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RESERVOIR SEDIMENTATION PART 2

IAHR AIRH
International Association for Hydro-Environment Engineering and Research

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Spain Water and IWHR, China

INNOVATIVE STRATEGIES FOR MANAGING RESERVOIR SEDIMENTATION IN JAPAN SEE PAGE 100

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RESERVOIR SEDIMENTATION: CHALLENGES AND MANAGEMENT STRATEGIES

EDITORIAL BY KAMAL EL KADI ABDERREZZAK & ANGELOS N. FINDIKAKIS

The last issue of Hydrolink focused on reservoir sedimentation with articles on the problems experienced in different parts of the world and the mitigation measures taken in response. Because of the large interest among IAHR members and the broader water resources management community, the current issue includes more articles on the subject where researchers and other technical experts from different countries share their views on how to deal with this problem. This is the second of three issues of Hydrolink focusing on the challenges related to reservoir sedimentation and aiming at disseminating knowledge and lessons learned on successful sediment management strategies.

Angelos N. Findikakis
Hydrolink Editor

Kamal El kadi Abderrezzak
Guest Editor

Each technique has its advantages and shortcomings in terms of cost, applicability and environmental impacts, as described by Kondolf and Schmitt in the previous issue of Hydrolink. A perfectly sustainable strategy for every situation does not exist, but efforts can be optimized for the particular conditions of each reservoir. In the current issue, examples of operations and strategies are given from Japan by Sumi and Kantoush and from Taiwan by Wang and Kuo, showing that current and new facilities need to be designed, re-operated, and/or retrofitted to limit the loss of reservoir capacity due to sedimentation. Both articles provide lessons to help guide planning and design of new dams, and establish design standards for sustainable reservoir management.

As already mentioned in several of the articles published in the previous issue, sedimentation reduces reservoir storage capacity and the benefits derived therefrom, such as flood and drought control, water supply, hydropower, irrigation, groundwater recharge, fish and wild life conservation, and recreation. In addition, the sediment imbalance throughout the water system caused by dams operated without sediment management facilities (*e.g.* bottom outlets, spillways, bypass tunnels) leads to significant infrastructure and environmental damages both upstream and downstream of the reservoir.

The traditional approach in the design of reservoirs was to create a storage volume sufficiently large to contain sediment deposits for a specified period, known as the economic life of the project or "design life" (typically 50 or 100 years). After their "design life" is reached, dams and reservoirs would have to be taken out of service, leaving future generations to have to deal with dam decommissioning and the handling of the sediments. Yet, dam decommissioning is getting costlier and removal of deposited sediment is not a simple task, because the volume of deposited sediment in a reservoir over its design life can amount to millions, if not billions, of cubic meters[1]. For example, the net cost of decommissioning the Tarbela Dam in Pakistan, whose storage capacity as of last year had been reduced by 40% due to sedimentation[2], according to one estimate is US$2.5 billion[1]. Dam owners and operators have therefore strong interest in finding ways for extending the life of reservoirs, continuing to generate economic and social benefits even if they are not as large as in the original condition of the project.

With increasing demand for water supply and hydropower, aging infrastructure, coupled with the limited number of feasible and economical sites available for the construction of new reservoirs[1], the importance of converting non-sustainable reservoirs into sustainable elements of the water infrastructure for future generations is evident. While the 20th century was concerned with dam reservoir development, the current century needs to focus on reservoir sustainability through sedimentation management[3]. Solutions are needed for the removal of both fine sediments (clay and silt), as well as coarse sediments (sand and gravel).

It is possible to manage reservoir sedimentation by using one or more techniques[4]. The three main strategies for dealing with reservoir sedimentation are:

(1) reducing incoming sediment yield into reservoirs through watershed management, upstream check dams and off-channel storage;

(2) managing sediments within the reservoir through suitable dam operating rules for protecting the intakes from the ingress of sediments, tactical dredging in the vicinity of the dam outlets, and the construction of barriers to keep the outlets clear; and

(3) removing deposited sediment from reservoirs by flushing, sluicing, venting of a sediment-laden density current, bypass tunnels, dredging, dry excavation or hydrosuction.

An example of a specific field case is presented in the current issue by Peteuil who describes a successful example of sediment management in cascade reservoir dams on the Rhône River from the Swiss border to the Mediterranean Sea. Sediment is managed in reservoirs and channels of the Upper Rhône by flushing, such that the opening of the gates for the sediment release is coordinated from dam to dam. Routing and regulation of fine suspended sediment concentrations discharged from the upper Swiss reservoirs are performed in the French Génissiat reservoir where the dam is equipped with three outlets. The sediment flushing is conducted under extremely strict restrictions on suspended sediment concentrations. This "environmentally friendly flushing" from the Génissiat Dam limits the potential adverse impacts to the downstream environment (*e.g.* aquatic life, restored side-channel habitats) and water supply intakes. An interesting analysis of the effects of sediment flushing is presented in the article by Castillo and Carrillo who investigated the morphological changes in the Paute River (Ecuador - South America) as a result of the future construction of the Paute - Cardenillo Dam and associated sediment flushing operations.

Water resources are limited in arid counties. In the case of the Sultanate of Oman, recharge dam reservoirs are widely used for enhancing groundwater resources through making use of stored flood waters, which otherwise would have flowed to the sea and or spread in the desert. These reservoirs are facing, however, serious problems of sedimentation, which reduces their storage capacity and decreases the rate of water infiltration in the subsurface, as described by Al-Maktoumi in the current issue. The same article discusses different measures for dealing with this problem.

Some of the problems associated with reservoir sedimentation are studied by different research organizations. For example, at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich, Switzerland, field, laboratory and numerical research projects on reservoir sedimentation are conducted. Research topics cover reservoir sedimentation in the periglacial environment under climate change, hydroabrasion of sediment bypass tunnels, and transport fine sediment through turbines as countermeasure against reservoir sedimentation. More details on these challenging research programs are given by Albayrak *et al.* in the current issue.

The U.S. Army Corps of Engineers (USACE) is continually sharing its sustainable reservoir management knowledge base. An example of such effort is given by Shelley *et al.* in this issue, illustrating a collaboration between reservoir sedimentation experts from the USACE and the Government of Lao People's Democratic Republic (Lao PDR). The overall goal of this collaboration is to improve the environmental and social sustainability of hydropower development in the Mekong River Basin.

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Cover picture: Wujie Reservoir on the Zhuoshui (also spelled Choshui) River in Taiwan; construction of the dam was completed in 1934; photograph taken in early 2018. (Courtesy Hsiao-Wen Wang, Department of Hydraulic and Ocean Engineering, National Cheng Kung University)

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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

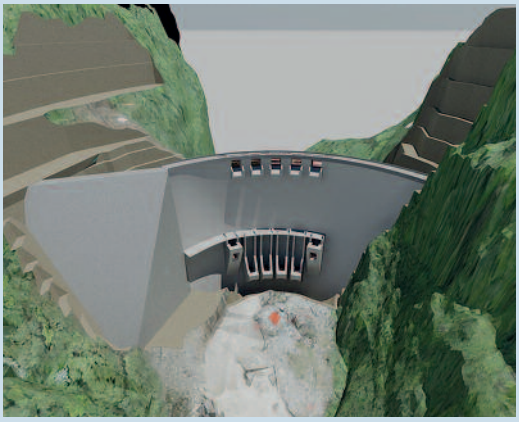
The time required for sediment deposition (bed load and suspended load) to reach the height of the bottom outlets (elevation 827 MASL) operating at reservoir levels was numerically investigated using the 1D HEC-RAS program[3]. The input flows were the annual mean flow (Q_{ma} = 136.3 m^3/s) equally distributed 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

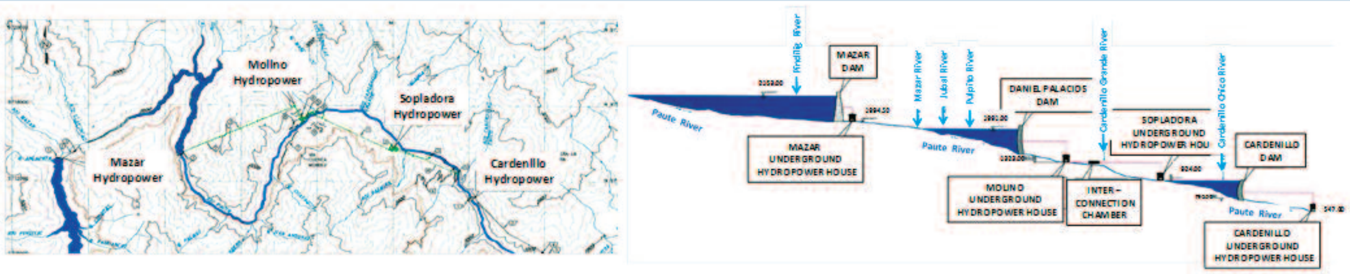
Table 1 shows the total volume of sediment deposited in the reservoir and the time required to reach the bottom outlets (827 MASL). Several water levels in the reservoir based on future operations at the dam were considered, *e.g.*, 860 MASL which is the water level considered to operate the bottom outlets, 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)

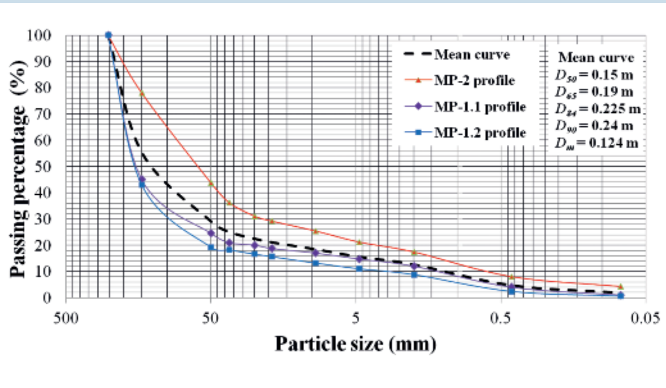


▲ Figure 3. Design of the Cardenillo Dam (maximum height of 136 m)

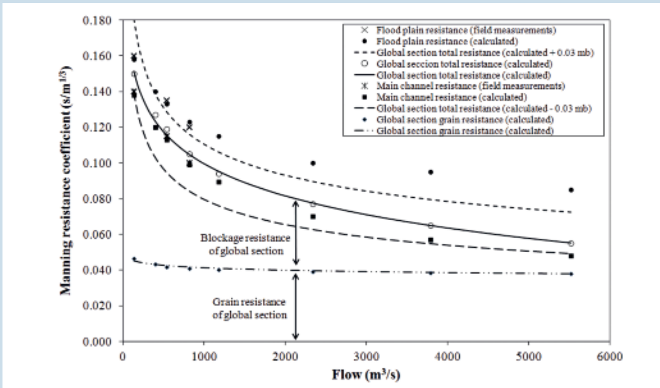
▲ Figure 5. Macro-roughness in Paute River at the Cardenillo Dam reach



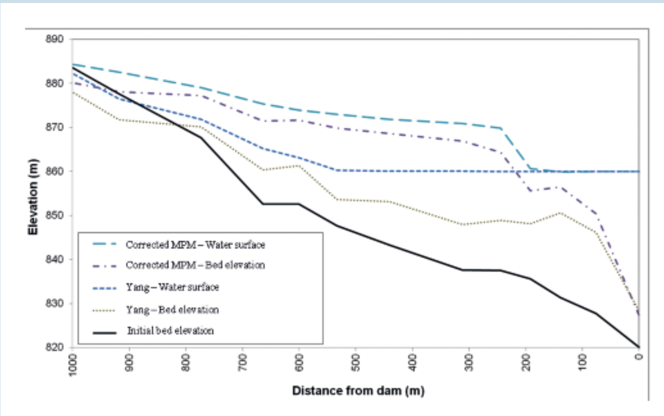
▲ Figure 2. Paute Hydropower Project: Mazar (170 MW), Daniel Palacios - Molino (1100 MW), Sopladora (487 MW) and Paute - Cardenillo (596 MW)



▲ 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

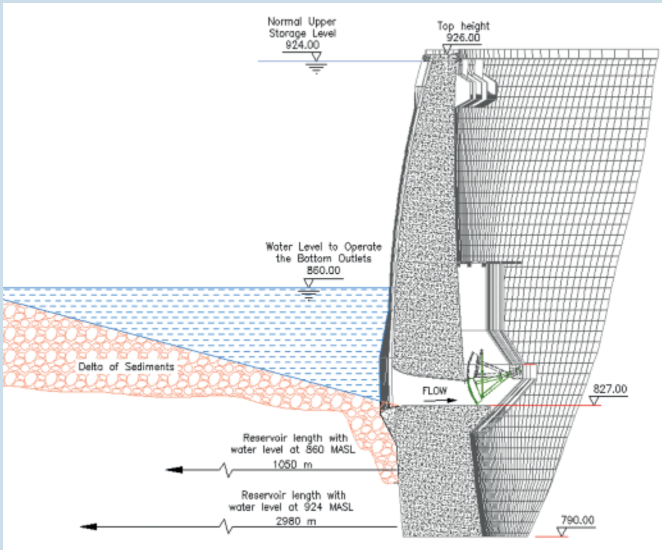


Figure 8. Scheme of the dam, water levels and sediment delta in the initial condition of the flushing ▶

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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.

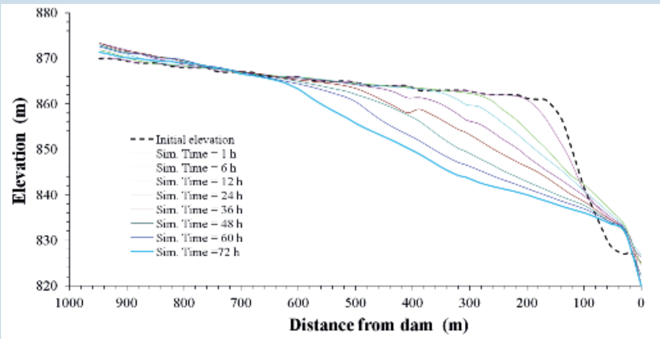
2-D numerical runs

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.

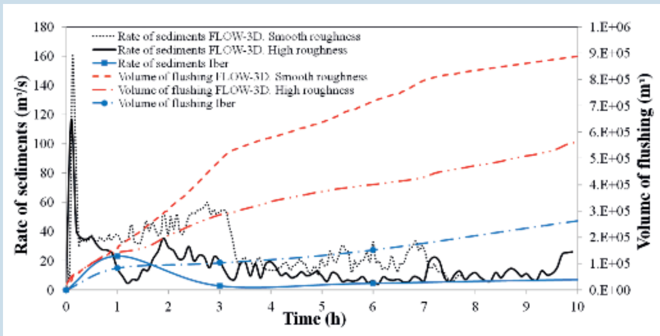
Figure 10 depicts the transversal profiles of the reservoir bottom before and after the flushing operation. Lai and Shen[9] proposed a geometrical relationship calculating the flushing channel width (in m) as 11 to 12 times the square root of the bankfull discharge (in m^3/s) inside the flushing channel.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

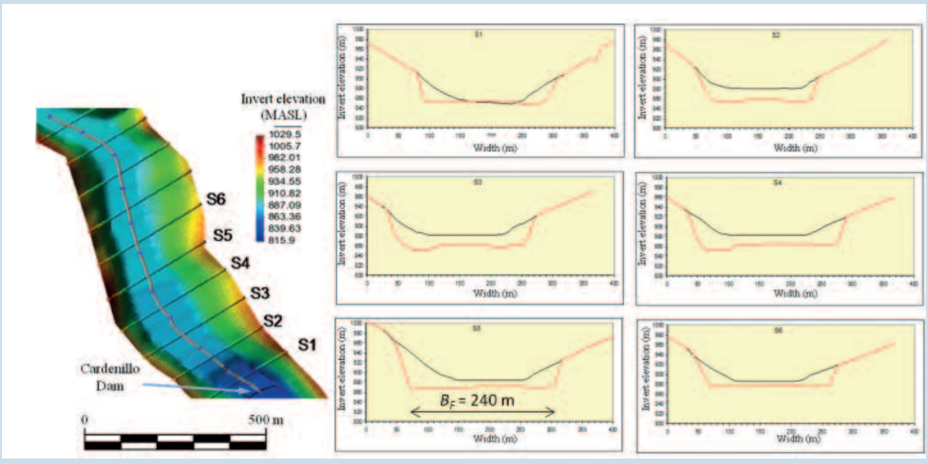


▲ Figure 9. Bed profile evolution during the flushing period of 72 h



▲ 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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IAHR EVENTS CALENDAR

IAHR World Congress

38th IAHR World Congress
1-6 September 2019 Panama City, Panama
http://iahrworldcongress.org/

39th IAHR World Congress
4-9 July 2021 Granada, Spain

30th IAHR Symposium on Hydraulic Machinery and Systems
Date to be confirmed Lausanne, Switzerland
Contact: Prof. Francois Avellan

8th International Conference on Physical Modelling in Coastal Science and Engineering (CoastLab 2020)
25-29 May 2020 Zhoushan, China

25th IAHR International Symposium on Ice
14-18 June 2020 Trondheim, Norway

IX Symposium on Environmental Hydraulics in Seoul Korea
18-22 July 2021. Seoul, Korea

9th International Symposium on Stratified Flows (ISSF 2021)
30 August- 2 September 2021 Cambridge, United Kingdom

IAHR Specialist Events

HydroSenSoft - 2nd International Symposium and Exhibition Hydro-environment Sensors and Software
February 26 – March 1, 2019 Madrid, Spain
http://www.ifema.es/hydrosensoft_06/

VI Jornadas de Ingeniería del Agua
22-25 October 2019 Toledo, Spain
http://www.jia2019.es/

11th River, Coastal and Estuarine Morphodynamics Symposium (RCEM 2019)
16-21 November 2019 Auckland, New Zealand
www.rcem2019.co.nz

14th International Conference on Hydroinformatics (HIC 2020)
June 2020 Mexico City, Mexico
http://hic2020.org/index.html

10th International Conference on Fluvial Hydraulics (River Flow 2020)
7-10 July 2020. Delft, Netherlands
www.riverflow2020.nl

International Conference on the Status and Future of the World's Large Rivers (World's Large Rivers Conference 2020)
10-13 August 2020. Moscow, Russian Federation
http://worldslargerivers.boku.ac.at/wlr/

8th International Conference on Flood Management (ICFM 2020)
17-19 August 2020. Iowa City, Iowa, U.S.A.

15th International Conference on Urban Drainage (ICUD 2020)
6-11 September 2020. Melbourne, Australia
http://www.icud2020.org/

IAHR Regional Division Congresses

6th IAHR Europe Congress "Hydro-environment Research and Engineering - No Frames, No Borders"
June 30- July 2 2020
Warsaw, Poland
http://iahr2020.syskonf.pl/

22nd Congress of the Asian Pacific Division of IAHR
2020. Sapporo, Japan
http://iahr-apd2020.eng.hokudai.ac.jp/

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