Economic Efficacy Assessment of Deteriorating Protection Structures Subjected to Natural Phenomena in Mountains

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ABSTRACT: Natural phenomena in mountains pose threat to people and material assets located downstream. Different types of protection structures are implemented in mountains to resist natural phenomena and to protect vulnerable exposed elements. However, these structures deteriorate over time and the level of protection they provide is reduced, which raises for example the issue of their maintenance. To be economically effective, there should be a balance between the level of protection provided by protection structures to downstream elements at risk and the expenses spent on them (e.g., maintenance costs), as done in classical cost-benefit analysis. This study aims in proposing a conceptual model that estimates the evolution of risk level induced by natural phenomena in mountains while considering different deterioration levels of protection structures. This is achieved by performing risk analysis that integrates hazard, vulnerability and exposure assessment. Cost-benefit analysis is then adopted to assess the economic efficacy of protection structures. Finally, a simple numerical application is carried out to clarify the proposed model.

1. INTRODUCTION

Mountainous regions (e.g., French Alpes) are usually exposed to different types of natural phenomena such as torrential floods and debris flows. These phenomena induce risk in downstream areas where vulnerable issues (e.g., people, houses, roads) are located. Depending on their nature and intensity, they can result in direct damages (e.g., causalities, injuries, destruction) and/or indirect damages (e.g., infrastructure disruption). Such consequences prompt risk managers to acquire a comprehensive knowledge about the dynamics of natural phenomena in mountains as well as the means and alternatives for protecting people and properties. Indeed, several types of protection structures (e.g., check dams, retention dams, dykes) are implemented in mountains to control torrents. These are civil engineering structures that act on reducing the causes of the phenomena (e.g., erosion) or their consequences (e.g., overflows, deposit).

During their lifetime, protection structures are exposed to several deterioration mechanisms due to their aging and the high intensity phenomena they are subjected to. Consequently, efficacy level of these structures is reduced over time. The efficacy of protection structures corresponds to the ratio between their capacity and functional objectives conditioning the risk reduction level they provide to downstream elements at risk. It is equivalent to the performance level of the structure expected at the design phase, after construction and in service. Assessing the dynamic efficacy of a protection structure involves evaluating three components: structural, functional and economic efficacy. The structure should be stable from a structural point of view (e.g., external and internal stability). Moreover, it should be operating while achieving all the desired functions (e.g., bed stabilization, flow centering, material storage). To be economically effective, the cost of damages triggered after natural phenomena should be less than the expenses spent on the construction and maintenance of protection structures, both considered in the same time period.

Recent studies have focused on developing stochastic approaches that make it possible to model and analyze the physics behind the deterioration process of protection structures when subjected to natural phenomena over their lifetime (Chahrour et al., 2021, 2023). The main objectives behind these approaches were to assess the technical efficacy (structural, functional) of protection structures and to support their maintenance decision-making. Moreover, Carladous (2017) has developed a decision-aiding model using cost-benefit analysis (CBA) in order to choose which protection measures to implement based on an economic efficacy assessment, which corresponds to the efficiency of reducing the risk induced by the natural phenomena and the cost of implementation of these measures. Nonetheless, the latter study has not considered assessing the evolution of the economic efficacy of protection structures over time. This means that the assessment was carried out from a static point of view, assuming that there was no technical efficacy reduction due to the deterioration of structures over time. Consequently, no maintenance operations were taken into account.

This study aims to fill the gap in the literature by proposing a simple model that makes it possible to estimate the dynamic (i.e., over time) economic efficacy of protection structures in combination with the evolution of their technical efficacy over time.

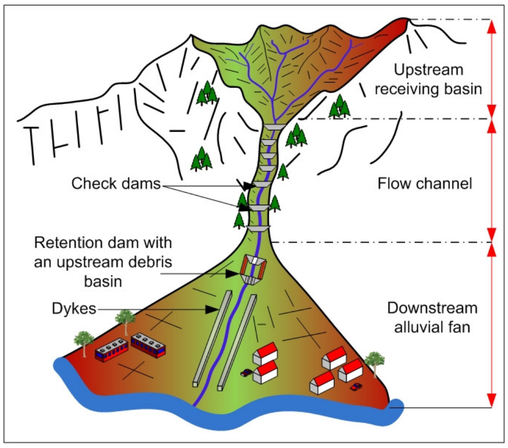

Figure 1: Torrential watershed and structural protection measures.

The developed model incorporates (i) risk analysis and (ii) cost benefit analysis. It starts by assessing the risk level imposed downstream due to natural phenomena while considering different deteriorating states of the protection structures and ends up by estimating the benefits (in €) of implementing the structures in each case. The latter is obtained by comparing the risk value (sum of expected (or probabilized) economic losses in €) to the expenses (in €) spent on the structures.

This paper is structured as follows: Section 2 provides a brief description of the studied context. The methodology developed to achieve the desired objectives is presented in Section 3. Section 4 describes a simple numerical application, in which the risk and cost-benefit analyses are carried out. Conclusions and perspectives are provided in Section 5.

2. Torrential Watersheds & Protection Structures

Torrential watersheds are located in mountains and are physically composed of three zones (Figure 1) as presented below (Surell, 1841).

Receiving basin: upstream area exposed to intensive precipitation (storms). It is a run-off production area and sediment supply source.

Flow channel: a narrow and steep path at which the torrential phenomenon (mixture of liquid and solid materials) flows.

Alluvial fan: downstream flat area where the transported flow is deposited. It involves vulnerable elements such as people, houses and infrastructures.

Intense rain events that occur in steep torrential watersheds lead to fast-moving flows (e.g., clear water floods, debris flows), which may be very destructive. The particular features of torrential watershed (steep slope, narrow channel) enhance the capacity of the flows to erode banks and to transport and deposit materials on fans where elements are risk are located. The impact and volume of the deposited materials could disrupt infrastructures (e.g., obstruction of roads), destroy houses and industrial structures and generate causalities. In France, risk management in torrential watersheds is largely based on structural protection measures. Structural measures are mainly civil engineering structures generally constructed along the flow channel (e.g., series of check dams) and in the alluvial fan (e.g., retention dam, dykes). These structures aim to provide protection by reducing the risk level imposed on downstream areas.

Protection structures do not function separately. The objectives of protection are only achieved within a protection system composed of several structures grouped together so that they participate collaboratively in protecting socio-economic assets. The efficacy of the overall protection system in reducing the risk level decreases with the increase of its deterioration level. Consequently, the system should be regularly inspected and maintained. However, these interventions cost much. This raises the following question: Is this protection system efficient from an economic perspective? In other words, does the total cost spent on the protection system (including construction, site visits and maintenance costs) exceed the benefit (reduction in total risk value)? Another key question is to know whether the protection system will still be economically effective when it deteriorates over time (i.e., after taking depreciation into consideration)? This study addresses these questions through the methodology developed in the next section.

3. Methodology

3.1. Protection System Efficacy Reduction

As mentioned before, the reduction of the technical efficacy of a protection system affects the risk level imposed on downstream exposed elements. Consequently, information concerning the deterioration process of the protection system should be acquired. This process can be defined as the evolution of the system from one deteriorated state to another as shown in Figure 2. In this study, three states of a protection system are considered: new, poor and failed. These states can be defined based on degradation indicators reflecting the efficacy level E of the system as presented below:

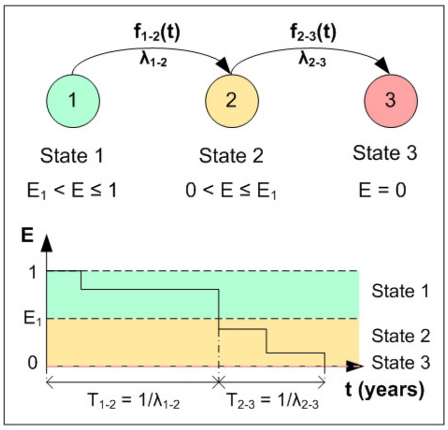

Figure 2: Deterioration process of a protection system.

State 1: $E_1 < E \leq 1$ new system

State 2: $0 < E \leq E_1$ poor system

State 3: $E = 0$ failed system

where 1 corresponds to maximum efficacy level, 0 corresponds to total failure and E_1 is an intermediate threshold that separates states 1 and 2.

Generally, the deterioration process of any deteriorating system is stochastic. The crucial elements needed for representing this process are the probability laws associated to the transition times between the defined states of the system. Figuring out these laws is not an easy task, especially when no or few monitoring data are available. Chahrour et al. (2021), has developed a physics-based model that makes it possible to estimate these laws through physically modeling the deterioration of protection structures over time. Other researchers usually assume these laws based on available data or expert assessment. Most of them assume an exponential distribution because of the simplicity in considering a constant deterioration rate. The probability density function presenting the law of transition times from state i to state j following an exponential distribution is given by:

$$f_{i-j}(t) = \lambda_{i-j} \exp\left(-\lambda_{i-j} \cdot t\right) \quad (1)$$

The mean transition time between states i and j can be then estimated as follows:

$$E(T_{i-j}) = 1/\lambda_{i-j} \quad (2)$$

3.2. *Risk Analysis*

Generally, risk induced by a natural phenomenon is defined as a combination between hazard, vulnerability and exposure. For each type of natural phenomenon, hazard is a combination of its probability of occurrence (likelihood) and its intensity, which reflects a physical quantity describing the phenomenon (e.g., velocity). Vulnerability represents the potential damage rate relative to the intensity of the hazard. Exposure refers to the combination between elements that are exposed to the hazard and their value (e.g., in euros). This definition of risk, given by Eq. (3), is provided by the intergovernmental panel on climate change (IPCC).

$$\begin{aligned}\text{Risk} &= \text{Hazard} \bigotimes \text{Vulnerability} \bigotimes \text{Exposure} \\ &= \text{probability} \otimes \text{intensity} \bigotimes \text{damage potential} \bigotimes \\ &\quad \text{elements at risk} \otimes \text{value}\end{aligned} \quad (3)$$

where the symbol $\otimes$ corresponds to a combination between the terms defining a risk level.

Depending on available data, risk assessment could be either based on discrete or continuous modeling of its components. Discrete modeling is much simpler to carry out, in which only four qualitative scenarios, representing the likelihood of a natural phenomenon, can be considered: exceptional, rare, occasional and frequent. On the other hand, continuous modeling provides better estimate of the risk but is more complex to obtain. It requires more information concerning the time series of the hazard, the exposed assets and the vulnerability of each. In this study, the methodology developed to evaluate the risk considers continuous modeling of its components. However, the modeling will be based on several assumptions, in which the goal is to show the principles behind the evolution of quantitative risk analysis considering deterioration states, which is not yet tackled in the context of torrential risk. To carry out this analysis, the following steps should be accomplished.

3.2.1. *Modeling the Hazard*

The first step concerns generating the "Intensity I - Probability P" curve, which characterizes a hazard linked to a specific type of natural phenomenon. This curve represents the probability of occurrence of an event (e.g., storm) that has the potential to trigger a dangerous natural phenomena (e.g., debris flow) of a given intensity (e.g., velocity of the flow) to occur in a specific area and time interval. It can be built using available historical databases where the intensities and the return periods ($T = 1/P$) of the events that have occurred in the past are recorded. If this data is available, a law that best fits the observed data can be assumed. If not, the modeling can be based on experts' assessment.

The presence of a protection system in a torrential watershed acts on reducing the intensity of natural phenomena. Consequently, for each state of the system (i.e., for each technical efficacy level), the "Intensity I - Probability P" curve should be established. In the case where system is in state 1 (new system), the intensity of the phenomena is reduced by a ratio α_1 and will be defined as I_1. If the system is in state 2 (degraded system), the intensity is reduced by a ratio $\alpha_2 < \alpha_1$ and will be referred to as I_2. In the case when the system is in state 3 (completely failed), it is assumed that as if there is no protection system. Therefore, the intensity I of the phenomena will not be reduced.

α_1 and α_2 are intensity reduction factors to be defined based on expert assessments. Moreover, these reduction factors can be only applied when the intensity of the phenomenon is less than a specific threshold I_{th}, to be also defined by experts.

3.2.2. *Estimating the Number of Exposed Assets*

The second step concerns estimating the number of downstream assets, which are touched (impacted) by a natural phenomenon. In fact, the area reached by a natural phenomenon varies depending on the probability of propagation of the phenomenon given the fact that it has already occurred. In this study, it is assumed that all the assets implemented in the reached area are touched by the phenomenon. To demonstrate calculation principles, a relation between the reached area $A_{reached}$ and the occurrence probability of the natural phenomenon P is assumed as follows:

$$A_{reached} = A_{max}^{(1-P)} \tag{4}$$

where A_{max} is the maximum area that can be reached by any natural phenomenon.

Assuming that all the material assets have the same area A_{asset}, the total area of touched assets $A_{\text{total assets}}$ and the total number of touched assets $N_{\text{touched assets}}$ can be obtained using Eq. 5 and Eq. 6.

$$A_{\text{total assets}} = \beta \cdot A_{reached} \tag{5}$$

$$N_{\text{touched assets}} = A_{\text{total assets}} / A_{asset} \tag{6}$$

where β is a constant occupation rate reflecting the density of construction in the reached area.

3.2.3. *Modeling the Damages on Assets*

The third step concerns constructing the physical vulnerability of the assets exposed to risk, which is given by a "Damage rate D - Intensity I" curve. The intensity of a natural phenomenon is associated with a damage rate, which is a physical quantity representing the percentage of damage caused on an asset. Indeed, the asset may be partially or totally destroyed depending on the intensity of the phenomenon. Kang and Kim (2016) has carried out a nonlinear regression analysis to relate the damage rate to the intensity of debris flow events. Different relations were obtained depending on the intensity parameter. For example, when considering the intensity parameter I of debris flows as the flow velocity υ (in m/s), the relation will be:

$$D = 1 - \exp(-0.0094 I^{2.775}) \tag{7}$$

Note that D is the damage rate in the case when there is no protection system or in the case when the system is in state 3. D_1 and D_2, corresponding to the damage rates in the case when the system is in state 1 or 2 can be also obtained using Eq. 7 by replacing the intensity I with I_1 and I_2 respectively.

3.2.4. *Estimating the Material Losses*

In this step, the objective is to estimate the total cost of the losses triggered after natural phenomena. This is given by a "Material loss L - Probability P" curve. In this study, it is assumed that only material losses (direct damages: assets' destruction) are considered. This means that indirect damages (e.g., human mortality, impacts on the environment) are not taken into account. The cost of material losses L (in €) can be estimated using the formula developed by Rheinberger et al. (2009) as follows:

$$L = (1-\varepsilon_D) \cdot D \cdot (1-\varepsilon_E) \cdot N_{\text{touched assets}} \cdot A_{asset} \cdot V_{asset} \tag{8}$$

where ε_D is the damage reduction rate linked to vulnerability reduction, ε_E is the exposure reduction rate and V_{asset} is the cost of asset (in €/m^2).

Note that L is the cost of material losses in the case when there is no protection system or in the case when the system is in state 3. L_1 and L_2, corresponding to the material losses in the case when the system is in state 1 or 2 can be also obtained using Eq. 8 by replacing the damage rate D with D_1 and D_2 respectively.

3.2.5. *Evaluating the Risk*

The final step is to evaluate the risk level, i.e., the expected financial cost of the risk induced due to a natural phenomena. This is achieved by estimating the area under the curve presenting the material losses multiplied by the probability. To calculate this area, the trapezoidal method can be used.

Since three different states of the protection system are considered, three different curves presenting the material losses are obtained. Consequently, each curve will provide a risk level. For states 1, 2 and 3, the risk level is respectively defined as R_1, R_2 and R_3.

3.3. *Cost-Benefit Analysis*

Cost-benefit analysis (CBA) is a method used to assess the potential benefits and costs of a specific decision by assigning monetary values to its outcomes. The main objective behind CBA is to determine whether the benefits outweigh the costs of investment and maintenance and finally if building the protection is worthwhile.

To assess whether a protection system is economically effective, a comparison between the risk level in the absence and in the presence of the protection system should be performed. Furthermore, to estimate the benefits (in €) of a protection system, the cost of its construction should be typically considered as an initial cost, also known as a "$t = 0$" cost. This includes all expenses that are incurred at the beginning of the project, such as materials, labor, equipment, and other miscellaneous expenses. However, since the protection system deteriorates over time, the cost-benefit analysis should also include the ongoing costs (e.g., maintenance costs) and the benefits of the project over its lifetime. This is due to the fact that as the state of the system evolves over time, its efficacy level is reduced, which in turn leads to a decrease in risk reduction as compared to when it was first put in place.

In this study, it is assumed for the sake of simplicity, that the deterioration of the protection system is continuous in time (as shown in Figure 2). In other words, maintenance operations are not carried out over the lifetime of the system. In this case, the costs C_c spent on the system are only those involved in the initial construction operation. Consequently, the evolution of the protection system's benefits B over time can be estimated as follows:

For $t = 0 \longrightarrow B = (R - R_1) - C_c$

For $0 < t \leq T_{1-2} \longrightarrow B = R - R_1$

For $T_{1-2} < t \leq T_{2-3} \longrightarrow B = R - R_2$

For $t > T_{2-3} \longrightarrow B = R - R_3$

where R is the risk level when there is no protection system.

4. Numerical Application

This section presents a simple numerical application of the developed methodology. Firstly, the risk levels in the absence and in the presence of a protection system are assessed. Secondly, the economic benefits behind the implementation of a protection system are estimated under simplified asumptions.

Table 1: Data necessary for estimating the number of assets touched by debris flow events.

A_{max} (km^2)	A_{asset} (m^2)	V_{asset} (€/m^2)	β
1	100	2000	0.4

4.1. *Absence of Protection System*

The available data necessary for hazard modeling are those related to the natural phenomena occurring in the Claret torrent in France. This torrent is very active and it is characterized by a steep slope and high sediment potential. It is mainly subjected to debris flow events of different volumes. The obtained data are the volumes V (in m^3) and the return periods T (ONF-RTM, 2013). The probability of occurrence P of each debris flow event is estimated using Eq. 9. In this application, the intensity is considered to be the velocity (in m/s) of an event. In this case, the intensity I is estimated using Eq. 11, given by Rickenmann (1999).

$$P = 1/T \tag{9}$$

$$I = 2.1 \cdot Q_p^{0.33} \cdot S^{0.33} \quad (m/s) \tag{10}$$

where $S = 0.53$ m/m is the average slope of the torrent's flow channel and Q_p is the event's peak discharge. Q_p can be estimated using the following equation, given by Rickenmann (1999).

$$Q_p = 0.1 \cdot V^{0.833} \quad (m^3/s) \tag{11}$$

The damage rate curve is constructed according to Eq. 7. All data necessary for estimating the number of assets touched by debris flow events are assumed and presented in Table 1. The curve presenting the material losses is then implemented using Eq. 8, considering $\varepsilon_D = 0.1$ and $\varepsilon_E = 0.1$.

The obtained results are presented in Figure 3. The mean risk level, corresponding to the area under the curve presenting the material losses is $R = 43.75$ M€.

4.2. *Presence of Protection System*

In the case where a protection system is present in the torrent, the intensity of a debris flow event is reduced depending on the state of the system.

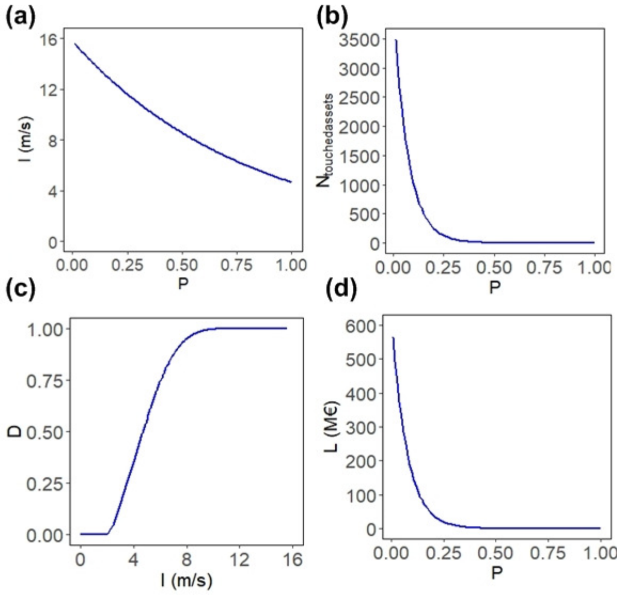

Figure 3: Results of risk analysis in the absence of a protection system. (a) hazard modeling; (b) number of assets touched by an event of a given probability; (c) damage rate; (d) material losses.

As mentioned before, three deterioration states are considered. The threshold, defined in Section 3.1, corresponding to the technical efficacy level of the intermediate state of the protection system, is considered to be $E_1 = 0.5$. It is assumed that if the system is in state 1, the intensity will be reduced respectively by $\alpha_1 = 0.8$. If the system is in state 2, the intensity will be reduced respectively by $\alpha_2 = 0.5$. If the system is in state 3, the intensity will not be reduced and therefore will be equal to the intensity of the events in the case of the absence of a protection system. These reduction factors make it possible to estimate the intensity I_1, I_2 and I corresponding to the cases when the system is respectively in state 1, 2 and 3 as shown in Figure 4. However, in all cases, the intensity will not be reduced if it exceeds $I_{th} = 13$ m/s, as it is considered too strong for a protection system to handle. The damage rate in each case can be then estimated using Eq. 7. Finally, the material losses in each case are computed using Eq. 8 and presented in Figure 5.

Results provided in Figure 5 make it possible to estimate the mean risk level induced by debris flows considering the different states of the protection system: $R_1 = 38.72$ M€, $R_2 = 42.28$ M€

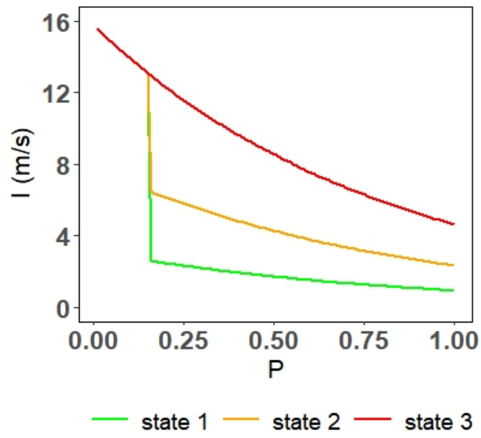

Figure 4: Hazard curve showing the intensity reduction depending on the state of the protection system.

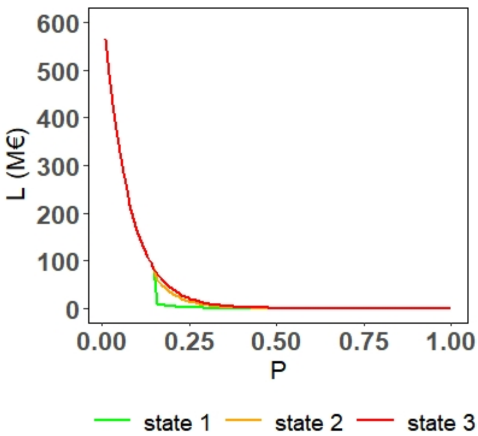

Figure 5: Results showing the reduction in the material losses depending on the state of the protection system. (e.g., for $P = 0.01$, $N_{touched\ assets} = 3483$, $L = 564$ M€)

and $R_3 = 43.75$ M€.

4.3. *Benefits: Reduction in Risk level*

In order to construct the evolution of the risk level over time in the presence of a deteriorating protection system, the deterioration process should be first developed. It is assumed that the deterioration rates following an exponential distribution are $\lambda_{1-2} = 0.05$ and $\lambda_{2-3} = 0.02$. This means that the transition times from state 1 to state 2 and from state 2 to state 3 are $T_{1-2} = 20$ years and $T_{2-3} = 50$ years. Considering that the modeling takes place over a duration of 100 years means that the protection system resides 20 years in state 1, 50

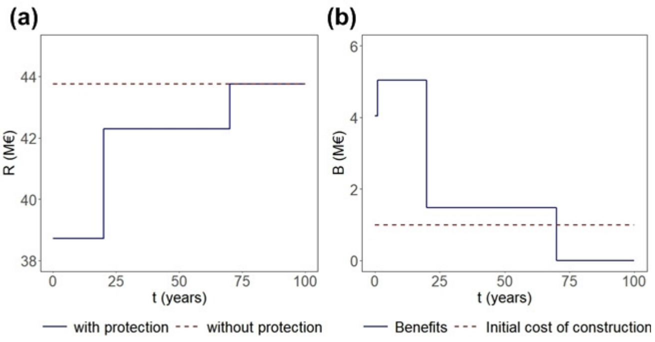

Figure 6: (a) Evolution of risk level in the absence and the presence of a protection system; (b) Evolution of economic benefits of the studied protection system.

years in state 2 and 30 years in state 3. These results make it possible to plot the evolution of the risk level over time as shown in Figure 6,a.

For estimating the economic benefits of a protection system, its cost of construction should be first defined. Let us assume a protection system composed of four check dams, in which the cost of construction of one dam is 250000 €. In this case the total cost of construction is $C_c = 1$ M€. Consequently, the evolution of the economic benefits over time are estimated based on Section 3.3 and presented in Figure 6,b. It can be noticed that the benefits outweigh the costs over the long term. This reveals that the project of implementing the protection system is cost-effective.

5. CONCLUSION

Natural phenomena in mountains can have devastating effects on communities and infrastructures. It is therefore crucial to implement protection systems/structures in order to minimize the risk of damage and loss of life and to insure economic stability. Moreover, assessing the economic efficacy of protection systems is essential for supporting risk managers to make decisions that balances between costs and benefits of the protection strategy. From this study, it has been revealed that risk and cost-benefit analyses are useful tools to compare the sum of potential economic losses resulted from natural phenomena with the costs spent on the protection system over its lifetime. Future work in this area could include considering maintenance operations, which will affect the deterioration process and therefore the evolution of risk level over the lifetime of the protection system. Maintenance costs and discount rates could be also considered in the cost-benefit analysis for more reliable evaluation of long-term cost-effectiveness in different time periods. Another avenue for future work could be to conduct a real-case study to validate the method and to provide real-world examples of its use.

6. ACKNOWLEDGEMENTS

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