Hurricanes and Sediment Management at Loíza Reservoir, Puerto Rico

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Abstract

Reservoir sedimentation is increasingly recognized as a critical challenge to the sustainability of society. However, sediment management can be costly, making it essential to perform the following fundamental activities to identify a viable sediment management strategy: (1) quantify the marginal benefit, or loss, associated with changes in reservoir capacity; (2) identify cost-effective strategies for sustaining reservoir services, which may include both sediment management and adaptive strategies; and (3) select a sustainable long-term management strategy based on the aforementioned analysis.

The Puerto Rico Aqueduct and Sewer Authority's Loíza water supply reservoir, operating since 1953, has lost nearly half of its gross capacity by sedimentation, despite costly dredging. The three activities cited above are performed at Loíza reservoir to identify the marginal benefit of storage gains or losses, to quantify the benefits of sluicing for sediment management, and to identify a sustainable long term management strategy. Data from the sluicing event during hurricane María (9/20/2017) are used to calibrate the sediment models.

Operational modeling shows that a volume change of 2 Mm^3 in this 15 Mm^3 reservoir has a very small impact on firm yield, yet to achieve this volume change by dredging costs over $90 million. However, the operational model also shows that conjunctive operation of the reservoir together with a standby wellfield with 1.1 m^3/s (25 Mgd) pumping capacity can increase firm yield by 0.88 m^3/s (20 Mgd), operating the wells only when reservoir levels drop. This limits the average rate of groundwater withdrawal of only 0.15 m^3/s (3.5 Mgd). This cost-effective adaptive strategy maximizes surface water use when available, relying on groundwater only during dry periods.

For sediment management, both field data and modeling show that sediment sluicing during large floods, passing flow through the reservoir at the lowest possible water level and shortest detention time, represents a viable strategy to sustain reservoir capacity. This stands in contrast to traditional reservoir management approaches which convert large floods into massive sediment-trapping events. Bathymetric data and modeling show that sluicing during hurricane María produced a net storage gain of 2.5 Mm^3 by avoided sedimentation plus scour of previously deposited sediment. This gain equals 8 years of sedimentation at the historical rate.

Experience at Loíza reservoir demonstrates that large storms can be used beneficially to control sedimentation, as opposed to the traditional mode of reservoir management under which hurricanes represent catastrophic sedimentation events.

Introduction

Society is dependent on reservoir storage to regulate natural hydrologic flows for water supply, hydropower, and flood control. The displacement of storage capacity by sedimentation is increasingly recognized as a critical challenge to sustainability, with a recent study suggesting as much as 26% of global reservoir capacity may be lost by 2050 (Perera et al. 2022).

Storage reservoirs occupy a wide variety of physical and operational environments, and a wide range of techniques for working toward a sediment balance have been summarized by Morris (2020), pointing out that “Reservoir design and management without a long-term sediment management strategy is not a sustainable approach, and no longer represents an engineering best practice.” To preserve long-term capacity requires that sediment inflow be balanced by an equivalent outflow. However, sediment management can be costly, making it necessary to understand the benefits of sediment management vs. alternative approaches to sustainably providing the services currently derived from reservoir storage. Although reservoir storage is absolutely necessary, the amount of storage needed depends on factors such as the economic benefits of storage and the cost and feasibility of both sediment management and adaptive measures that can compensate for benefits lost due to sedimentation.

Puerto Rico is heavily dependent on reservoirs for municipal water supply. By 2020 the 20 reservoirs that provide the majority of the supply had lost, on average, over one-third of their original capacity to sedimentation. One such case is the Loíza (Carraízo) reservoir, owned by the P.R. Aqueduct & Sewer Authority (PRASA). It is the largest single source of water supply for San Juan with a draft rate on the order of 3.5 m^3/s (80 Mgd). Gross capacity declined by 44% from 1953 to 2019, despite dredging in 1997.

A particularly attractive management strategy is sediment sluicing, which routes sediment-laden floods through a reservoir at the highest possible velocity (lowest detention time). This minimizes sedimentation and, under favorable conditions, can scour previously deposited sediment. This strategy can be particularly useful in tropical environments where intense storms can deliver large sediment loads in a short time. Additional parameters that increase the potential for successful sluicing include: narrow reservoir geometry, large-capacity flood gates that allow high flow velocities to be developed along the length of the reservoir, and relatively fine-grained sediments (fine sands and silts) that can be passed through the reservoir or eroded if previously deposited. These conditions are met at Loíza reservoir.

The water supply firm yield is the supply that is available on a reliable basis. In our analysis of reservoir yield in Puerto Rico, we calculate firm yield as the withdrawal rate that can be sustained on 99% of the days, with a 30% reduction in water delivery on the remaining 1% of the days (“rationing” days). These rationing days are concentrated in drought years. This analysis is performed using historical daily inflow records from USGS gages with over 60 years of record.

However, sluicing may not be able to recover and sustain the original full capacity of the reservoir’s operational pool. Therefore, an analysis of adaptive opportunities available to the water supply system can identify cost-effective strategies to compensate for reduced reservoir capacity. The analysis undertaken demonstrates that through conjunctive use, the total firm yield of the overall system can be increased beyond the original firm yield of the reservoir, despite significant sedimentation. Furthermore, this firm yield may also exceed the combined firm yield of the reservoir and groundwater resources, if each were operated independently.

Operational modeling of Loíza reservoir is used to evaluate the relationship between storage and yield for the reservoir when operated independently as compared to operation under a conjunctive use rule. One-dimensional sediment transport simulations are used to simulate the effectiveness of sluicing for sediment management, using data from hurricane María in 2017 to achieve model calibration. The calibrated model is then used to evaluate the effectiveness of sustaining long-term reservoir capacity.

Employing both operational and sediment modeling it is demonstrated that not only is the combination of sediment sluicing plus conjunctive use a cost-effective long-term strategy, but that this strategy can actually increase the system-wide firm yield substantially beyond that available from the reservoir alone with zero sediment.

Study Area Description

Project Description

The Loíza reservoir regulates a moist and mountainous 538 km² watershed which can generate a 100-year discharge of 6400 m³/s at the damsite. The plan view of this 10 km long reservoir is seen in Figure 1. The configuration of the dam in relationship to the storage pool is illustrated in Figure 2, showing that the crest gates extend below the bottom of the operational pool. By 2019 the original 1953 gross capacity of 26.8 Mm³ had been reduced to 15.06 Mm³, despite dredging 6 Mm³ in 1997, and the operational pool was reduced from 17.8 to 13.0 Mm³.

The Capacity:Inflow (C:I) ratio, the ratio of storage capacity to mean annual inflow, is equivalent to the average hydraulic residence time (HRT), expressed in years, and indicates the reservoir's hydrologic size. By 2019 this value was only 0.041 for Loíza reservoir, and during extreme events the HRT can be quite short. During hurricane María (9/20/17), the 24-hour discharge from the dam (USGS gage 50059050) was sufficient to fill the reservoir 10 times in 24 hours. This produces a HRT of 2.4 hrs at normal pool level, but under 1 hour for drawdown sluicing.

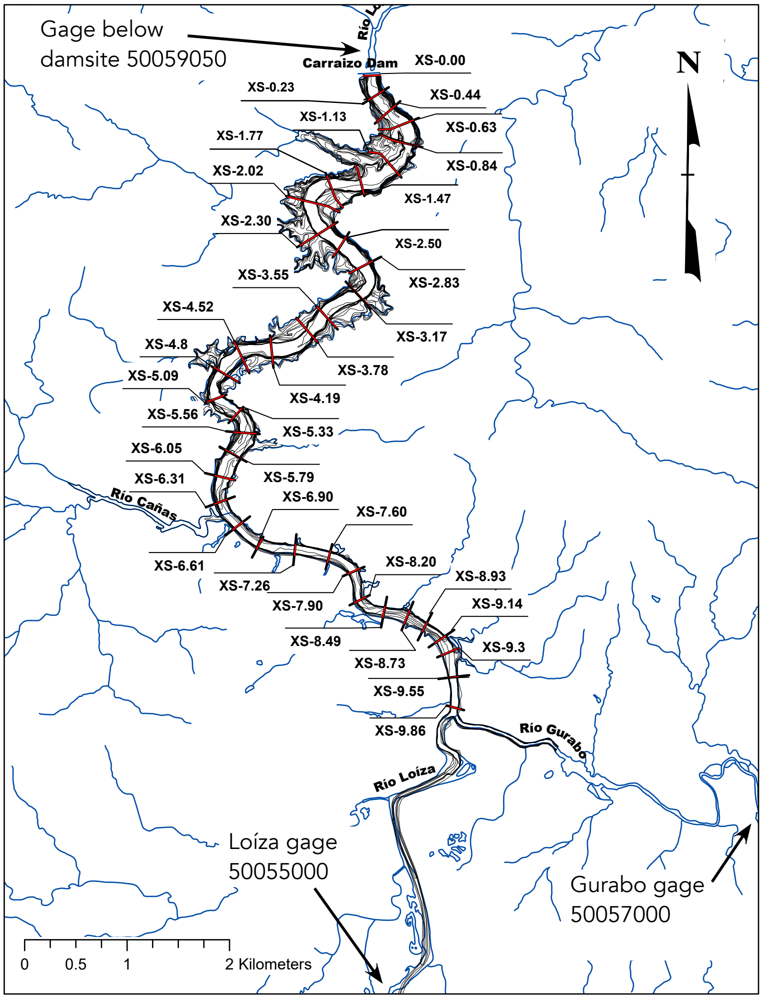


Figure 1. Plan view of Loíza reservoir impounded by Carraízo dam, showing the reservoir, cross sections (XS) used in the SRH-1D transport model, and USGS gage stations. Watercourses shown in blue.

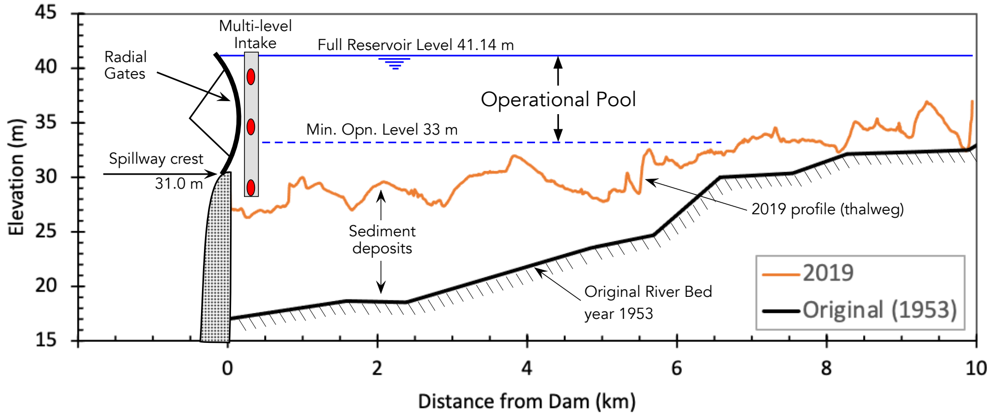


Figure 2. Longitudinal reservoir thalweg profiles also showing dam configuration and operational pool levels

Prior Studies

Multiple surveys of Loíza reservoir have been conducted by the NRCS, USGS and GLM Engineering. A history of sedimentation up to November 1994 was prepared by Webb and Soler-Lopez (1997). A sluicing system for Loíza reservoir was first analyzed by Morris and Hu (1992) using HEC-6 software, and hydrologic-hydraulic software was developed to guide gate operations for sluicing events (Morris et al. 1992). A description of sediment management options for Loíza reservoir is presented as a case study in Morris and Fan (1998), outlining the sluicing strategy shown in Figure 3 and described below.

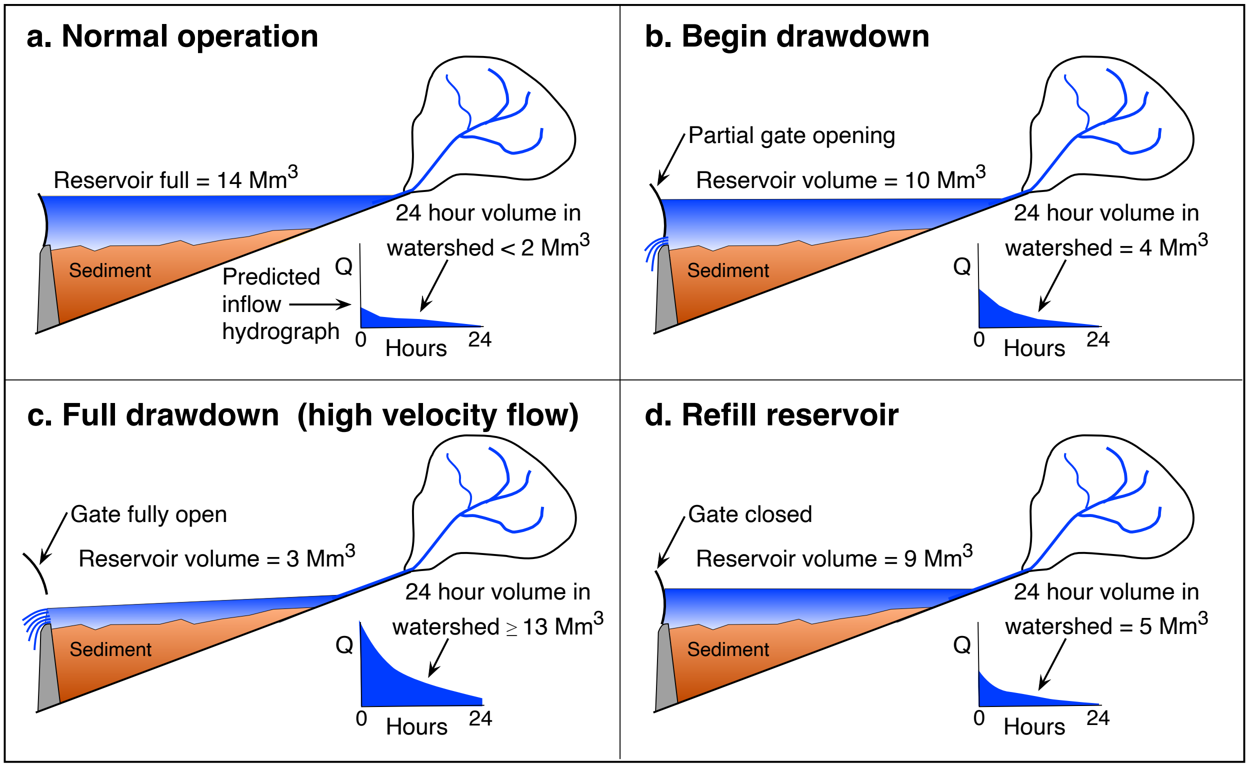


Figure 3: Sluicing strategy for single events at Loíza reservoir (modified from Morris and Fan 1998).

1. During periods of unremarkable weather the reservoir is operated normally.
2. When a large storm approaches and begins to deliver rainfall into the watershed, a hydrologic model operating with real-time data continuously predicts the firm inflow for the next 24 hours based on received rainfall, and an equivalent volume of water is released from the reservoir to begin gradually lowering the water level prior to arrival of the flood wave.
3. If the storm continues to develop, additional gates are opened until all gates are fully open with free flow over the spillway, thereby minimizing water level and maximizing the flow velocity through the reservoir.
4. As the storm abates, reaching the point that there is only enough predicted runoff from the watershed to refill the reservoir, the gates are closed and the reservoir is refilled over the next 24-hours.

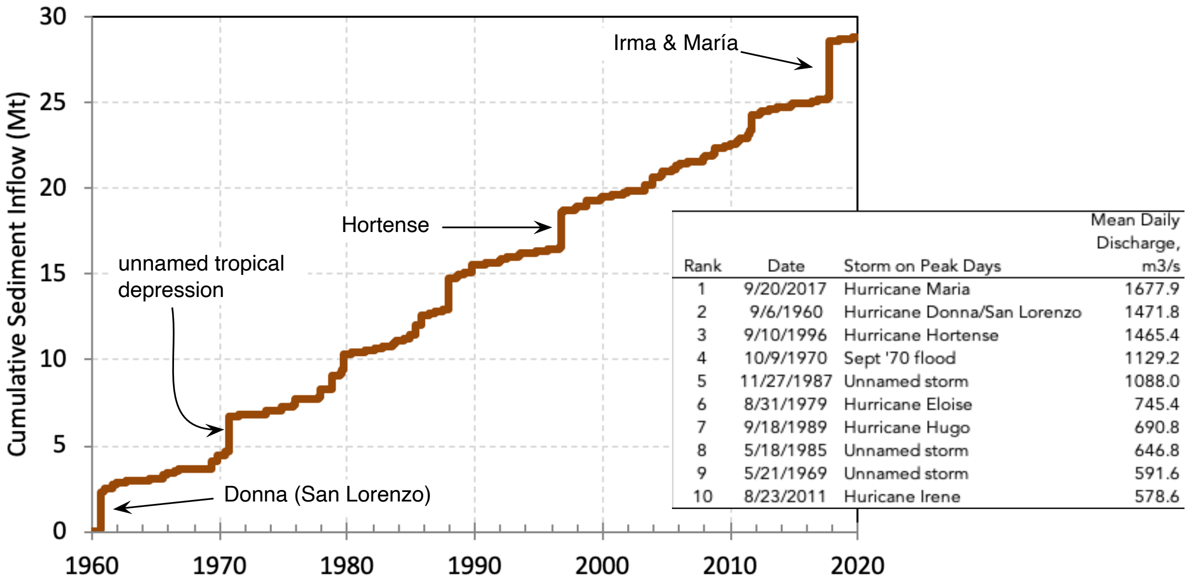
By using a real-time hydrologic-hydraulic model with soil moisture accounting to predict 24-hour runoff volume based on rainfall received, it is possible to ensure the reservoir is refilled within 24-hours of gate closure. Thus, sluicing will have no impact on reservoir firm yield, other than preserving long-term storage capacity.

Sluicing was not implemented at Loíza pending rehabilitation of the radial gates, a project that was not completed until more than a decade after the studies were performed. However, the reservoir was dredged in 1997, removing 6 Mm^3 at a cost of \$60 million (Morris and Fan 1998). By 2019 this dredged volume had been lost to additional sedimentation, and an additional 2 Mm^3 of dredging is scheduled to start in 2023 at a cost of \$93 million. The reservoir has historically been held at a high level during floods, with limited drawdown during storms and opening gates only as needed to control water levels. However, during hurricane María all 8 gates were fully opened resulting in free discharge over the spillway, making this the only sluicing event known to have occurred since dam construction.

Adaptive strategies can also be a critical element in addressing the impacts of reservoir sedimentation (Morris 2020). Potential adaptive strategies to offset yield losses from reservoir sedimentation include reduction of physical water losses (65% of production in fiscal year 2021, Arcadis 2022), development of new supply projects, and conjunctive use of surface and groundwater resources. Conjunctive use is a long-established procedure to optimize water resource management from multiple sources, especially ground and surface supplies (U.S. Army Corps of Engineers 1988; Winter et al. 1999). The benefits of this strategy to increase water supply firm yield was analyzed by operational modeling in the P.R. Water Plan and found to be highly effective given Puerto Rico's climate (PR DNER 2016). Given that there is already approximately 0.88 m^3/s (20 Mgd) of out-of-service well capacity connected to the PRASA system (MP Engineers 2015), the ease of implementing this alternatives (as compared to the control of water losses, for example), together with the large increases in firm yield available from a conjunctive use strategy, the analysis of adaptive strategies at Loíza reservoir focused on conjunctive use.

Sediment Delivery

A rating relationship was developed from suspended sediment data collected from 1981 to 2001 at USGS gages on the two main tributaries, Río Loíza and Río Gurabo (Figure 1). Applying the rating relationship to the discharge series from 1960 through 2021, with adjustment for the ungaged tributary area, produces the cumulative daily sediment load plotted in Figure 4, which shows the importance of extreme events. On average, 7 days per decade had a daily inflow volume at least double the reservoir's current gross capacity of 15 Mm^3, making these days prime candidates for reservoir drawdown to conduct sediment sluicing. These 7 days days account for 57% of the total sediment inflow, and the four largest storm days named in Figure 4 accounted for 24% of the total 63-year sediment load (1960-2022 inclusive).



Rank	Date	Storm on Peak Days	Mean Daily Discharge, m3/s
1	9/20/2017	Hurricane Maria	1677.9
2	9/6/1960	Hurricane Donna/San Lorenzo	1471.8
3	9/10/1996	Hurricane Hortense	1465.4
4	10/9/1970	Sept '70 flood	1129.2
5	11/27/1987	Unnamed storm	1088.0
6	8/31/1979	Hurricane Eloise	745.4
7	9/18/1989	Hurricane Hugo	690.8
8	5/18/1985	Unnamed storm	646.8
9	5/21/1969	Unnamed storm	591.6
10	8/23/2011	Huricane Irene	578.6

Figure 4. Cumulative suspended sediment load and hurricane names. The 4 indicated storms accounted for 24% of the total 63-year sediment load.

Figure 4: Inset table: temporal ordering might be better for consistency with plot, instead of ranking by mean daily discharge. Removing "rank" column would allow the text size to be increased.

Benefits of Storage and Conjunctive Use

Without storage the firm yield available from a river is limited to the daily run-of-river flow. At Loíza the 99% exceedance flow is 1.2 m³/s (27 Mgd). As storage is added the firm yield increases, but as storage capacity continues to be added the incremental or marginal yield benefit per unit of additional capacity will decline. This is reflected in Figure 5 as a declining slope for the yield curves as storage capacity increases.

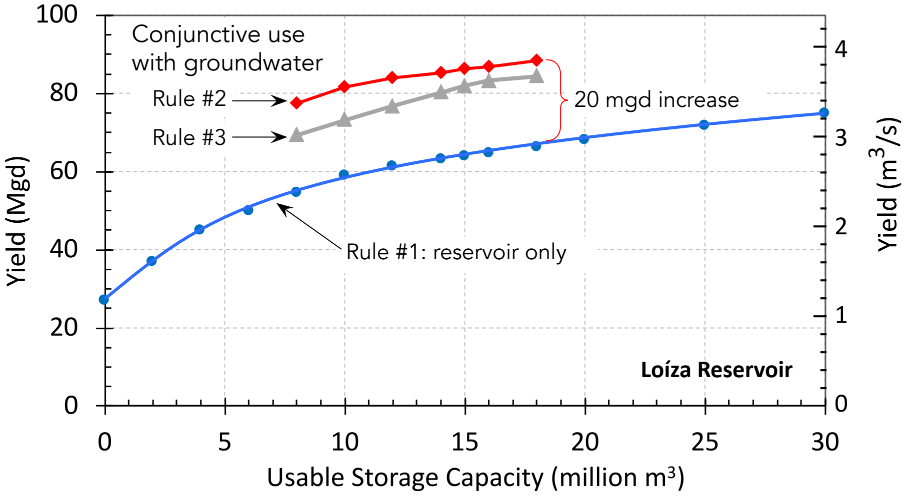


Figure 5. Storage-yield curve for Loíza reservoir under three different operational scenarios

Because not all reservoir storage generates equal benefits, in developing a strategy to preserve storage capacity a critical question is, "*How much capacity is needed?*" This is particularly relevant from the standpoint of sluicing because, as reservoir capacity declines in relation to inflow, it becomes increasingly easy to sluice sediment due to the reduced HRT. Also, while the reservoir may itself be irreplaceable, this does not mean that all the capacity is irreplaceable. Within certain limits, it may be possible to offset the yield reduction due to capacity loss using more cost-effective "adaptive" measures such as conjunctive use with groundwater sources.

The storage-yield relationships for Loíza reservoir shown in Figure 5 were calculated by a hydrologic operational model developed in Excel and using 63 years of historical inflow data and applying three alternative operational rules:

- Rule #1: Constant draft. The reservoir has historically operated at a constant withdrawal rate. For simulations, firm yield is defined as the draft rate that produces water rationing 1% of the time (modeled as a 30% decline in deliveries when reservoir storage drops to 35% of full capacity), with the reservoir never going dry. Rationing does not occur in most years, but dry years can produce prolonged rationing periods. Historically, low inflows during 1967-68, 1972, 1994, 1995, 2015, and 2020 have resulted in rationing with rotating water deliveries, in some cases delivering water to customers every third day. Thus, the simulated operational rule represents an improvement over historical operating conditions during drought.
- Rule #2: Conjunctive use with rationing. The second case considers variable-rate reservoir operation in conjunction with a 1.1 m^3/s (25 Mgd) standby well field that operates only when reservoir levels drop to a pre-determined threshold. Many of the wells required for this operation already exist and are connected to the system, but were abandoned when a new surface water project, the 4.4 m^3/s (100 Mgd) Superaqueduct, began operating in 2001 (MP Engineers 2015). Under this rule water rationing occurs using the same trigger and rate as Rule #1.
- Rule #3: conjunctive use without rationing. The third case uses the same trigger levels to initiate operation of 1.1 m^3/s (25 Mgd) of standby well capacity, but water rationing is not allowed. Firm yield is defined by avoiding an empty-reservoir condition. The requirement to sustain normal water deliveries during all drought events produces a lower firm yield under this rule as compared to Rule #2.

By comparing the storage-yield curves it may be seen that there is no unique "must have" storage volume. Rather, a target yield can be achieved through the integrated use of both the reservoir and groundwater supplies across a range of reservoir capacities. Alternative curves could also be developed with different capacities for the standby wellfield, for different trigger levels, etc.

In practice, this surface-groundwater integration would be developed considering the operation of the four north coast reservoirs interconnected through the existing 72" diameter Superaqueduct pipeline. However, for this analysis only Loíza reservoir is evaluated.

The advantage of conjunctive use is that the large increase in firm yield offered by wells is achieved with a very low average rate of groundwater withdrawal. For example, conjunctive use Rule #2 typically increases firm yields by ~0.88 m^3/s (~20 Mgd). However, despite an installed pumping capacity of 1.1 m^3/s (25 Mgd), the wells are pumped only intermittently, on average less than 50 days per year, resulting in a long-term pumping rate averaging less than 0.15 m^3/s (3.5 Mgd). This is far less than historical groundwater pumping rates, which were excessive. Due to dramatically reduced pumping from both industrial and municipal wells since year 2001, water levels in the north coast aquifer have recovered from prior over-pumping (Richards 2020). This condition makes a conjunctive use strategy feasible without endangering the recovered aquifer.

The importance of understanding the marginal value of storage and adaptive management strategies is underscored by the dramatic cost difference between different alternatives. At the end of 2022 PRASA awarded a contract for the dredging of 2 Mm^3 at a bid price of $93 million, which does not include owner-side engineering, permitting and management costs. The storage-yield relationship shows that a 2 Mm^3 increase in reservoir volume by dredging will produce only a 0.088 m^3/s (2 Mgd) change in firm yield under any of the scenarios. In contrast, rehabilitation and reconnection of groundwater sources is likely to cost less than half as much as dredging, while producing 10-times more firm yield than dredging 2 Mm^3.

Methodologies for Analysis of Sediment Sluicing

Overview

The simplest approach to analyze potential sluicing benefits is to evaluate the impact of reduced HRT on the reservoir's trap efficiency (TE) using the Brune (1953) or Churchill (1948) methods, performing TE computations using a daily time step. This analysis can be performed from a limited dataset: daily water inflow, historical reservoir operations (water levels), and historical bathymetric data for model calibration. As a limitation, TE modeling cannot evaluate scour.

A more comprehensive analysis of sluicing uses a sediment transport model to evaluate both deposition and scour. This requires more data: daily inflow of both water and sediment, particle size of the sediment load, reservoir geometry, historical reservoir operations (water levels), and hydraulic characteristics of existing or proposed dam outlets to construct the daily operating rule required for modeling future conditions. Calibration requires historical bathymetric data and, hopefully, particle size data along the length of the reservoir. This analysis is usually performed as a long-term simulation using a 1-dimensional transport model. Alternatively, short-duration multi-dimensional simulations could be used to analyze individual floods if detailed data were monitored during one or more flood events. (Use of a multi-dimensional model would be poorly suited to long-term simulations due to the excessive computational requirements).

Trap Efficiency Modeling

Trap efficiency is defined as the percentage of the inflowing sediment load trapped in a reservoir over any specified period of time. The most common method uses the curves presented by Brune (1953) to estimate average TE over a multi-year period. The Brune median curve for long-term sediment trapping can be expressed by an equation having the following form (Heinemann 1981):

$$Trap\ Efficiency = \frac{C/I}{B_1 + B_2(C/I)} = \frac{C/I}{0.012 + 1.02\ (C/I)} \qquad (1)$$

where C = gross reservoir capacity (m^3), I = mean annual inflow (m^3), and B_1 and B_2 are dimensionless calibration coefficients. Trap efficiency varies as a function of HRT, and both HRT and TE can be defined daily. Recognizing this, Brune included as Figure 4 of his paper Borland's graph of measured TE vs. HRT for sediment trapping at Imperial Dam Reservoir on the lower Colorado River, for HRT values from 0.5 to 7 days. Brune's curves are traditionally employed by computing a capacity:inflow ratio from annual inflow, producing a long-term average TE. However, as described by Lewis et al. (2013), Brune's TE approach can also be adapted to a daily time step. This approach has been adopted for Loíza reservoir, performing HRT calculations using daily volume in storage (V) instead of gross reservoir capacity (C), and the daily inflow volume (I). The relevant equations were incorporated into a spreadsheet model.

During sluicing events, with reservoir gates fully open, daily volume was estimated based on water levels computed from the spillway rating curve. Maximum reservoir volume was also reduced over time to account for sediment accumulation. Scour cannot be simulated by this methodology.

Churchill Method

Churchill (1948) developed a relationship for sediment "release efficiency" (the inverse of trap efficiency), as a function of the reservoir's sedimentation index, which is the retention period divided by mean flow velocity. Lewis et al. (2013) concluded that the Churchill provided a somewhat better predictor of sedimentation at the reservoirs they were working with in NE Australia, characterized by large inter-annual flow variations. They expressed the Churchill equation in the following form:

$$TE = 112 - 800\left[\frac{V/_{Q}}{Q/_{A}}\right]^{-0.2} \tag{2}$$

where the value of V/Q in the numerator is an indicator of hydraulic residence time (in seconds) computed from volume V (m^3) and inflow Q (m^3/s). The term A in the denominator is calculated as $A=V/L$ where L is reservoir Length (m). For use at Loíza reservoir the equation was re-written as:

$$TE = C_1 - C_2\left[\frac{V/_{Q}}{V/_{A}}\right]^{C_3} \tag{3}$$

where C_1, C_2 and C_3 are coefficient values that can be adjusted in the calibration process. For Loíza reservoir the exponent value of C_3 = -0.2 used by Lewis et.al. was retained but the coefficients C_1 and C_2 were modified two ways. First, they are divided by 100 to express the trap efficiency as a decimal fraction. Second, both values were adjusted by calibration against the historical reservoir capacity data from bathymetric surveys. The alternative forms of the Churchill equation presented by (Heinemann 1981) and the U.S. Bureau of Reclamation (1987) were also tested but did not offer any improvement when applied to Loíza reservoir during the calibration process.

Sediment Transport Modeling

The U.S. Bureau of Reclamation's SRH-1D sediment transport modeling software ver 4.0.1 (Greimann and Huang 2018) was used to simulate the Loíza reservoir. The model has the ability to analyze permanent and transient flows, various boundary conditions, complex river systems lateral flows of both water and sediment, and a wide range of both coarse and fine sediments. Structures such as weirs and gates can also be simulated. This software can simulate armoring by coarse sediments as well as erosion, deposition and consolidation of cohesive sediments. Multiple transport equations are available for both suspended and bed load transport.

For Loíza the channel boundary was modeled by the Exner continuity equation as a series of steady flows. The downstream time-stage boundary was set at the reservoir spillway, using an operational model to establish these water levels for different scenarios. The upstream boundary consists of 63 years of daily inflow data from the USGS gages, adjusted for the ungagged portion of the watershed. Particle size distribution of the inflowing load was based on data from borings performed in the reservoir in 2021, and the load was estimated from the sediment rating curves previously described. Lacking pre-impoundment topography, and given the poorly-documented template for the 6 Mm^3 of dredging performed in 1997-98, the January 2004 bathymetric survey was used as the starting geometry for all sediment transport modeling.

Transport Model Calibration

Transport model calibration was performed against the October 2019 bathymetry which followed sluicing during hurricane María. The discharge hydrograph and water levels at the dam for hurricane María are shown in Figure 6. For long-term simulations, and based on the available long-term data format, boundary conditions for both water level and inflow were set using a 1-day time step. Model calibration was performed on this basis using the average daily inflow, with water level at the dam during sluicing computed from the spillway rating curve.

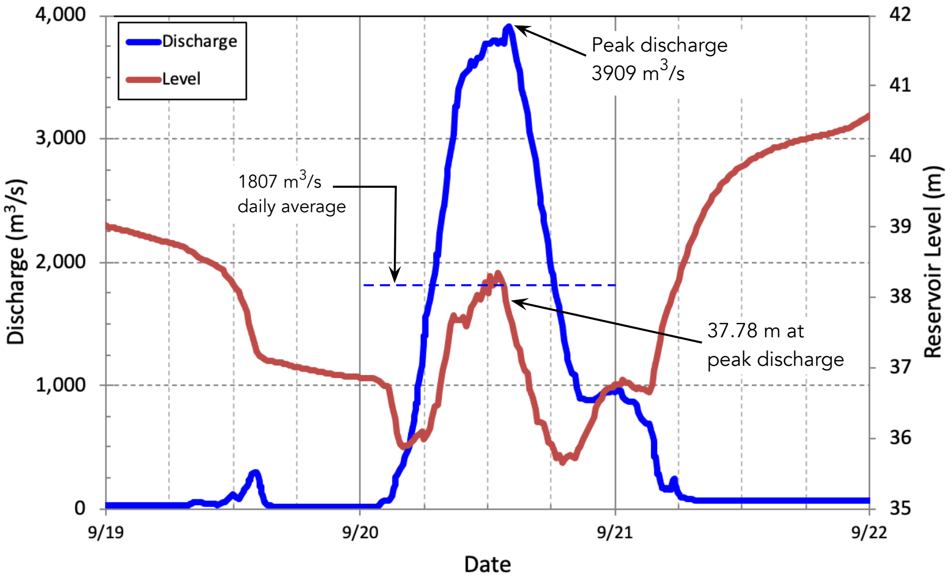


Figure 6. Discharge hydrograph and water levels during hurricane María on Sept. 20, 2017. (*Data from USGS gages 50059050 and 50059000*)

The particle size distribution entering the reservoir was simulated to vary with discharge, averaging about 25% clay, 45% silt and 30% sand. The Ackers-White transport equation was found to provide the best results during model calibration. Although this equation is known to over-estimate the transport of smaller sediment, because the inflow dataset uses mean daily flows instead of instantaneous discharges, the actual peak discharges will not be reflected in the dataset. It appears that the Ackers-White equation can produce more accurate results in situations where the instantaneous peak discharges are not simulated.

The 2004 bed profile for the start of the calibration simulation, the measured 2019 profile, and the simulated 2019 profile, are all seen in Figure 7. The scour caused by the hurricane flood was successfully simulated by the mode using the Ackers-White transport equation.

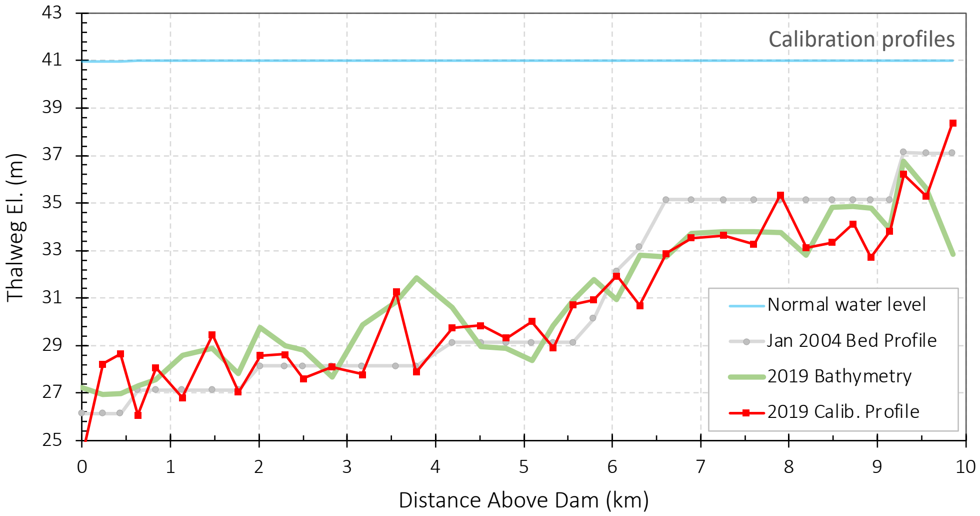


Figure 7. Thalweg profiles along Loíza reservoir including the model calibration profile

Results

Trap Efficiency Modeling

Loíza reservoir began impounding 7 years prior to installation of upstream USGS gages on the Loíza and Gurabo rivers. Therefore, the time series used in the TE analysis starts on 1/1/1960 and the capacity of the reservoir on that date is estimated at 24.43 Mm^3 by linear interpolation between the initial reservoir capacity of 26.8 Mm^3 in 1953 and 23.4 Mm^3 reported by the first bathymetric survey in 1963.

Coefficient values for the Brune and Churchill curves were calibrated against historical bathymetric data, producing the curves of daily reservoir capacity shown in Figure 8. The TE vs HRT relationship underlying these curves were developed by calibrating coefficient values for the Brune (1) and Churchill (3) equations.

Computations were undertaken each day starting on January 1, 1960, using the computational methodology previously summarized. The daily reservoir capacity was then graphed and compared to the capacities determined by reservoir survey on the corresponding dates, adjusting the calibration coefficients to best match the pre-María bathymetric survey values. Because sediment scour occurred during María, post-María bathymetric data were not used for calibration. The resulting calibration coefficients are:

Brune	$B_1 = 0.00090$, $B_2 = 0.9814$
Churchill	$C_1 = -0.2$, $C_2 = 1.15$, $C_3 = 6.0$

Extending the calibrated curves to the date of the October 2019 bathymetric survey, the measured capacity in October 2019 was 2.0 Mm^3 greater than the capacity predicted by TE modeling. However, in the 2-year post-hurricane period, from October 2017 – 2017, both the Brune and Churchill TE models predicted about 0.46 Mm^3 of sedimentation. Thus, the total amount of sedimentation avoided by sediment sluicing during hurricane María is probably on the order of 2.46 Mm³ of reservoir capacity. Sedimentation avoided by sluicing includes both sediment passed through the reservoir during the flood plus sediment removed by scour. As can be seen from Figure 8, once calibrated, the Churchill and Brune equations gave essentially identical results.

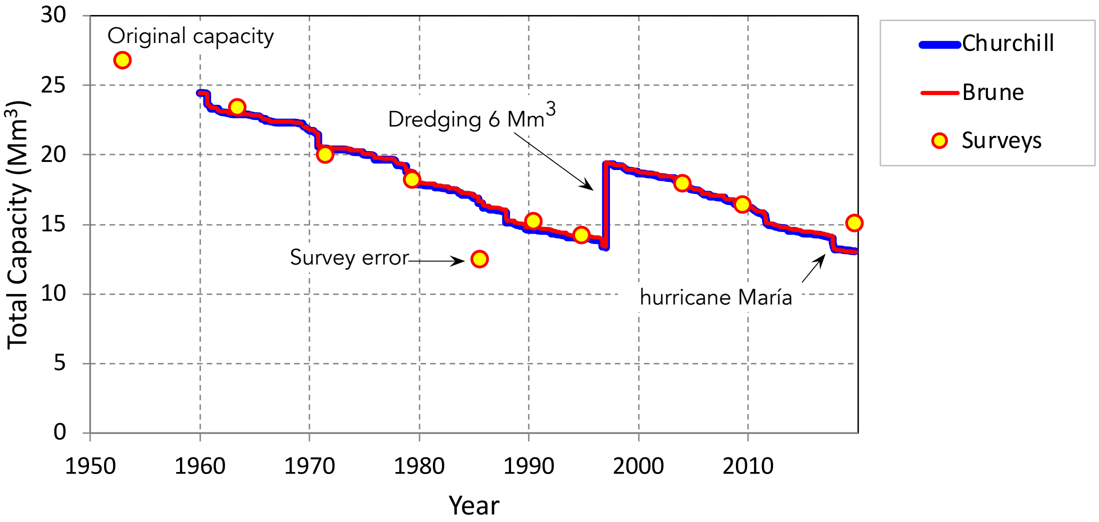


Figure 8. Results of model calibration showing change in reservoir capacity over time compared to historical volume surveys based on daily computations of sediment and trap efficiency by the Brune and Churchill methods

Transport Modeling of Sediment Sluicing

Transport modeling using SRH-1D was used to evaluate the effectiveness of sediment sluicing using 63-year simulations. For these simulations the full 63-year historical inflow time series was used, and the starting date of the dataset (1/1/1960) was assigned to January 1, 2004. The downstream boundary, the water level at the dam, varied depending on the operational scenario:

1. High-level operation: the reservoir is maintained continuously at a high level, opening the crest gates only as required to release the inflowing flood while maintaining reservoir level.
2. Sluicing operation: sediment sluicing was simulated by fully opening the gates for every event in which the 24-hour inflow exceeded twice the gross reservoir capacity (i.e. daily inflow > 30 Mm³). On sluicing days the water level at the dam is established by the spillway rating curve for free discharge, all 8 gates fully open. This rule resulted in, typically, 6 to 7 sluicing events per decade.

The bed profile after 60 years of high-level operation, shown in Figure 9, may be compared against the profile under the sluicing operation shown in Figure 10. This simulation demonstrates that there is considerable energy available for sediment transport along this narrow reservoir, and sluicing alone can be an effective sediment control mechanism if performed during hurricanes and other large floods.

Under the sluicing operation, reservoir volume, as calculated by the average end-area method from model cross-sections, varied from 14.0 to 16.0 Mm³, varying depending on the sequence of sluicing events. The final volume at year 63 was only 1.1 Mm³ less than the simulation starting volume. In contrast, for the high-level operational alternative (without sluicing), the final volume was reduced by about 9 Mm³, a 58% volume reduction compared to the start of the simulation.

Also, over the course of the simulation the reservoir bed transitioned from silt-dominated to sand-dominated. This has already been observed in the field data. Vibracore data revealed a layer of sandy sediment that extended downstream to within about 1 km of the dam, deposits carried deep into the reservoir by hurricane María.

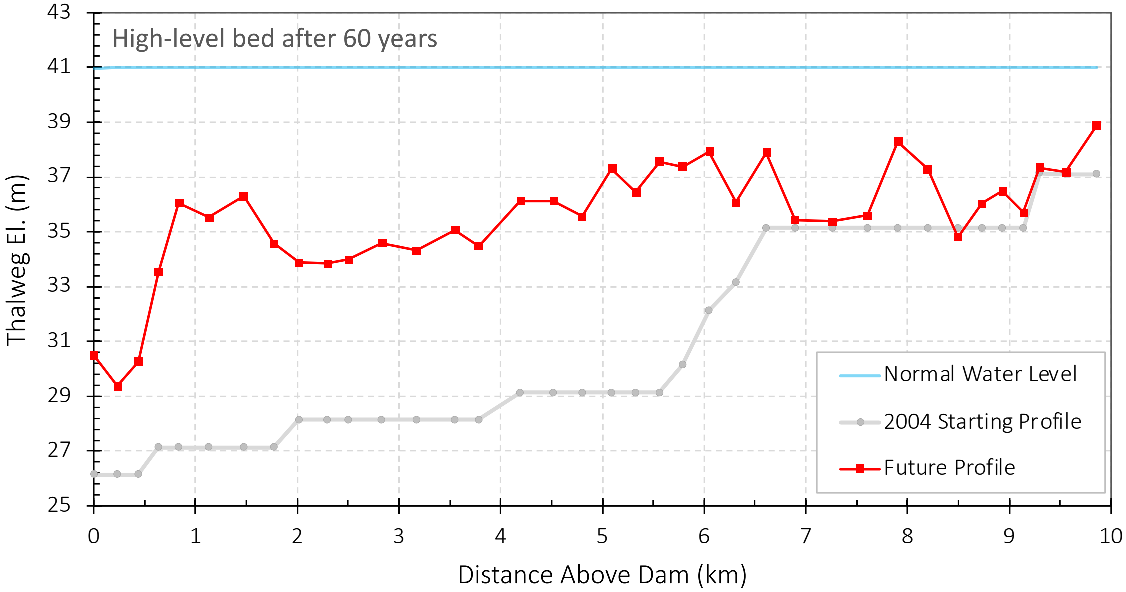


Figure 9. Reservoir bed profile after 60 years of operation at high level

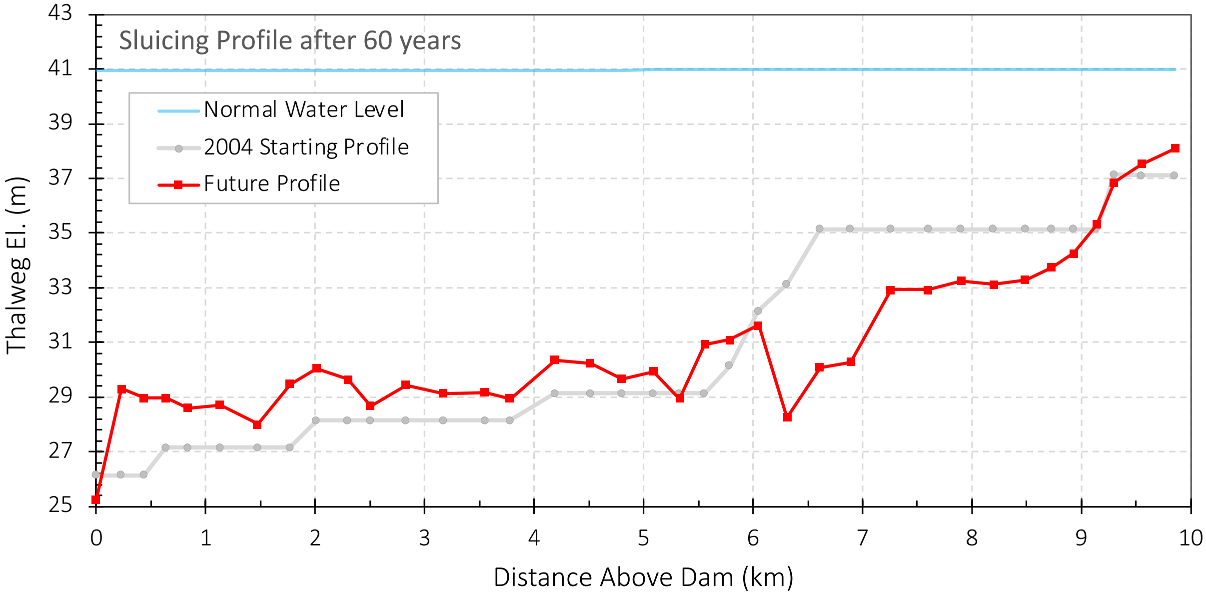


Figure 10. Reservoir bed profile after 60 years of sluicing operation

Discussion and Conclusions

Operational analysis showed that a 2 Mm^3 increase or decrease in live storage will produce not more than a 0.088 m^3/s (2 Mgd) change in reservoir firm yield. In contrast, conjunction operation of the reservoir with a 1.1 m^3/s (25 Mgd) standby wellfield can increase firm yield by 0.88 m^3/s (20 Mgd) despite extracting, on average, only 0.15 m^3/s (3.5 Mgd) from the aquifer. This strategy maximizes the utilization of surface water when available (most years), and extracts groundwater only on an as-needed basis when reservoir levels decline.

This conjunctive use adaptive strategy is far more cost-effective than storage recovery activities such as dredging. The yield analysis summary (Figure 5) also shows that the conjunctive use strategy can even produce a higher yield than would be available from the reservoir if there were zero sedimentation. These results are certainly not applicable to all hydrologic environments, but for the moist climate on Puerto Rico's north coast, with rather well-distributed rainfall throughout the year, the benefits of conjunctive use are large.

Having defined the benefits of storage capacity, and showing that high firm yield can be maintained by adaptive strategies despite some loss in capacity, an analysis was performed to evaluate the feasibility of sustaining reservoir capacity by implementing a sediment-guided operational rule to perform sluicing using the existing crest gates. Two approaches were demonstrated for analyzing the potential benefits of sediment sluicing:

- Trap efficiency modeling was used for a preliminary evaluation of the benefits achieved by sluicing during hurricane María. Trap efficiency modeling clearly showed the impact of sluicing in reducing sedimentation (Figure 8). This approach clearly provides a more detailed picture of sedimentation conditions over time within the reservoir, including in particular the effect of diminished HRT in reducing sediment accumulation from the largest sediment-producing storms. However, a significant limitation of this method is that it cannot evaluate scour.
- One-dimensional sediment transport modeling using SRH-1D software showed dramatic differences in long-term capacity between high-level reservoir operation (Figure 9) and a sluicing operation (Figure 10). This indicates that sluicing can be a highly successful technique for maintaining long-term reservoir capacity, potentially eliminating the need for costly dredging, especially when combined with a conjunctive use water supply strategy.

Sluicing activities conducted in accordance with the procedure outlined in Figure 3 will not impact reservoir yield; the reservoir will always be refilled at the end of each sluicing event. On a preliminary basis, sluicing is also not expected to have a significant impact on operation at the Sergio Cuevas filter plant supplied by Loíza reservoir, since that the filter plant was able to sustain operation throughout the sluicing operation during hurricane María.

These simulations demonstrate that large floods spawned by tropical storms can be converted into opportunities for sediment release to sustain long-term storage capacity, by the sediment-guided operation of existing reservoir gates. This stands in stark contrast to the current paradigm which commonly views these storms as catastrophic sediment-accumulation events.

Acknowledgments and Conflict of Interest

No funding was solicited or used for the completion of this research. No potential conflict of interest was reported by the authors.

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