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Comprehensive numerical simulations of sediment transport and flushing of a Peruvian reservoir

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ABSTRACT: Numerical modeling of sediment transport in reservoirs, especially for sudden events such as flushing, is still a challenging research topic. In the present study, sediment transport and sediment flushing are simulated for a Peruvian reservoir. Situated in the Peruvian Andes, the watershed is affected by high erosion rates and the river carries high amounts of suspended sediment whose estimated annual volume is about 5 Million m^3. This study aims to investigate the reservoir sedimentation using different numerical models. A one-dimensional (1D) sediment transport model, a horizontal two-dimensional (2D) hydraulic model and a vertical 2D model are used for this purpose. Annual sedimentation, full drawdown flushing, and sediment concentration in power intakes are particularly investigated.

1 INTRODUCTION

The present study aims to investigate the reservoir sedimentation aspects by means of numerical simulations. The main purpose is to provide a state of knowledge that can be used later for reservoir sedimentation management. Atkins (1996) developed a technical model for flushing which quantifies aspects of reservoirs that are likely to be successful in flushing at complete drawdown. However, numerical simulations have been used to assess reservoir sedimentation for the last two decades.

Olsen (1999) reproduced the main features of the erosion pattern using a two-dimensional numerical model simulating flushing of sediments from water reservoirs that solves the depth-averaged Navier-Stokes equations on a two-dimensional grid. A 2D horizontal model was used by Bessenasse et al. (2003) for a reservoir in Algeria in which sediment was modeled by concentration thanks to advection-diffusion modelling. Harb et al. (2012) presented the application of TELEMAC-2D numerical model for an Alpine reservoir in Austria. Leite et al. (2005) and Möller et al. (2011) applied a three-dimensional numerical model (FLOW-3D) to study pressurized sediment flushing and respectively sediment management in reservoirs.

2 PROJECT AREA AND SPECIFICATIONS

The studied dam is situated in the Peruvian Andes, where the watershed of the project is located in the eastern side of the Andes. Therefore, the flowing water released after several hundreds of kilometers in the Amazonian area is affected by high erosion rates and carries high amounts of suspended sediment.

The hydrology and sedimentology of the catchment need to be fully understood in the planning of flushing facilities for new or existing reservoirs and to provide the background for analyses of past sedimentation and flushing performance. As such, a brief list of the most important parameters is presented hereafter.

2.1 *Catchment data*

The watershed area of the reservoir is 28’096 km². The reservoir length is 10.2 km with an average river slope of 0.7% at the dam site. A brief list of the most important catchment data is presented in Table 1.

Based on the catchment data and reservoir capacity presented in Table 1 and according to the World Bank experience (Palimieri et al., 2003) for the studied reservoir, where the storage capacity is about 0.5% of the mean annual river run-off, the most adapted remedial measure for this project is regular full drawdown flushing. White (2001) also mentioned that flushing is vital for the preservation of long-term storage where the sediment deposition potential is greater that 1–2% annually of the original capacity, which is the case in the present study.

2.2 *Hydrological and sediment data*

Daily flow data are available over 46 years with important gaps. The annual mean daily flow is 270 m³/s. The mean daily flow over one year is shown in Figure 1.

In addition, the concentration of suspended load is defined as a function of discharge for each month of the year. The relationship ($Q_s = a \cdot e^{b \cdot Q_W}$) gives the suspended load concentration, Q_s, as a function of water discharge, Q_w, where a and b parameters for each month are given. The sediment data for both bed load and suspended load is presented in Table 2.

Table 1. Watershed data.

Reservoir capacity [million m³]	37
Annual flow [million m³]	7900
Total annual sediment yield [million m³]	5.0
Annual bed load yield [million m³]	1.7
Annual suspended load yield [million m³]	3.3

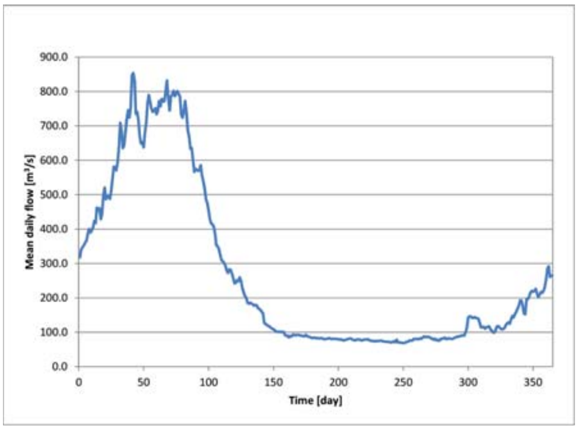

Figure 1. Mean daily flow.

Table 2. Sediment data.

Diameter	Bed load	Suspended load
D_{50} [mm]	24	0.05
D_{90} [mm]	87	0.09

Table 3. Geometric data of the dam.

Dam bed level elevation [m asl]	1480.0
Bottom outlet sill level [m asl]	1495.0
Power intake sill level [m asl]	1526.0
Normal water elevation [m asl]	1556.0
Dam crest elevation [m asl]	1560.1
Bottom outlet number [m asl]	6
Bottom outlet dimensions [m]	Height 6.0; width 4.6

2.3 *Dam geometry data*

For effective full drawdown flushing, the bottom outlets must be low enough and of sufficient capacity to allow a natural flow through the dam. Some geometrical properties of the dam are summarized in Table 3.

3 METHODOLOGY

To understand and evaluate the reservoir sediment management, several numerical models have been used. A one dimensional model (HEC-RAS) is firstly used to define the bed load and suspended load transport over long time periods up to 5 years. In a second step, a two dimensional horizontal hydraulic model (BASEMENT, with averaged values over the depth) is applied for short term simulations of flushing events. By calculating the hydraulic capacity of the bottom outlets, the bed-level shear stress and consequently flushing efficiency is computed. The horizontal 2D model also helps to assure the lateral flow homogeneity and justify the use of a two dimensional vertical model. Finally, the vertical two-dimensional model (CE-QUAL-W2) provides the suspended sediment concentration evolution in the reservoir and brings up the suspended sediment concentration in water intakes for the power plant.

4 ANNUAL SEDIMENTATION

The well-known HEC-RAS model is used to perform a mobile bed sediment transport analysis in the entire reservoir for different long term scenarios. Current sediment capabilities in HEC-RAS are based on a quasi unsteady hydraulic model. The quasi-unsteady approach approximates a flow hydrograph by a series of steady flow profiles associated with corresponding flow durations. The sediment transport equations are then solved for each time step.

4.1 *Geometry and parameters of the model*

The model is built with sections at a distance of 10 m over the 10.2 km length of the reservoir. The Manning roughness coefficient, n, is equal to 0.05 $s/m^{1/3}$.

In HEC-RAS model, a transport function model needs to be selected by the user. Sediment transport results are strongly dependent on which transport function is selected. Usually when measurements are available, the proper function can be choosen in the model calibration step. In the present study, several functions are tested. Considering the range of assumptions, hydraulic conditions, and grain sizes, the Toffaleti (Tofaletti, 1968) function is selected. Tofaletti appears to be the most addapted function for modeling suspended load and for the range of grading.

4.2 *Boundary conditions and transport function*

To define the bed load transport capacity as a function of water discharge, different relationships such as modified Meyer-Peter & Müller (MPM) (Meyer-Peter & Müller, 1948), modified MPM (Wong & Parker, 2005) and Smart-Jäggi (1983) are compared. For this purpose a representative section of the river upstream of the reservoir is selected and the solid transport capacity is calculated over a year with a daily time step. The water flow is the mean daily flow. The total bed load sediment volume in one year is then calculated and compared with the 1.7 Mm^3 of expected bed load. The modified MPM method by Parker gives a total annual bed load of 1.69 Mm^3 and is therefore chosen. In addition, the MPM method is the most well suited for the range of slopes in the Mantaro River and the sediment grading.

4.3 *Results*

The HEC-RAS model is firstly used to model sediment transport over a mean year. For this purpose the model is run two times, once for the bed load and once for the suspended load. The upstream flow boundary conditions is the flow series with daily values. At downstream, a fixed water elevation equal to the normal water elevation of the dam is considered. The upstream sediment boundary condition is specified as sediment load series for the uppermost section.

As it can be expected, the bed load forms a delta at the entrance of the reservoir. Due to the grain size and the low velocities in the reservoir, the delta cannot move forward downstream and the material accumulates at the upstream limit of the model. However, the suspended material remains on suspension while entering the reservoir and settles down in the its middle.

The simulations start on October 1st and end on September 30th of the next year. As it can be seen in Figure 2 the deposition starts on January and continues over the wet season until end of April. From April to September, during the dry season, the sediment yield is negligible and there is no more deposition in the upper part of the reservoir. However, minor erosions can occur on the upper part of the deposited delta and produce a small amount of material moving downstream.

To better illustrate the same results, a plan view of deposition zones is shown in Figure 3. No sedimentation happens for the first 2’300 m of reservoir upstream. Then the deposited layer height increase to 8.9 meters at a distance of about 6’000 m from the dam. The deposition thickness reduces then to 2 m behind the dam.

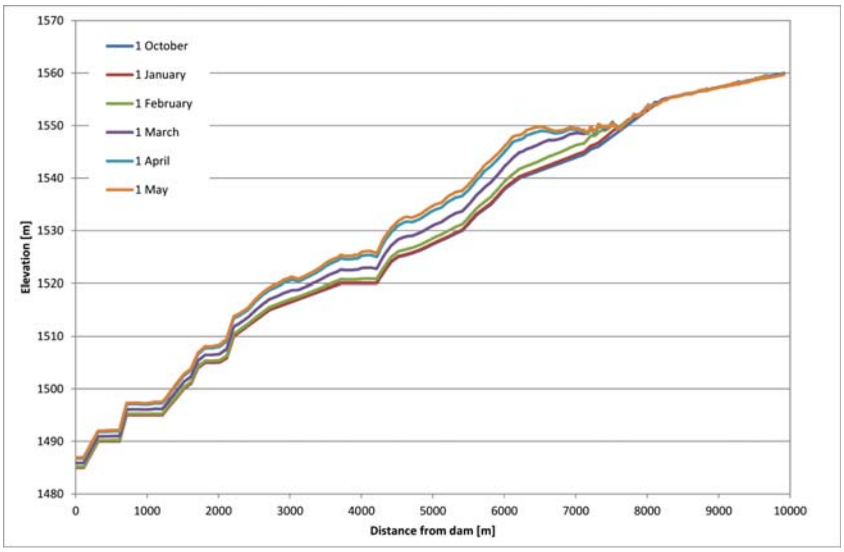

Figure 2. Suspended load deposition during one year (reservoir normal water elevation 1556 m asl).

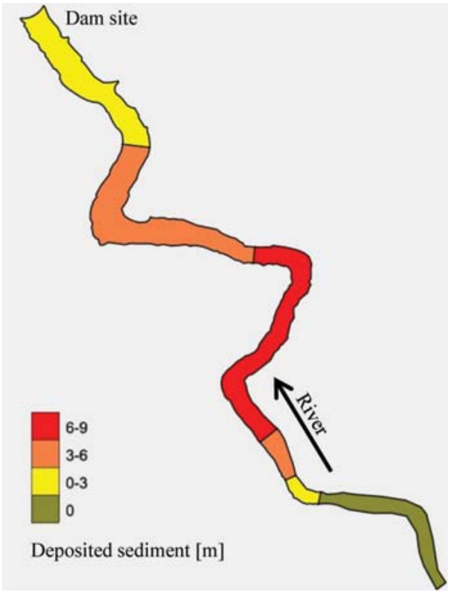

Figure 3. Suspended load deposition zones after one year.

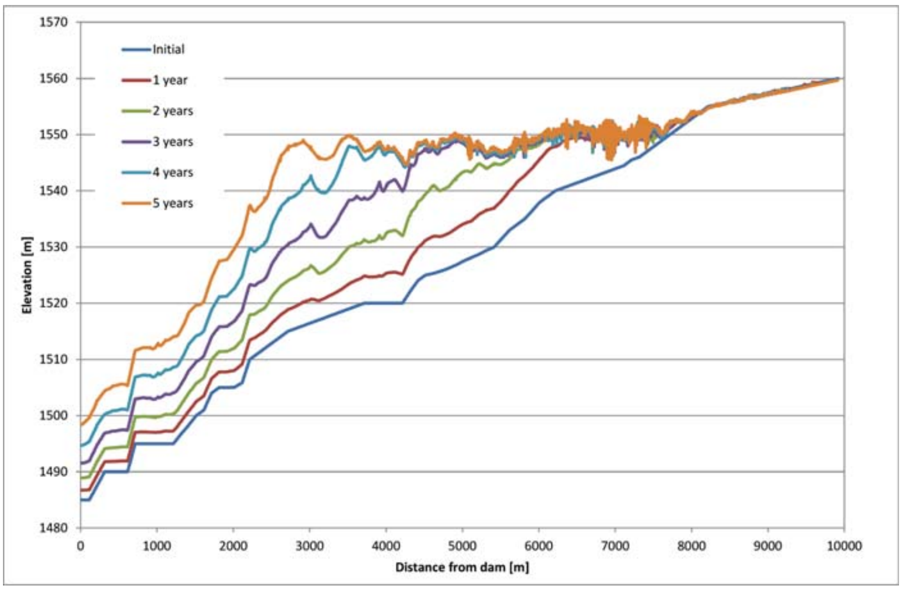

Figure 4. Suspended load deposition during five years (reservoir normal water elevation 1556 m asl).

For the long term deposition, a simulation is carried out over five years. The results are plotted in Figure 4. It is shown that the deposited delta moves on downstream by 2 km each year. A removal measure then seems crucial as the reservoir loses more than half of its capacity in only five years. Figure 5 shows the bed level evolution during 5 years just behind the dam (5 m upstream). As it is shown, during wet seasons high amounts of sediments are deposited behind the dam, whereas for dry seasons there is no deposition.

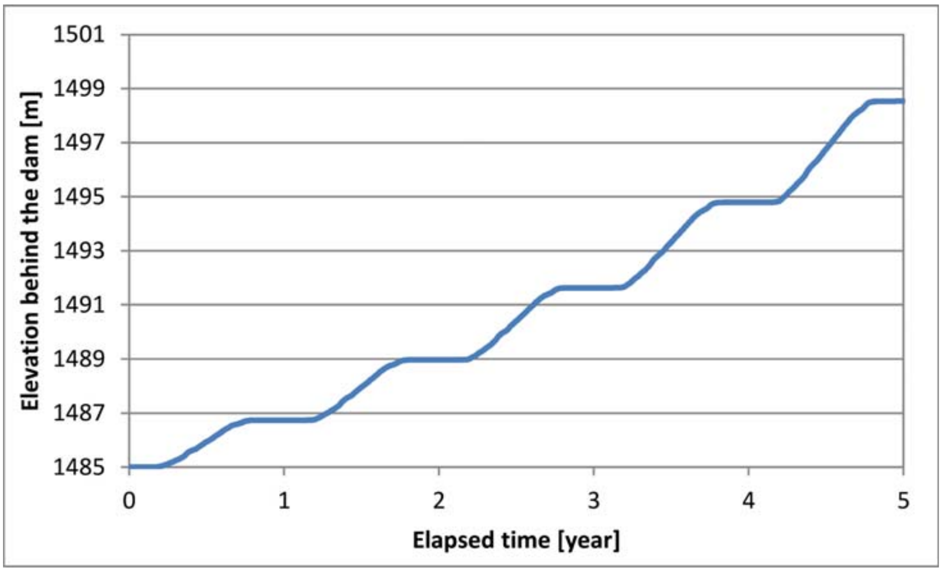

Figure 5. Suspended load deposition behind the dam during 5 years.

The annual sediment deposition at this section is increased each year comparing to the previous one as the delta approaches the dam. The deposition height at fifth year (about 4 meters) is approximately two times more important than that of the first year (about 2 meters).

5 FULL DRAWDOWN FLUSHING

The entire reservoir is modeled using the 2D BASEMENT model. BASEMENT is well-known for flow and sediment transport modeling. It is developed by the VAW (Laboratory of hydraulics, hydrology and glaciology) of the Swiss Federal Institute of Technology in Zurich. The velocity magnitude distribution over the reservoir and the bed-level shear stress obtained from the model also help to predict deposition zones of transported sediments. The model can be used to evaluate the effect of different hydraulic parameters, such as initial water elevation in the reservoir, or inlet/outlet boundary conditions. Due to long calculation times, it was not used for sediment transport simulations, only clear water simulations are performed instead.

Flushing during annual flood is modeled for different reservoir water surface elevations. The initial reservoir bathymetry is imported from the HEC-RAS model after one year of suspended load deposition (Fig. 2). Sediment transport is not simulated. Only the shear stresses are analyzed during the drawdown. The initial water surface elevation is set to three different levels, 1’556, 1’526 and 1’500 m asl. These elevations are held at these levels throughout the flushing period. The upstream boundary condition is defined as water inflow hydrograph with a peak of 1’400 m^3/s which is equal to a flood discharge of 1 year return period.

Figure 6 illustrates the shear stresses at the reservoir bottom for different water surface elevations. For the normal water elevation (1556 m asl) the shear stress at the reservoir bottom is less than 25 N/m^2 except in the first 3 km. The flow therefore, cannot mobilize the deposited sediments. For water surface elevation of 1526 m asl high shear stresses are obtained for the upstream 7 km of reservoir and more deposited sediment can be mobilized during flushing. Drawing the water surface elevation down to 1500 m asl exposes the whole reservoir bed to

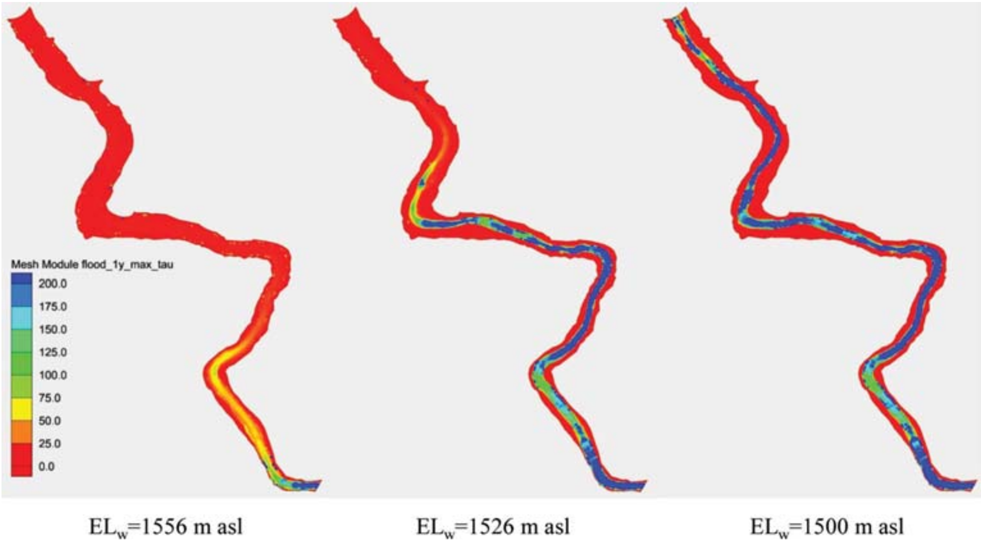

Figure 6. Bed-level shear stress [N/m^2] model during an annual flushing for three different water elevations.

high shear stresses (about 180 N/m^2). The critical shear stress for the suspended load and bead load grains with D_{50} is 1 and 70 N/m^2 respectively. As such, the deposited sediment in the whole reservoir can be mobilized and washed out.

6 SEDIMENT CONCENTRATION IN POWER INTAKES

In order to assess the general distribution of suspended sediment concentrations especially in a main power intake and a small hydropower intake, CE-QUAL-W2 program is used. CE-QUAL-W2 is a two-dimensional, laterally averaged, longitudinal/vertical, hydrodynamic and water quality model. Since the program assumes lateral homogeneity, it is best suited for relatively long and narrow water bodies exhibiting longitudinal and vertical water quality gradients. The model has been applied to rivers, lakes, reservoirs, estuaries, as well as a combination of water bodies (Motamedi, 2012). The model predicts water surface elevation, velocities and temperature being also able to solve transport equations for sediments and inorganic suspended solids. Any combination of constituents can be included in the simulation. To model the suspended load deposition in the reservoir, a settling velocity for the grains is needed. The falling velocity is calculated using the relationships presented by Jimenez & Madsen (2003).

Different long and short term scenarios are modeled to assure a better understanding of suspended material distribution evolution in the reservoir. To get more plausible results, several simulations are performed using a range of grain diameters between 0.01 to 0.05 mm. The total annual sediment volumes passing the main power intakes for suspended load with different diameters are listed in Table 4. The results for concentrations at the main power intake are shown in Figure 7.

The concentrations at the small power intake are slightly lower than those of the main power intake. The results also show that for grains with a nominal diameter more than 0.05 mm the suspended material concentration in the intakes becomes zero. This latter can be explained by very high rate of settling at the upstream part of the reservoir, which causes material deposition at the entrance. As a matter of fact, the suspended material cannot reach the power intakes.

Table 4. Total annual sediment volume passing and the maximum concentration (C_{max}) at the main power intake and suspended load with different diameters.

D_{50} [mm]	Sediment volume [Mm^3]	C_{max} [g/m^3]
0.01	0.97	1660
0.02	0.62	1160
0.03	0.32	740
0.04	0.11	330
0.05	0.03	100

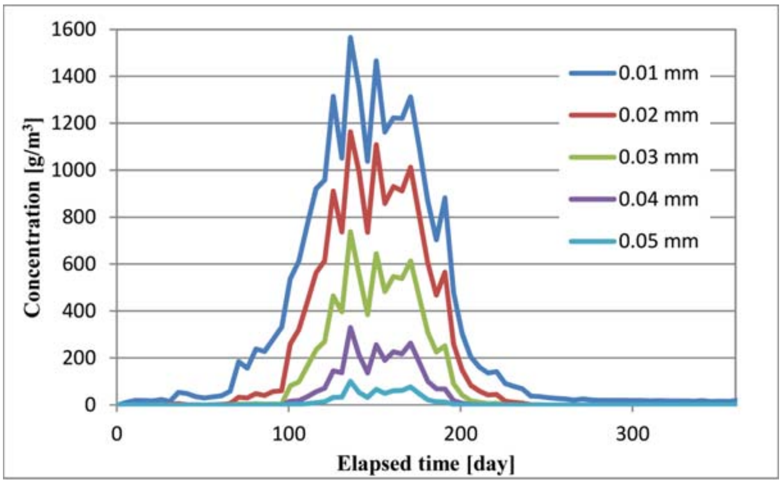

Figure 7. Concentration at power intake for different grain diameters.

7 CONCLUSION

Sediment transport modeling is notoriously difficult. The data used to predict bed changes is fundamentally uncertain and the theory employed is empirical and highly sensitive to a wide range of physical variables. However, with good data, long term trends for planning decisions can be modeled.

When the river reaches the reservoir, due to the increase in water depth in the latter, the flow velocities, turbulences and bed shear stresses are reduced. The bed load part is therefore settled down and forms a delta. The suspended load, however, can be carried by water over a longer distance than the bed load, and the delta that it forms can approach the dam.

The total flushing efficiency of a reservoir is principally guaranteed if a free surface flow can be established during the flushing process.

An important volume of the suspended load is evacuated through the power intakes and then the turbines and does not accumulate in the reservoir. This volume is significantly influenced by the size of the suspended material. For an average size of 0.03 mm, the volume passing through the turbines is estimated to 320’000 m^3 annually, which represents 10% of total incoming suspended sediment volume.

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