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Articles

Management of dam discharge to reduce flood risk

Manejo de las descargas de presas para reducir el riesgo de inundación

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Abstract

Management of dams and reservoirs must be dictated by local conditions; in Mexico, extreme precipitation events cause severe flooding that socioeconomic factors can convert to a disaster. A theoretical method is proposed for the management of the controlled release of water to reduce the risk of flooding. The methodology involves climatological and hydrological analysis, seasonal climate forecasting, meteorological nowcast, climatology of extreme events, and hydrological projections of dam filling and basin response. It focuses mainly on three aspects: a) scheduled emptying time before the rain starts, b) closing the water release during the extreme precipitation event and c) maintaining a safety margin in the level of the reservoir to gain response time. Early weather predictions allow for early release of water, thereby effectively exploiting river capacity before precipitation begins. The proposed method offers a non-structural, and hence low-cost, option for dam management to mitigate flood risk.

Keywords: dams, reservoirs, floods, risk management, precipitation, hydrology, weather forecasting, climatology.

Resumen

La gestión de presas y embalses debe estar dada por las condiciones locales; en México, los eventos de precipitación extrema provocan inundaciones severas que los factores socioeconómicos pueden convertir en un desastre. Se propone un método teórico para la gestión de la liberación controlada de agua para reducir el riesgo de inundaciones. La metodología involucra análisis climatológico e hidrológico, pronóstico climático estacional, pronóstico meteorológico inmediato, climatología de eventos extremos y proyecciones hidrológicas de llenado de presas y respuesta de cuenca. Se enfoca principalmente en tres aspectos: a) tiempo programado de vaciado antes del inicio de la lluvia, b) cierre de la liberación de agua durante el evento de precipitación extrema y c) mantenimiento de un margen de seguridad en el nivel del embalse para ganar tiempo de respuesta. Las predicciones meteorológicas tempranas permiten la liberación anticipada de agua, maximizando así de manera efectiva la capacidad del río antes de que comience la precipitación. El método propuesto ofrece una opción no estructural y, por lo tanto, de bajo costo para la gestión de presas, mitigando el riesgo de inundaciones.

Palabras clave: presas, embalses, inundaciones, gestión de riesgos, precipitación, hidrología, predicción meteorológica, climatología.

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Introduction

Floods cause some of the most severe forms of disaster in terms of incidence, fatalities and economic losses. They are increasing in frequency as a result of population growth across vulnerable terrain, land degradation, inadequate protection measures, and the changing climate (Berz, 2000).

Flood risk has two parts: a) the hazard, related to physical phenomena such as precipitation and geomorphology, and b) vulnerability, associated with the human-social component, as human settlements on river banks, towns on the seashore, dam management, etc. Vulnerability to floods associated with dams has not yet been efficiently reduced, despite the scheduled release of stored water in the case of extreme precipitation events. Multivariate extreme events present risks whose analysis requires a multivariate approach (Brunner, 2023); an increasing awareness of the climatic context of floods has demonstrated the need for a multidisciplinary approach (Merz *et al*., 2014).

Recognition of a flood risk based on hydrological data must lead to mitigation of its potential consequences, by structural means and non-structural measures (García, Suárez-Lima, & Herbas, 2017). Where historical data are sparse or flood probability is low, flood risk analysis may be based on the total risk factor (Chen & Lin, 2018). Some studies of reservoir-related floods have focused on the design of dams to minimize the associated risks (Łydżba *et al*., 2021); others focus on the planning of responses to flood events (Ansori, Damarnegara, Margini, & Nusantara, 2021). The risk of flooding downstream of a dam can be evaluated, and hence its costs be assessed, by considering the variability of the level in the reservoir and using the long-term operating policy (Huerta-Loera & Domínguez-Mora, 2016). The outflow from a reservoir is determined flexibly and the safety of the procedure depends on the accuracy of the rainfall forecasts and the efficiency of the real-time hydrological data collection (Someya, 2018). Management of a dam must consider hedging to reduce the risk of shortages in the event of future drought (You & Cai, 2008). To determine the optimal hedging strategy, a proposed method combines particle swarm optimization with a simulation of the water system to represent a system of reservoirs that are jointly operated (Spiliotis, Mediero, & Garrote, 2016). Since conditions may vary over time, an extension of this method proposes a different set of rules for each hydrological year, with input from a hydrological forecast if available (Garrote, Granados, Spiliotis, & Martin-Carrasco, 2023).

Rainfall predictions can be used in model cascades to produce hydrological forecasts. However, errors in rainfall prediction propagate within the model, interacting at the basin level and affecting the estimation of area and depth of a predicted flood (Rodríguez-Rincón, Pedrozo-Acuña, & Breña-Naranjo, 2015). Stochastic models have been developed to determine optimal reservoir levels in a hydropower system entailing dams operating in series; this can enhance prediction and management of flood risks associated with dam operation (De-la-Cruz-Courtois, Guichard, & Arganis, 2020).

In operating a dam for energy generation, the volume of the reservoir is managed until maximum levels are reached, following a reactive scheme. The volume of water that dams retain changes over time, according to requirements and in response to varying patterns of storms and precipitation (Merz *et al*., 2014), including the frequency and intensity of extreme weather events (Mokhov, 2023). Reduction of the risk of flooding triggered by extreme precipitation events requires real-time management for each dam to avert or mitigate an ensuing disaster (Chen & Lin, 2018; Someya, 2018; Boulange, Hanasaki, Yamazaki, & Pokhrel, 2021; Nakamura & Shimatani, 2021).

In Mexico, floods are the main and most costly disaster faced almost yearly, owing to the country's geography and high vulnerability to hydrometeorological events (Pedrozo-Acuña, Breña-Naranjo, & Domínguez-Mora, 2014; Zuñiga-Tovar & Magaña-Rueda, 2018). Severe floods have occurred in recent years, such as those in Veracruz in 2005 and 2010, in Tabasco in 1999, 2007, 2020, and in Guerrero in 1997 and 2013 (Tejeda-Martínez, 2006; Gama *et al*., 2010; Rivera-Trejo, Soto-Cortés, & Méndez-Antonio, 2010; Tejeda-Martínez, 2011; Pedrozo-Acuña *et al*., 2014; Fernández-Rivera, Rodríguez-Rincón, Alcocer-Yamanaka, Breña-Naranjo, & Pedrozo-Acuña, 2019). These floods are linked to extreme precipitation events, but this is compounded by vulnerability due to socioeconomic factors.

Mexico has a history of more than 100 years in the construction of hydroelectric dams due to the advantages they offer compared to other energy sources (Ramos-Gutiérrez & Montenegro-Fragoso, 2012). Management of dams and reservoirs has been governed partly by operation manuals issued by government institutions according to the initial construction considerations. On the other hand, recent risk and response studies have considered the minimization of loss of electrical energy generation (Huerta-Loera & Domínguez-Mora, 2016; Pedroza-González, 2016). Despite the existence of the aforementioned flood control methodologies, floods continue to occur.

We here present a theoretical model that can be implemented in managing a dam in the lead-up to any precipitation event, and particularly when an extreme event is forecast; the combination of hydrological theory with knowledge of meteorology and climatology will enhance efforts to avert a disaster downstream.

Theoretical background and methodology

Hydrology and climate

For any given region the hydrological behavior of the basin is linked to the pattern of the rainy season. Much of Mexico experiences a climate with a clear demarcation into dry season (November to April) and rainy season (May to October). At the end of the dry season, the reservoirs are at their lowest point; as time goes by, they fill up and the risk of flooding gradually increases in the event of any extreme precipitation. Since water is an asset in terms of politics as well as energy, decision-makers delay the release from dams to conserve this asset, so that the next dry period will be faced with the largest amount of water stored. Furthermore, towards the end of the rainy season, several factors come together to increase the risk of flooding: the soils are saturated, the capacity of the rivers to transport the extra water decreases, the reservoirs fill at a higher rate due to an increase in runoff, and in the region of Mexico, meteorological phenomena associated with the summer-autumn transition occur, and these increase the possibility of extreme precipitation events.

Precipitation behavior is the most important factor in determining runoff, although it does not determine it completely. Generally, for Mexico, annual precipitation can have a normal or bimodal behavior (Figure 1). The northeast, central, south and southeast regions have bimodal precipitation behavior (Magaña, Amador, & Medina, 1999), but with different magnitudes, with the total accumulated annual precipitation being higher in the south and southeast.

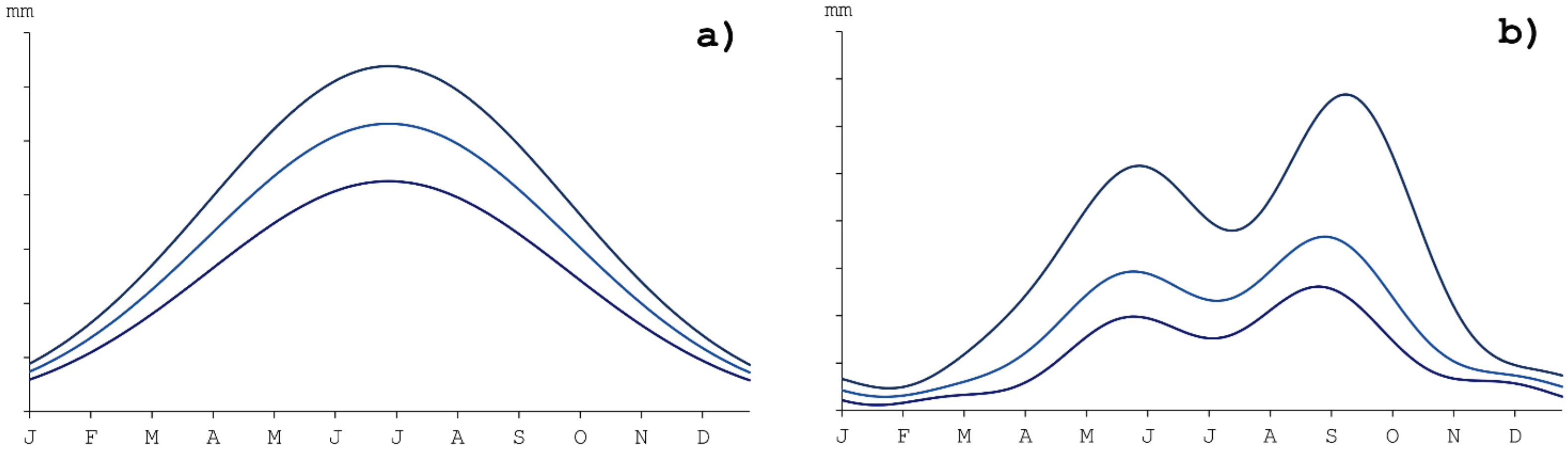

Figure 1. Theoretical examples of monthly precipitation distribution (vertical axis) and time (months, horizontal axis): a) normal and b) bimodal. Variability is indicated by curves for maximum, average and minimum.

With the precipitation distributions for a given region or basin, the accumulated precipitation curves are obtained, that is, the accumulated volume function (Figure 2), for which there will be a minimum and maximum margin determined by meteorological and climatological factors for each year.

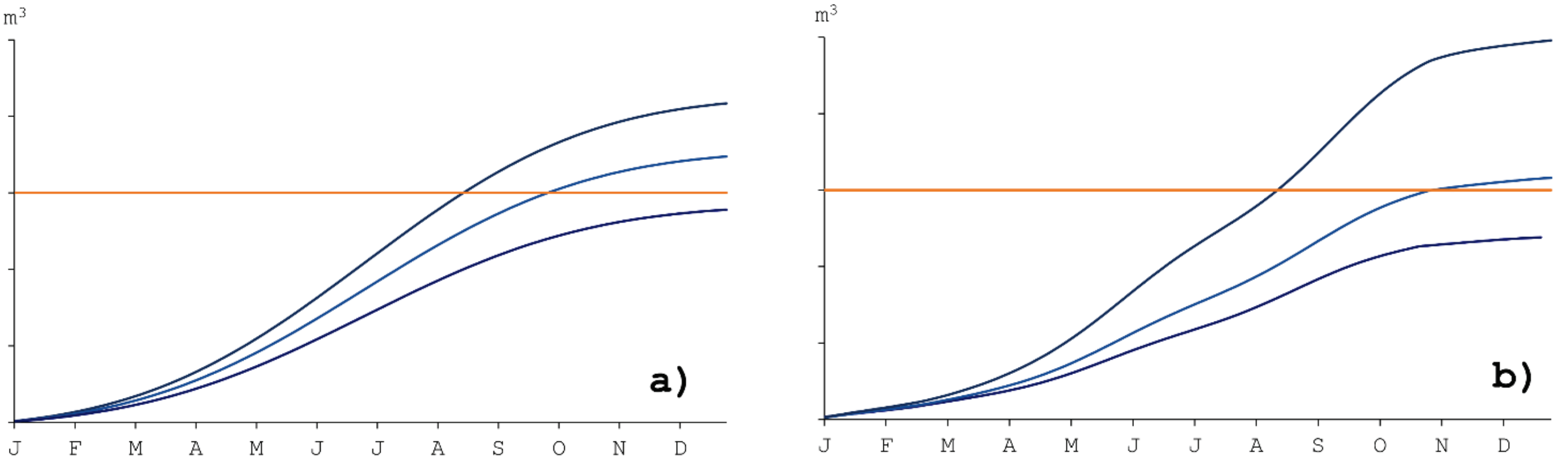

Figure 2. Annual accumulated precipitation volume corresponding to a precipitation distribution, volume (m^3, vertical axis), time (months, horizontal axis): a) normal and b) bimodal, with their respective potential variations. Horizontal orange line: Assumed maximum water level for a reservoir. Intersection of orange line and blue curve: Date on which maximum level is reached (determined by the pattern of precipitation, mentioned above).

Climatological considerations allow seasonal projections or forecasts of the rainy season for a given region, but this will depend on knowledge of the influence of meteorological and climatological phenomena on precipitation. In the case of Mexico, these are tropical cyclones (Dominguez & Magaña, 2018), easterly wave activity (Pazos, Magaña, & Herrera, 2023), the Caribbean low-level jet (CLLJ), the mid-summer drought (Magaña *et al*., 1999; Herrera, Magaña, & Caetano, 2014; Ochoa-Orozco, Rivera, & Herrera, 2022), the North American Monsoon (Adams & Comrie, 1997), cold fronts, climatic oscillations such as El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO), and intraseasonal variability

(Magaña *et al*., 1999; Méndez & Magaña, 2010; Rivera, 2021). Among the climatic oscillations, precipitation in Mexico is strongly influenced by ENSO; in general, under El Niño/La Niña phase conditions, the rainfall of the season decreases/increases in the center and south of the country and increases/decreases in the north (Méndez & Magaña, 2010).

Climate forecasts for the rainy season can allow reservoir filling to be planned several months in advance. Given the maximum filling volume levels of each reservoir (Maximum operating level, MOL; Maximum flood level, MFL), each forecast precipitation regime will determine the likelihood of overfilling, which will also have some variation over time depending on whether the season behaves close to average or with a significant anomaly (Chen & Lin, 2018). Furthermore, variability around the peak (normal) or peaks (bimodal) of precipitation may increase. In many bimodal cases, variability is greater at one of the precipitation peaks, and this leads to greater uncertainty in the seasonal forecast around that peak; hence, it is advisable to conduct a systematic week-by-week review of both precipitation behavior and water levels in the reservoir and rivers (Semenova, Simonov, & Khristoforov, 2023; Vuglinskii, Cretaux, Izmailova, Gusev, & Kurochkina, 2024).

Meteorological forecasting

The meteorological forecasts for each region have achieved good precision and reliability for four or five days on average, reducing uncertainty to such an extent that it is now possible to consider them as input data for hydrological models (Rodríguez-Rincón *et al*., 2015). Weather forecasting is crucial for the controlled discharge from dams, since the more accurate and the longer the forecast period, the greater the volume that can be extracted in a controlled manner, without waiting for the days of maximum rainfall to occur or for the reservoir to reach maximum levels, which would lead to a greater risk of rupture or flooding in downstream settlements, leaving decision makers with little room for maneuver. To anticipate the hydrology of a basin, many models require the input of predicted precipitation rates; waiting for precipitation to occur decreases the time available to discharge from the dam without flooding the downstream river. The basin response time provides the forecast window or time that decision makers have to act; if the time provided by the meteorological forecast is added to this forecast window, decision makers will have greater room for maneuver to operate and empty dams. Both hydrological and meteorological forecasts provide quantitative information on precipitation, necessary to reduce uncertainty in decision making.

A warning of extreme precipitation events is crucial, but these are sometimes unforeseen due to lack of information or to incorrect interpretation of meteorological models; the products related to possible precipitation may be underestimated, and this feeds deficient information to the hydrological models (Méndez-Antonio, Soto-Cortés, Rivera-Trejo, & Caetano, 2014; Lerch, Thorarinsdottir, Ravazzolo, & Gneiting, 2017). Therefore, the meteorological nowcast must be carried out by a team of experts focused mainly on the period of the season with the that the reservoir will reach maximum levels; working together with experts in hydrology, they should be able to accurately predict a flash flood.

Hydrological response

Each basin has a variable response to precipitation throughout the year, mainly because it has a greater infiltration capacity during dry periods and this infiltration decreases as the rainy season progresses and the soil becomes saturated. Evaporation is also greater before the rainy season and decreases as the atmosphere becomes saturated.

The runoff *Q* (m^3/day) across a basin changes as the saturation of the soil and atmosphere (*s*, %) increases (Figure 3a). This relationship responds to varying precipitation (*p*, mm/day) (Figure 3b).

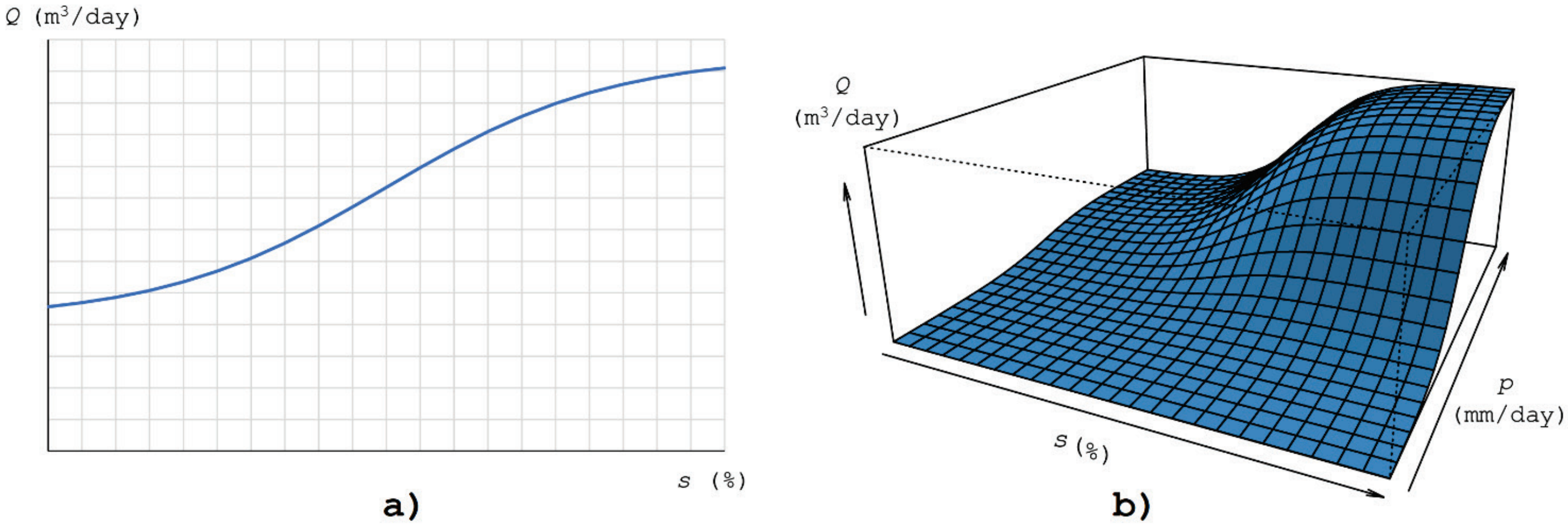

Figure 3. Effect on runoff *Q* (m^3/day) of soil and atmosphere saturation *s* (%) for a) a fixed precipitation and b) for different values of precipitation *p* (mm/day).

At the beginning of the rainy season, the climate forecast allows estimation of the dates on which the point will be reached where, if the outflow of water from the reservoir is not managed, the maximum water levels (MOL and MFL) will be reached. So, from the beginning of the rainy season, it is possible to know when to have greater monitoring of meteorological events. In general, these levels are reached towards the end of the rainy season (Figure 2), when the runoff is at its maximum (Figure 3).

If Q is integrated over a time interval (t), we obtain the volume V (m^3) accumulated in the reservoir:

$$V = \int_{t_1}^{t_2} Q(s(t), p(t))dt \quad (1)$$

From the specifications of each dam, the equivalence of the accumulated volume in terms of water level N (m) can be obtained, considering that there is no discharge, even if the capacity of the storage has decreased due to siltation, since it can be integrated from an initial level N_1 to a final level N_2:

$$V = \int_{N_1}^{N_2} A(h)dh, \quad (2)$$

Where the volume V is the integral of the area $A(h)$ with respect to the height h. In addition, it is possible to establish empirically, for each dam, the relationship between the precipitation (mm/day) that occurs in the basin area for a period of interest within the season (e.g., 3 to 5 days) and the accumulated volume in the reservoir due to the runoff Q. This can use data on the levels of the reservoir of interest, and spatial data on precipitation in the basin historically and in recent years. This ensures that the current behavior of the basin is described, as successive changes in land use, erosion, and other factors alter its response to precipitation over time.

It is imperative that the maximum levels (MOL and MFL) are never exceeded. However, the reservoir is often managed in a reactive manner, that is, water is released until precipitation begins or the amount is released so as not to put the dam at risk, regardless of the capacity of the river downstream, and this can cause flooding. The dam should be discharged at an earlier stage than is currently the case; it should begin a matter of days before the rain associated with the meteorological phenomenon arrives. The method proposed here helps to minimize flooding downstream, regardless of the use of the reservoir water (electricity generation, human consumption, agriculture, etc.).

Proposed solution

Gaining time with weather forecasting

The meteorological nowcast enables a more accurate prediction of the range of precipitation volume in the basin due to approaching atmospheric systems. This prediction can be made several days in advance, allowing the discharge of the dam to begin before the precipitation occurs. The advantage of this is that the volume *q* can be discharged when the river still has a greater capacity to carry water from the dam; when precipitation is already occurring in the region, a large part of the volume that the river can carry derives directly from the precipitation that runs into the river from its vicinity, and the volume of dam discharge that can be accommodated is reduced.

As we have seen, for a given basin, the runoff *Q* depends on the precipitation *p(t)* and the saturation of the soil and atmosphere *s(t)*. Precipitation (Figure 4a shows example values) leads to runoff to the reservoir (Figure 4b), taken as a filling rate. To avoid flooding downstream, the discharge rate must be limited by the river capacity. The volume that will have accumulated in the reservoir is the integral of *Q* over time (see Figure 4c, where V_1 and V_2 correspond to the maximum levels MOL and MFL). With t_0 as the time at which the MOL would be reached, the volume *q* will be the integral of *Q* from t_0 to t_b. This volume *q* must be evacuated several days before the MOL and MFL levels are reached. Let *S* be the flow rate from the dam that the river can accommodate (Figure 4d); this, like *Q*, depends on the precipitation and the saturation of the soil and the atmosphere. The changes in *S* will indicate the period (days) by which the discharge should precede the predicted meteorological phenomenon and what volume per day should be allowed to escape in order not to exceed the river capacity. Thus, *q* is also equal to the integral of *S* during the estimated period before the occurrence of precipitation.

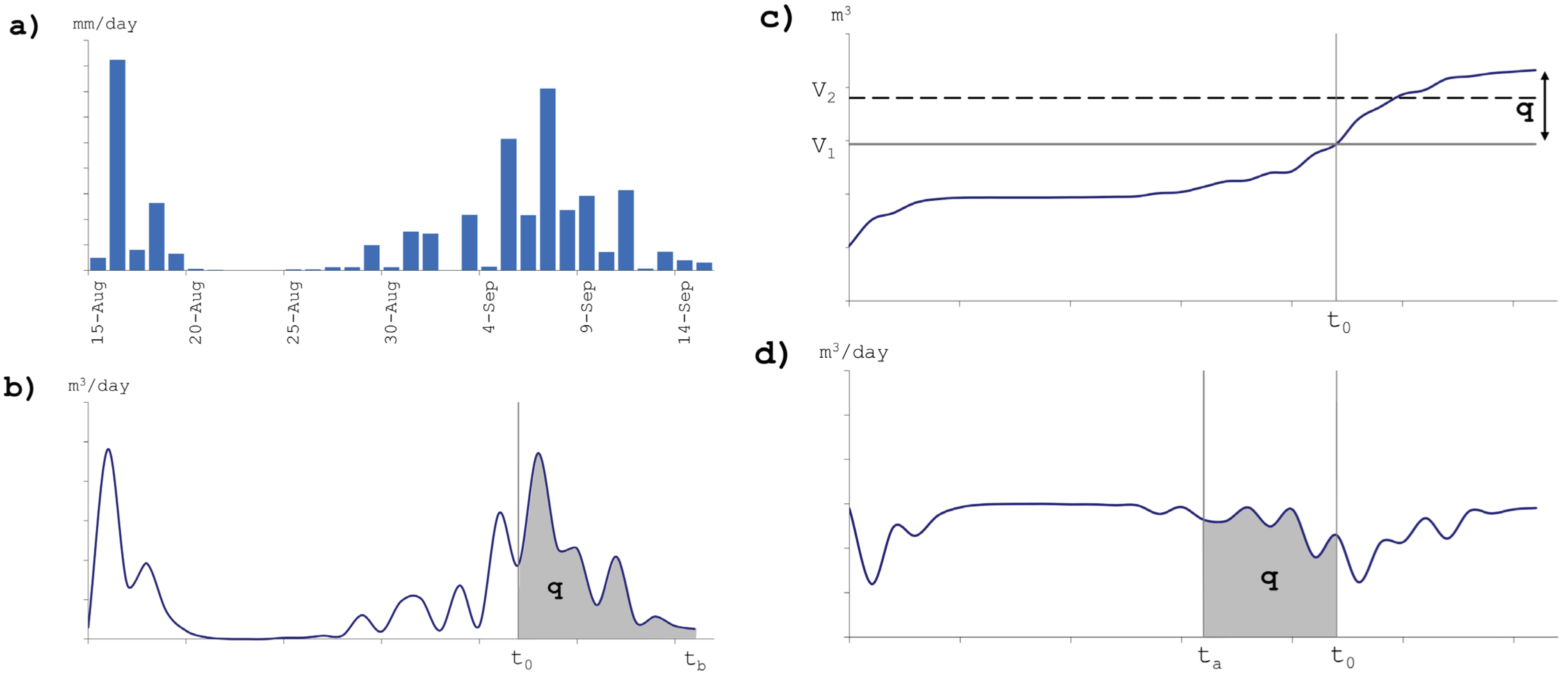

Figure 4. a) Illustrative precipitation (mm/day) for an example period (15 August to 15 September), typifying patterns in Mexico; b) runoff function (*Q*) for a basin (m^3/day) in response to the precipitation recorded in Figure 4a; c) volume (m^3) that would accumulate behind the dam if the water were not allowed to flow out. Solid gray line, volume (V_1) that corresponds to the MOL; dashed black line, volume (V_2) that corresponds to the MFL; d) Flow rate *S* (m^3/day) that the river can accommodate from the dam discharge (river capacity minus the water it carries due to runoff from its own vicinity).

$$\int_{t_0}^{t_b} Q\big(p(t), s(t)\big)dt = q = \int_{t_a}^{t_0} S(p(t), s(t))dt \tag{3}$$

The *S* function may also depend on the conditions at the eventual river outlet; for example, its discharge into the ocean may be hindered by a storm surge or some other phenomenon.

These are composite functions. These must be studied by both meteorologists and hydrologists who collaborate daily for the best management of dams and reservoirs.

Gaining time by keeping a water volume deficit

Time can also be gained by having a reserve of empty volume in the reservoir.

It is expected that towards the end of the rainy season the reservoir levels will be very close to the maximum. Therefore, with emphasis on this period, a climatological study of extreme events should be carried out (Brooks & Stensrud, 2000; Herrera, Magaña, & Morett, 2018; McPhillips *et al*., 2018; Brunner, 2023). Extreme precipitation events are studied from diverse perspectives; knowledge of the meteorological phenomena involved has been discussed above. In this section, we focus on the statistical aspect of extreme precipitation events.

A greater understanding of these events requires that regional daily precipitation data spanning several decades be reviewed. Precipitation maxima are identified and the time interval [(1–*n*) days] of duration of the events for which the accumulated precipitation exceeds maximum thresholds is determined; this can be above a standard deviation or values above some percentile of interest (Figure 5). With these climatological analyses of the extreme precipitation events, the expected volumes that run off to the reservoir and the river can be determined.

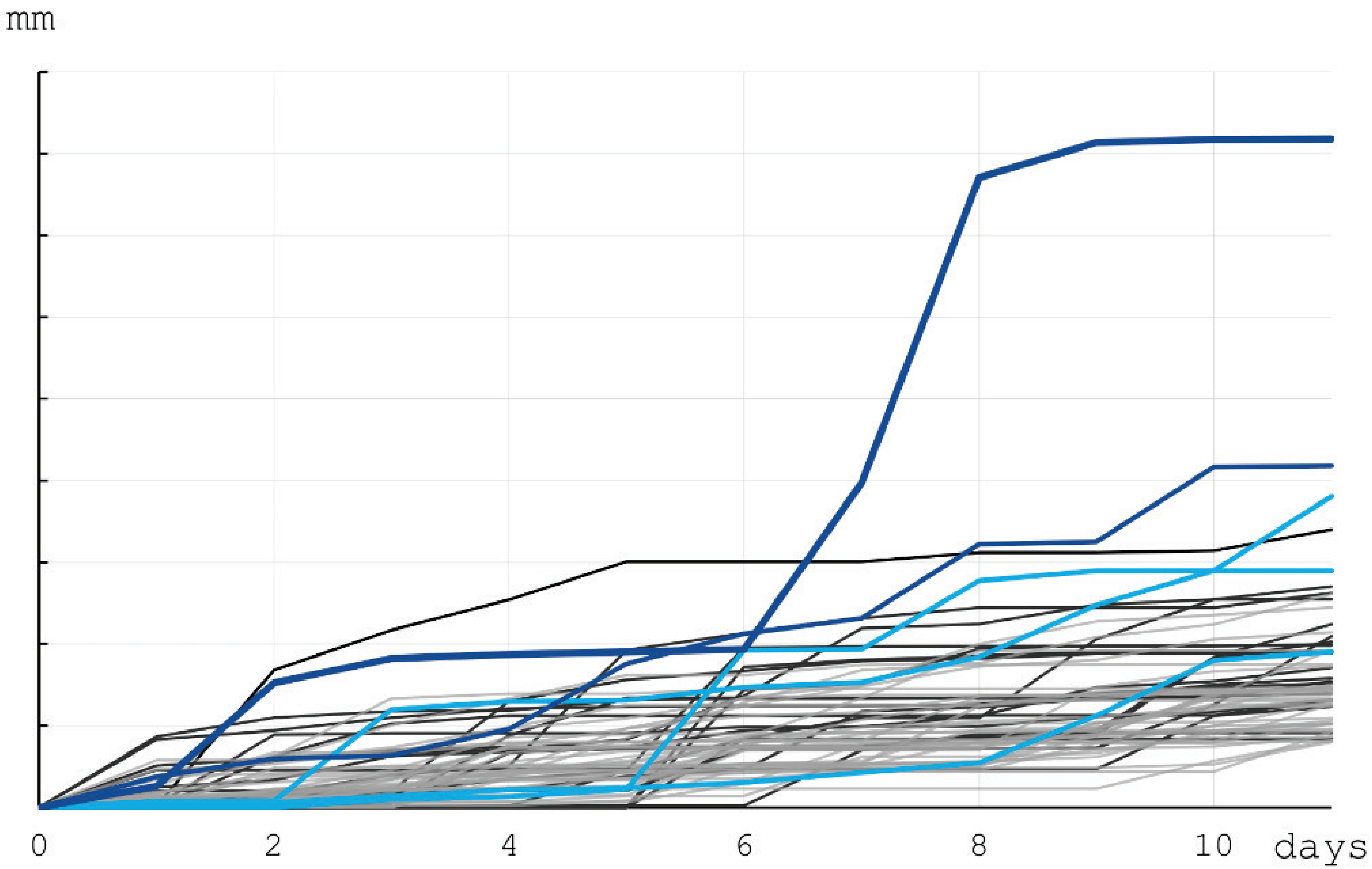

Figure 5. Example of accumulated precipitation (mm) for different extreme precipitation events occurring over an 11-day period and exceeding one standard deviation (σ). Periods during which the precipitation exceeds the threshold for three days (dark blue), for two days (light blue), or for one day (black); also, periods during which the threshold was not exceeded (gray).

Taking the maximum expected precipitation volumes, it is possible to calculate the period (discharge time in days, t_d) during which water may be safely discharged from the dam without exceeding the river's capacity.

Let t_p be the lead time (days) with which the arrival of an extreme event can be predicted. For each basin, we can compare the safe discharge time with the forecast window time. If the forecast window turns out to be less than the required safe discharge time ($t_d > t_p$), their difference gives the equation: $t_s = t_d - t_p$. This time t_s which is not available, is equivalent to the volume that cannot be discharged during the forecast window. Then, it is necessary to keep an empty volume in the reservoir. This volume can be safely discharged in t_s days.

The practice of retaining unfilled a proportion of the reservoir, the "volume deficit", allows the dam gates to be closed during extreme precipitation events so that the river receives only the runoff downstream of the dam.

Methodology of the proposed solution

The methodology of the proposed solution has a series of steps:

1. Hydrological and climatological characteristics are determined for the region of interest, including the mechanisms of interaction between them (this is done when the dam is designed and must be reviewed from time to time).
2. A hydrological projection of the dam filling and the basin response is made based on the climatological forecast (this is done when the dam is designed and must be reviewed from time to time).
3. A climatological analysis of the extreme events that have occurred in the region is carried out and thresholds for maximum accumulated precipitation, spatial patterns and maximum duration time

are determined (this is done when the dam is designed and must be updated).

4. Hydrological simulations of reservoir management using past data determine the volume deficit required to allow sufficient time to discharge the dam when extreme events occur.

5. The seasonal climatological forecast for the current year is made as an ensemble.

6. Weekly monitoring is carried out on point 1, and on the filling of the dam according to point 2. The weather forecast is reviewed daily (mainly for the period in which maximum volume levels may be reached); in case of a possible extreme event, monitoring must be carried out frequently (nowcast).

7. The weather forecasts and the results of the analysis in point 4 are used to determine the volume *q* that must be discharged before the extreme event and the period of time (the lead time, days) during which this must be done.

The theoretical method can be applied to a single dam or to a cascading system of dams.

Discussion and conclusions

The method presented above offers a theoretical solution to the flood risk associated with dam management. It should now be tested for diverse dam systems; field studies must obtain data to validate and adjust the proposed model for each case.

Climate change is increasing the frequency and severity of extreme events, and this has increased the need to manage the flood risk associated with reservoirs. It is essential that reservoir prediction and management models are continually updated to incorporate the latest climate projections and to ensure that planned strategies for water release remain effective. Previous research has demonstrated the effectiveness of similar methods in different contexts and the present study confirms their applicability in Mexico. For example, in the context of Japan, many cases of disaster have been examined to discover the most unfavorable spatial patterns for a basin; this led to a detailed methodology using models that consider the maximum spatial area of precipitation observed in the basin (storage function model), climatology, hydrological models, depth-area-duration curves estimated by historical analyses, radar, and regionalization (Takeuchi & Tanaka, 2021).

The cost of building a dam to ensure that there will never be a flood downstream is very high. For dams already built, there is a risk of flooding associated with them; to the original cost of construction and maintenance is added the cost of repeated flooding over time. This second cost can be reduced by making both structural and non-structural investments.

The method proposed here will enhance a range of strategies that regulate the operation of dams (Gabriel-Martin, Sordo-Ward, Santillán, & Garrote, 2020; Brunner, 2021). It contributes a non-structural investment towards the effective regulation of storage in a reservoir. It entails the costs of human resources: hydrologists and meteorologists to monitor each reservoir; staff training; and collaborative agreements with educational and research institutions, as well as with government agencies. However, these costs are low compared with the costs that would be incurred by structural amendments.

Adoption of these regulatory measures will reduce the risk of flooding and will thereby contribute to the shaping of communities that are more resilient to climate change.

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