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Long-term Water Management Model in the Presence of Extraordinary Events

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Abstract
The stretched exponential model describing the sedimentation process of a reservoir was extended to appropriately encompass extraordinary events. These were divided into rapid and sudden events and programmatic events. Among the uncontrollable events, we analysed landslides or extreme weather events. Scheduled events included the construction of satellite dams upstream of the reserve. In addition, a continuous process that reaches a stationary condition is analysed. Finally, it was indicated how to become aware of non-routine events by having a limited number of bathymetric surveys available. The management plot in the presence of two sudden events, which take place at two different times in the life of the dam, was illustrated and discussed.

Keywords Bathymetric data · Sedimentation · Extraordinary events · Management plot

1 Introduction

Reservoirs are critical infrastructure in water resource management, serving multiple essential functions such as irrigation, drinking water supply, flood control, and hydropower generation (Khagram 2018). These multifaceted roles make reservoirs indispensable in sustaining agricultural productivity, providing clean water to communities, and supporting energy production. However, reservoirs face significant operational challenges due to sedimentation, a process wherein soil and organic matter accumulate over time, diminishing their efficiency

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and longevity) (Cimorelli et al. 2021). Sedimentation presents several critical issues for reservoir management (Nath et al. 2024). Firstly, the accumulation of sediment reduces the storage capacity of reservoirs, which can lead to water scarcity during periods of high demand or drought. This reduction in capacity also affects the reservoir's ability to manage floodwaters, potentially increasing the risk of flood damage (Bloutsos et al. 2024). From an environmental perspective, sedimentation impacts aquatic habitats and water quality. The build-up of sediment can alter the natural flow and depth of water bodies, affecting the flora and fauna that rely on these ecosystems. Sediment-laden waters are often turbid, reducing sunlight penetration and impacting photosynthetic aquatic plants. Furthermore, sediments can carry pollutants (Venditti et al. 2011), such as heavy metals and agricultural runoff, which degrade water quality and harm aquatic life. The financial implications of sedimentation are substantial (Bagarani et al. 2020). Sediment removal is a costly and labor-intensive process that places a financial burden on water management authorities and stakeholders (Espinosa-Villegas and Schnoor 2009). The need for frequent dredging and maintenance activities can strain budgets and divert resources from other critical infrastructure projects. Additionally, sedimentation accelerates the aging of reservoirs, necessitating premature investments in rehabilitation or replacement, which further adds to the economic burden. To mitigate the adverse effects of sedimentation and maintain sustainable reservoir capacity, several management strategies are commonly employed. Soil erosion control measures in surrounding areas are crucial in reducing sediment input into reservoirs. Techniques such as vegetation planting (Wagner et al. 2006), terracing (Deng et al. 2021), and sustainable agricultural practices (Piñeiro et al. 2020) help stabilize soil and prevent erosion. Effective storm water management practices, including the implementation of collection basins and vegetative filters, reduce sediment transport from urban, agricultural, and industrial areas into reservoirs. Regular sediment removal, typically through mechanical dredging, is vital to preserving storage capacity (Cui et al. 2017). Dredging involves the use of excavators or specialized dredges to remove accumulated sediment from the reservoir bottom, ensuring continued functionality. Watershed management practices upstream of reservoirs are also essential (Darko et al. 2024). Sustainable forest management, the creation of vegetative conservation zones, and minimizing the impact of human activities on water resources help mitigate sedimentation at its source. Routine monitoring and evaluation of sediment accumulation and water quality provide essential data for assessing the effectiveness of sediment management strategies (Sumi and Kantoush 2011). This information guides corrective actions and informs adaptive management approaches. Engaging local communities in reservoir management efforts fosters a better understanding of sedimentation issues and encourages active participation in conservation initiatives. Community involvement, through awareness campaigns and education on sustainable water resource management, is crucial for the long-term success of sedimentation mitigation efforts (Wilderer 2007; Afzalsoltani and Yazdi 2023).

We recently showed that the sedimentation process in water reservoirs can be mathematically described by a stretched exponential (Molino et al. 2023). The semi-empirical model provides a useful tool for a long-term management of a reservoir's water in a sustainable way. The model was able to fit the bathymetric data with the assumption that the extraordinary events were of negligibly small magnitude. However, sedimentation in reservoirs is a complex process influenced by a combination of natural and human-induced factors so that extraordinary effects not foreseen in the standard process can take place. In this paper we expand the model to include extraordinary events such as large landslides or the construction of lamination basins, which drastically increase or reduce sediment supplies to the dam. The expanded model takes into account events that are generally not considered in routine reservoir management. Thus, the model provides a useful basis for long-term planning of water stored in the reservoir.

Analysis of bathymetric data from dams located in different parts of the world and accessible in the literature have allowed the events to be divided into two categories. The first category consists of rapid and sudden events, the second of schedulable events. As non-schedulable events we discuss landslides or extreme weather phenomena with unpredictable impact. How the planned construction of satellite dams upstream of the reservoir changes the sediment profile in the reservoir is analyzed.

2 Model Details

2.1 Natural Sedimentation Process

Typically the settling process consists of several phases including transport and deposit of sediments. Understanding these phases is crucial for managing reservoirs effectively ensuring their longevity and mitigating adverse impacts on water resources and ecosystems. From now on we will refer to this as a *natural* process.

Through the analysis of various dams scattered around the world, we recently showed that the natural process of sedimentation of solid particles in a reservoir is well described by the following equation

$$\frac{dV_s}{dt} = K(t)(V_\infty - V_s) \tag{1}$$

where, V_s, is the sediment volume at a generic time t, V_∞ is the sediment volume at equilibrium (i.e. completely filled reservoir), $K(t)$ is a proportionality constant (time^{-1}). Empirically, it was established that the sediment level in reservoirs can be monitored by assuming the following form for $K(t)$,

$$K(t) = \frac{\sigma}{\tau}\left(\frac{t}{\tau}\right)^{\sigma-1} \tag{2}$$

where σ and τ are empirical parameters, determined by bathymetric measurements.The solution of Eqs. 1-2 leads to a stretched exponential function

$$V(t) = V_\infty\left[1 - \exp - \left(\frac{t}{\tau}\right)^{\sigma}\right] = V_\infty\left[1 - E_{\sigma,\tau}(t)\right] \tag{3}$$

where, for simplicity,

$$E_{\sigma,\tau}(t) = \exp\left[-\left(\frac{t}{\tau}\right)^{\sigma}\right] \tag{4}$$

has been placed.Equation 4 governs the *natural* process of sediment accumulation and it is the key tool for long-term management in order to preserve sustainable useful capacity of reservoir. However, Eq. 3 does not take into account external factors, such as landslides, secondary catchments, which alter the natural course of sedimentation. Hereafter, we will refer to these events as extraordinary.

2.2 Quick Extraordinary Events

Let us assume that *N* extraordinary events take place which add up $u_1, u_2, \cdots, u_N$ sediment volumes at times $t_1, t_2, \cdots, t_N$. Assume further that *M* extraordinary management activity are coordinated so as to subtract U_1, U_2, U_M volumes of sediment a times $t'_1, t'_2, \cdots, t'_M$. In any case, events develop over a much shorter period of time than the natural unfolding of the sedimentation process. Finally, we assume that the first period of dam activity $(0, t_1)$ is completed without any extraordinary occurrences. Hence, Eq. 1 can be written as where $\delta(x)$ is the Dirac delta function (Li and Wong 2008) An additional volumetric function is defined incorporating the equilibrium volume, i.e.

$$Z(t) = V_\infty - V_s(t) \tag{5}$$

furthermore the new time variable is introduced

$$\phi(t) = \int_0^t K(u)du \tag{6}$$

so that Eq. 6 can be re-written as

$$\frac{dZ}{dt} = -K(t)Z(t) - \sum_{j=1}^{N} u_j\delta(t-t_j) + \sum_{i=1}^{M} U_i\delta(t-t_i) \tag{7}$$

Now, we seek the solution of Eq. 7 in the form

$$Z(t) = \gamma(t)\exp\left[-\phi(t)\right] \tag{8}$$

Substitution of Eq. 8 into Eq. 7 yields

$$\frac{d\gamma(t)}{dt}\exp\left(-\phi(t)\right) = -\sum_{j=1}^{N} u_j\delta(t-t_j + \sum_{i=1}^{M} U_i\delta(t-t_i) \tag{9}$$

whence

$$\gamma(t) = B - \sum_{j=1}^{N} u_j \exp\left[\phi(t_j)\right] + \sum_{i=1}^{M} U_i \exp\left[\phi(t_i)\right] \tag{10}$$

where B is an integration constant. To determine the constant B, the initial condition $V_s(0) = 0$ is used. Thus, the general solution of Eq. 7 becomes

$$V_s(t) = V_\infty(1 - E_{\sigma,\tau}(t))\mathcal{L}(t - t_1) + \sum_{j=1}^{N} u_j \mathcal{H}(t - t_j)\frac{E_{\sigma,\tau}(t)}{E_{\sigma,\tau}(t_j)} - \sum_{1=1}^{M} U_i \mathcal{H}(t - t_i)\frac{E_{\sigma,\tau}(t)}{E_{\sigma,\tau}(t_i)} \tag{11}$$

where the following abbreviations have been used

$$\mathcal{L}(t) = \mathcal{H}(t) - \mathcal{H}(t - t_1) \tag{12}$$

The Heaviside step function is defined as

$$\mathcal{H}(x) = \begin{cases} 0 & \text{if} \quad x \le 0 \\ 1 & \text{if} \quad x > 0 \end{cases} \tag{13}$$

Equation 11 indicates that in order to calculate the sediment volume at a given time, we first compute the parameters σ and τ for the natural sedimentation using the procedures described in Molino et al. (2023). Once the parameters are known, it is possible to calculate the amount of sediment due to the extraordinary events and the times at which they take place. It is important to point out that this class also includes extreme weather events, due to climate change, which move large amounts of solid material towards the dam.For numerical example, let us consider a process characterized by $\sigma = 0.4$ and $\tau = 120$ y. Four and 15 years after the dam was commissioned, two landslide events occurred that increased the natural sediment volume by 0.2% and 1% respectively. Figure 1 illustrates the example described and makes it clear that due to landslides, after only 15 years of operation, the reservoir has exhausted 50% of its maximum capacity. Figure 1 also shows how it is possible to intervene with *ad hoc removal*, which roughly restores the natural course of the sediment.

2.3 Sediment Trapping Upstream of the Dam

In this case, in order to reduce the amount of sediment reaching of the reservoir, a series of upstream dams a are built that retain the sediment bulk. The untrapped sediment reaches the dam naturally and follows the stretched exponential law, albeit with different parameters.

Let $[t_{j-1}, t_j]$ the time interval where sedimentation occurs naturally, i.e. with a stretched exponential law with parameters σ_{j-1}, τ_{j-1}. Thus, sediment evolution, on each interval, takes the form

$$\frac{dV_s}{dt} = \mathcal{L}_{j-1}(t)(V_\infty - V_s(t)) \tag{14}$$

where the function

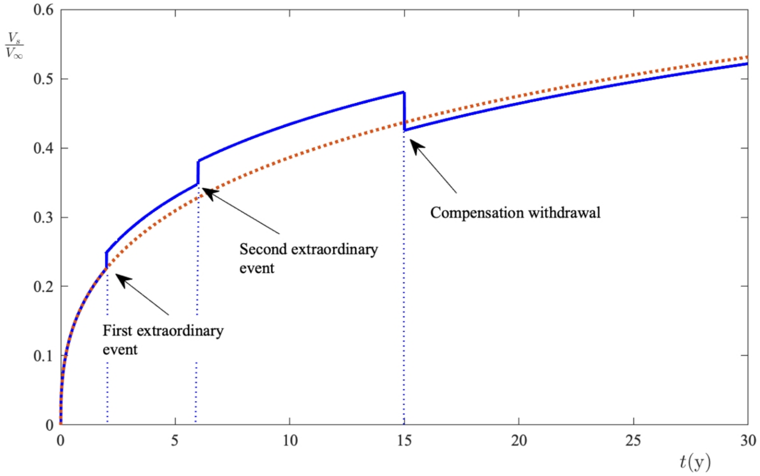

Fig. 1 Simulation of a sedimentation process whose natural evolution is described by the parameters $\sigma = 0.4$ and $\tau = 120$ y (curva rossa a punti). Four and 15 years after the dam was commissioned, two landslide events occurred that increased the natural sediment volume by 0.2% and 1% respectively (blue curve). Removal of the sediment (compensation withdrawal) almost completely re-establishes the natural course of sedimentation

$$\mathcal{L}_{j-1}(t) = \frac{\sigma_{j-1}}{\tau_{j-1}}\left(\mathcal{H}(t - t_{j-1}) - \mathcal{H}(t - t_j)\right) \tag{15}$$

has been introduced.Equation 14 can be easily solved on each time interval to give

$$V_s^{(j-1)}(t) = V_\infty - A^{(j-1)}E_{j-1}(t) \tag{16}$$

where, for simplicity's sake, the abbreviation

$$E_{j-1}(t) = E_{\sigma_{j-1},\tau_{j-1}}(t) \tag{17}$$

has been used.From the continuity condition on each interval one finds

$$A^{(j)} = A^{(j-1)}\frac{E_{j-1}(t_j)}{E_j(t_j)} \tag{18}$$

Since $A^{(0)} = V_\infty$, Eq. 18 provides

$$A^{(j)} = V_\infty \prod_{j=1}^{N} \frac{E_{j-1}(t_j)}{E_j(t_j)} \tag{19}$$

2.4 Sediment Volume Control by a Removal Plan

If the input of sediment turns out to be much greater than expected at the design stage of the dam, drastic removal measures are required.

Now, the sediment volume evolution equation becomes

$$\frac{dV_s}{dt} = K(t)(V_\infty - V_s(t)) - f(t, V_s) \tag{20}$$

The function $f(t, V_s)$ is the rate at which the sediment is removed from the dam. In the most general case, it depends on both time and the volume of solids in the reservoir. We will assume that this function can always be factorised into two functions one dependent only on t and the other only on V_s, i.e.

$$f(t, V_s) = \varphi(V_s)\psi(t) \tag{21}$$

Let us observe, first of all, that Eq. 20 admits a stationary solution, i.e. $dV_s/dt = 0$, namely

$$\frac{V_\infty - V_s}{\varphi(V_s)} = \frac{\psi(t)}{K(t)} \tag{22}$$

This equation states that if the functions $\varphi(V_s)$ and $\psi(t)$ are known, the amount of V_s in the reservoir is immediately calculated. If, for example, $\varphi(V_s) = V_s$ and $\psi(t) = h$ =constant, one finds

$$\frac{V_s(t)}{V_\infty} = \frac{1}{1 + \frac{h\tau}{\sigma}\left(\frac{t}{\tau}\right)^{1-\sigma}} \tag{23}$$

Now we consider the general case. For $0 \leq t < t_1$ sedimentation proceeds naturally and Eq. 20 can be solved as

$$V_s(t) = V_\infty[1 - E_{\sigma,\tau}(t)] \quad \text{for} \quad 0 \leq t < t_1 \tag{24}$$

For $t \geq t_1$, sediment extraction is very effective so that the sedimentation rate is only given by $f(t, V_s)$. Using Eq. 21 we have

$$\int_0^{V_s} \frac{V_s'}{\varphi(V_s')} dV_s' = -\int_0^t \psi(t')dt' \tag{25}$$

The functions $\varphi(V_s)$ and $\psi(t)$ are determined by the operating conditions. Herein, to cover most operational situations, we again assume

$$\varphi(V_s) = V_s; \quad \psi(t) = h \tag{26}$$

whence

$$V_s(t) = A \exp(-ht) \quad \text{for} \quad t_1 \leq t < t_2 \tag{27}$$

where A is the integration constant and is determined by the initial conditions, i.e.

$$A = V_\infty \frac{1 - E_{\sigma,\tau}(t_1)}{\exp(-ht_1)} \tag{28}$$

For $t \geq t_2$ the sedimentation process could either return to natural values or be maintained at a value set by ’external’ conditions

2.5 Recognition of Extraordinary Occurrences from the Few Bathymetric Data Available

As mentioned elsewhere (Molino et al. 2023), sufficient bathymetric data are not always available. Moreover, the presence of any extraordinary events further complicates the calculation of the sediment volume. We now show that, in such cases, a simple method can be used to highlight the extraordinary event and assess its magnitude. Equation 1 represents the evolution of sediment in a reservoir where the deposition process occurs naturally. Since $K(t) > 0$ and $V_\infty - V_s(t) > 0$, it follows that in the natural process $V_s(t)$ is an increasing function of *t*. If, however, extraordinary events occur, this condition may not be fulfilled, i.e. the curve $V_s(t)$ may vary its slope. Thus, the presence of a possible inflection in the bathymetric curve $V_s(t)$ identifies a non-natural process.

Let us derive Eq. 1 with respect to time

$$\frac{d^2 V_s}{dt^2} = \left(\frac{dK}{dt} - K^2 \right) (V_\infty - V_s) \tag{29}$$

From Eq. 29 one deduces that an inflection point will only occur at times for which

$$\frac{dK}{dt} = K^2 \tag{30}$$

namely

$$t_I = \tau \left(\frac{\sigma - 1}{\sigma} \right)^{1/\sigma} \tag{31}$$

where t_I is the inflection point and Eq. 2 has been used. Equation 30 states that for $0 < \sigma < 1$ the curve $V_s(t)$ has no inflection points. Thus, natural settling is well represented by a stretched exponential. On the contrary, for $\sigma > 1$ an inflection point exists, which is indicative of a change in velocity induced by a non-natural event. This implies that a compressed exponential is emblematic of an additional event to the natural process.

3 Results and Discussion

In this section, some of the problems described are applied to discuss the management of different dams located in different parts of the world.

3.1 Efficient Sediment Trapping: The Case of the Pong Dam

The Pong Dam, also known as the Maharana Pratap Sagar, is a renowned embankment dam located on the Beas River in the Kangra district of Himachal Pradesh, India. The reservoir area is designated as a wildlife sanctuary, providing habitat for a variety of bird species, making it a popular spot for bird watching and ecotourism. The construction of the dam led to the displacement of local communities, and efforts were made to resettle the affected population. Sedimentation has been a significant challenge for the Pong Dam. The upstream Pandoh Dam has affected sediment flow, initially reducing sedimentation in the Pong Dam, but as the Pandoh Dam silted up, sedimentation rates in the Pong Dam increased again. The Pandoh Dam functioned as a sedimentation reservoir, trapping sediments and preventing a significant portion from reaching the Pong Dam, which is located downstream of Pandoh. After approximately 10 years, the sedimentation rate of the Pong Dam began to decrease significantly. By 1996, when the Pandoh Dam had reached a high level of siltation (about 60%), greatly reducing its trapping capacity, the sedimentation rate of the Pong Dam started to increase again, albeit at a lower rate compared to the initial period. The bathymetric data displayed in Fig. 2 indicate that the evolution of this dam can be divided into three main periods. On each of which the sedimentation proceeds with stretched exponential law.

The experimental results are fitted separately to each period according to Eq. 19. The first period, covering the first 9/10 years of operation, is characterised by the absence of extraordinary events, only natural sedimentation takes place. The fitting to the experimental data provides $\sigma_0 = 0.97$ and $\tau_0 = 208$ y.

The second period ranges from 9 to 15/16 years of dam activity. In this period, the opening of the Pandoh dam reduces the sediment supply to the Pong dam and the fitting of bathymetric data yields $\sigma_1 = 0.42$ and $\tau_1 = 1.4 \cdot 10^4$. In the third period, from 16 years to the present, the Pandoh dam drastically reduces its trapping function and the sediment in the

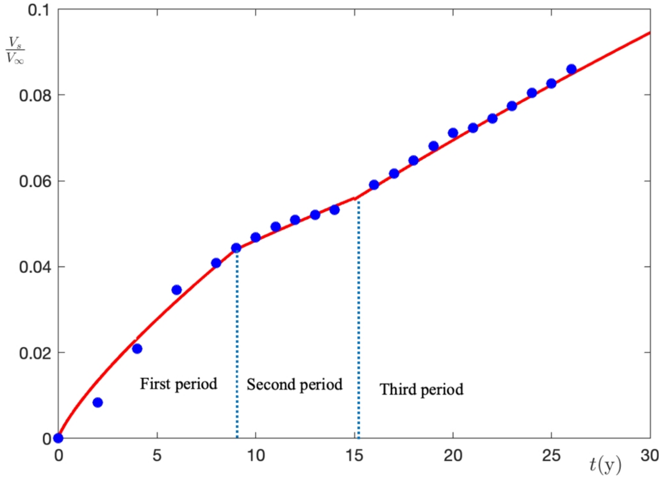

Fig. 2 Sediment evolution in the Pong Dam. In the first period, the sediment front proceeds naturally. The upstream construction of the Pandoh Dam changes the (σ_0, τ_0) parameters and the sedimentation rate is reduced (The second period). In the third period, Pandoh Dam reduces its sediment trapping capacity and the sedimentation curve in Pong Dam begins to rise again

Pong dam starts to rise again. Indeed, the adaptation to bathymetric results gives $\sigma_2 = 0.75$ and $\tau_2 = 655$ y.

3.2 Achieving Steady State: The Sanmenxia Dam Case

The Sanmenxia Dam, located on the Yellow River in Henan Province, China, has grappled with significant siltation problems since its construction in the late 1950s. The Yellow River is renowned for carrying one of the highest sediment loads of any river in the world, transporting an estimated 1.6 billion tons of sediment annually (Wang et al. 2005). This immense sediment load has led to rapid and substantial accumulation within the Sanmenxia Reservoir, causing a myriad of issues. One of the primary problems has been the dramatic reduction in the reservoir's storage capacity. Soon after the dam's completion, it became evident that sediment was filling the reservoir far more quickly than anticipated, severely diminishing its ability to store water. This reduction in capacity compromised the dam's critical functions, including flood control, irrigation, and hydroelectric power generation.

The diminished storage capacity reduced the dam's effectiveness in mitigating floods, thus increasing the risk to downstream communities and agricultural lands. The sediment accumulation also adversely affected hydroelectric power generation. Sediment buildup around the turbines and other operational areas hindered their efficiency, leading to reduced power output. This issue was exacerbated by the operational challenges posed by the need to manage and periodically remove the accumulated sediment, adding to the dam's maintenance and operational costs (Yuan et al. 2015). To address these issues, various strategies have been employed over the years. These include the installation of sluice gates for sediment flushing, construction of sediment bypass tunnels, and periodic controlled releases of water to help transport sediment downstream. Additionally, efforts have been made to reduce upstream soil erosion through afforestation, terracing, and the construction of check dams, which aim to lower the amount of sediment entering the river system. Despite these efforts, siltation remains a persistent challenge for the Sanmenxia Dam. The experience gained from managing this issue has provided valuable insights into the complexities of sediment management in large dam projects, particularly on sediment-laden rivers like the Yellow River. It underscores the necessity for comprehensive, adaptive approaches to managing sediment to maintain the functionality and safety of such critical infrastructure. To discuss the bathymetric results shown in Fig. 3, we observe that the authorities, in order to cope with the very rapid growth of sediment in the Sanxemenia dam, intervene drastically by bringing the sedimentation rate almost to zero. The dam works naturally for the first seven years. In this time interval, fitting the bathymetric data to the stretched exponential gives $\sigma_0 = 0.46$ and $\tau_0 = 42.7$y. The plot in Fig. 3 shows the results of the fitting. For $7 < t < 13$ y, the V_s volume decreases due to the sediment removal. At the beginning, in order to cope with the rapid increase in sediment, the removal is so rapid that the process is brought to a steady state (overall velocity = 0). From the plot in Fig. 3 an estimate $h = 0.011$ y^{-1} of removal frequency is obtained. Introducing, then, the values of σ_0, τ_0 and h in eq(23) generates the red curve displayed in the plot. The root mean squared error RMSE = 0.002 and R^2=0.97 confirm that the sediment-extraction process has reached a steady state. For $t > 13$ y the removal of sediment continues at a milder rate. Indeed, the overall sedimentation rate is kept low but not zero. This implies that the $V_s(t)$ curve is a straight line whose

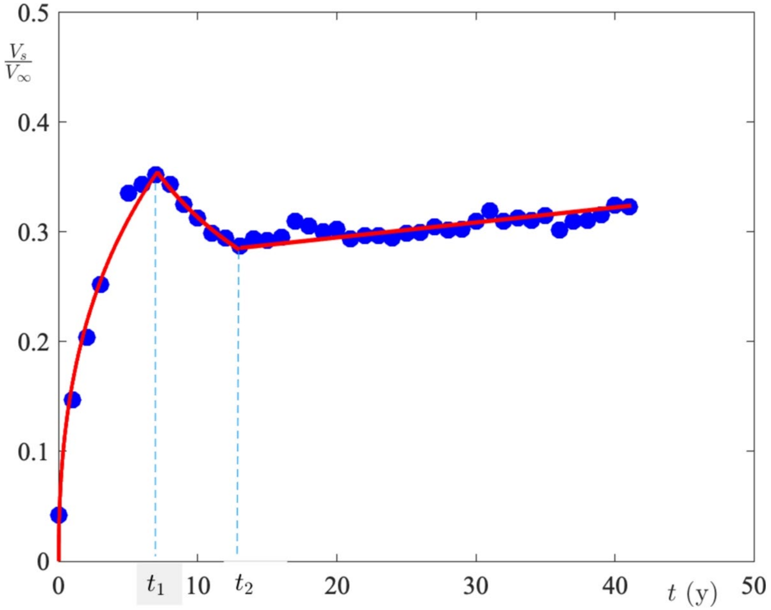

Fig. 3 Evolution of sediment in the Sanmenxia dam. In the time interval $[0, t_1]$, sedimentation follows the natural stretched exponential law. In the time region $[t_1, t_2]$ steady state is reachedThe coefficient of determination R2 measures the goodness of fit to sedimentation data.and the sediment volume evolves according to Eq. 23. For $t > t_2$ it starts to grow again very slowly

slope is precisely the overall speed of the process. As one can see in Fig. 3, for $t > 13$y the Vs curve exhibits a linear trend.

3.3 Verification of Extraordinary Events Through a Limited Number of Bathymetric Surveys: The Hirakud Dam

The Hirakud Dam is built across the Mahanadi River, about 15 kilometers from Sambalpur in Odisha. Its construction began in 1948 and was completed in 1956. The Hirakud Dam spans a total length of approximately 25.8 kilometers, making it one of the longest earthen dams in the world. The primary purposes of this dam are flood control, irrigation, and hydroelectric power generation (Nayak 2010). The Hirakud Dam is a significant engineering feat and continues to be an essential asset for Odisha in terms of water management, power generation, and agriculture.

The Hirakud Reservoir was designed with a large storage capacity to accommodate sedimentation over its lifespan without significantly impacting its functionality. Indeed, the dam is equipped with sluice gates at lower levels, which can be opened to flush out accumulated sediments. This process involves releasing water at high velocities to carry sediments downstream. Regular monitoring of sediment levels in the reservoir allows for timely interventions. Sediment surveys and bathymetric studies help track sediment deposition patterns. By implementing these measures, the Hirakud Dam effectively manages sedimentation, ensuring the long-term sustainability of its water storage, flood control, irrigation, and power generation functions. Unfortunately, only very little bathymetric data are available for this dam, as displayed in Fig. 4. However, numerical analysis of these data establishes that $\sigma = 1.35$ and $\tau = 66.0$ y, indicating that the process is governed by a compressed exponential. Thus, the presence of an inflection at $t_I = 24$ y confirms that other events were superimposed on the natural sedimentation process. Since the sedimentation rate slowed down in the first 24 y, we can infer that the upstream Narmada Sagar dam efficiently and effectively trapped the sediment.

3.4 Application to Ordinary Management of a Dam

We show that in the absence of extraordinary events, the amount of water available for users' needs is given by Molino et al. (2023)

$$W(t) = E_{\sigma,\tau}(t) \tag{32}$$

In order to illustrate how sudden and unpredictable events are reflected in the day-to-day management of the dam, let us consider $\sigma_0 = 0.4$ and $\tau_0 = 60$ y. In addition, two small landslides occur 2 and 6 years after the dam was commissioned.In Fig. 5 the water capacities in the presence and absence of extraordinary events are displayed. The same plot also shows the maximum possible consumption (horizontal line). As one can see, the straight line meets the actual curve at point P' and the natural curve at point P. i.e. the risk zone is reached more than 4 years earlier. This may create major management problems. In fact, the landslide effects are small so that the manager could underestimate them and find himself in the unfortunate situation of not being able to distribute the right amount of water to the various users.

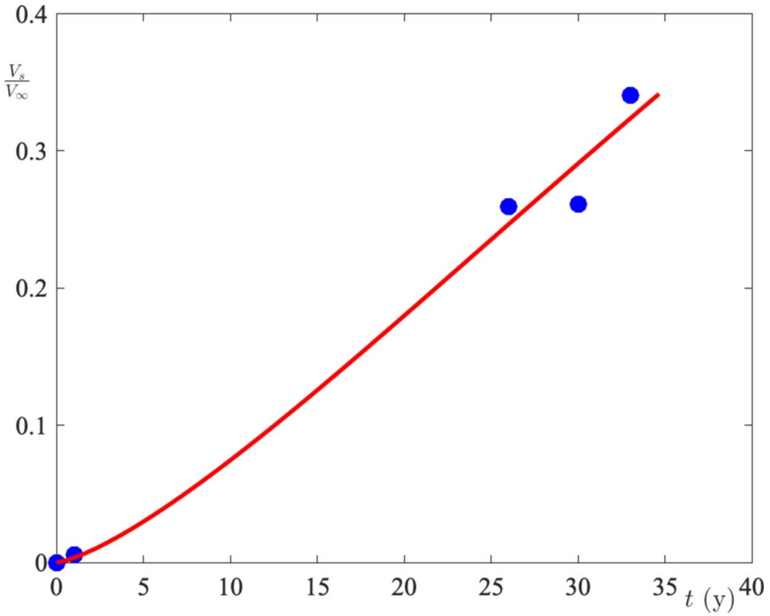

Fig. 4 Sediment evolutionary profile in the Hirakud Dam. The curve has an inflection point $t_I = 24$y indicating that some non-ordinary event took place

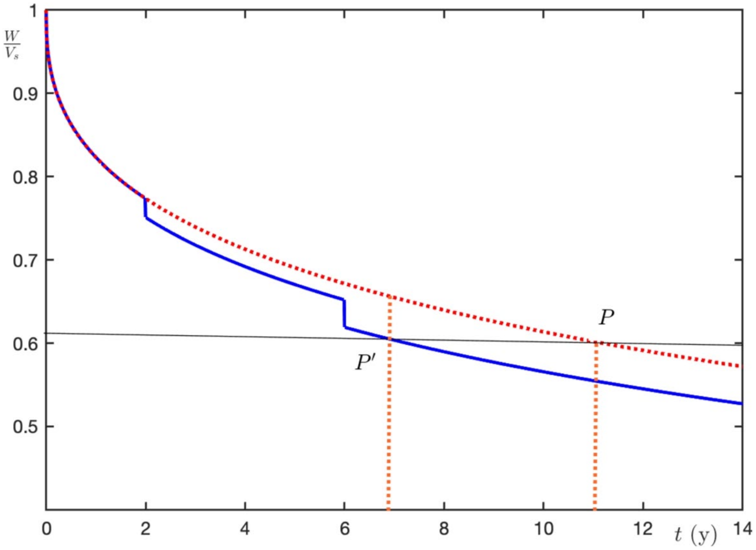

Fig. 5 Management plot in the presence of two extraordinary events

4 Conclusions

A semi-empirical model of sedimentation which contemplates the presence of extraordinary events is discussed. Extraordinary events are landslides or extreme meteoric events, which cause a rapid increase in sedimentation in a very short time, and sediment removal approaches from a reservoir (e.g., dredging, flushing...) or the construction of sedimentation basins, dams and check dams upstream of the reservoir, which cause a reduction in the natural sedimentation rates in specific and longer time interval. The proposed model was tested through bathymetric surveys related to several dams located in different parts of the earth. The goodness of the model was measured by the determination coefficient of fitting (R^2) to the experimental results (i.e. bathymetric surveys). According to the model, in the case that a limited number of bathymetric surveys are available, any change in the concavity of the sedimentation curve implies a non-natural process.

The model is able to predict the temporal variation in the useful capacity of the reservoir associated with extraordinary events either increasing or decreasing the sedimentation rate. In other words, the mathematical model allows to re-modulate the maximum possible consumption of water also in the presence of extraordinary rates of sedimentation. In this regard, it is a valuable tool both for the long-term management of water resources and the drafting of sediment management plans of a reservoir.

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Data Availability The data used in this research are taken from the literature. They are the official data of dam managers in different countries of the world.

Code Availability Custom code based on MATLAB R2024a has been used.

Declarations

Ethics approval All work is in compliance with Ethical Standards.

Consent to participate Authors consent to their participation in the entire review process.

Consent for publication The authors give their permission to publish.

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