



Implementation of Strategies for the Management of Dams with Sedimented Reservoirs

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Abstract

Dams accumulate sediment by interrupting the continuity of rivers, resulting in a loss of reservoir water storage capacity and decreased productive life. These issues raise a growing concern about the decreasing benefits of projects. This paper contributes to the implementation of sediment transit strategies and operating rules of reservoirs to reduce overflows and recover the technical–economic viability of sedimented reservoirs by maintaining ecological flow. The main difficulty lies in the fact that sedimentation of the reservoir limits the mobility of dredging equipment and blocks the intake. To regain the viability of the reservoir, the commonly used strategies to manage water resources and reservoir sedimentation were analyzed. To control reservoir sedimentation and restore the generation capacity, different sediment management strategies were implemented and evaluated at the entrance, body of the reservoir and intake; these strategies included reduction of the entry of sediments, restoration of the storage capacity, clearing of the water intake for the turbines to restore power generation, trash rack cleaning during the power generation process and modification of the hydroelectric power plant operating rules to optimize the economic income. The implemented strategies successfully reduced overflows from 88 to 40% in 3 years and stabilized the reservoir storage capacity by balancing the inflow and removal of sediments. Although the water intake for the turbines was cleaned, accumulation increased in other areas of the reservoir. Finally, root cause analysis (RCA) was employed, and solutions were proposed to increase the capacity of the reservoir and reduce overflows to 15%.

Keywords Dam management · Dredging · Overflows · Reservoir sedimentation · Water resource management

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1 Introduction

Currently, worldwide, there are more than 45,000 large dams (with a reservoir storage capacity greater than 1,000,000 m³), and it is estimated that there are more than 800,000 smaller capacity dams (Palmieri et al. 2001; Wang and Hu 2009). The accumulation of sediment in reservoirs produces a loss in freshwater storage capacity at an annual rate of 1% globally (Huffaker and Hotchkiss 2006; Schleiss et al. 2016; Wang and Hu 2009). Small dams are usually dismantled when they are filled (Sawaske and Freyberg 2012). According to Schleiss et al. (2016), if the current trend continues, in the next 60 years, between 70 and 80% of the storage capacity of reservoirs globally will have been lost because of sedimentation.

According to Huffaker and Hotchkiss (2006), the large environmental and economic costs related to storage capacity recovery by new dam project construction is prompting a paradigm shift toward managing existing projects as renewable resources. This shift requires sediment control strategies to stabilize reservoir storage capacity by balancing sediment inflow and removal rates. Although several authors indicate that there is increasing concern about this issue in several countries, on a global basis, the trend has not changed. In fact, until now, the common engineering practice has been to design and operate reservoirs by anticipating slow filling with sediments, thereby producing a reservoir with a finite life span. (Palmieri et al. 2001). Eslami et al. (2021) developed a multicriteria-based decision-making methodology to determine the best implementation strategy to mitigate the adverse effects of dam construction and maximize economic benefits.

Shin et al. (2021) developed a model for evaluating the engineering conditions of small dams using an analytical hierarchy process. Beiranvand and Komasi (2021) performed numerical analysis to estimate the seepage rate of a dam. Several authors (Clement and Djebou 2018; Khaba and Griffiths 2017; Zamarron et al. 2017) developed models for decision-making support considering not only cost but also social and environmental aspects to prioritize dam management activities throughout their productive lives. These models were applied mainly to dams with billions of cubic meters of volume with sedimentation in the reservoir while maintaining a substantial storage volume. This paper shows the strategies and operating rules implemented for sediment transit to recover and manage an important dam in the Colombian electrical system, which has a strategic location and potential for generating 370 GWh per year. The dam was designed with a storage volume of 5.1 million m³, but sedimentation caused the loss of reservoir capacity to values lower than 0.2 million m³.

According to some studies (Kondolf et al. 2014; Morris 2020; Wang and Hu 2009), the following strategies are used to manage the sedimentation of reservoirs:

- Reduce the amount of sediments entering the reservoir from upstream through catchment erosion control (its benefits in reducing sediment inflow to reservoirs has not been clearly demonstrated) or the installation of check dams. Check dams can reduce sediment flow to a downstream reservoir in two ways. The first method is to induce debris flow deposition and reduce the rate of hillslope erosion. The second way is to intercept sediment before it reaches the downstream reservoir. The volume of sediment that is trapped is usually trivial, and check dams fill with sediment quickly, creating a new set of problems, resulting in sediment-filled reservoirs that are potentially unstable and costly to maintain.

- Implement sediment flushing, whereby the flow velocities in a reservoir are increased such that deposited sediments are removed through bottom outlets. Flushing is frequently used during floods, where high sediment concentrations are discharged during short periods of time. This system was implemented as a dam in the present study and was used from 1963 to 2000.
- Sediment bypassing is a method used to manage sediments by preventing them from entering the reservoir during flooding.
- Sediment dredging, which is used to gradually renovate the storage capacity of the reservoir, causes less environmental impact than other sediment management alternatives. It is used mainly in small dams.

Good environmental conditions can be achieved only if appropriate flow and sediment regimes and river morphology quality are guaranteed. E-flow, or ecological flow, is defined as discharge of flow magnitude and frequency that is necessary for a river system to remain environmentally, socially, and economically healthy. A model holistic approach for deciding E-flow was presented by Ćosić-Flajsig et al. (2020).

The hydroelectric power plant that is the focus of this study began operations in 1955, and a few years later, the reservoir lost its storage volume due to the accumulation of sediments from road construction, high deforestation due to agricultural activities and soil erosion. Since 1962, it has been necessary to incorporate hydraulic and mechanical dredging to remove sediments. Sediment dredging and sediment flushing has conserved the storage volume and generation capacity of the reservoir over the past 53 years. The hydroelectric power plant is located within a national natural park; therefore, major changes to dredging equipment and bottom outlet openings must be authorized by the environmental national authority. In 2001, sediment flushing was forbidden, and subsequently, the sedimentation rate of the reservoir increased considerably. In 2017, the storage capacity of the reservoir was lost at 94%, and the intake was totally obstructed, causing overflows at an annual average of 88% and forcing the generation of the plant to stop for a long time. In 2017, the dredging equipment reached an average age of 48 years, presenting a decrease in productivity and a projected short life-span. Figure 1 shows two images: the reservoir with a storage capacity greater than 60% and the sedimented reservoir.

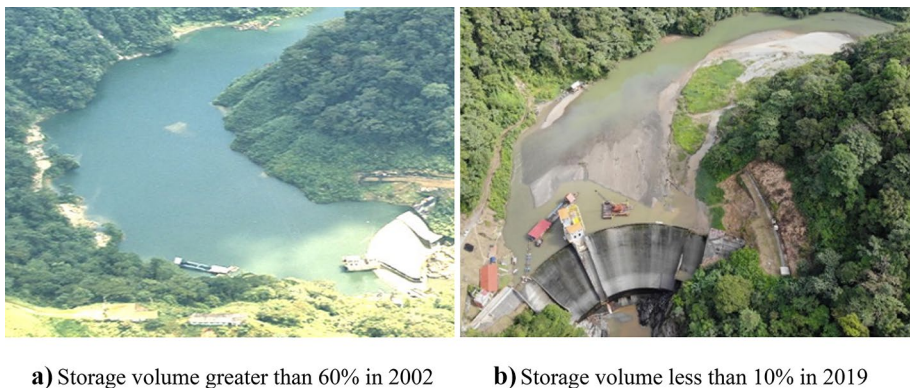


Fig. 1 Reservoir storage capacity. **a** Storage volume greater than 60% in 2002, **b** storage volume less than 10% in 2019

The sedimentation of the reservoir limits the mobility of the dredging equipment and blocks the intake. This paper shows the results of five strategies implemented to restore the capacity of electricity generation of the sedimented reservoir and to recover the economic viability of the hydroelectric power plant. The solutions can be implemented in other sedimented reservoirs to recover the storage volume and extend their productive life.

2 Description of the Problem

Since 2001, when sediment flushing was suspended, the generation capacity of the reservoir has depended only on the removal of sediment by dredging. Under these conditions, energy generation was conserved without a decrease (overflows less than 15%) for 7 years (2002 to 2008). Since 2009, the generation capacity gradually decreased (overflow increase) until 2017 when the intake was completely blocked by sediment. In 2017, overflows were 88%, and the loss of storage capacity of the reservoir was 94%. (Fig. 2). The loss of reservoir volume causes sediment transported by the river to be deposited in the intake, which makes it difficult to operate the hydraulic power plant in times of flooding. Mubeen et al. (2021) proposed a methodology to determine the most suitable intervention for flood risk reduction.

Sediment removal was affected by different factors, such as the deterioration of dredging equipment and external factors, such as weather conditions, logistics and the skill of maintenance and operation staff, which caused the low utilization of dredging equipment (weighted average of less than 30%, Fig. 3) and reservoir sedimentation. The utilization of dredging equipment can be expressed by Eq. 1 (Dredging equipment utilization rate).

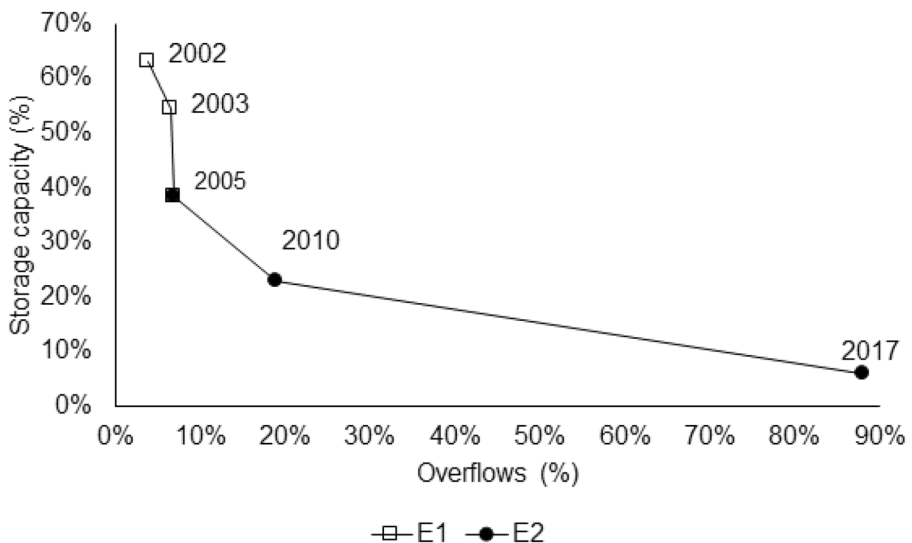
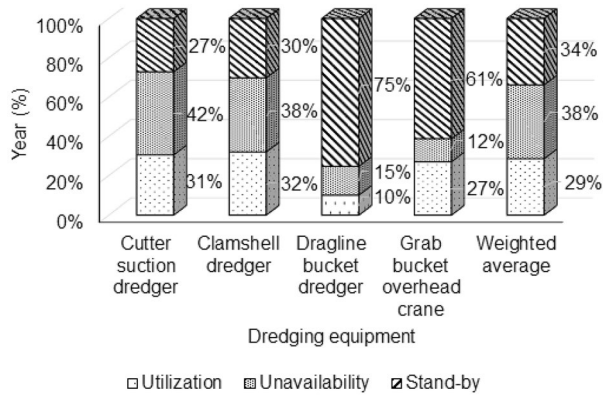


Fig. 2 Overflows versus reservoir storage capacity: curve E1-reservoir with storage volume greater than 60%; curve E2-sedimented reservoir

Fig. 3 Average utilization rate of dredging equipment (2018–2020)



$$Utilization\ rate(U) = \frac{Hours\ worked}{Total\ available\ hours} \times 100 \tag{1}$$

The main goals are to reduce the overflows to 15% and restore the electricity generation capacity of the reservoir. These goals require sediment control strategies that stabilize and increase the reservoir storage capacity by balancing sediment inflow and removal rates by dredging without considering the use of flushing.

3 Materials and Methods

The sediment balance in a reservoir can be modeled with the mass conservation equation, where sediment inflow is equal to the sediments removed plus the sediments accumulated. The sediment balance can be expressed as Eq. 2 (Sediment balance).

$$S_{inflow} = S_{Dredge} + S_{Turbine} + S_{Overflows} + S_{Accumulated} \tag{2}$$

where S is the sediment mass.

The sustainable management of the dam aims to stabilize or increase the storage capacity of the reservoir by balancing sediment inflow and removal rates. Removing sediments through the turbines and overflowing the sediments depends on flow rates, and considering that flushing is not allowed, it is necessary to increase the removal of sediments by dredging to achieve the objective.

3.1 Strategies to Restore the Generation Capacity of the Reservoir

To reduce overflows and restore the reservoir’s generating capacity, the following strategies for dredging and water resource management are implemented:

1. *Reduce the entry of sediments to the reservoir.* A dragline bucket dredger builds a trench underwater to retain and remove coarse-grained sediments, stones, and debris, which are then discharged into a bypass tunnel.

2. *Restore the storage capacity of the reservoir* using the hydraulic-dredging sediment-removal system.
3. *Clear the water intake* for the turbines to restore electricity generation by using mechanical dredging at great depths via a Clamshell Dredger and grab bucket overhead crane.
4. *Implement trash rack cleaning during the power generation process.*
5. *Modify the hydroelectric power plant operating rules* for optimal electricity generation. The hydroelectric power-generating capacity of the dam has decreased with the sedimentation of the reservoir, and it is not possible to sustain power generation for long periods of time. To optimize the income of the company, trash rack cleaning is implemented during low power generation loads during night hours to maintain a low energy cost, and generation at high loads during daytime hours with a high energy cost is implemented (Fig. 4).

Figure 5 shows the reservoir scheme with the location of the dredging equipment according to the proposed sediment management strategies.

3.2 Sediment Inflow

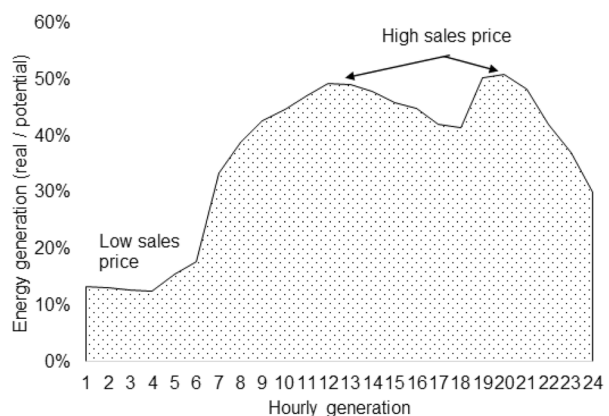
According to Anand et al. (2021), several authors have analyzed the sediment transport rates and the estimation of the flow intensity at which sediment movement begins. They concluded that slope is not a determining factor for the sediment transport rate because the angle of internal friction is 39° .

Bathymetries of the reservoir (Fig. 6) and water quality analysis (upstream, in the reservoir and downstream) were performed (2018 to 2020) to determine the correlation between liquid and solid flows and changes in the storage capacity and to balance the annual sediment in the reservoir. According to Zhang (2019), a variety of methods were used to assess water quality. The water quality index (WQI) considers general water quality factors, such as DO, pH, temperature, and total dissolved solids (TDS).

To evaluate the water quality parameters, variables were analyzed in the field and laboratory:

- Field variables included pH, temperature, dissolved oxygen (DO), conductivity, turbidity, sedimentable solids (Imhoff cone), and color.

Fig. 4 Annual average hourly electricity generation



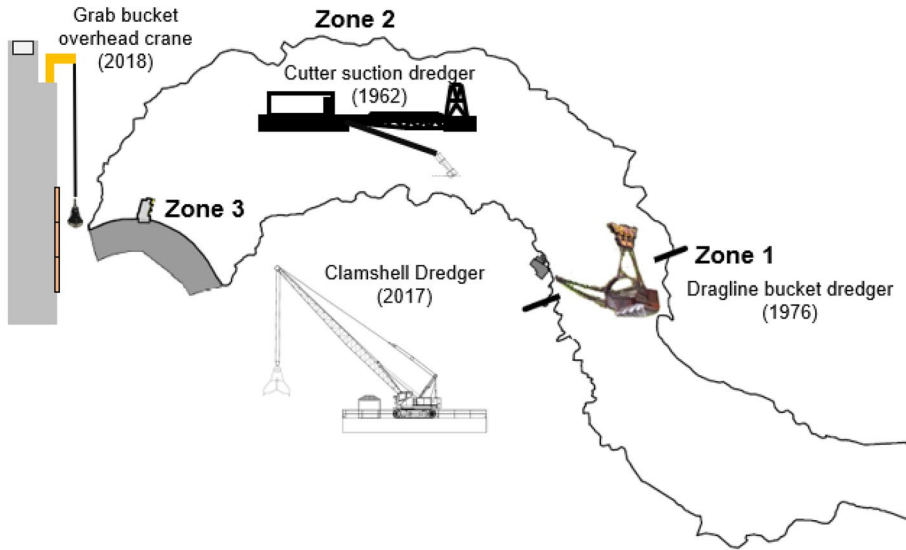


Fig. 5 Strategic location of dredging equipment: zone 1-entrance to the reservoir; zone 2-reservoir; zone 3- intake Where a *dragline bucket dredger* consists of a bucket that is moved by a cable suspended between a mast and a fixed point on the banks of the river to build a transverse underwater ditch with a width of 6 m at the bottom and a depth of 18 m; a *cutter suction dredger* is a unit designed to pump materials such as mud and sand from the bottom of rivers or reservoirs and drive them through a pipe as a mixture of solids and water to the discharge area; a *clamshell dredger* is an excavating machine used to move large amounts of soil or sediment using a clamshell bucket; and a *grab bucket overhead crane* is a piece of equipment that travels by monorail over the intake to extract sediments at great depths

- Laboratory variables included phosphates (total phosphorus), nitrites, nitrates (total nitrogen), hydrocarbons, mercury, sulfates, Biochemical Oxygen Demand (BOD), total

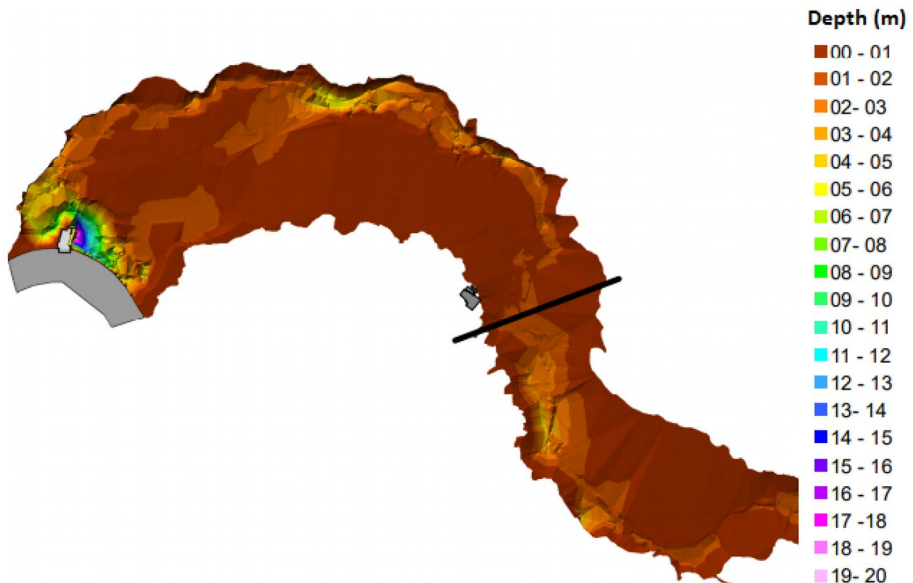


Fig. 6 Bathymetry of the reservoir

dissolved solids (TDS), total organic carbon (TOC), hydrogen sulfide, and fecal and total coliforms.

DO and pH were taken as reference parameters, with limit or contingency values of 4.0 mg/l for DO and within 5.5–8.5 for pH. During water quality monitoring, average values were obtained at the reservoir inlet of 6.2 mg/l for OD and a pH of 6.9. At the reservoir outlet, average values of 7.8 mg/l were obtained for OD and an average pH of 7.0 was obtained. The implemented sediment transit and E-flow scheme did not affect the water quality variables; therefore, the quality of the water at the outlet of the reservoir remained within a normal range for the proper development of the biota.

With this information (bathymetries and water quality analysis) plus the flows recorded for more than 30 years in meteorological stations in the area, the sediment transport capacity was determined, with the conclusion that the reservoir retains 67.9% of the sediment inflow (Fig. 7), which must be removed later. More than 70% of the sediments are transported less than 20% of the time. According to Jimenez et al. (2005), one or two floods can carry as much sediment as normal runoff carries in a year. In studies carried out by Duque and Posada (2011), solid contents between 35 and 45% were recorded during floods.

In the last 3 years, the balance between sediment inflow and removal rates have been preserved, with variations in the accumulation of sediments between -0.03 and 0.03 million m^3 per year. To increase the volume of storage, it is necessary to increase the sediment dredging in the reservoir.

For the development of this research, information was collected for more than three years, including the operation and maintenance of dredging equipment, historical records of bathymetries, flows and electrical generation of the hydroelectric power plant.

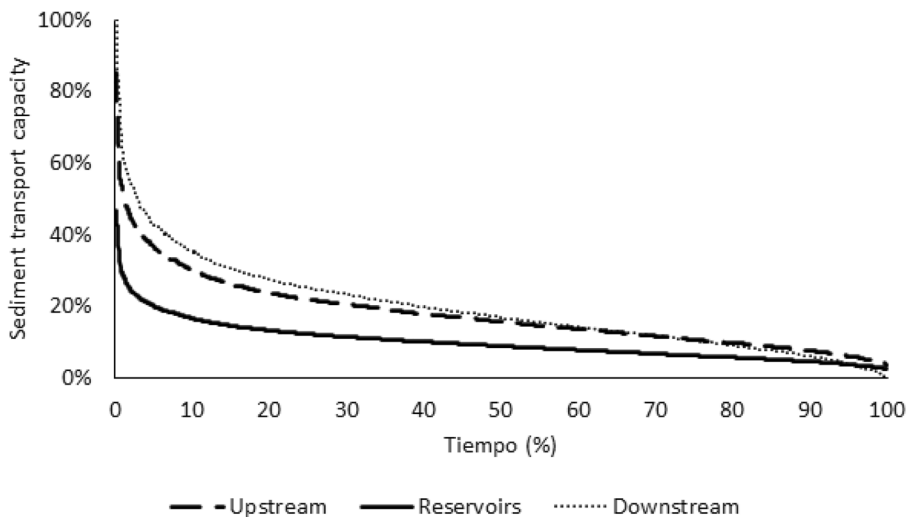


Fig. 7 Sediment transport capacity (upstream, in the reservoirs, and downstream)

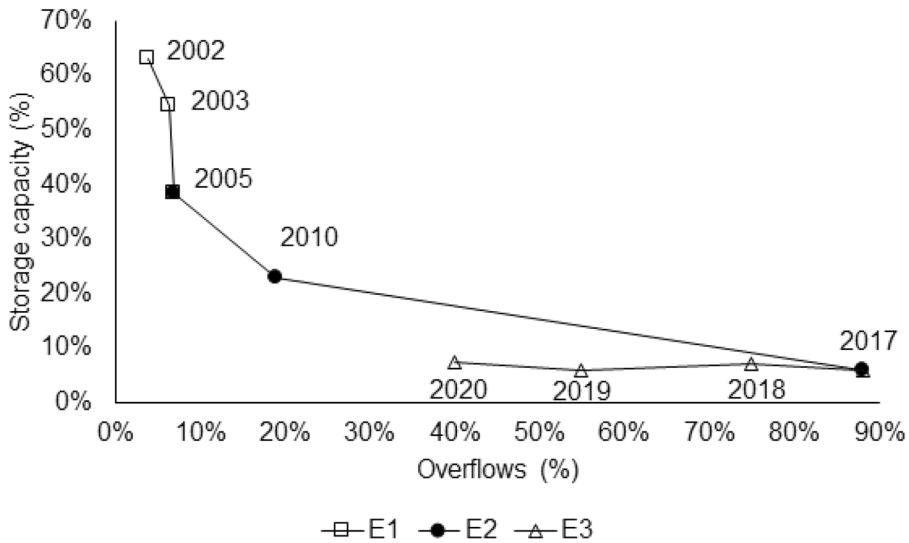


Fig. 8 Overflows versus reservoir capacity

3.3 Ecological Flow (E-flow)

To define E-flows, Čosić-Flajsig et al. (2020) proposed a procedure with the following four main stages: (1) morphological characterization of the river system, (2) hydrological and sediment regime study, (3) ecological behavior of the altered flow regime and selection of target species, and (4) comparison and selection of possible E-flows. To guarantee adequate environmental conditions necessary for the river system to remain environmentally, socially, and economically healthy, an E-flow or ecological flow of 11 m³/s was defined by environmental experts; this ecological flow is mandatory.

4 Calculations and Results

At the end of 2017 and the beginning of 2018, a strategy of high-depth mechanical dredging was implemented in the intake with a clamshell dredger and grab bucket overhead crane, which added to the operation of the dragline bucket dredger and cutter suction dredger, managed to stabilize the sediment balance in the reservoir and reduce overflows from 88 to 40% (Figs. 8 and 9), thereby increasing electricity generation and decreasing the demand for new water projects or the consumption of fossil fuels.

The historical records of inflow in the reservoir revealed that the E-flow of 11 m³/s corresponds to 13% to 17% of the total inflow, with an average inflow of 15%. The goal of reducing overflows was maintained until the overflows were equal to the ecological flow, i.e., an average annual flow of 15%.

This strategy required reducing the electricity generation of the hydroelectric power plant (less than 15% of the capacity) during 46% of the year (Fig. 10) for trash rack cleaning, which made it difficult to achieve an overflow reduction of 15%.

In the past, when the reservoir had a storage capacity greater than 30%, the overflows were less than 20%; most of the year, the hydroelectric power plant generated

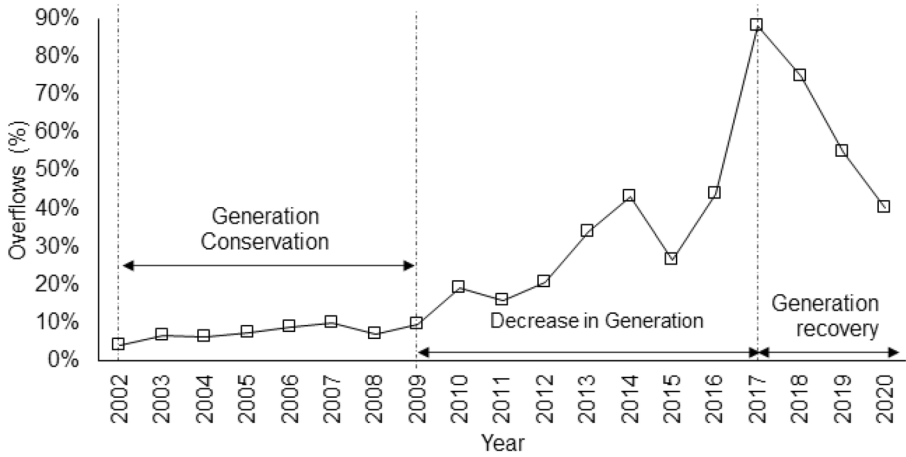


Fig. 9 Historic overflows

between 90 and 100% of its capacity, and only 20% of the year, the hydroelectric power plant operated at low power (less than 15% capacity) for trash rack cleaning. This condition is denoted as E1.

The loss of 94% of the reservoir’s storage capacity (without a sediment transit strategy) required operating at low load during 75% of the year, and it was not possible to reach an hourly generation above 30%. This condition is denoted as E2.

After implementing the sediment transit strategies, the need to operate the plant at low load was reduced from 75 to 46%, and the hydroelectric plant generated between 90 and 100% of its capacity during 5% of the year; however, the loss of the reservoir storage capacity remained at 93%. This condition is denoted as E3.

The sedimentation of the reservoir caused continuous obstruction of the intake due to the sediments transported by the river. This situation made it difficult to generate electricity at full load for long periods of time, even with the intake 100% clear, as shown in Fig. 11.

Fig. 10 Electricity generation for different reservoir conditions

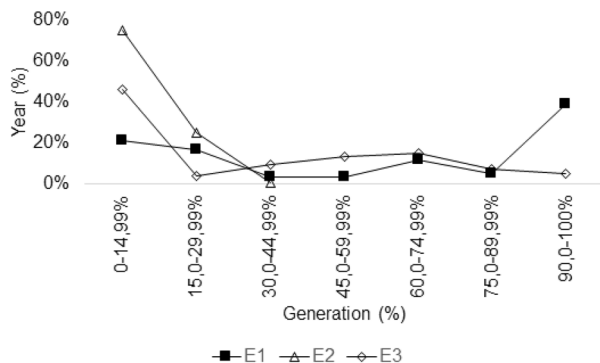
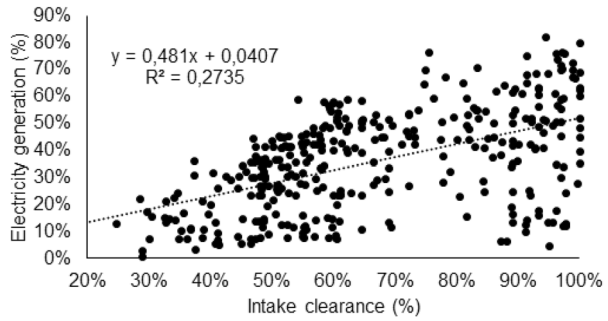


Fig. 11 Electricity generation versus intake clearance



4.1 Sediment Dredging

The maximum amount of sediments to be removed per year was approved by the national environmental authority. To estimate the required utilization of dredging equipment to remove these sediments, equations that consider the effect of each piece of equipment on the restoration of storage capacity and restoration of electricity generation without exceeding the annual dredging limit are developed (Eq. 3 (Removed sediment)).

$$S_R = (E * h)_{Dragline\ bucket\ dredger} + (E * h)_{Cutter\ suction\ dredger} + (E * h)_{Clamshell\ Dredger} + (E * h)_{Grab\ bucket\ overhead\ crane} \tag{3}$$

where S_R = removed sediments (m3/year), E=dredging capacity (m3/hour), h=dredging (hours/year).

To solve Eq. 3, the following considerations were made according to the operating context to estimate the theoretical operating hours of each equipment and compare with the operation recorded in the field:

- The grab bucket overhead crane operates only during hours of lower energy sales; therefore, the maximum available operation time is 8 h per day.
- Dragline bucket dredgers operate upstream of the reservoir only on day shifts; personnel are present 40% of the time compared to that of dredgers.
- The cutter suction dredger and clamshell dredger have the same time available to operate.

The hours of operation of each piece of equipment were determined, and knowing the weight of each piece of equipment in the removal of sediments, the weighted average utilization of reservoir dredging was calculated (Eq. 4 (Hours of average operation required)).

$$h_{Weighted\ average} = (W * h)_{Dragline\ bucket\ dredger} + (W * h)_{Cutter\ suction\ dredger} + (W * h)_{Clamshell\ Dredger} + (W * h)_{Grab\ bucket\ overhead\ crane} \tag{4}$$

where W is the participation of each piece of equipment in the global balance of removed sediments.

The environmental management plan of the reservoir states that the largest sediment volume to be extracted is 1,092,000 m³ per year. Considering this restriction, the participation (W) is determined as the dredging capacity of each of the pieces of equipment over the capacity of all of the equipment. To achieve the extraction of the

Table 1 Information for each dredger type

Dredger type	Capacity (m ³ /h)	W	Theoretical utilization (%)
Dragline bucket dredger	58	0.10	22
Cutter suction dredge	160	0.70	55
Clamshell dredger	36	0.16	55
Grab bucket overhead crane	12	0.04	33
Weighted average	124		48

required sediments, sensitivity analysis was performed considering the following operating restrictions of each of the cutter suction dredger and clamshell dredger equipment operated between 14 and 18 h per day, the dragline bucket dredger operated between 4 and 6 h per day and the grab bucket overhead crane operated between 6 and 8 h per day. Only in the scenario in which all the equipment operates at the greatest possible number of hours per day is the dredging objective achieved; for all other cases, the dredged sediments are less than the allowed limit.

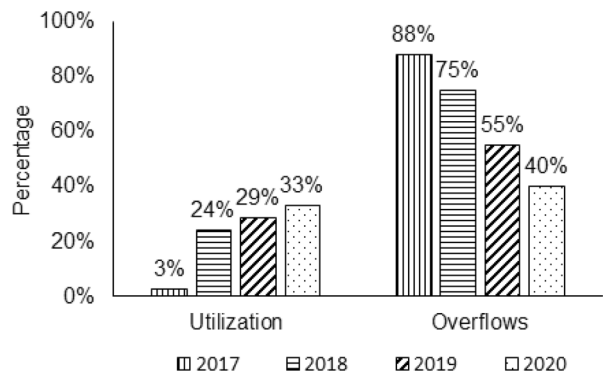
According to Eq. 1, by dividing these weighted average hours over the hours of the year, a weighted average utilization of 48% is required for the dredging equipment. Table 1 shows the values for each of the pieces of equipment.

Between 2018 and 2020, there was a decrease in overflows and an increase in the utilization of dredging equipment (Fig. 12), with a weighted average utilization of 29%.

4.2 Electricity Generation Versus Reservoir Storage Capacity

The last year with overflows less than 10% was 2008 (Fig. 9), when a reservoir volume of 29% was estimated (0.66 million m³). Therefore, the objective is to recover the storage capacity of the reservoir to 29%. The current volume is 7% (0.15 million m³), two years is needed to restore the reservoir volume to 29%, and using the aforementioned method, it is necessary to increase the minimum weighted average utilization to 36%.

The strategy of sediment transit and water resource management that was implemented allowed us to reduce overflows; however, since the storage capacity of the

Fig. 12 Utilization of dredging equipment and overflows

reservoir continues at minimum values, it is necessary to continue generating at low loads to clean the intake.

4.3 Root Cause Analysis (RCA) of Low Sediment Extraction

The RCA of low sediment extraction was carried out through the logical tree methodology using the Proact ® tool, from which the base causes and impacts were determined with the following negative impact percentages: 29.70% because of aging of the cutter suction dredger (58 years) and impossibility of operating the trash rack cleaner with the hydroelectric power station operating and poor predictive and preventive maintenance program, 3.70% because of insufficient staff, 2.40% because of electrical circuit faults and 2.0% because of floods.

Solutions were proposed to mitigate or eliminate the causes and increase the removal of sediments to reduce the discharges to 15%. The proposed solutions range from equipment modernization, maintenance and operation management, resource management, staff skills development, and monitoring and control.

4.3.1 Solutions Proposed to Reduce the Discharges to 15%

- Modernize the cutter suction dredger to allow it to move through a sedimented reservoir.
- Modernize the trash rack cleaner to operate during the energy generation process.
- Develop failure mode and effect analysis (AMFE).
- Implement predictive and preventive maintenance plans aimed at eliminating or mitigating the consequences of failure modes.
- Prepare a materials inventory (stock of materials) with quantities, locations, maximums and minimums and reorder points.
- Implement indicators of reliability, availability, mean time between failures (MTBF), and mean time to repair (MTTF).
- Evaluate the person-hour requirement to achieve the required utilization.
- Assess the specific competencies of the maintenance and operation staff.
- Perform a life cycle cost (LCC) analysis of dredging assets.

LCC analysis is a technique that assesses the viability of the operational continuity of existing assets or the need for renewal for selecting the best economic and socially responsible decision for companies, and it considers economic, technical, environmental, physical safety and occupational health and safety principles (Ferreira and Santos 2012; Kambanou 2020; Kim et al. 2015). The cutter suction dredger has a weight of 60% during the removal of sediments; for this reason, its modernization should be one of the main focuses.

5 Conclusions

A sedimented dam was recovered, and its productive life cycle continues by applying water resource management and sediment transit strategies through dredging. The implemented strategies reduced overflows from 88 to 40% in 3 years; however, due to the sedimentation

of the reservoir, it has been necessary to operate the hydroelectric power plant at low loads during 46% of the year, which implies a decrease in the overflows to 20% in the best of the cases. Strategies were proposed to reduce discharges to 15% and to increase the storage capacity of the reservoir to 29%. The results of the proposed solutions will be discussed in a future paper.

Abbreviations AMFE: Failure mode and effect analysis; BOD: Biochemical oxygen demand; DO: Dissolved oxygen; E: Dredging capacity (m^3/h); E1: Storage capacity greater than 30%; E2: Storage capacity less than 6% (without sediment transit strategy); E3: Storage capacity less than 6% (with sediment transit strategy); Eflow: Ecological flow; h: Dredging (h/year); LCC: Life cycle cost analysis; MTBF: Mean time between failures; MTRF: Mean time to repair; RCA: Root cause analysis; $S_{\text{Accumulated}}$: Accumulated sediment mass; S_{inflow} : Inflow sediment mass; $S_{\text{Overflows}}$: Overflows sediment mass; S_{R} : Sediments removed (m^3/year); S_{Turbine} : Turbine sediment mass; TDS: Total dissolved solids; TOC: Total organic carbon; U: Utilization rate; W: Participation of each equipment in the global balance of sediments removed; WQI: Water Quality Index

Author Contributions PWCF and CAMV contributed to the study concept and design. Material preparation, data collection and analysis were performed by PWCF. CAMV has made analysis and validation of data. The first draft of the manuscript was written by PWCF. CAMV commented on previous versions of the manuscript. PWCF and CAMV read and approved the final manuscript.

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Data Availability Data and material are available upon request to the corresponding author.

Declarations

Consent to Participate Not applicable.

Consent to Publish All authors agree to publish.

Conflict of Interest The authors declare no conflicts of interest.

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