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Sedimentation and flushing in a reservoir - the paute - cardenillo Dam in Ecuador

Hydrolink

SEDIMENTATION AND FLUSHING IN A RESERVOIR – THE PAUTE - CARDENILLO DAM IN ECUADOR

BY LUIS G. CASTILLO AND JOSÉ M. CARRILLO

Flushing is one possible solution to mitigate the impact of reservoir impounding on the sediment balance across a river. It prevents the blockage of safety works (*e.g.* bottom outlets) and the excessive sediment entrainment in the water withdrawal structures (*e.g.* power waterways). This study is focused on the morphological changes expected in the Paute River (Ecuador - South America) as a result of the future construction of the Paute - Cardenillo Dam.

Project Characteristics

The Paute River is in the southern Ecuador Andes. The river is a tributary of the Santiago River, which is a tributary of the Amazon River (Figure 1). Paute - Cardenillo (installed capacity of 596 MW) is the fourth stage of the Complete Paute Hydropower Project that includes the Mazar (170 MW), Daniel Palacios - Molino (1100 MW) and Sopladora (487 MW) plants (Figure 2).

The double-curvature Paute-Cardenillo Dam is located 23 km downstream from the Daniel Palacios Dam (Figure 3). The reservoir is 2.98 km long and the normal maximum water level is 924 m above sea level (MASL). The study drainage area is 275 km^2 and the mean riverbed slope is 0.05 m/m (Figure 2). The bed material is composed of fine and coarse sediments. The use of a point counting method allowed characterizing the coarsest bed material (diameters larger than 75 mm) (Figure 4). The estimated total bed load is 1.75 Mm^3/year and the maximum volume of the reservoir is 12.33 Mm^3.

In order to prevent the accumulation of sediment into the reservoir, the dam owner proposes periodic discharges of bottom outlets or flushing[1]. These operations should transport sediment far downstream, avoiding the advance of the delta from the tail of the reservoir. Reservoir sedimentation and flushing were investigated using empirical formulations as well as 1D, 2D and 3D numerical modelling.

Flow Resistance Coefficients

Estimation of the total resistance coefficients was carried out according to grain size distribution, sediment transport capacity rate and macro-roughness (*e.g.* cobbles, blocks)[2] (Figure 5). The flow resistance due to grain roughness (*i.e.* skin friction) was estimated by means of ten different empirical formulas. For each analyzed flow discharge, calculations were carried out by adjusting the hydraulic characteristics of the river reach (mean section and slope) and the mean roughness coefficients. To estimate the grain roughness, only formulae whose values fall in the range of the mean value - one standard deviation of the Manning resistance coefficient of all formulas were considered. The formulas that gave values out of this range were discarded. The process was repeated twice. It was observed that the mean grain roughness was between 0.045 and 0.038. Using measured water levels for flow discharges of 136 m^3/s, 540 m^3/s and 820 m^3/s, the floodplain and the main channel resistance coefficients were obtained through the calibration of the 1D HEC-RAS v4.1 code[3]. Figure 6 shows Manning's roughness coefficients for flow rates of different return periods, considering the blockage increment due to macro roughness.

According to the feasibility study[1], the minimum flow discharge evacuated by the bottom outlet to achieve an efficient flushing should be at least twice the annual mean flow (Q_{ma} = 136.3 m^3/s). The dam owner adopted a conservatively high flow of 409 m^3/s (» 3Q_{ma}) for the design dimensions of the bottom outlet.

Reservoir Sedimentation

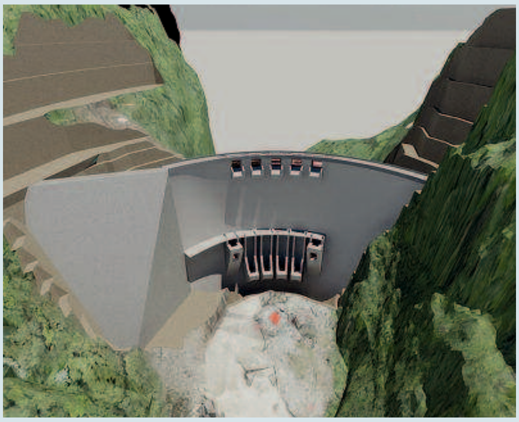
The time required for sediment deposition (bed load and suspended load) to reach the height of the bottom outlets (elevation 827 MASL) operating at reservoir levels was numerically investigated using the 1D HEC-RAS program[3]. The input flows were the annual mean flow (Q_{ma} = 136.3 m^3/s) equally distributed in the first 23.128 km and the annual mean flow discharge of the Sopladora hydroelectric power plant ($Q_{ma\text{-}sop}$ = 209 m^3/s). The Sopladora discharge comes from two dams located upstream. Sediment transport was computed using Meyer-Peter and Müller's formula corrected by Wong and Parker[4] or Yang's[5] formula. Figure 7 shows the initial and final states of the water surface and bed elevation. The suspended sediment concentration calculated numerically with HEC-RAS at the inlet section of the reservoir was 0.258 kg/m^3. This value takes into account the sediment transport from the upstream river and the annual mean sediment concentration from the Sopladora Hydroelectric Power Plant.

	Yang		Corrected Meyer-Peter & Müller	
Reservoir elevation (MASL)	Required time (years)	Sediment volume (hm^3)	Required time (years)	Sediment volume (hm^3)
860	**0.35**	**0.65**	**0.32**	**1.47**
892	5.10	2.77	2.58	3.86
918	12.90	6.07	8.80	7.34
920	13.60	6.33	9.50	7.64
924	14.80	6.62	10.90	8.97

Table 1. Sediment deposition volume in the reservoir and the time required to reach the bottom outlets. Results are presented for two sediment transport capacity formulas

Table 1 shows the total volume of sediment deposited in the reservoir and the time required to reach the bottom outlets (827 MASL). Several water levels in the reservoir based on future operations at the dam were considered, *e.g.*, 860 MASL which is the water level considered to operate the bottom outlets, 920 MASL the pondered average water level, and 924 MASL the normal upper storage level (Figure 8). Results show that the sedimentation volume in the reservoir increases with the water level in the reservoir, and requires a longer time to reach the bottom outlet elevation. Using the corrected Meyer-Peter and Müller formula, with the level of the reservoir being at 860 MASL, yields the largest sedimentation volume (1.47 hm^3) and the smallest time to reach the level of the bottom outlets (3 months and 27 days).

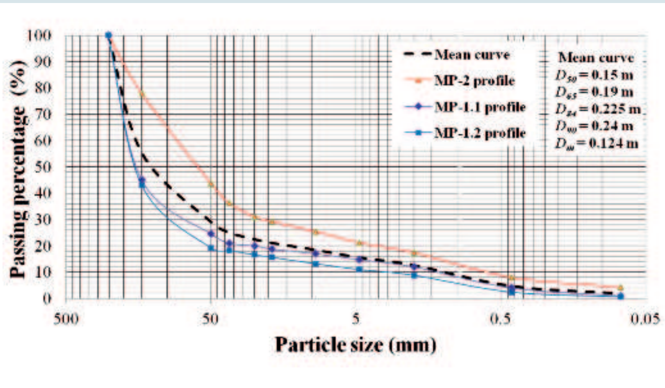
▲ Figure 1. Geographical situation of the Paute River (Ecuador - South America)



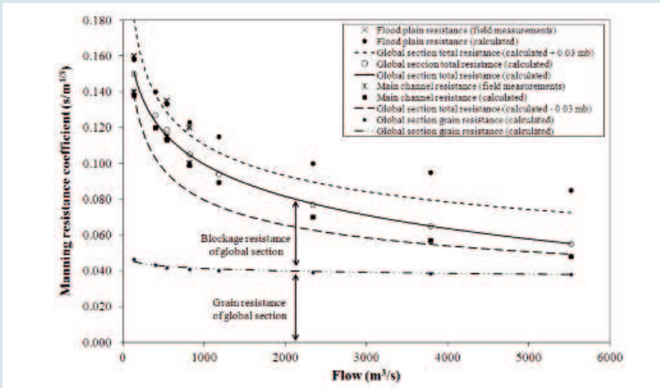
▲ Figure 3. Design of the Cardenillo Dam (maximum height of 136 m)

▲ Figure 5. Macro-roughness in Paute River at the Cardenillo Dam reach

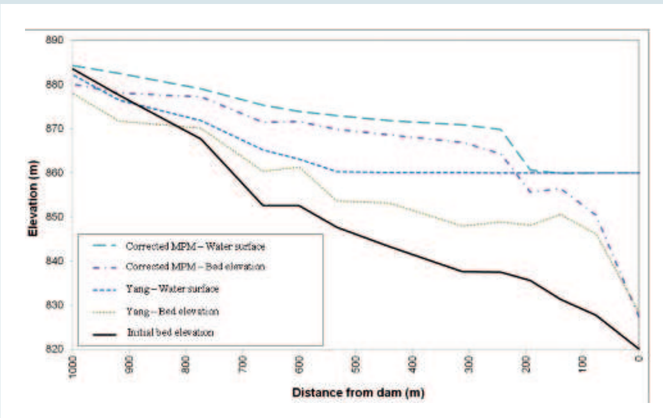
▲ Figure 2. Paute Hydropower Project: Mazar (170 MW), Daniel Palacios - Molino (1100 MW), Sopladora (487 MW) and Paute - Cardenillo (596 MW)



▲ Figure 4. Sieve curves of coarse bed material near Cardenillo dam



▲ Figure 6. Manning resistance coefficients in the main channel and flood-plain according to the flow discharge



▲ Figure 7. Bed and free surface profiles near the dam; the level of the bottom outlets is 827 MASL

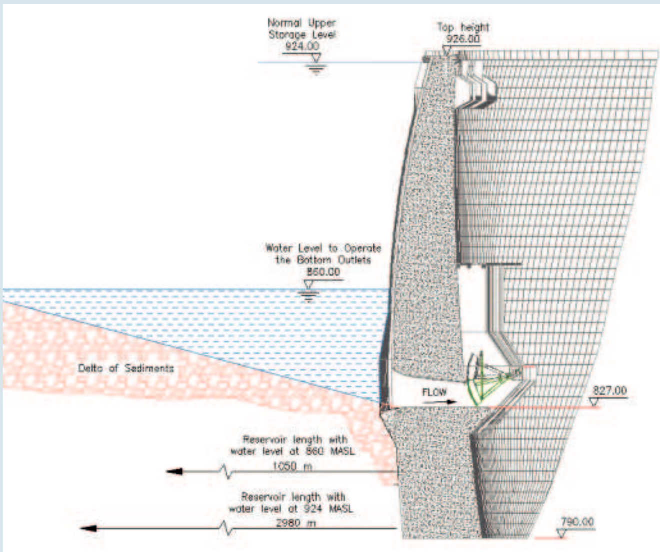


Figure 8. Scheme of the dam, water levels and sediment delta in the initial condition of the flushing ▶

Flushing Simulations

The efficiency of the hydraulic flushing depends on the ratio between the storage volume of the reservoir and the annual amount of incoming runoff. Annandale[6] indicates that flushing is effective if this ratio is less than 0.02, whereas Basson and Rooseboom[7] raised this threshold to 0.05. The Cardenillo Reservoir ratio is about 0.003. Hence, an effective flushing process may be expected.

2-D numerical runs

The flushing process was analyzed using the 2D depth-averaged, finite volume Iber v1.9 program[8]. The sediment transport rate was calculated by the corrected Meyer-Peter and Müller formula[4]. The evolution of the flushing over a continuous period of 72 h was studied, according to the operational rules at the Paute-Cardenillo Dam. The initial conditions for the sedimentation profile (the lower level of the bottom outlet) was 1.47 hm^3 of sediment deposited in the reservoir. The suspended sediment concentration at the inlet section was 0.258 kg/m^3. In accordance with the future dam operations, the initial water level at the reservoir was set at 860 MASL. Figure 9 shows the time evolution of bed elevation during the flushing operation. After a flushing period of 72 hours, the sediment volume transported through the bottom outlets is 1.77 hm^3. This volume is due to the regressive erosion of the delta of sediment (1.47 hm^3) which is almost removed in its entirety during the flushing operation, and to the erosion of prior deposits accumulated at the reservoir entry (due to the inlet suspended load) during the first times of flushing.

Figure 10 depicts the transversal profiles of the reservoir bottom before and after the flushing operation. Lai and Shen[9] proposed a geometrical relationship calculating the flushing channel width (in m) as 11 to 12 times the square root of the bankfull discharge (in m^3/s) inside the flushing channel. In the present study, the mean width of the flushing channel is 220 m, which is about 11 times the square root of the flushing discharge.

3-D numerical runs

Two-dimensional simulation might not properly simulate the instabilities of the delta of sediment that could block the bottom outlets. A 3D simulation could clarify the uncertainly during the first steps of the flushing operation. The computational fluid dynamics (CFD) simulations were performed with FLOW-3D v11.0 program[10]. The code solves the Navier - Stokes equations discretized by a finite difference scheme. The bed load transport was calculated using the corrected Meyer-Peter and Müller formula[4]. The closure of the Navier-Stokes equations was the Re-Normalisation Group (RNG) *k-epsilon* turbulence model[11]. The study focused on the first ten hours. The initial profile of the sediment delta was the deposition calculated by the 1D HEC-RAS code. As in the 2D simulation, the water level in the reservoir was 860 MASL. Due to the high concentration of sediment passing through the bottom outlets, the variation of the roughness in the bottom outlets was

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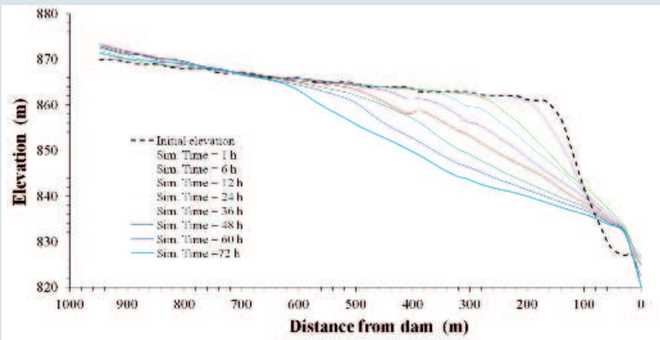
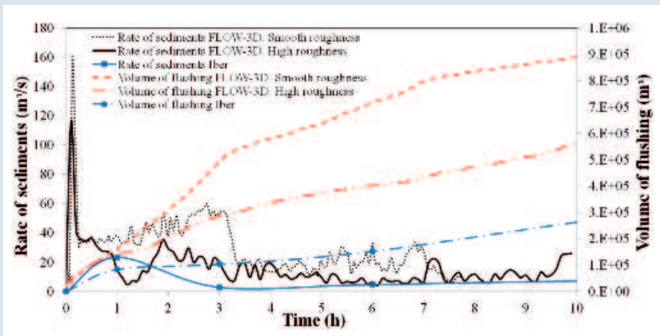
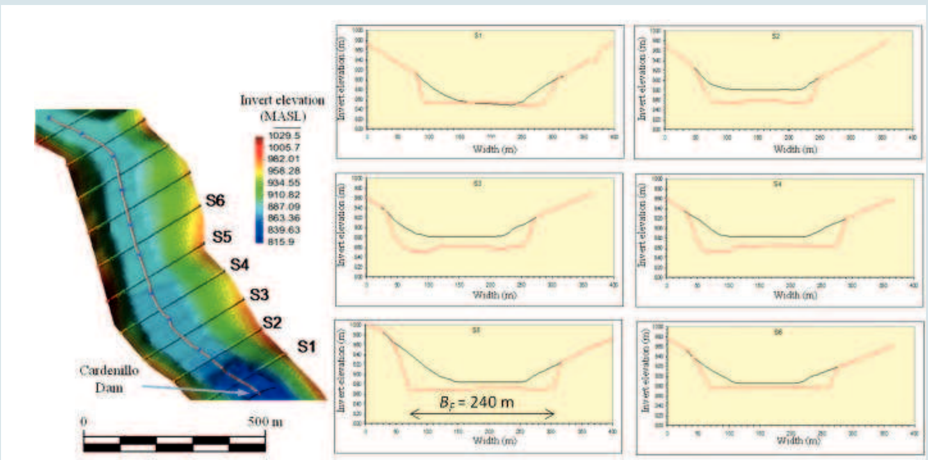


▲ Figure 9. Bed profile evolution during the flushing period of 72 h



▲ Figure 11. Comparison of the flushing operations simulated with 2D and 3D codes

Figure 10. Sediment deposition before and after a flushing period of 72 hours. B_F is the flushing channel width ▶



considered. The Nalluri and Kithsiri formula[12] was used to estimate the hyperconcentrated flow resistance coefficient on rigid bed (bottom outlets).

Figure 11 shows the volume of sediment flushed and the transient sediment transport during the first few hours of the flushing operation. There is a maximum of 117 m^3/s of sediment for an associated flow of 650 m^3/s (volumetric sediment concentration of 0.180), at the initial times for the high roughness 3D simulation. Later, the sediment transport rate tends to decrease to values similar to those obtained with the 2D model. The total volume of sediment calculated by FLOW-3D is higher than with the Iber program. The 2D simulations considered that all the total volume of sediment (1.47 hm^3) may be removed in 60 hours. Considering that sediment transport would continue during the entire flushing operation, the 3D simulation with high roughness would require 54 hours to remove all the sediments. A more detailed analysis is given by Castillo *et al*.[13].

Principal conclusions

Empirical formulas and 1D simulations are used to estimate sedimentation in the reservoir. Two-dimensional simulations allow the analysis of a flushing operation in the reservoir. Three-dimensional simulations show details of the sediment transport through the bottom outlets, where the effect of increasing the roughness due to the sediment transport through the bottom outlets was considered. The results demonstrate the utility of using and comparing different methods to achieve adequate resolution in the calculation of sedimentation and flushing operations in reservoirs. Suspended fine sediments in the reservoir may result in certain cohesion of the deposited sediments, which might influence the flushing procedure. Carrying out a flushing operation every four months, the cohesion effect in increasing the shear stress can be avoided.

Designers must take into account the high degrees of uncertainty inherent in sediment transport (numerical modeling and empirical formulae). Sensitivity analysis must be performed to prove the models are robust to various inputs and not limited to only a single scenario. ■

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