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# Decision-Aiding Towards Improved Resilience of a Deteriorating Debris Retention System Subject to Maintenance Strategies

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## Abstract

*Protection systems against natural phenomena in mountains are critical infrastructures that deteriorate over time and necessitate regular maintenance. Debris retention systems, for example, are one type of protection systems that aim to mitigate natural phenomena such as torrential floods and debris flows by storing a specific volume of solid materials and by regulating the passage of the flows. They thus reduce negative consequences and provide protection to downstream exposed assets. The deterioration of a retention system overtime, including its filling by debris, reduces its efficacy in achieving the desired objectives. One key issue in natural risk context is that budgets provided by State or local authorities for the management of protection structures will always be somewhere limited. Consequently, it is essential and expected to develop models that facilitate ensuring the resilience of such critical structures while respecting available human, material and financial resources. This paper proposes a maintenance decision-aiding model that makes it possible to assess and prioritize different maintenance strategies applied to a retention system over its lifetime. The overall framework involves a (1) physical deterioration model, which contributes in building degradation trajectories of the system; (2) a stochastic deterioration surrogate model learnt from the degradation trajectories, developed using stochastic Petri nets and (3) a maintenance model, which is constructed as an additional layer in the stochastic Petri nets degradation model and which contributes in figuring out the most cost-effective maintenance strategy. A numerical analysis is performed using the data from a real retention system located in the Claret torrent in France and subjected to debris flows over a period of 50 years.*

## 1 Introduction

Modern societies highly rely on infrastructure systems that provide the economy and well-being with essential utilities and services. The consequences of infrastructure malfunction or failure can be significant (evacuations, economic loss, environmental impacts, etc.). However, the complexities involved in the design of these critical systems make it difficult for the managers to predict when the system could fail. On the other hand, the rehabilitation of such complex systems requires high monetary budgets, which could not be always affordable by the State or by local authorities.

Infrastructure systems resilience is among the main concerns of those managing complex systems. In the context of critical infrastructures, resilience is defined according to four different principles: anticipation, absorption, adaptation and recovery [1]. These principles refer respectively to the ability of the system to resist and manage a crisis, to maintain its functioning during its lifetime, to cope with changing conditions and to return rapidly back to normal conditions after disruption [2]. It is therefore, essential to have a comprehensive knowledge concerning the mechanisms of the system (efficacy, deterioration, maintenance, etc.) associated with each principle, seeking for a high resilient system. Indeed, understanding when and how the system could fail make it possible to know when to apply preventive maintenance operations instead of carrying out corrective maintenance operations, which are much more expensive than preventive ones.

Protection systems in mountains can be considered as one type of critical infrastructures. They aim in reducing the causes or the consequences of natural phenomena (e.g. torrential floods, debris flows, etc.) thus protecting people, assets and properties that are exposed to these events [3]. These systems (e.g. check dams series, debris retention system, etc.) are supposed to attain high efficacy levels that permit them to fulfil their assigned functions over time. However, over their lifetime, their efficacy is reduced because of aging or because of structural and/or functional failures that occur due to the impacts and consequences of natural phenomena on the system itself. This could in turn prevents them from providing the desired protection level to elements at risk.

Debris Retention systems, are usually implemented in downstream areas of torrential watersheds. They aim in storing specific volume of solid materials transported by debris flows. Therefore, their main objective is to prevent huge volumes of sediments and big blocks or boulders to be transferred to areas where vulnerable elements are located. The system is composed of several components that functions collaboratively in order to provide high level of protection [4]. These components could differ from one system to another depending on the desired functions. However, a debris basin, retention dam and a maintenance access track should at least be present in every debris retention system regardless their type, shape and sizes (fig. 1). The debris basin is a deposition area where solid materials (boulders, woody debris, etc.) are stored. It has a specific storage capacity. The retention dam is built downstream the debris basin. It has openings (slot, slit, weir, etc.) that allow it to moderate the flow by reducing its intensity and to trap large debris materials. The maintenance access track permits technicians, trucks and engines to reach the system in order to carry out maintenance operations (e.g. cleaning the basin). A recent study provides a thorough review concerning the design (structural, hydraulic, etc.), functions (flow moderation, debris storage, etc.), malfunctions (excess trapping, flow lateral bypass, etc.) and maintenance (e.g. cleaning) of retention systems constructed in French torrents (e.g. Alpes) [5].

In France, the level of degradation of retention systems is based either on field inspection or on expert predictions. Maintenance operations are then made on these bases. According to historical experience, the managers of these systems adopt a specific maintenance

**Figure 1.** Claret retention system: (1) retention basin, (2) retention dam, (3) lateral dykes, (4) access track and (5) downstream counter dam. © ONF-RTM/S. Carladous 23/05/2018.



policy for each system depending on its components and on the features of the torrent at which it is located. For example, for the retention system located in the Claret torrent in France, cleaning operations are carried out after each debris flow event whatever is the debris volume stored in the basin. The problem is that in the Claret torrent, debris flows are frequent (one event every two years). This requires frequent maintenance operations, which in turn necessitates high budgets. However, limited monetary budgets are provided by the French State for the management of protection systems. This sheds the light on the importance of developing decision-aiding models that use and analyse available information in order to choose the most cost-effective maintenance strategy to be applied on deteriorating protection systems.

A very recent decision-aiding model was developed in order to support maintenance-decision-making of check dams subjected to clear water floods [6]. In this paper, the objective is to develop further the model by considering the case of retention systems, as they exist in most French torrents. For this purpose, a holistic approach integrating several stages is developed. The approach starts by physically modelling the filling of the debris basin when subjected to a series of debris flows over its lifetime. The obtained deterioration trajectories are then used in order to estimate the probability laws corresponding to the transition times between the states of the basin. These laws are then used in a stochastic Petri net model (SPN) in order to model the stochastic behaviour of the system when subjected to different maintenance strategies implemented based on a condition-based maintenance (CBM) policy. Finally, the outputs of the SPN model are used to compare the modelled maintenance strategies in terms of the total cost of each strategy. The main contributions behind this approach is to (1) define and implement a maintenance policy that can efficiently improve the resilience of retention systems and (2) support risk managers to make optimal decisions thus contributing to a safer and better world.

Section 2 thoroughly describes the global developed modelling approach that can be used for analysing the behaviour of any retention system. In section 3, the approach is adopted in order to analyse the behaviour of a real case retention system located in the Claret torrent in France. Conclusions and perspectives are provided in Section 4.

## **2 Methodology**

Improving the resilience of retention systems necessitates understanding first their deterioration mechanisms when subjected to debris flows over time. However, knowledge concerning the deterioration trajectories of these systems is often partially or totally missing. This section proposes an integrated approach that combines several sources of information (expert assessments, historical data and numerical simulations) in order to estimate these trajectories over the lifetime of the system and then to implement a CBM policy that makes it possible to optimize maintenance strategies. The approach considers only the functional failure of retention systems and does not consider the failure of the system from a structural point of view. It models the filling of the debris basin over time, which could lead to insufficient storage capacity. The different modelling stages of the overall approach are detailed in the following subsections.

### **2.1 Building Deterioration Trajectories of a Debris Basin**

Retention systems are implemented in mountains aiming to reduce the risk level induced due to debris flows by trapping a specific volume of the flow. However, the trapping of low magnitude events that do not pose harm to vulnerable issues increases the stored volume and thus reduces the capacity of the debris basin. Indeed, the jamming of the retention dam's openings by big boulders transported by the flow will prevent small events to pass through the dam. In this section, a physical model that models the routing of debris flows through a retention system is proposed. The model results in the final volume stored in the basin after each debris flow event. The steps involved in the physical model are explained below.

### 2.1.1 Random Generation of Debris Flow Events

The first step of the physical model is to generate series of debris flow events occurring over a period of 50 years. This requires having data concerning the frequency and the magnitude of the events that have really occurred in the studied torrent. Indeed the frequency-magnitude curve of a given torrent makes it possible to generate random debris flow events with random volumes  $V_{event}$  and random dates of occurrence  $D_{event}$ .

The routing of a generated debris flow series through the retention system will result in one deterioration trajectory corresponding to the filling of the debris basin over 50 years. However, the end purpose of the physical model is to have a set of these trajectories in order to attain a stochastic vision of the system's dynamic behaviour. Therefore, a satisfying number  $n$  of debris flow series that allow having a good vision of the resulted trajectories should be generated. Each generated debris flow series will be referred to as a scenario.

Each debris flow event in a scenario is represented by a hydrograph, which provides the inlet discharge as a function of time over the whole duration of the event. In this study, triangular hydrographs are assumed. Therefore, the hydrograph is characterized by three parameters: peak discharge, time to peak and duration of the event. The peak discharge is estimated as follows [7]:

$$Q_{peak} = 0.0188 * V_{event}^{0.79} \quad (1)$$

The time to peak  $t_{peak}$  is assumed based on the historical data. It corresponds to the time at which the flow reaches its peak discharge. The duration of the event  $t_{end}$  is estimated using the following equation:

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

### 2.1.2 Stochastic Arrival of Boulders to the Retention Dam's Openings

The second step of the physical model is to randomly sample the number of boulders in a given debris flow volume that approaches towards the dam's openings. The jamming of the retention dam's openings by boulders during a debris flow is a very recent field of study. Indeed, a recent model that studies the stochastic arrival of boulders to the dam and whether each arriving boulder is blocked in the dam's opening has been proposed by [8]. The developed model assumes that the stochastic arrival of boulders to the dam follows a binomial distribution. The model starts by classifying the boulders transported by the flow into classes of different diameters. Each class  $j$  corresponds to a range of diameters  $[D_{j,min}; D_{j,max}]$ . For each class  $j$ , the average diameter  $D_j$  and the volume  $V_j$  of the boulders is computed.

In order to perform trials via the binomial distribution, the number  $N_j$  of elementary volumes  $V_j$  that constitutes the whole volume of the debris flow event  $V_{event}$  and that will arrive to the dam should be estimated as follows:

$$N_j = \frac{V_{event}}{V_j} = \frac{V_{event}}{\pi D_j^3 / 6} \quad (3)$$

Note that  $N_j$  corresponds to the number of trials required for a class  $j$  of boulders per time step, covering the duration of the debris flow event. The binomial distribution then provides, at each time step, the probability  $p_j$  that an elementary volume  $V_j$  which arrives to the retention dam involves a boulder of class  $j$ . The number of successes gives the number of boulders  $n_j$  of class  $j$  involved in  $V_{event}$ .

$$n_j = N_j * p_j \quad (4)$$

However, when randomly sampling  $n_j$  of all the boulder classes,  $V_{event}$  should be progressively reduced by the volume of boulders of larger classes that have already been identified at a given time step ( $k = 1, 2, \dots, \sum n_{j-1}$ ). Consequently, eq. (3) becomes:

$$N_j = \frac{V_{event} - \sum_{k=1}^{n_{j-1}} V_k}{V_j} = \frac{V_{event} - \sum_{k=1}^{n_{j-1}} \pi D_k^3/6}{\pi D_j^3/6} \quad (5)$$

Finally, the dimensions of the jamming of the retention dam's openings by boulders arriving to the dam are estimated based on classical jamming conditions that depend on the configuration of jamming (horizontal, vertical or both) and on the size of boulders relative to the size of the openings [8].

### 2.1.3 Discharge Capacity of the Retention dam's Openings

The third step of the physical model is to calculate the total discharge that is released through the retention dam. The openings of the dam are the elements responsible for releasing a specific volume of the flow to the downstream. The discharge capacities through the dam's openings (spillway, slots) are estimated based on the following stage-discharge equations provided in literature [9]:

$$Q_i^{spillway} = 0.385 * w_i(t) * \sqrt{2 * g * (h(t) - y_i(t))^3} + 0.308 * \frac{1}{\tan(\varphi)} \sqrt{2 * g * (h(t) - y_i(t))^5} \quad (6)$$

$$Q_i^{slot} = 0.65 * w_i(t) * \frac{2}{3} * \sqrt{2 * g * ((h(t) - y_i(t))^{3/2} - (h(t) - y_i(t) - a_i)^{3/2})} \quad (7)$$

where  $Q$  ( $m^3/s$ ) is the discharge capacity through opening  $i$ ,  $t$  ( $s$ ) is the time,  $w_i(t)$  ( $m$ ) is the width of the opening not jammed by boulders (free width),  $g$  ( $\sim 9.81 m/s^2$ ) is the gravitational acceleration,  $h(t)$  ( $m$ ) is the depth of the flow over the dam's base level,  $y_i(t)$  ( $m$ ) is the base level of the flow which is equal to the base level of the opening if it is not jammed by boulders,  $\varphi$  ( $^\circ$ ) is the angle between the spillway's wing and the horizontal and  $a_i$  ( $m$ ) is the slot's height.

The total discharge capacity  $Q_{out}$  of a retention dam is equal to the sum of the discharge capacities of all its openings.

### 2.1.4 Buffering Capacity of the Debris Basin

Retention systems aim to regulate debris flows by reducing their peak discharges. This means that the volume stored in the debris basin during a debris flow event is expected to be released gradually through the openings of the retention dam. This phenomenon is referred to as "buffering". However, the jamming of the dam's openings by boulders reduces the total discharge capacity of the dam. Therefore, the stored volume in the basin will progressively increase not being able to escape through the jammed dam. In other words, the buffering capacity of the debris basin will be reduced. The retention dam will thus no more be able to self-clean a filled basin. In this case, the debris basin has to be cleaned by performing maintenance operations.

The fourth step of the physical model is to estimate the buffering capacity of a debris basin using the following mass conservation equation:

$$(Q_{in}(t) - Q_{out}(h(t))) * \Delta t = \Delta V_b(h(t)) \quad (8)$$

Where  $Q_{in}$  ( $m^3/s$ ) is the inlet discharge provided by the hydrograph of the event,  $Q_{out}$  ( $m^3/s$ ) is the discharge capacity of the retention dam estimated according to section 2.1.3,  $\Delta t$  ( $s$ ) is the time step,  $h$  ( $m$ ) is the flow level and  $\Delta V_b$  ( $m^3$ ) is the variation of the volume stored in the basin. In order to use eq. (8), data concerning the input hydrograph of the event, retention dam's outlet discharge capacity, storage capacity of the debris basin, deposition slope and the stage - volume capacity curve ( $h$  versus  $V_b$ ) should be acquired.

### 2.1.5 Computational Analysis and Expected Outputs

The physical model is implemented in an R code that makes it possible to solve all the previously mentioned steps. The developed model is general and can be used to analyse any retention system just by changing input data concerning the features and characteristics of the system (e.g. basin storage capacity, deposition slope, dimensions of the dam's openings, etc.). Concerning the first step, presented in section 2.1.1, each scenario will be simulated separately using the R code. The steps represented in sections 2.1.2, 2.1.3 and 2.1.4 should be performed at different time steps, covering the whole duration of each debris flow event involved in a scenario. This is due to the fact that the openings of the dam will be progressively jammed during the event and therefore the outlet discharge capacity of the dam and the buffering capacity of the basin will be different at each time step. This in turn provides time-evolving indicators that makes it possible to plot their evolution trajectories.

The model results in several outputs such as the evolution of the inlet discharge  $Q_{in}(t)$  ( $m^3/s$ ) outlet discharge  $Q_{out}(t)$  ( $m^3/s$ ) vertical and horizontal jamming rate (%) of the dam's openings by boulders, flow level  $Z(t)$  ( $m.a.s.l$ ) at the dam and the cumulative volume stored in the basin  $V_b(t)$  ( $m^3$ ). In this study, the focus will be on the evolution of  $V_b$ , which is already dependent on the evolution of the other indicators. Therefore, the main interest will be to extract, from the R code results, the final stored volume in the basin attained at the end of each event. This will help to build the deterioration trajectories of the stored volume in the debris basin over the studied period (50 years).

## 2.2 Surrogate Deterioration Model using SPNs

A stochastic Petri net (SPN) degradation model is composed of four different elements: places, tokens, transitions and arcs [10]. A place represents the state (level of deterioration) of the deteriorating system. The presence of a token in a place means that the system is residing in the state corresponding to this place. Transitions permit the token to move from one place to another according to the stochastic firing time assigned to each transition. Arcs link between places and transitions thus showing the possible paths between the states of the system. Consequently, in order to build a deterioration model using SPNs, two main steps described below should be achieved.

### 2.2.1 States Definition of a Deteriorating Retention Basin

The first step required for building a SPN deterioration model is to define different states of the studied system reflecting different levels of deteriorations. In this study, four different states at which the debris basin can reside are considered. It is assumed that the stored volume in the basin  $V_b$  evolves progressively from an initial state (empty basin) to a completely failed state, reaching the maximum storage capacity of the basin  $C_b$ . Therefore, each of the defined states corresponds to a range of stored volume in the basin as follows:

- State 1:  $0 \leq V_b \leq V_{b1}$  (good condition)
- State 2:  $V_{b1} < V_b \leq V_{b2}$  (poor condition)

- State 3:  $V_{b2} < V_b \leq V_{b3}$  (very poor condition)
- State 4:  $V_{b3} < V_b \leq C_b$  (almost totally failed condition)

The choice of thresholds  $V_{b2}$ ,  $V_b$  and  $V_{b3}$  can be based on expert assessments. Moreover, the deterioration process is not necessarily gradual. In other words, the state of the debris basin could either evolve gradually between the states (e.g. evolution from state 1 to state 2 to state 3 to state 4) or could be rapid (e.g. direct evolution from state 1 to state 3, from state 2 to state 4, etc.). Fig. 2, (a) represents the SPN deterioration model, which better illustrates all the possible transitions between the states of the basin.

### 2.2.2 Estimation of Transition Probability Laws

The stochastic transitions that link between the states of a system are the main elements responsible for the functioning of a deterioration SPN model. In literature, the probability laws of these transitions are either assumed by experts to follow a specific distribution (e.g. Exponential, Gamma, Weibull, etc.) or estimated using available real data about time to failure. In the case of torrent protection structures, such data are either totally missing or are imperfect [11]. Moreover, this imperfection makes conflicts between experts' judgments. Consequently, Chahrour et al. recently proposes a surrogate deterioration SPN model that uses the physical modelling of the system in order to estimate empirical non-parametric transition probability laws [6].

In this study, the physical modelling concerning the filling of the debris basin is used in order to estimate non-parametric probability laws of the stochastic transitions involved in the SPN model of fig. 2, (a). Indeed, after defining four states of the debris basin, the simulation of the  $n$  generated scenarios makes it possible to have several estimates of the transition times between the states. The transition probability laws are therefore built based on the deterioration trajectories obtained from the physical model using non-parametric estimations.

### 2.3 Maintenance SPN Model Implementing a CBM Policy

The developed surrogate deterioration SPN model makes it possible to extend the model so that it integrates a maintenance model by easily implementing a CBM policy. Different CMB maintenance policies can be used. However, in the present study, the following policy is adopted:

- If the debris basin is in state 1, no maintenance operation is carried out.
- If the debris basin is in state 2, minor maintenance operations are carried out.
- If the debris basin is in state 3, major maintenance operations are carried out.
- If the debris basin is in state 4, corrective maintenance operations are carried out.

The maintenance operations in all cases are cleaning operations. The only difference between minor, major and corrective operations is in the volume of debris to be cleaned. Moreover, when a maintenance operation is carried out, all the stored debris volume in the basin should be cleaned. In other words, upon maintenance, the debris basin returns back to its initial state (empty basin). Fig. 2, (b) represents the CBM policy implemented in the SPN model. Each maintenance operation is linked to a deterministic transition of a constant firing time reflecting the time required for the operation to be performed. The figure also shows an inspection process that is necessary for detecting the state of the system over time. Inspection is assumed to take periodically every one year.

When Monte-Carlo simulation starts, the token present initially in place  $P_1$  (state 1) starts to move between the states based on the assigned probability laws to the stochastic transitions thus revealing the evolution of the volume present in the debris basin over time. Every year, an inspection is performed in order to detect the state of the basin. According



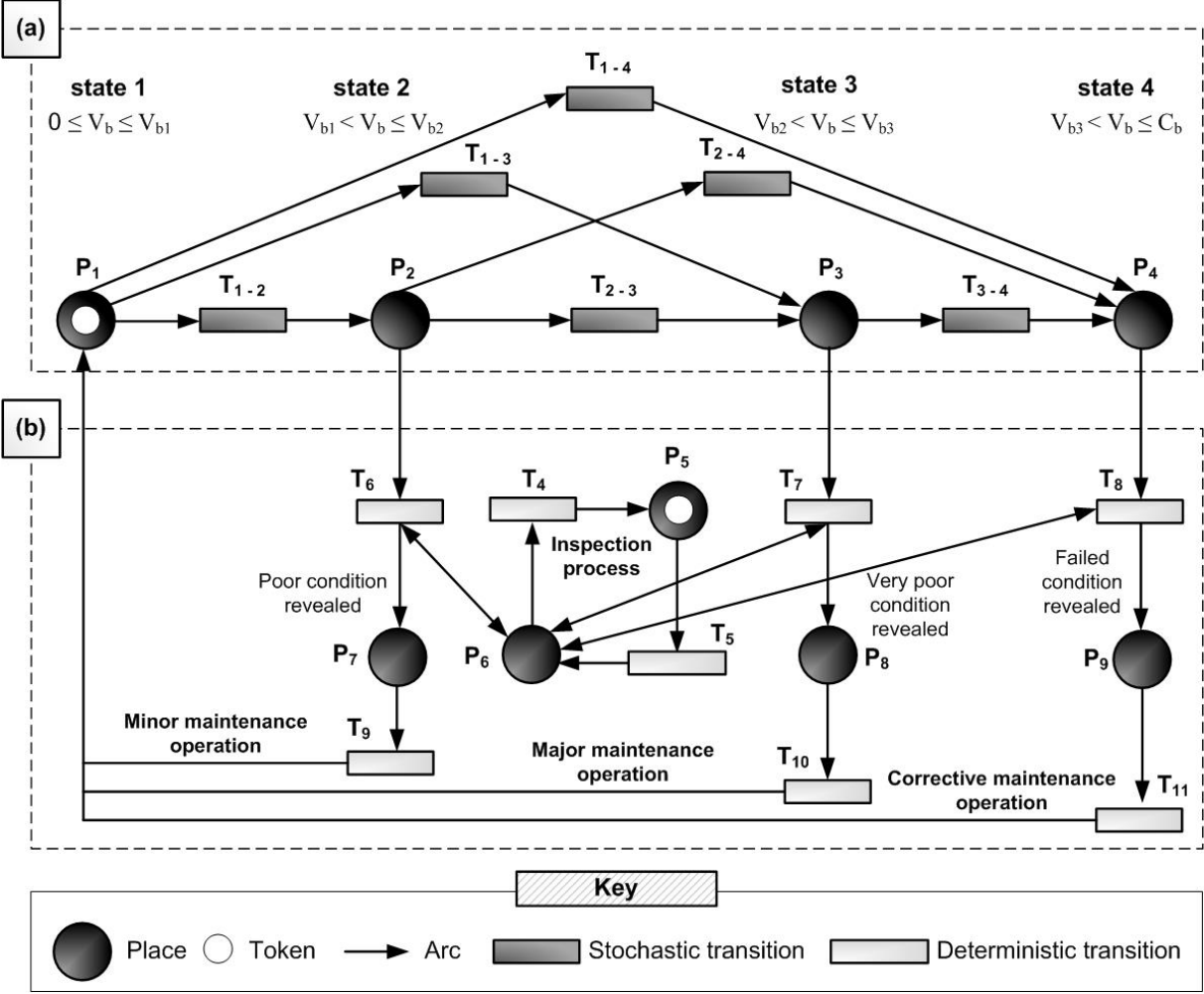
to the detected state, the assigned maintenance operation is carried out. After the time needed for the operation to be accomplished, the token returns back to place  $P_1$  revealing that the basin is restored back to a good state and the evolution starts again. When the simulation duration (50 years) is attained, the SPN model results in the number of maintenance operations carried out over a period of 50 years.

In order to compare the results provided by the SPN model for different maintenance strategies, four strategies are proposed:

- Strategy 1: all maintenance operations are allowed.
- Strategy 2: minor operations are inhibited.
- Strategy 3: major operations are inhibited.
- Strategy 4: minor and major operations are inhibited.

Knowing the cost of each maintenance operation, the results of the SPN model permits computing the total cost of each proposed maintenance strategy. This in turn support risk managers and decision-makers to be aware of the most cost-effective strategy.

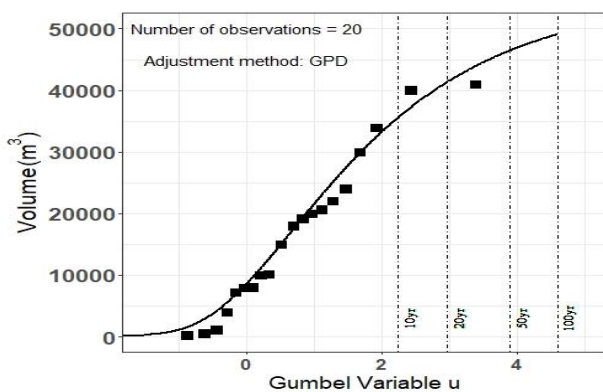
**Figure 2.** SPN model showing the stochastic deterioration model and the implemented CBM policy: (a) deterioration process, (b) inspection and maintenance processes (Adapted from [6]).



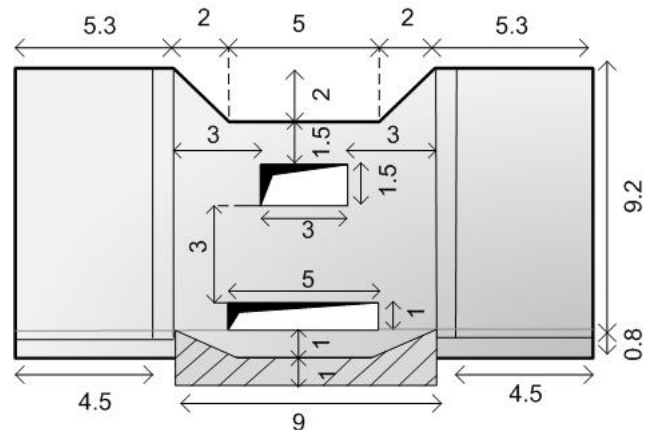
### 3 Case Study: Modelling of the Claret Retention System

The Claret torrent in France is very active in producing destructive debris flow events. Fig. 3 provides the Claret's Frequency - Magnitude curve resulted after the adjustment of real observations of debris flow events using Generalized Pareto distribution (GPD) [12]. In 1991, a retention system was built in the torrent in order to protect vulnerable exposed issues. The capacity of the debris basin is 22,000 m<sup>3</sup>. The retention dam is made of reinforced concrete and has three openings: a spillway and two slots as shown in fig. 4. Since the construction of the system, it was noticed that the dam is trapping big volumes of debris materials even those corresponding to small debris flow events. Therefore, excessive volumes rapidly fill the debris basin. The managers of the Claret adopt an event-based maintenance policy, in which after each debris flow event, they carry out cleaning operations whatever is the stored volume in the basin. However, this policy requires very high monetary budgets. The aim of this section is to use the developed approach presented in section 2 in order to (1) model the progressive filling of the Claret debris basin when subjected to debris flow scenarios over a period of 50 years, (2) compare the costs of different maintenance strategies by adopting a CBM policy and (3) support the managers of the Claret to make cost-effective maintenance decisions.

**Figure 3.** Frequency - Magnitude curve of debris flow events in the Claret torrent [17].



**Figure 4.** Dimensions of the Claret retention dam (m).



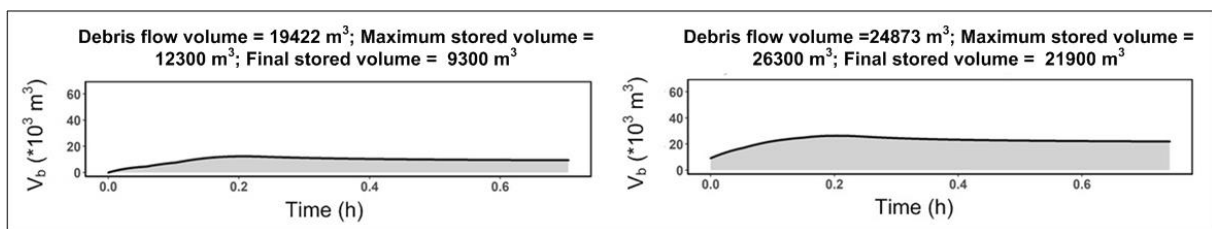
#### 3.1 Physical Modelling Results and Discussions

In order to reach the desired objectives, 100 scenarios of debris flow series are generated. Data concerning the monthly distribution of the recorded torrential flood events in the Claret are given by [13]. It is also known that three torrential events triggered by big storms occur in average in the Claret every year, but not all triggering debris flows. Therefore, the dates of three torrential events are extracted, every year, from the provided monthly distribution of events. This means that for each scenario, the dates of 150 torrential flood events are obtained over a period of 50 years. A binomial distribution is then used in order to specify which event succeeded in triggering a debris flow events. Knowing that a debris flow occurs once every two years, the success probability in the binomial distribution is considered as  $p = 1/6$  (one debris flow event every six torrential flood events). Random volumes of the revealed debris flow events are finally generated from the Frequency-Magnitude curve of fig. 3.

In order to start simulations using the developed R code, an initial configuration of the retention system should be set up. Therefore, before the simulation of the first event of each scenario, the openings of the retention dams are assumed to be initially empty from boulders and the debris basin is assumed to be initially empty ( $V_b = 0 \text{ m}^3$ ). Fig. 5 shows the results obtained for the first two debris flow events involved in scenario 1. The first event has a volume  $V_{event} = 19,422 \text{ m}^3$  and the second event has a volume  $V_{event} = 24,873$

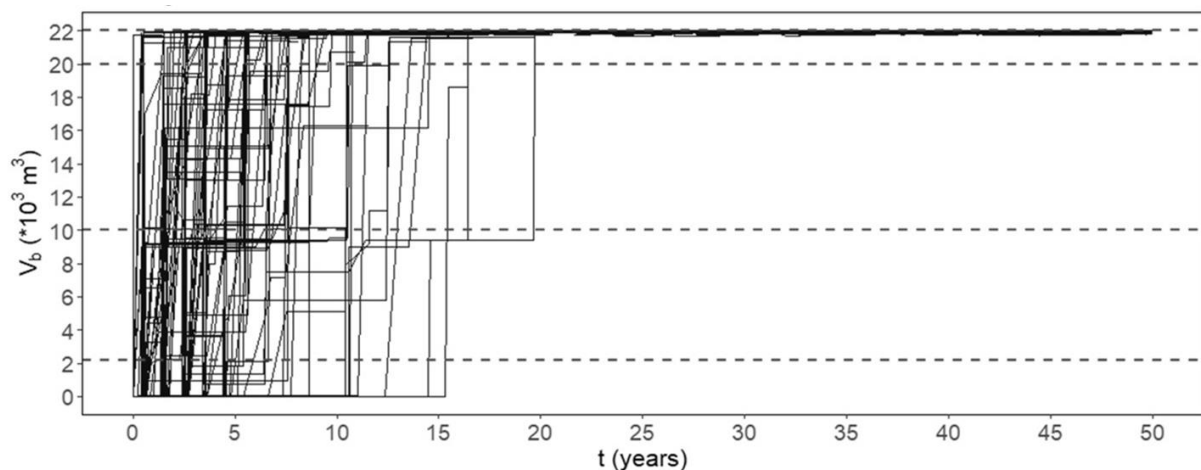
$m^3$ . The difference in the dates of occurrence of both events is approximately 1 year. The final stored volume in the basin attained after the second event is  $V_b = 21,900 m^3$ , which is approximately equals to the maximum storage capacity of the basin  $C_b = 22,000 m^3$ . It is also clear from the figure that the final stored volume in the basin is not the maximum attained stored volume during the event. Indeed, the maximum stored volume is usually greater than the final stored volume due to self-cleaning. In other words, within a short duration ( $< 12 min$ ), the basin stores a maximum volume and then starts to release some materials through the dam's openings. This example also shows the rapid deterioration (in 1 year), in which the basin is almost completely filled after the second debris flow event in a scenario, which consists of 29 debris flow events occurring over a period of 50 years. Similar results are obtained for the rest of events involved in the scenario and for the others generated scenarios.

**Figure 4.** Results showing the volume stored in the debris basin at the end of the first and the second debris flow events involved in the first generated scenario.



The obtained final stored volume after each debris flow event involved in a scenario permits building deterioration trajectories of the debris basin. Fig. 5 shows the evolution of the volume stored in the debris basin over time for the 100 generated scenarios. It is revealed that in most scenarios, the debris basin is completely filled within 5 years (after two or three debris flow events). Moreover, in all scenarios, the basin reaches its maximum storage capacity before 20 years. Consequently, cleaning maintenance operations are required at very early stages.

**Figure 5.** Deterioration trajectories showing the evolution of the stored volume in the basin over time. Dashed lines: chosen thresholds defining the states of the basin.



### 3.2 SPN Model Results and Discussions

As mentioned in section 2.2.1, four states of the debris basin should be defined. The thresholds representing these states are chosen, based on expert assessment as follows:

- State 1:  $0 \leq V_b \leq 2,200 \text{ m}^3$  (until 10% of the basin's capacity)
- State 2:  $2,200 \text{ m}^3 < V_b \leq 10,000 \text{ m}^3$  (before reaching 50% of the basin's capacity)
- State 3:  $10,000 \text{ m}^3 < V_b \leq 20,000 \text{ m}^3$  (before reaching 90% of the basin's capacity)
- State 4:  $20,000 \text{ m}^3 < V_b \leq 22,000 \text{ m}^3$  (until the basin is completely filled)

Based on the deterioration trajectories provided in fig. 5, the time spent in each of the defined states can be computed for all the scenarios. The achieved results allow estimating a probability law for each transition. Indeed, an empirical cumulative distribution function (CDF) is obtained for each transition using Kaplan-Meier estimator. These distributions are used then as an input to the SPN deterioration model. After inserting all the necessary inputs to the SPN model (e.g. time to inspection, maintenance duration), Monte-Carlo simulations are executed. In the studied case, 200 simulations were enough to reach convergence in results. Table 1 provides the results of the SPN model obtained after simulating each of the proposed maintenance strategies. Results reveal that almost in all the strategies, corrective cleaning operations are the most performed. This reassures the issue revealed by the physical model that the basin reaches almost its storage capacity within a short duration.

In order to estimate the total cost of each maintenance strategy, the cost of each maintenance operation should be specified. Real data dedicated to Claret retention system shows that the cost of cleaning operations is 2.83 €/m<sup>3</sup> [13]. Assuming mean cleaning operations, the costs of minor, major and corrective operations are respectively 17,000 €, 42000 € and 59,000 €. Table 2 reveals that all the proposed maintenance strategies have more or less the same average total cost. However, strategy 4 is the most-cost effective and strategy 2 is the most expensive. Consequently, for the Claret retention system, it is better to wait until the debris basin is almost completely filled and then to carry out corrective cleaning operations.

**Table 1.** Average number of maintenance operations performed over a period of 50 years.

Strategy	Minor	Major	Corrective
1	4.84	3.66	4.14
2	0	4.09	5.29
3	4.09	0	6.44
4	0	0	7.48

**Table 2.** Average total cost of each maintenance strategy.

Strategy	Total cost (K€)
1	480.175
2	483.890
3	449.195
4	441.025

## 4 Conclusions

In this paper, a surrogate deterioration model that benefits from the physical modelling of a retention system is developed using SPNs. The model makes it possible to implement easily a CBM policy concerning cleaning operations of the system. Indeed, the physical modelling results in deterioration trajectories that show the evolution of the volume stored in the debris basin. These trajectories are then used in order to estimate the transition probability laws to be used in the SPN model. The overall developed approach provides a better understanding of the trapping process governed by the retention dam and the debris. It also supports the managers of retention systems in making cost-effective maintenance decisions by avoiding unnecessary cleaning costs. The model can be developed further by considering not only the cost of the proposed maintenance strategies, but also their efficiency in increasing the protection level provided by the system.

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