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Designing Protection Systems in Mountains for Reduced Maintenance Costs: Claret's Retention Dam Case Study

Nour CHAHROUR

Univ. Grenoble Alpes, INRAE, ETNA, 38000 Grenoble, France.

Univ. Grenoble Alpes, CNRS, Grenoble INP, GIPSA-lab, 38000 Grenoble, France.

E-mail: nour.chahrou@grenoble-inp.fr

Guillaume PITON, Jean-Marc TACNET

Univ. Grenoble Alpes, INRAE, ETNA, 38000 Grenoble, France.

E-mail: guillaume.piton@inrae.fr

E-mail: jean-marc.tacnet@inrae.fr

Christophe BÉRENGUER

Univ. Grenoble Alpes, CNRS, Grenoble INP, GIPSA-lab, 38000 Grenoble, France.

E-mail: christophe.berenguer@grenoble-inp.fr

Debris retention dams are one type of critical protection structures implemented in torrents in order to provide protection against natural phenomena. They mainly aim in moderating, through their openings, the passage of the flow to the downstream where elements at risk are located. This is achieved by storing specific volumes of debris materials in their upstream debris basins and then, eventually, releasing this volume with a lower discharge. The filling of a debris basin by debris material over time, reduces the efficacy of the dam in achieving its functions. Consequently, cleaning maintenance operations of a debris basin should be regularly performed. This necessitates high monetary budgets, which can not be always affordable by the State for the management of protection structures in mountains. This paper proposes a model that makes it possible to model the passage of debris flows through retention dams. The case of the Claret retention dam in France is considered, in which the proposed model is used to analyze the performance of the dam considering its initial and new designs. A numerical analysis, over a period of 50 years, is performed using real data. The obtained results permit the managers of the Claret to figure out which of the designs is more favorable in terms of reducing maintenance costs and in terms of increasing protection efficacy.

Keywords: Debris retention dam, debris flows, basin filling, maintenance cost, protection efficacy.

1. Introduction

Protection structures in mountains are one type of critical infrastructures that provide the people, the society and the economy with protection. They aim to resist natural phenomena (e.g. floods, debris flows, snow avalanches) by either reducing their causes or their consequences. The failure in achieving their functions could lead to dramatic consequences (e.g. injuries, deaths, economic loss, environmental impacts). The complex design of these structures makes it difficult for their managers to predict the time of their failure. In France, this knowledge is often based on field inspections followed by expert assessments (Carladous, 2017). However, the limited monetary

budgets provided by the French State for the management of protection structure pose constraints on the managers concerning maintenance operations. It is therefore, necessary to develop models that support risk managers in making maintenance decisions thus contributing to better resilience of protection structures (Chahrou et al., 2021).

Debris Retention dams are one type of protection structures that aim to reduce the consequences of debris flows. They are usually made of reinforced concrete and can have different shapes (slit, orifices). They are usually built at the outlet of a debris basin that has a specific storage capacity. Their main functions are to filter the flow through their openings, store specific volume of

debris in their basins and to buffer the flow by reducing its intensity (discharge) when released to the downstream. A comprehensive review on the design, functions, failure modes and maintenance experience of debris retention dams in French torrents (Alpes, Pyrénées) has been recently carried out (Carladous et al., 2022).

The Claret torrent in France is a very active torrent subjected to frequent storms (up to three events per year). Some of these storms have the potential to trigger debris flow events that carry large boulders (one event every two years, on average – Hugerot (2015)). A retention dam was initially built in 1991 to protect downstream assets (Fig. 1a). It was designed with three openings: a trapezoidal spillway and two separate small orifices (bottom and middle orifices). Moreover, the dam is built at the outlet of a debris whose storage capacity is $22,000 m^3$. The managers realized that the dam was storing excessive volumes of debris. It was noticed that the dam's orifices were rapidly jammed by boulders thus preventing the dam from self-cleaning the debris basin during the event, or during subsequent smaller events. Therefore, frequent cleaning operations were performed to remove the stored volume in the basin and to ensure the efficacy of the dam. This in turn required, since the construction of the dam, high monetary budgets. In 1995, the ONF/RTM service “*Office national des forêts - Restauration des terrains de montagne*” thought to ask for modifying the configuration of the dam. Indeed, in 2018, the dam was redesigned and the two orifices of the initial design were joined together (Fig. 1b). The main objective of the adaptation was to reduce maintenance costs while maintaining a satisfying protection efficacy.

Chahrour et al. (2022) developed an integrated approach to optimize maintenance strategies in the case of the initial design of the Claret's retention dam considering only the costs of maintenance. The performed analysis revealed that waiting until the debris basin is almost completely filled, and then cleaning all the stored volume is the most-cost effective strategy. However, maintenance decisions should be optimized while maintaining or enhancing the level of protection provided by

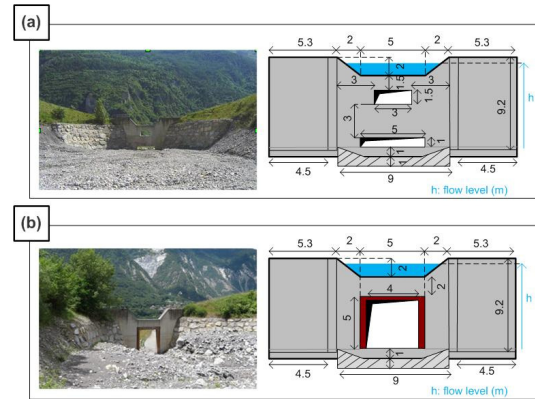


Fig. 1. Upstream and downstream views of the Claret retention dam: (a) initial design © ONF-RTM/S. Carladous May, 23rd 2018 and (b) new design © INRAE/J.-M Tacnet July, 5th 2021.

the retention dam (Hübl, 2018). The objective of this study is to cross-compare the debris retention dam functioning in its initial and new design and to characterize the required maintenance operations. In the case where maintenance operations are frequently required, a condition-based maintenance (CBM) approach is implemented, in which maintenance operations are planned based on the condition revealed after inspection (not systematic and periodic operations). The objective is to optimize maintenance actions based on their efficiency in increasing the protection efficacy provided by the dam. In order to achieve the desired objectives, a general physics-based model that models the routing of debris flows through a retention dam is proposed in this paper.

Section 2 presents the proposed physics-based model whose end purpose is to model the filling of the debris basin by debris materials over time. In section 3, the developed model is adopted in order to perform analysis on the case of the Claret retention dam. Conclusions and perspectives are provided in Section 4.

2. Routing of Debris Flows through a Retention Dam

In order to assess the dynamic efficacy of a deteriorating system, knowledge concerning the deterioration trajectories over time of the system is essential. Using these trajectories, it will be

possible also to implement a CBM policy. In this section, a physics-based model that accounts for the evolution of the volume stored in the basin by routing debris flows through a retention dam over time is proposed. The model consists of sequential steps presented in the following subsections.

2.1. Step 0: Scenario generation

Prior to modeling, random debris flow scenarios should be generated. In the present study, a scenario is defined as a series of debris flow events occurring over a specified period of time. Each debris flow event is defined by a volume V_{event} and a date of occurrence D_{event} . Historical archives concerning the magnitude, the frequency and the time series of debris flow events that have already occurred in the studied torrent were used to generate random volumes and random dates of occurrences, thus creating fictive series of debris flow events for a chosen duration.

The routing of several generated debris flow series through a retention dam results in deterioration trajectories corresponding to the evolution of the volume stored in the debris basin over time. These deterioration trajectories provide a stochastic vision of the system's (dam, basin) dynamic behaviour. Each of the generated scenarios will be used as an input to the physics-based model and the events involved in the scenario will be modeled one after another.

2.2. Step 1: Inlet hydrographs definition

Assuming triangular hydrographs, the hydrograph of each debris flow event in the generated scenarios is characterized by the three parameters: (1) Q_{peak} is the peak discharge representing the maximum discharge attained during the event, which can be estimated based on the total volume of the event, see Eq. 1 (Mizuyama et al., 1992); (2) t_{peak} is the time at which Q_{peak} is attained. It is usually estimated based on monitoring data. For the Claret torrent, it is assumed that $t_{peak} = 5$ s; (3) t_{end} is the time at which the event ends. It represents the duration of the debris flow event and can be estimated using Eq. 2.

$$Q_{peak} = 0.0188 \cdot V_{event}^{0.79} \quad (m^3/s) \quad (1)$$

$$t_{end} = 2 \frac{V_{event}}{Q_{peak}} \quad (s) \quad (2)$$

2.3. Step 2: Dam's openings resizing

When subjected to debris flows, the openings of a retention dam would be partially or totally jammed by boulders transported by the flow. As the rate of jamming increases, the volume of debris released out of the dam decreases and therefore the stored volume in the basin increases. Consequently, it is essential to consider the aspect of jamming when modeling the evolution of the stored volume in the basin.

An approach was recently developed in order to model the stochastic arrival of boulders to a retention dam (Piton et al., 2022). The approach starts by defining J classes of boulders corresponding to ranges of boulders' sizes based on field observation. Then, a given debris flow reference volume is split in a number of packets N_j , each packet has the volume of a boulder of class j . The binomial law with a calibration probability p_j is then used in order to check which of the packets in each class are real boulders that will arrive to the dam. Eq. 3 is used in order to calculate p_j , which depends on the actual number of boulders n_j that have been recorded in a given volume of a reference debris flow event:

$$p_j = n_j / N_j \quad (3)$$

Depending on the sizes of the boulders that are approaching towards the dam and their levels with respect to the dam's openings, it is possible to know which boulders will pass through one of the openings and which boulders will jam one of the openings. The jamming of an opening could be horizontal and/or vertical. Therefore, in the case where a boulder jams an opening, the jammed opening area should be reduced considering the size of the boulder. In other words, the width w and the base level y of each opening will vary over time with their progressive obstruction.

2.4. Step 3: Outlet discharge estimation

In order to estimate the volume of debris stored in the basin, the volume of debris that is released

out of the retention dam should be estimated first. This in turn necessitates estimating the discharge capacity of each of the dam's openings. Classical hydraulic equations provided in literature are used for this purpose (Piton and Recking, 2015). These equations involve the flow level at the dam h (fig. 1), the width of the opening w and the base level of the opening y . However, since h , w and y change with time, the discharge capacity Q_i of opening i will also vary over time. The total outlet discharge Q_{out} is finally obtained by summing up the discharge capacities of the n openings of the dam (Eq. 4).

$$Q_{out}(t) = \sum_{i=1}^n Q_i(t) \quad (m^3/s) \quad (4)$$

2.5. Step 4: Stored volume estimation

The buffering capacity of a retention dam corresponds to the ability of the dam to self-clean a debris basin. If well functioning, the dam should release gradually and with low discharge the volume stored in the debris basin during or after a debris flow event. Nonetheless, the jamming of the dam's openings by boulders reduces the discharge capacity of each of the dam's openings which in turn reduces the total outlet discharge. In this case, the stored volume in the basin will progressively or rapidly increase and the dam's buffering capacity will be reduced. The mass conservation equation (Eq. 5) makes it possible to estimate the buffering capacity of the dam by estimating in a given time interval Δt , the variation in the volume stored in the basin ΔV_b .

$$(Q_{in}(t) - Q_{out}(h(t))) * \Delta t = \Delta V_b(h(t)) \quad (5)$$

2.6. Step 5: Building deterioration trajectories

As mentioned before, the end purpose of the developed physics-based model is to represent the filling of a debris basin over time in order to assess the efficacy of a retention dam. Therefore, in order to obtain time evolving indicators, steps 2, 3 and 4 of the model should be performed at different time steps that cover the whole duration

of each debris flow event in each scenario. This makes it possible to plot the time-series of the different model's outputs such as the outlet discharge $Q_{out}(t)$ (m^3/s), the jamming rate of the openings (%) and the volume stored in the basin $V_b(t)$ (m^3). It is then possible in turn to extract the final volume stored in the basin after each event involved in a scenario and thus to build deterioration trajectories corresponding to the filling of basin over the specified period of simulation. These trajectories facilitates implementing a CBM policy by choosing thresholds at which cleaning operations can be performed.

3. Modeling and Analysis of the Claret Retention Dam

The model proposed in the previous section is developed using R language. It is totally generic and can be adopted for modeling and analyzing any retention dam. In this section, the developed physics-based model is used in order to study the filling of the Claret's debris basin over a period of 50 years in the case of the initial and the new design of the retention dam. The results obtained are presented in the following subsections.

3.1. Debris flow scenarios

In this study, it is assumed that three storm events occur every year in the Claret torrent. Therefore, in order to do the modeling over 50 years, 150 storm events should be generated. The dates of these events are randomly extracted from the monthly distribution of events provided by the ONF/RTM service based on historical databases of storm events that have occurred in the Claret torrent (ONF-RTM, 2013). The binomial law is then used in order to check which of the generated storm events triggers a debris flow. Since, on average, one debris flow event occurs every two years, it is expected to have on average one debris flow event every six storm events. Therefore, the success probability used in the binomial law is $p = 1/6$. If a debris flow is triggered, its volume V_{event} is randomly extracted from the "Frequency - Magnitude" curve of the Claret represented in Fig. 2. Otherwise, the volume of the event is set to be zero. Consequently, the generated scenarios

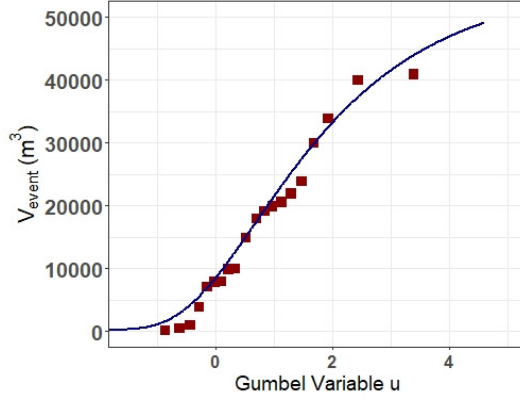


Fig. 2. Claret's Frequency - Magnitude curve obtained after the adjustment of recorded debris flow events using generalized Pareto distribution (Adapted from (Morel et al., 2022)).

differ in the number of debris flow events occurring over a period of 50 years. In order to have good stochastic vision of the results, 100 scenarios are generated.

Prior to modeling, an initial configuration should be set up. It is assumed that initially, the jamming rate of the dam's openings is 0 % and the volume stored in the basin is $V_b = 0 \text{ m}^3$.

3.2. Case of initial design

In this section, the modeling is performed considering the initial design of the Claret retention dam (fig. 1, a). Fig. 3 provides the results obtained through the physics-based model for the first two consecutive debris flow events involved in the first generated scenario. In scenario 1, within the 150 storm events occurring over a period of 50 years, 29 events have triggered debris flows. The first debris flow event (fig. 3a) has a volume $V_{event} = 19,422 \text{ m}^3$ and the second debris flow event (fig. 3b) has a volume $V_{event} = 24,873 \text{ m}^3$. The second event has occurred approximately a year after the first event. It can be seen that after the first event, the bottom orifice was almost totally jammed by boulders. This reveals that the discharge capacity of the dam was higher during the first event than during the second event. The final volume stored in the basin was $V_b = 9,300 \text{ m}^3$ after the first event and has reached $21,900 \text{ m}^3$ after the second

event. Consequently, after the second event, the basin has reached almost its maximum storage capacity ($C_b = 22,000 \text{ m}^3$) and both the bottom and the middle orifices were almost totally jammed.

Similar outputs are obtained for the rest of events involved in the first scenario and for other generated scenarios. The final volume stored in the basin after each debris flow event involved in each scenario is finally used for building deterioration trajectories corresponding to the filling of the debris basin over time. Fig. 4 represents the deterioration trajectories after modeling the 100 generated scenarios. It can be noticed that in most scenarios, the debris basin has reached its maximum storage capacity within five years, after the first two or three debris flow events. In addition, in all scenarios, the debris basin is completely filled within 20 years. These results are consistent with the observation that the dam, as initially designed, was trapping most debris material and costly cleaning maintenance operations were therefore frequently required.

In order to optimize maintenance strategies considering the aspect of protection efficacy, four maintenance strategies are proposed. The strategies differ according to the state of filling of the basin at which maintenance operations are carried out. Indeed, strategies 1, 2, 3 and 4 are proposed to be carried out when the volume stored in the basin is respectively 0, 2, 200, 10,000 or 20,000 m^3 . These thresholds are assessed by experts and are represented in Fig. 4. In order to compare the protection efficacy provided by each maintenance strategy, the defined thresholds are assumed to correspond to the initial volumes stored in the basin before the first debris flow event occurs.

Seven debris flow events of different input volumes V_{event} corresponding to different return periods are extracted from the Claret's "Frequency - Magnitude" curve (Fig. 2). Each of these events is modeled separately using the physics-based model in order to obtain the output volume V_{out} that will be transported to the downstream. In addition, each event is modeled in four different situations corresponding to the four different initial volumes stored in the basin V_b^i . The physics-based model provides the evolution of the final

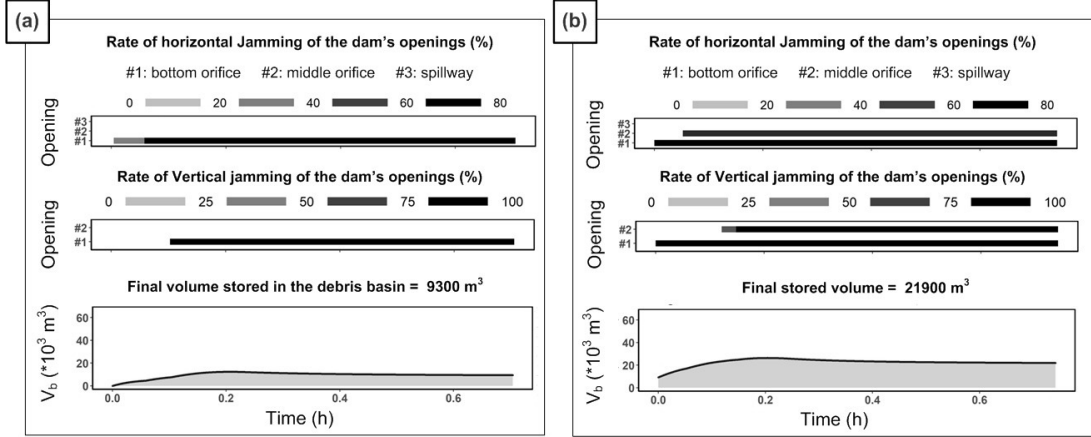


Fig. 3. Results obtained from the physics-based model showing the variation of the dam's openings jamming rate and the volume stored in the basin over time: (a) event 1 in scenario 1 and (b) event 2 in scenario 1 - Initial design.

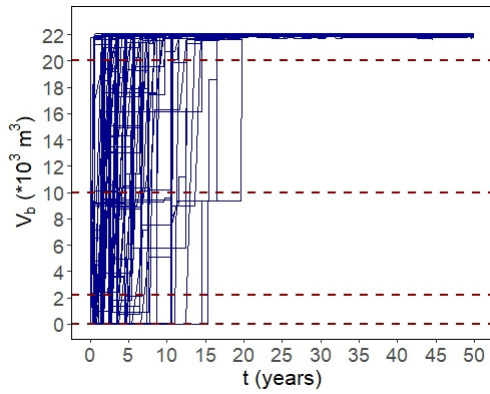


Fig. 4. Deterioration trajectories showing the filling of the Claret's debris basin over time for the 100 generated scenarios - Initial design. Dashed lines are the chosen thresholds corresponding to the proposed condition at which maintenance operations are carried out: $V_b^i = 0, 2, 200, 10,000$ and $20,000 \text{ m}^3$.

volume stored in the basin V_b^f after each event. V_{out} is then estimated as follows:

$$V_{out} = (V_{event} + V_b^i) - V_b^f \quad (6)$$

Fig. 5 represents the Claret's "Frequency - Magnitude" curves providing the output volumes of the seven modeled debris flow events' when considering the four states of initial filling of the basin at which maintenance can be applied. It is revealed that the higher V_{event} is, the higher the V_{out} is and the higher V_b^i is, the higher the V_{out}

is. Since V_{out} is the volume released through the retention dam and transported to the downstream where elements at risk are located, the protection efficacy provided by the dam will be higher for lower V_{out} . Therefore, Fig. 5 reveals that applying maintenance at early stages increases the protection efficacy of the dam. This leaves the managers in confusion whether to rely on reduced maintenance costs or on increased protection efficacy. Consequently, the maintenance strategy that provide an acceptable balance between both criteria could be the best option. The main challenge is indeed to maximize the output volume and minimize the stored volume while considering downstream protection needs.

3.3. Case of new design

In this section, the new design of the Claret retention dam is considered (Fig. 1b). Fig. 6 represents the results obtained for the first two consecutive debris flow events involved in the first generated scenario. It can be seen that after the first and the second events, both the orifice and the spillway were totally empty from boulders (jamming rate = 0 %). This reveals that the discharge capacity of the dam was more or less the the same during both events. The final stored volume attained after the first event was $V_b = 0 \text{ m}^3$ meaning that the basin was still empty before the occurrence of the second event. At the end of the second event, since the orifice was still not jammed by any boulder,

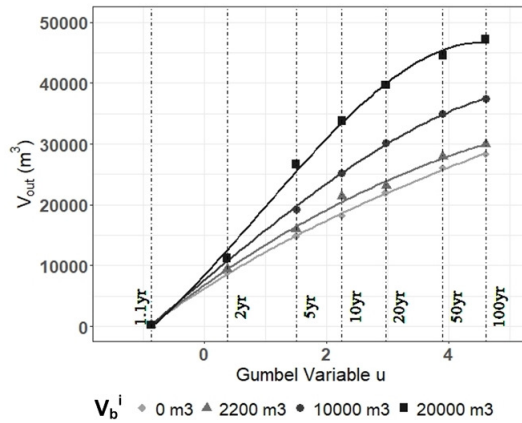


Fig. 5. Frequency - Magnitude curve presenting the output volumes of different debris flow events based on the initial volume stored in the basin.

the dam was still able to self clean and to evacuate all the flow keeping the basin empty again.

Similar outputs are obtained for the rest of events involved in the first scenario and for other generated scenarios. Indeed, after simulating the 100 generated scenarios, it was revealed that the new design of the dam with its large orifice is able to, progressively, self clean and evacuate the whole volume of a debris flow event in most of the scenarios. In other words, most of the scenarios have resulted in a 0% jamming rate and an empty basin ($V_b = 0 \text{ m}^3$). Fig. 7 represents the deterioration trajectories after modeling the 100 generated scenarios. It can be seen that in most of the scenarios, the volume stored in the basin was 0 m^3 all over the duration of simulation. In few scenarios, the basin was not empty but the maximum volume stored in the basin did not reach $6,000 \text{ m}^3$ over a period of 50 years. Only in two scenarios, the basin has reached its maximum storage capacity due to the jamming of the whole openings by a cluster of large boulders.

The considerable difference between the results obtained for both designs of the Claret's retention dam assures the necessity of redesigning the initial dam and verifies the efficiency of the new design in reducing maintenance costs. Since the dam, with its new design, does not store huge volumes of debris in the basin, there is no need to think

about a cost-effective maintenance policy regarding cleaning operations. However, the results of the physics-based model reveal that, in the case of the new design, the dam is releasing almost all the volume of the debris flow event to the downstream with a lower discharge. Consequently, the dam is achieving its function in buffering but not in storing a specific volume of debris materials. Maybe for what is located downstream, the transported volume could be excessive and in this case the retention dam will not be completely efficient in providing protection.

4. Conclusions and Perspectives

Retention dams are effective only if they are correctly maintained. The presented work supports risk managers in choosing optimal maintenance strategies concerning cleaning operations. In this paper, a physics-based model is developed in order to model the filling of a debris basin by debris materials over time. The model is used to analyze the initial and the new designs of the Claret's retention dam. Results make it possible to assess the deterioration rate of the basin in the case of both designs, to check which case necessitates frequent costly maintenance operations and to analyze the protection efficacy provided by the dam when adopting different maintenance strategies. It is revealed that in the case of the new design of the dam, there is rarely need for cleaning maintenance operation. Indeed, the new design of the dam has reduced maintenance costs. On the other hand, it is essential to estimate the level of protection provided by the new design of the dam considering that the whole volume of the debris flow event is transported to the downstream in most events.

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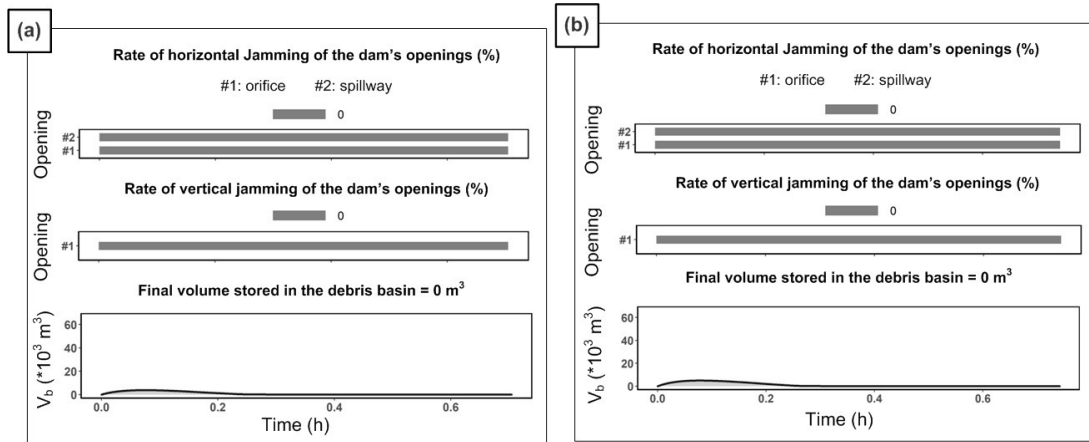


Fig. 6. Results obtained from the physics-based model showing the variation of the dam's openings jamming rate and the volume stored in the basin over time: (a) event 1 in scenario 1 and (b) event 2 in scenario 1 - New design.

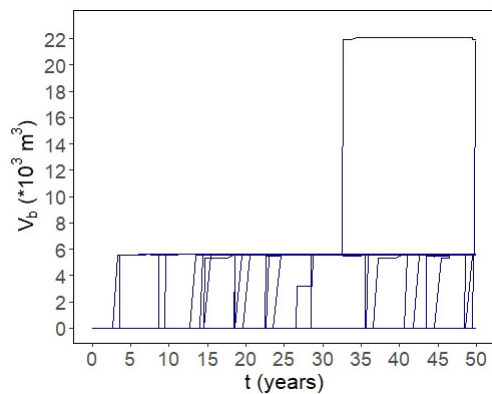


Fig. 7. Deterioration trajectories showing the filling of the Claret's debris basin over time for the 100 generated scenarios - New design.

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