Simulation of the flushing into the dam-reservoir Paute-Cardenillo

Luis G. Castillo
Hidr@m Group, Universidad Politécnica de Cartagena, Spain

José M. Carrillo
Hidr@m Group, Universidad Politécnica de Cartagena, Spain

Manuel A. Álvarez
GEAMA Group, Universidade da Coruña, Spain

ABSTRACT: The study analyzes the expected changes in the Paute River in Ecuador as a result of the construction of the Paute-Cardenillo Dam (owned by Celec Ep-Hidropaute). This dam will integrate the National Electric System of Ecuador. Given that the project must remain viable throughout its useful life, the operational rules at the reservoir are required to include sedimentation effects. Sediment transport and flushing are studied by using four complementary procedures: empirical formulae, one-dimensional simulations (time required for sediment level to reach the height of the bottom outlets), two-dimensional simulations (flushing) and three-dimensional simulations (detail of the sediment transport through bottom outlet). Besides this, three-dimensional simulations have been used to considerer the effect of increasing the roughness due to the sediment transport in the bottom outlets.

1 MAIN CHARACTERISTICS OF THE PROJECT

The study zone is situated in the Paute River basin in Ecuador 23 km downstream from the Amaluza Dam. The area to be analyzed is of 275 km^2 of draining surface and the average slope of the river reach is 0.05 (Fig. 1).

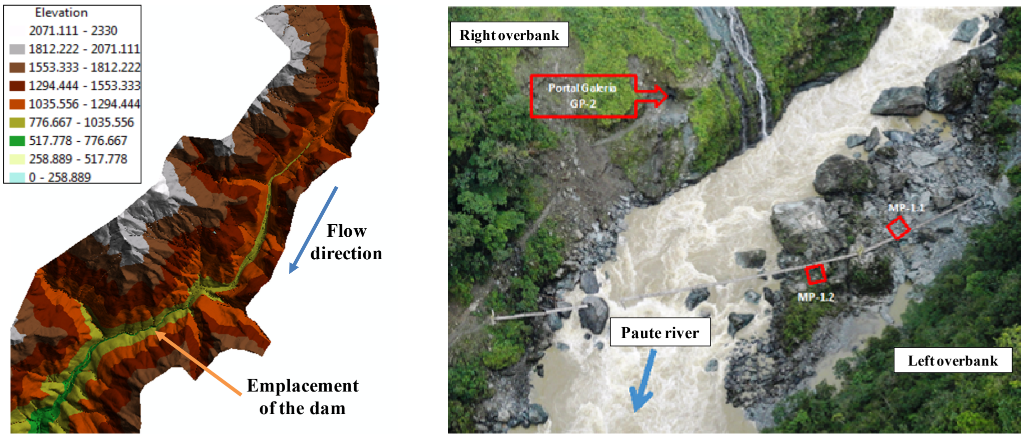

Figure 1. (a) Zone of study in Paute River basin. (b) Paute river.

Paute-Cardenillo is a double curvature arch dam with a maximum height of 135 m to the foundations. The top level is located at 926 meters. The reservoir has a length of 2.98 km, with normal maximum water level being located at 924 meters.

Figure 2 shows the sieve curves obtained at three sites of the river and the mean curve used in the calculations.

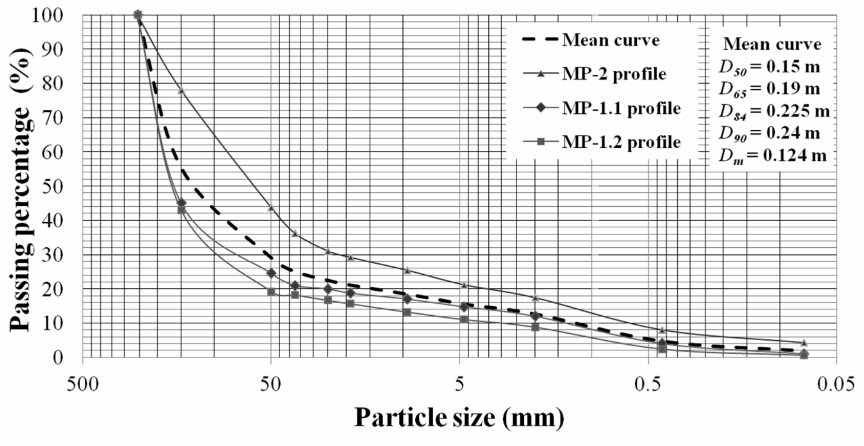

Figure 2. Sieve curves of three sites of the river and the sieve mean curve.

The total bed load (excluding wash load) was determined as 1.75 Mm^3/year and the maximum volume of the reservoir 12.33 Mm^3. In order to prevent the deposition of sediments into the reservoir, periodic discharges of bottom outlet or "flushing" have been proposed. These operations should be able to remove the sediments, avoiding the advance of the delta from the tail of the reservoir. The hydraulic flushing is considered an efficient technique in narrow reservoirs and strong slopes (Lai and Shen 1996, Janssen 1999).

Initial studies indicate that the minimum flow 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). For the safe side, a flow of 408.9 m^3/s ($3Q_{ma}$) was adopted.

2 SEDIMENT TRANSPORT FORMULAE

Sediment transport may be divided into the following: wash load (very fine material transported in suspension), and total bed transport (bed sediment transported and/or in suspension, depending on the sediment size and flow velocity). The main properties of sediment and its transport are: the particle size, shape, density, settling velocity, porosity and concentration.

2.1 *Estimation of the Manning resistance coefficient*

Following the methodology applied in Castillo et al. (2000), four aspects were checked to determine hydraulic characteristics of the flow: macro roughness, bed form resistance, hyper concentrated flow, and bed armoring phenomenon.

Ten formulae were applied for estimation of the roughness coefficient (Castillo and Marin, 2011): Strickler, Limerinos, Jarret, Bathurst, van Rijn, García-Flores, Grant, Fuentes and Aguirre-Pe, and Bathurst. These formulae are calculated by coupling iteratively the hydraulic characteristics with the sediment transport.

A macro roughness behavior may be identified in all the flows analyzed, which also present the armoring phenomenon. This leads to a significant increase in the various Manning coefficients. The calculation of these coefficients was carried out in a section type, through an iterative procedure by using the formulation of Fuentes and Aguirre-Pe (1991) and Aguirre-Pe et al. (2000). Figure 3 shows the Manning coefficients for the flow rates.

2.2 *Estimation of sediment transport*

Fourteen formulations of sediment transport capacity were used coefficient (Castillo and Marin, 2011): Meyer-Peter and Müller, Einstein and Brown, Einstein and Barbarrosa, Colby, Engelund and Hansen, Yang, C.T., Parker et al., Smart and Jaeggi, Mizuyama and Shimohigashi, van Rijn, Bathurst et al., Ackers and White, Aguirre-Pe et al., and Yang, S. From these, the formulations that fell within a range of the mean value +/- 1 standard deviation were selected. Figure 4 indicates that the transport capacity could vary between 1 and 100 t/s, if the mean values of the analyzed reach are considered. However, these values are reduced between 0.5 and 10 t/s when the river complete reach is considered (erosion and sedimentation processes are simulated). Finally, the net sediment transport in dam site was only 0.2 t/s.

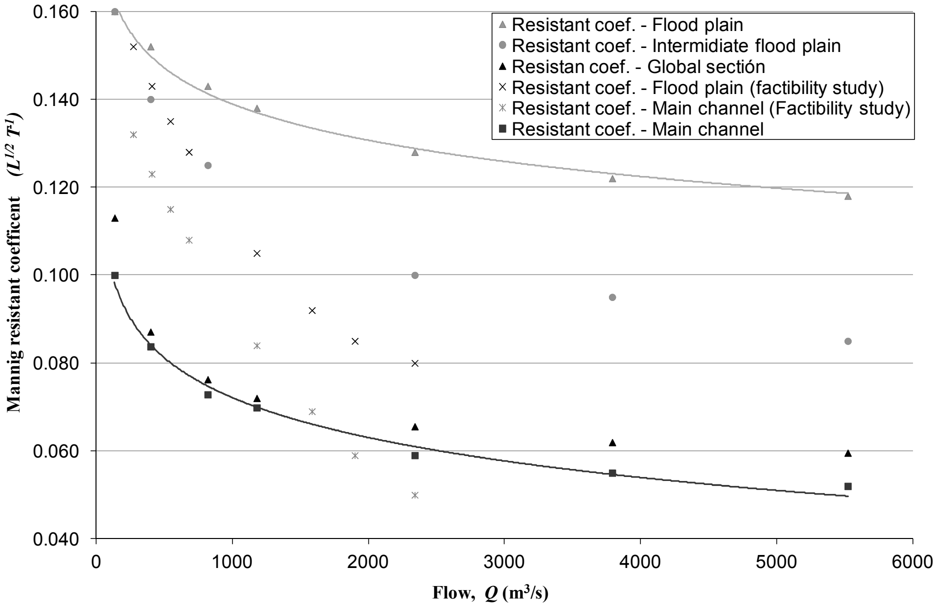

Figure 3. Manning resistance coefficients in the main channel and floodplain.

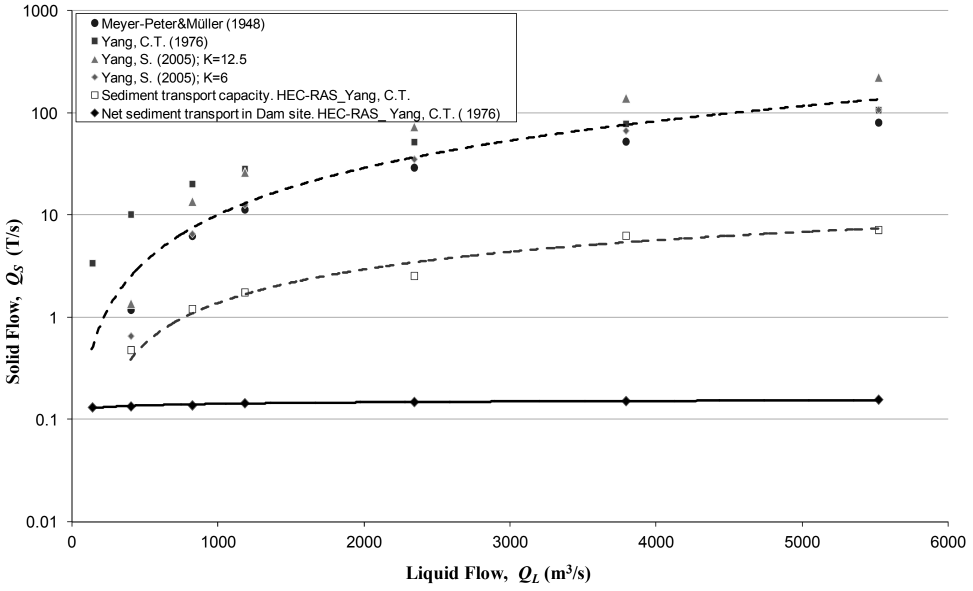

Figure 4. Sediment transport capacity (reach mean values), sediment transport (simulation of all reach) and net sediment transport in dam site.

3 NUMERICAL SIMULATIONS

The bed level change Z_b can be calculated from the overall mass balance equation for bed load sediment (Exner equation):

$$(1\text{-}p)\frac{\partial Z_b}{\partial t}+\frac{\partial Q_{bs}}{\partial s}+\frac{\partial Q_{bn}}{\partial n}=0 \tag{1}$$

where p is porosity of the bed material; Q_{bs} and Q_{bn} are the bed load flux in the main flow direction s and in the cross flow direction n, respectively. They are calculated from the non-equilibrium bed load equation:

$$\frac{\partial(Q_b\alpha_{bs})}{\partial s}+\frac{\partial(Q_b\alpha_{bn})}{\partial n}=-\frac{1}{L_s}(Q_b-Q_e) \tag{2}$$

where α_{bs} and α_{bn} are the cosines of the direction vector that determines the components of the bed load transport in the s and n directions, respectively. The model considers that the non-equilibrium effects are proportional to the difference between non-equilibrium bed load Q_b and equilibrium bed load Q_e, and related to the non-equilibrium adaptation length L_s.

3.1 *Reservoir sedimentation*

The time required for sediment level to reach the height of the bottom outlets (elevation 827 m) operating at reservoir levels was analyzed. Simulations were carried out with the one-dimensional HEC-RAS 4.1 program which employs a continuity equation of sediment.

The input flows are the annual mean flow (Q_{ma} = 136.3 m^3/s) equally distributed in the first 12 km and the incorporation (2.44 km upstream from the Paute-Cardenillo Dam) of the annual mean discharge flow of the Sopladora hydroelectric power plant (Q_{ma_sop} = 209.0 m^3/s).

The suspended sediment concentration at the inlet section was 0.258 kg/m^3. This value is similar to the mean concentration at the Sopladora hydroelectric power plant. The sediment characteristic diameter in the dam emplacement was D_{50} = 0.150 m. The sediment transport was calculated by considering the Meyer-Peter and Müller (1948), and the Yang (1976), formulae.

Table 1 shows the volume of sediments in the reservoir obtained when the bottom outlet level was reached. According to the results, the volume of sediment in the reservoir rises with the increasing of the water level in the reservoir, and requires a longer duration to reach the bottom outlet elevation.

Table 1. Time required and volume of sediment when the bottom outlets are reached.

	Yang		Meyer-Peter & Müller	
Reservoir elevation	Required time (years)	Sediment volume (hm^3)	Required time (years)	Sediment volume (hm^3)
860	0.33	0.65	0.33	1.47
918	12.90	6.07	8.80	7.34

The least favorable condition (the first one in which the sediment reaches the elevation of 827 m) was obtained with the expression of Meyer-Peter and Müller and the level of the reservoir located at 860 m, requiring a time of 3 months and 27 days.

3.2 *Flushing simulation*

3.2.1 *Two-dimensional simulation*

The flushing process was analyzed by using the Iber two-dimensional program. Iber can be divided in three modules: hydrodynamic, turbulence and sediment transport. The program uses triangular or quadrilateral elements in an unstructured mesh and finite volume scheme. The hydrodynamic module solves shallow water equations (2-D Saint-Venant equations). Diverse turbulence models with various levels of complexity can be used. The sediment transport module solves the transport equations by the Meyer-Peter and Müller expression and the evolution of the bottom elevation is calculated by sediment mass balance.

According to the operational rules of the Paute-Cardenillo Dam, the evolution of the flushing is studied over a continuous period of 72 hours. The initial condition of sedimentation profile was obtained with the HEC-RAS simulation (1.47 hm^3 of sediment). The input flow was three times the annual average flow (408.9 m^3/s). The suspended sediment concentration at the inlet section was 0.258 kg/m^3. The initial water level at the reservoir was 860 m. Effective flushing was observed during the operation of the bottom outlets. Figure 5 shows the profiles of the sediment at the reservoir during the flushing operation.

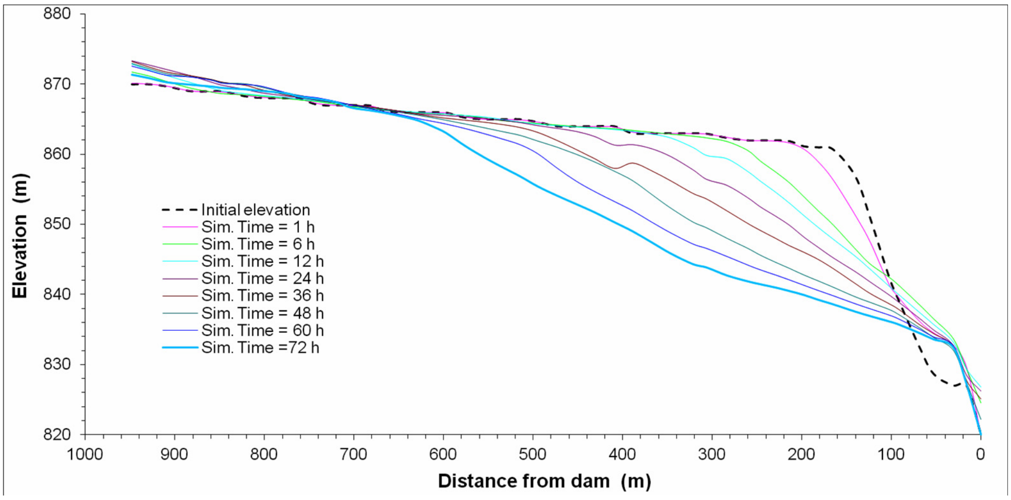

Figure 5. Evolution of the level of sediments during a flushing period of 72 hours.

After a flushing period of 72 hours, the volume of sediments removed by the bottom outlets was 1.76 hm^3. This value is bigger than the initial sediment value (1.47 hm^3).

3.2.2 *Three-dimensional simulation*

The computational fluid dynamics (CFD) program FLOW-3D, which solves the Navier-Stokes equations discretized by finite differences, was used. It incorporates various turbulence models, a sediment transport model and an empirical model bed erosion (Guo, 2002; Mastbergen and Von den Berg, 2003; Brethour and Burnham, 2010), together with a method for calculating the free surface of the fluid without solving the air component (Hirt and Nichols, 1981). The bed load transport is calculated by using the Meyer-Peter & Müller (1948) and Van Rijn (1986) expressions.

The operation of the bottom outlets, starting from the initial conditions of sedimentation obtained with the HEC-RAS program, was analyzed. Due to the high concentration of sediments that pass through the bottom outlets, the variation of the roughness in the bottoms has been considered. The estimation of the hyperconcentrated flow resistance coefficient on rigid bed has been calculated by using the formulae proposed by Nalluri (1992):

$$\lambda s = 0.851 \lambda_0^{0.86} C_v^{0.04} D_{gr}^{0.03} \tag{3}$$

where λ_s = Darcy-Weisbach's resistance factor on rigid bed with sediment transport, λ_0 = Darcy-Weisbach's resistance factor on rigid bed with clean water, C_v = volumetric sediment concentration, D_{gr} = grain size non-dimensional factor.

The bottom outlets are four rectangular ducts (5.00x6.80 m). The slope corresponding to the stretch under study is S = 0.001. The C_v has been estimated in 0.04. According to Wan and Wang (1994), the energy supplied by the solid phase, for a volume unit and a distance unit downstream (in non-dimensional way) is:

$$\frac{E_d}{\gamma} = C_v S = 0.00014 < 0.004 \tag{4}$$

This value is really lower than the limit between the hyperconcentrated flow and mudflow (0.004). The coefficient of cinematic viscosity of water with sediments concentration has been estimated by using the following formulae (Graf, 1984):

$$\frac{v_s}{v} = 1 + K_e C_v + K_2 C_v^2 \tag{5}$$

where v = the coefficient of cinematic viscosity of clean water (for T = 15ºC, $v \cong 1.14 \times 10^{-6}$ m^2/s), K_e = Einstein viscosity constant ($\cong$ 2.5), K_2 = particles interaction coefficient ($\cong$ 2).

Therefore, v_s = 1.26 × 10^{-6} m^2/s, a value 10.5% higher than v. The non-dimensional size of the grain corresponding to D_{50} = 0.150 m is:

$$D_{gr}=D_{50}\left[\frac{(s\text{-}1)g}{v_s^2}\right]^{1/3}=3254.74 \qquad (6)$$

Ducts are covered by iron, so the absolute roughness ε = 5 × 10^{-5} m. With the Coolebrok-White formula, λ_0 = 8.32 × 10^{-3} has been obtained. By using the Nalluri formula, λ_s=1.55 × 10^{-2}. This value corresponds to an absolute roughness ε_s = 2.37 × 10^{-3} m. The value ε_s has been used in the three-dimensional simulations.

Due to the high-capacity equipment and long simulation times to calculate the flushing of all the reservoir during 72 h, the results are focused in the first 10 h. The initial conditions of sedimentation was obtained with the HEC-RAS program. The inlet boundary was situated upstream the dam reservoir, considering that the water level is 860 m in the start condition.

Figure 6 shows the discharge flow at each bottom outlet, together with the total flow discharged for the first 3000 s of simulation, considering the roughness of the bottom outlets according to clean water and sediments transport. Outlets worked in a pressured and unsteady regime at the initial emptying of the reservoir, reaching a discharge near 2700 m^3/s. After the steady regime was reached (around 1000 s of simulation), there was a free surface flow and the discharged flow was the expected (408.90 m^3/s during the flushing operation). With the smooth roughness, the bottom outlets are block due to the high sediment transport (approximately 200 s after the beginning), although later it is swept without problems.

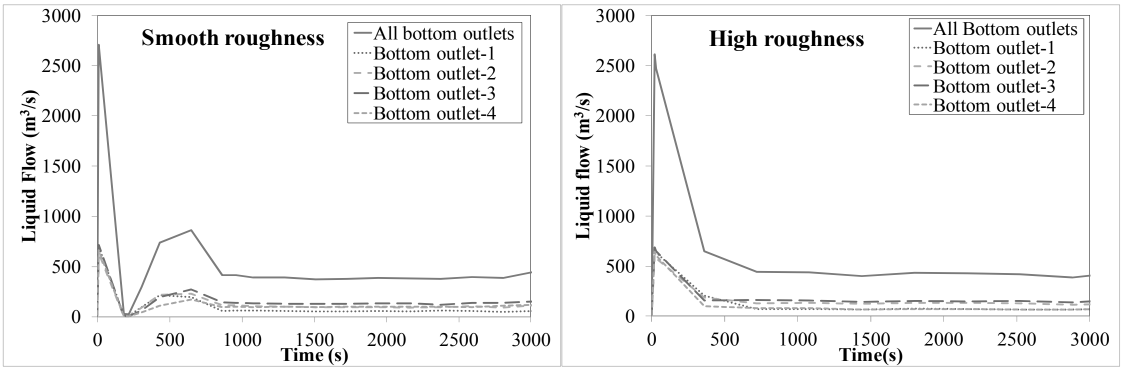

Figure 6. Liquid flows considering smooth and high roughness during the flushing operation simulated with three-dimensional program.

Figure 7 shows the solid flow at each bottom outlet, together with the total solid flow discharged for the first 3000 s of simulation. The roughness of the bottom outlets has been considered with clean water and sediments transport. With the smooth roughness, the peak of sediment transport (430,000 kg/s) is bigger than with the high roughness (310,000 kg/s). The peaks appear during the first steps of the flushing due to the emptying of the reservoir. Later, simulations seem to reach a constant rate of sediments removed, which is higher in the case of ducts with smooth roughness.

Figure 8 shows the volume of sediment removed and the transient sediment transport during the first ten hours of operation. Like in the two-dimensional simulation, there is significant sediment transport at the beginning of the simulation. There is a maximum of 160 m^3/s of sediments near the first hour with the smooth roughness, while it is reduced to 120 m^3/s for the high roughness. Later, the sediment transport rate in both cases tends to decrease until near 6 m^3/s which is similar to the two-dimensional result. The total volume of sediment calculated by FLOW-3D is much higher than with Iber program due to the simulations of the flushing phenomenon are very different in the first three hours.

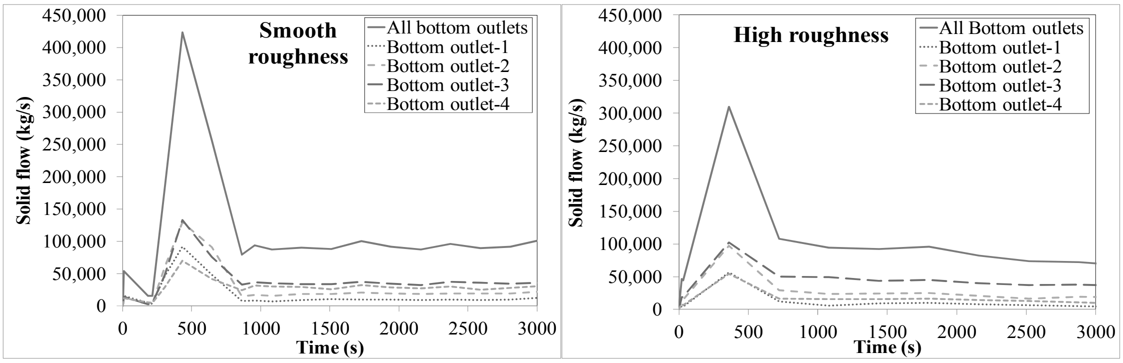

Figure 7. Solid flows considering smooth and high roughness during the flushing operation simulated with three-dimensional program.

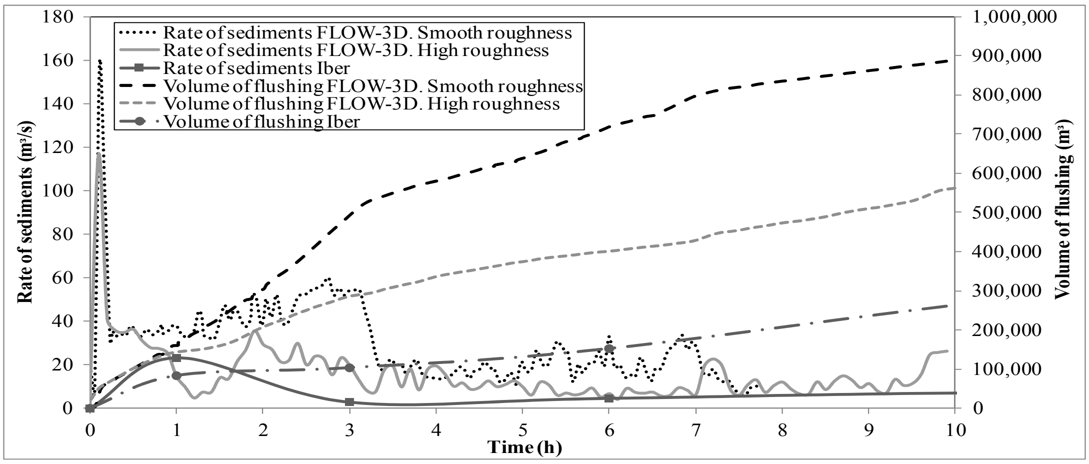

Figure 8. Comparison of the flushing operation simulated with two-dimensional and three-dimensional simulations.

The two-dimensional simulations considered that all the sediments (1.47 hm^3) may be removed in 60 hours. Considering that the rate of sediments is going to continue during the rest of the flushing operation, the three-dimensional simulations with the high roughness would require near 45 hours to remove all the sediments. Hence, the Iber simulations are from the safety side. They require longer times to remove the same volume of sediment than the three-dimensional simulations (theoretically more accurate).

4 CONCLUSIONS

In this paper, the complex phenomenon of flushing has been analyzed by using four interrelated methodologies: empirical formulations, one-dimensional simulations, two-dimensional simulations and three-dimensional simulations. Empirical simulations constitute an upper envelope of the sediment transport capacity. This procedure allowed an estimate of the coefficients of resistance or Manning roughness applied in the numerical simulations.

Due to the time period (one year) required to analyzing the sedimentation process in the reservoir, and the length of the reach (23.128 km), simulations were carried out with a one-dimensional program (two and three-dimensional programs need high-capacity equipment and long simulation times). Flushing operation was simulated with two-dimensional (Iber) and three-dimensional (FLOW-3D) programs. For 72 hours of flushing simulation, the Iber program required near 24 hours (Intel Core i7 CPU, 3.40 GHz processor, 16 GB RAM and 8 cores). The FLOW-3D program, by using the same equipment, would require more than 2400 h (100 days). Hence, the three-dimensional simulations were only used to analyze the behavior of the flow in the first 10 h of the flushing (343 h of real time each simulation).

The increase of the roughness in the ducts drives to a reduction of the amount of sediment removed in the reservoir.

The results demonstrated the suitability of crossing different methodologies to achieve an adequate resolution of complex phenomena such as flushing operations.

ACKNOWLEDGMENTS

The authors are grateful to CELEC EP - Hidropaute and the Consorcio POYRY-Caminosca Asociados for the data provided.

REFERENCES

Aguirre-Pe, J., Olivero, M.I. and Moncada, A.T. 2000. Transporte de sedimentos en cauces de alta montaña. *Revista Ingeniería del Agua*, 7(4), 353-365 (in Spanish).

Brethour, J. & Burnham, J. 2010. Modeling Sediment Erosion and Deposition with the FLOW-3D Sedimentation & Scour Model. *Flow Science Technical Note. FSI-10-TN85*: 1-22.

Castillo, L., Santos, F., Ojeda, J. Calderón, P., and Medina, J.M. 2000. Importancia del muestreo y limitaciones de las formulaciones existentes en el cálculo del transporte de sedimentos. *XIX Congreso Latinoamericano de Hidráulica. Córdoba, Argentina.*

Castillo, L. & Marín, M.D. 2011. Characterization of Ephemeral Rivers. *34th IAHR World Congress. Brisbane, Australia.*

Fuentes, R. & Aguirre-Pe, J. 1991. Resistance to flow in steep rough streams. *J. Hydraulic Engineering* 116(11): 1374-1387.

Graf, W.H. 1984. *Hydraulics of Sediment transport.* Water Resources Publications, LLC. Colorado, USA.

Guo, J. 2002. Hunter Rouse and Shields diagram, *1th IAHR-APD Congress, Singapore* 2: 1069-1098.

Hirt, C.W. & Nichols, B.D. 1981. Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries. *Journal of Computational Physics* 39 (201).

Janssen, R. 1999. *An Experimental Investigation of Flushing Channel Formation during Reservoir Drawdown*. Dissertation presented to the University of California at Berkeley, in partial fulfillment for the requirements for the degree of Doctor of Philosophy.

Lai, J.S. & Shen, H.W. 1996. Flushing sediment through reservoirs. *J. Hydraulic Research* 24(2).

Mastbergen, D.R. & Von den Berg J.H. 2003. Breaching in fine sands and the generation of sustained turbidity currents in submarine canyons. *Sedimentology* 50: 625-637.

Meyer-Peter, E. & Müller, R. 1948. Formulations of the Bed-load Transport. *Proc. of the II IAHR, Stockholm*: 39-64.

Nalluri Chandra 1992. Extended data on sediment transport in rigid bed rectangular channels. *Journal of Hydraulic Research* 30(6): 851-856.

Van Rijn, L.C. 1986. Manual sediment transport measurements in rivers, estuaries and coastal seas. *Rijkswaterstaat and Aqua publications*.

Yang, C.T. 1996. *Sediment Transport: Theory and Practice*. McGraw-Hill International Ed., NY, USA.

Wan, Z. & Wang, Z. 1994. *Hyperconcentrated Flow*. IAHR Monograph Series. Rotterdam, The Netherlands.