An accurate prediction of the efficiency of an upcoming flushing is important information for designer and owner of reservoirs. The use of only theoretical approaches is problematic because of the complex mechanisms and the huge amount of involved parameters (Scheuerlein, 1990). An alternative for predictions can be a numerical investigation. Numerical models are more and more

common in river engineering because of a time and cost reduction compared to physical model studies (Gessler and Rasmussen, 2005; Chandler et al., 2003). Previous work in this field was done by Lai and Shen (1996) with a one-dimensional diffusion model for estimating the general trend of the bed evaluation. A two-dimensional model was used for simulating the flushing of the Kali Gandaki reservoir (physical model study) by Olsen (1999). An example for the successful use of a three-dimensional approach is the simulation of the sediment transport in the Three Gorges project by Fang and Rodi (2003).
For this study the Bodendorf reservoir in Austria is chosen. Especially run-of-river power plants, like the Bodendorf reservoir, are highly influenced by sediment deposition (Wu, 2008). A detailed study of the 2004 flushing was carried out in the Interreg IIIb project ALPRESERV for a sustainable sediment management of alpine reservoirs considering ecological and economical aspects. In addition to the analysis of the amount of flushed out sediments, cross section measurements were performed before and after the flushing to get better knowledge about the areas of erosion. Because of this, data with high quality and quantity are available for the computation. Also CFD was involved in this project. Badura (2007) used a commercial two-dimensional approach and presented good agreement between the measured bed level changes and the simulated ones. For the current numerical study bathymetry data, grain sizes, discharge rates and water levels from the 2004 flushing were used. The simulated results were compared with the measured data to show flushing effects, like the erosion pattern in three cross sections. Two different empirical bed-load transport formulas were used to show the dependency of the results related to the used equation.

Site description and Input data

The Bodendorf hydropower plant is located at the river Mur in the province of Styria in Austria. It is designed as run-of-river power plant with a drainage area of about 1,360 km^2 and a capacity of 7.5 MW. The reservoir has a length of about 2.5 km and is due to an average width of only 40 m relatively narrow (Knoblauch et al., 2005). The reservoir had a designed volume of about 900,000 m^3 in 1982. After 12 years of operation about 600,000 m^3 of the reservoir was filled with sediments. So the average deposition is about 35,000 m^3 per year, which represents a sedimentation rate of 4 % of the reservoir volume per year. The amount of flushed out sediments was 47,300 m^3 in 2004, where around 31,500 m^3 were flushed out as bed-load (Badura et al., 2006). This represents a special challenge for the numerical model, where the bed-load transport is simulated by an empirical formula. The grain size distributions show a large variation along the reservoir. The d_{50} at the entrance of the reservoir was 32 mm were in front of the weir the d_{50} showed a value of 1.5 mm. The density for the deposited sediment was 2.55 g/cm^3 (Badura, 2007).
During the flushing a minimum discharge of 80 m^3/s is required to increase the bed shear stress so that the armoring layer breaks up and erosion starts (Knoblauch et al., 2005). The flushing of 2004 showed next to this a flood peak with a discharge of 134 m^3/s during the free flow conditions. The used discharge rates and water level changes at the weir are shown in Figure 1.

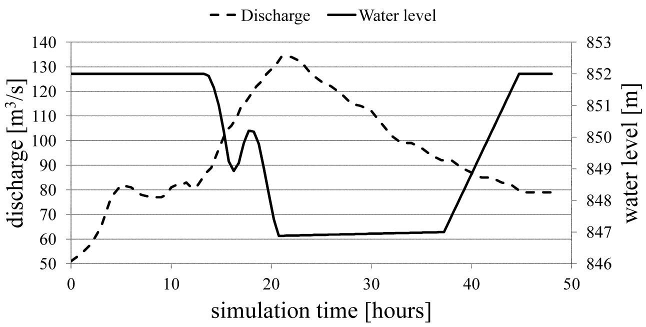

Figure 1: Discharge rates and water levels during the flushing

A detailed bathymetry survey was carried out before and after the flushing. This data is used for setting up the numerical model and for evaluating the amount of flushed out sediments. The bed geometry after the flushing was also used for comparisons of the areas where erosion happens.

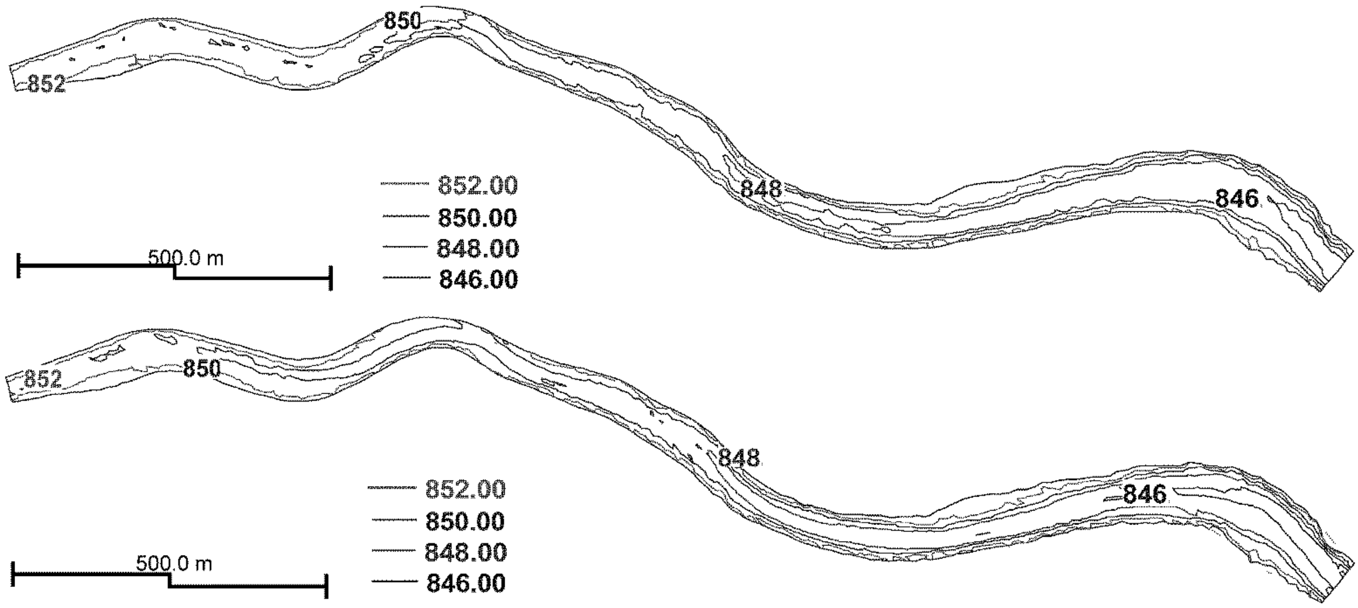

Figure 2: Bed geometry of the Bodendorf reservoir before the flushing (at the top) and after the flushing (below)

Numerical Model

The CFD code SSIIM was used for this study (Olsen, 2012). In SSIIM the RANS-equations are solved in three-dimensions together with the continuity equation to compute the flow field for turbulent flow (Versteeg and Malalasekera, 1995; equation 1 and 2).

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left(-P\delta_{ij} - \rho \overline{u_i u_j} \right) \tag{2}$$

with i= 1, 2, 3; where U_j is the averaged velocity, x is the spatial geometrical scale, ρ is the water density, P is the dynamic pressure, δ_{ij} is the Kronecker delta and $-\rho \overline{u_i u_j}$ are the turbulent Reynolds stresses.

As discretication scheme the finite-volume method is used together with a first order upwind scheme (Olsen, 2012). The turbulent Reynolds stresses are calculated by the k-ε model (Launder and Spalding, 1972) and the unknown pressure field is computed by the SIMPLE method (Patankar, 1980). The sediment transport in SSIIM is modelled for multiple sediment sizes, where the suspended sediment transport is modelled by solving the convection-diffusion equation (equation 3).

$$\frac{\partial c}{\partial t} + U_j \frac{\partial c}{\partial x_j} + w \frac{\partial c}{\partial z} = \frac{\partial}{\partial x_j} \left(\Gamma \frac{\partial c}{\partial x_j} \right) \tag{3}$$

where U is the water velocity, w is the fall velocity of the sediment, Γ is the turbulent diffusity and c is the sediment concentration over time t and over the spatial geometrical scales x and z.

For simulating the quantity of the bed-load transport, an empirical formula by van Rijn (1984a) was used as first approach (equation 4).

$$\frac{q_{b,i}}{d_i^{1.5} \sqrt{\frac{(\rho_s - \rho_w)\, g}{\rho_w}}} = 0.053 \frac{\left(\frac{\tau - \tau_{c,i}}{\tau_{c,i}} \right)^{2.1}}{d_i^{0.3} \left(\frac{(\rho_s - \rho_w)\, g}{\rho_w \nu^2} \right)^{0.1}} \tag{4}$$

where $q_{b,i}$ is the transport rate of the ith fraction of bed load per unit width, d_i is the diameter of the ith fraction, τ is the shear stress, $\tau_{c,i}$ is the critical shear stress for d_i which was calculated by an analytical form from the Shields curve, ρ_s is the density of the sediment, ρ_w is the density of the water, g is the acceleration of gravity and ν is the kinematic viscosity.

As an alternative bed-load transport formula the Meyer-Peter Müller formula was used (equation 5). This formula is recommended for rivers with steeper slopes and sediment transport mainly at the bed.

$$q_{b,i} = \frac{1}{g}\left[\frac{\rho_w g r I - 0.047 g(\rho_s - \rho_w) d_{50}}{0.25 \rho_w^{\frac{1}{3}} \left(\frac{\rho_s - \rho_w}{\rho_s}\right)^{\frac{2}{3}}}\right]^{\frac{3}{2}} \quad (5)$$

where $q_{b,i}$ is the transport rate of the total bed load per unit width, d_{50} is the characteristic sediment size, I is the slope of the energy line and r is the hydraulic radius.

Because of the influence of bed forms during the flushing, the bed roughness (k_s) was calculated by the numerical program as a combination of the grain-size distribution and the bed-form height (equation 6).

$$k_S = 3.0\, d_{90} + 1.1\Delta\left(1.0 - e^{\left(\frac{-25\Delta}{7.3y}\right)}\right) \quad (6)$$

where d_{90} is the characteristic sediment size, Δ is the bed-form height and y is the water depth.

The bed form height was predicted by an empirical formula (van Rijn, 1984c; equation 7).

$$\frac{\Delta}{y} = 0.11\left(\frac{d_{50}}{y}\right)^{0.3}\left(1 - e^{-0.5\left(\frac{\tau - \tau_{c,i}}{\tau_{c,i}}\right)}\right)\left(25 - \left(\frac{\tau - \tau_{c,i}}{\tau_{c,i}}\right)\right) \quad (7)$$

where d_{50} is the characteristic sediment size, τ is the shear stress and $\tau_{c,i}$ is the critical shear stress for each fraction.

In SSIIM an unstructured and adaptive grid is used. The adaptive grid moves accordingly to changes in the bed and water level. An algorithm for wetting/drying is implemented in the code, which allows a change of number of cells. The used algorithm removes dried up cells from the grid and generates new cells in areas which get wetted during the time depend simulation, so also lateral movements during the computation are possible. For calculating the fluxes and velocities for the non-staggered grid the Rhie and Chow (1983) interpolation is used. The free-water surface is simulated based on the computed pressure field (Olsen and Haun, 2010). An implicit time discretization is used.

Numerical Simulation of the Reservoir Flushing

Based on the existing bathymetry data, grids with a different number of cells were made for the computation domain. The chosen grid had 15,358 cells (Figure 3), and showed grid independent results. In the vertical direction a maximum number of 11 cells were selected. During the computation the number of cells decreases, because of the draw down of the water level, to 5,292. For the simulation a time step of 10.0 seconds was chosen. A zero gradient outflow boundary condition was set for the outflow and a Dirichlet boundary condition for the inflow. At the walls of the domain wall laws by Schlichting (1979) were used. Changes in the water level and discharge rates during the flushing were kept similar to Figure 1.

Due to changes of the grain size distribution along the reservoir a distribution at the weir and at the entrance of the reservoir was specified. Between these areas the grain sizes were linearly interpolated. Table 1 shows the grain sizes chosen at the weir and the entrance area with the corresponding fractions.

Table 1: In the simulation used grain sizes and fractions at the weir and at the entrance area of the reservoir

Grain Size [mm]	Fraction at the weir [%]	Fraction at the entrance of the reservoir [%]
100 - 72	5	25
72 - 52	5	20
52 - 36	10	15
36 - 24	10	15
24 - 11	10	10
11 - 6	20	10
6 - 3	15	3
3 - 1.5	15	1
1.5 - 0.5	10	1

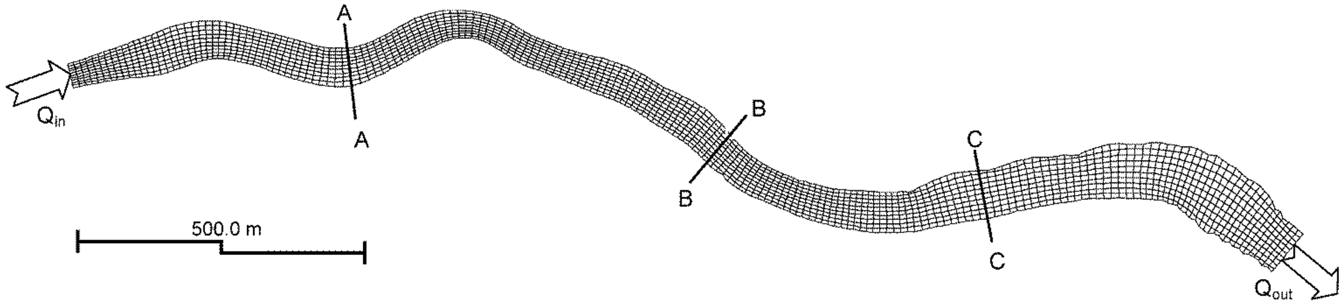

Figure 3: Grid for the flushing simulation with 15,358 cells and the cross sections A – C

Geotechnical failures are in the program taken into account by a sand slide algorithm. The angle of repose, used in this algorithm, was set to φ= 32 ° for this study. During the flushing simulation no sediment inflow was specified. The active sediment thickness was set to be 0.5 m. The roughness at the bed was set to 0.28 m.
The computation time for the flushing on two cores of the CPU (Intel Q9650 3.00GHz) was about 12 hours.

Results

In the presented study the number of flushed out sediments and the bed level changes after the flushing simulation were compared. Three cross sections (A-C; Figure 1) were presented to show the erosion pattern of the simulation (Figure 4 a-c).

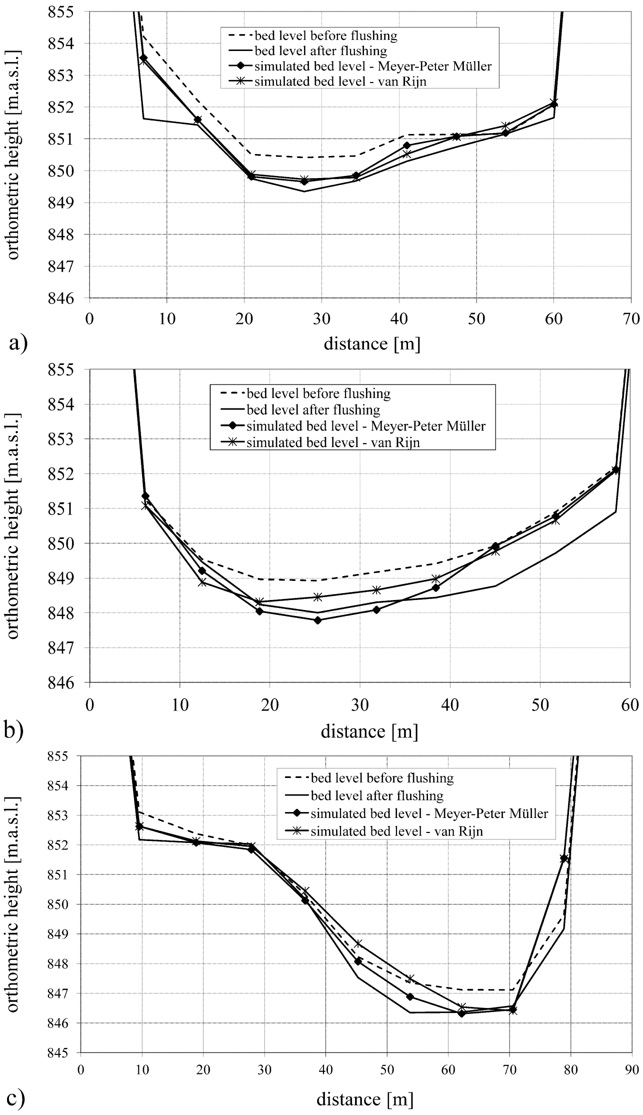

Figure 4: Bed level changes, measured and simulated with van Rijn and Meyer-Peter Müller bed-load transport formulas

The cross sections were chosen in different sections of the reservoir, where varying effects influence the computed erosion. It clearly can be seen that the erosion pattern in cross section A is similar compared with the measurements. However, the erosion is not as deep as measured for both used bed-load transport formulas. Cross section B shows that the erosion in the simulation occurs more at the outer site of the small bend. The measurements show a smaller influence of the secondary currents, and a more uniform erosion patter over the cross section. The results by using the Meyer-Peter Müller formula show better agreement in the shape and depth. Cross section C shows a distinctive channel, which is in the simulation too narrow compared with the measured one. In this cross section the total erosion is much smaller compared with the measurements. The total bed shear stress increases during the free flow condition to a maximum value of 50 N/m^2 in different sections of the reservoir and up to 22 N/m^2 in the area in front of the weir. However, during the simulation the sediment transport capacity in this area is at a maximum value for both formulas. So no additional sediments can be removed from the bed.
The observed bed forms during the flushing were not measured. The bed forms in the simulation show a height of around 1.5 m, which is probably overestimated. This could also influence the estimation of the secondary currents and the erosion pattern in the bends.
The calculated amount of flushed out sediments is in the same range as the measured ones. This is the result of an intensive calibration process. The most important factors are a correct distribution of the sediments and the fraction of compacted sediments in the bed. The difference in the used bed-load transport formulas by van Rijn (23,400 m^3) and the Meyer-Peter Müller formula (31,200 m^3) shows the advantage of using Meyer-Peter Müller for this case.

Conclusion

The numerical simulation of the 2004 reservoir flushing of the Bodendorf reservoir is presented in this study. Bathymetry data and collected field data were used for adjusting the model. The results show that the range of the amount of eroded sediments (47,300 m^3) can be better predicted with the formula from Peter-Meyer Müller (31,200 m^3) compared to the bed-load transport formula from van Rijn (23,400 m^3). However, the erosion pattern shows differences between the simulation and the measurements. Mainly the cross sections located in the downstream region of the reservoir show an irregular erosion pattern in the simulation. Both used empirical bed-load transport formula gave too little transport capacity in the downstream area of the reservoir, which results in too little erosion in this area. Coarse material, eroded in the inflow area of the reservoir, will in addition settle in the area in front of the weir. In areas where the reservoir shows slight bends, the program overestimates the secondary currents, which results in too deep erosion at the outside of the bend and into too less depth at the inner site of the bend. Field measurements are required to compare the angle of the secondary currents to the results derived by the model. The influence of the bed-load transport formula is also presented in the cross sections. Where the empirical formula by van Rijn is successfully used in previous works with the CFD code SSIIM, the Meyer-Peter Müller formula shows an advantage for this case. The equation is recommended for steeper rivers which transport mainly coarse sediments close to the bed. However, there is no unique formula available at the moment, which can be used for all cases. Further research work is required in allocating of bed-load transport formulas for specific cases.

The observed anti dunes highly influence the erosion rates of the numerical simulation for the flushing. Bed forms are in the numerical program taken into account by an empirical formula. During the flushing no measurements of the bed form heights or a wave length were possible. So it is not possible to compare the results regarding the bed form height of the simulation with field data. However, the numerical model is able to give a range of the amount of erosion for a prediction of an upcoming flushing.

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