Chapter 28
Lessons from a Century-Tradition on Ecosystem-Based Disaster Risk Reduction (Eco-DRR) in Mountains: The Case of the Torrential System *Los Arañones* (Canfranc, Pyrenees)

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28.1 Introduction

Mountain regions are characterized by the occurrence of extreme hydrogeomorphic events, favored by the high energy relief, complex geology, and extreme climate conditions [1, 2]. The occurrence of torrential floods, snow avalanches, rockfall, or landslides have the potential to affect exposed infrastructure, cultural and economic assets as well as human life [3]. Such extreme events can disrupt the status quo of communities and may put the future welfare of people living in mountain valleys

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at risk [4, 5]. Torrential floods are especially common, representing about half of all-weather related disasters that occurred between 1995 and 2015 [5]. The impact of torrential floods, often connected to large floods down the valley, have affected millions of people and caused many tolls worldwide [6].

People living in mountain areas are especially vulnerable to the impact of natural hazards [7]. In these regions, social systems are characterized by isolating settlements which livelihood is linked to agriculture, animal husbandry, and/or gathering, especially in low-income countries [8]. Besides, in medium–high income countries, mountain regions are well connected to major population centers favoring permanent residents, economic migrants, amenity migrants, tourists, and other transients [9], which increases the elements-at-risk. In the next decades, the occupation of prone areas to natural hazards with the expected climate change impact could lead to a potential increase in losses and damages, as identified already in global trends [10]. According to the IPCC, climate change is both increasing the frequency, intensity, spatial extent, duration and changing the seasonality of extreme weather events [10]. The rate of change is dissimilar across the world, but there is a certain confidence that hydrological extreme events will be more common, with mountain regions being especially sensitive to these changes [11]. Besides, mountain regions are highly sensitive to land-use changes and present a higher hazard for coalescence of high energy processes and cascading events. People living in mountain regions are, therefore, especially vulnerable to these extreme events [12] (Fig. 28.1).

Improving our capacity to mitigate future disaster in mountain regions will be essential for sustainable development, representing one of the main goals of different international and national frameworks, such as Disaster Risk Management Sendai Framework and the 2030 Agenda for Sustainable Development [13]. Overall, all these policies underline the need to improve our knowledge on extreme scenarios with preparedness purposes [3, 14], considering the efficiency of land-use planning as a tool to reduce damages and death tolls. Assertive land-use maps, where the hazard and risk for each process are represented, allow to refrain the installation of new settlements in places where exposure is too high, as well as the construction of defense structures following the principle of environmental and economical effectiveness. Hazard planning and long-term protective measurements are especially relevant in mountain regions, where the implementation of warning systems could be challenging due to the rapid hydrological response of catchments [15] and the high energy processes taking place in them [16–18]. Finding the right balance between safety and sustainability is, therefore, a real scientific-technical challenge with large implications in many socio-economic sectors.

In this context, the implementation of Ecosystem-based disaster risk reduction (Eco-DRR) strategies represents a paradigm shift to reduce vulnerability and promote resilience-disaster communities [19, 20]. Eco-DRR refers to the reduction of risk by (i) reducing the exposure of elements-at-risk in natural hazard prone areas; and (ii) improving ecosystem health and functioning by means of the use of environmentally and economically viable measurements, as a buffer for protecting lives and infrastructures. Being promoted in newer DRR-frameworks, the implementation of Eco-DRR

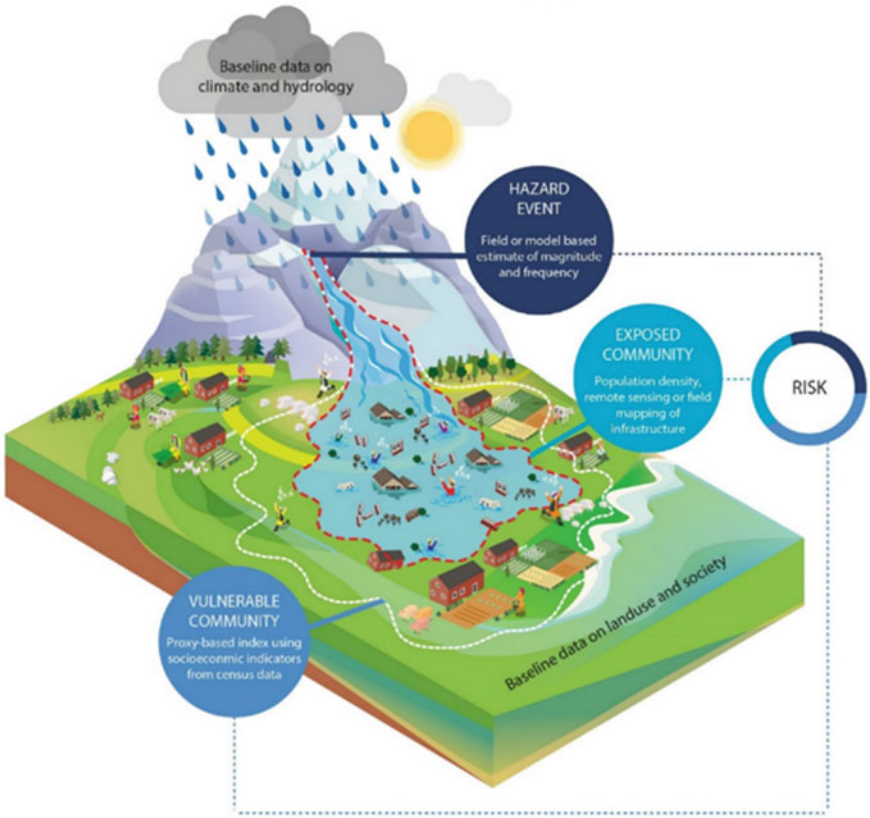

Fig. 28.1 Schematic framework for risk assessment of hydrological-related hazards [12]

can capitalize the long-term forest engineering experience in classical hydrological-forest correction strategies [21] aimed at improving the ecosystem's state of highly degraded mountain catchments. Thus, under such scheme, hydrological-correction dams, levees. or anti-erosion corrective works have been installed to reduce soil losses, promote forest establishment, and, ultimately, reduce impacts from natural disasters [22]. Thus, the implementation of structural and non-structural measures are currently increasing as a more flexible, effective, and efficient solution for increasing resilience, especially in mountain regions [23]. However, even considering this as the most appropriate way to cope with future disasters, little is still known about the reliability of such Eco-DRR solutions for long term. The reasons are (i) the systematic evaluation of such Eco-DRR measurements have not been broadly performed, and (ii) when such analyses have been done, the monitoring period is short, as such analyses are mostly focused on recently implemented Eco-DRR.

Here, we review the long-term Eco-DRR implementation combined with the installation of large measurements to protect critical infrastructure in the Pyrenees mountain range. In particular, we present the century accumulated experience derived from the implementation of Eco-DRR in *Los Arañones*. Particularly, we show the protection strategy case of the International Railway Station and related infrastructures of Canfranc on the border between Spain and France against recurrent snow avalanches, debris and torrential flow, rockfall, and soil losses. Long-term analyses of the reliability of Eco-DRR could contribute to identify the weakness and robustness of such approach, and therefore, determine their effectiveness under ongoing climate change scenarios.

28.2 *Los Arañones*: A Century History of Eco-DRR in the Spanish Pyrenees

The Pyrenees is a mountain range that separates the Iberian Peninsula (IP) from the European continent and constitutes the natural border between Spain and France. The Pyrenees extends over 500 km connecting the Atlantic Ocean and Mediterranean Sea, although, from a geological point of view, it is an extension of the Cantabrian mountains located over the entire northern coast of IP. Geologically, the Pyrenees is older than the Alps and are formed by sediment deposited during the Paleozoic and Mesozoic, which were lifted during the Hercinic orogeny. The middle sector of the Pyrenees is composed of gneiss and granitic material, being the Aneto Peak (i.e., 3404 masl) its highest elevation. The main landforms in the Pyrenees are related to fluvial, periglacial, and glacier activities. Today, the Pyrenees still have several small glaciers at high altitudes, although all of them are in highly recessive stages [24]. The climate in the Pyrenees changes from oceanic (Norwest sectors) toward Mediterranean climate (in South-east sectors), with certain continental climate in central sectors. These conditions define temperate oceanic and sub Mediterranean bioclimes which, together with altitudinal gradient, condition the existing vegetation. Overall, vegetation can be divided into a montane belt (mixed deciduous and conifer trees, Fagus sp, Pinus sp), subalpine belt (mostly conifer trees, *Pinus* sp, *Abies* sp, *Piceas* sp), alpine belt (conifer trees and the presence of *Alnus* sp), and finally a sub and nival belt.

The Pyrenees are intersected by several valleys that connect France and Spain throughout mountain passes. Although there is physical evidence (Roman bridges, Roman roads) that indicates that some valleys were used for trading since the Roman period, the agreement “Treaty of the Pyrenees” signed between France and Spain in 1659 A.D. stipulated the international border and gave the importance of some valleys as routes for international trade between countries. Since then, corridors of communication have been developed. An example was the route to the Somport pass built in 1876 A.D. following the path of the Caesar Augusta Roman road. In particular, the Somport pass became a strategic mountain pass since it was the pass with the lowest altitude in the central Pyrenees. In 1882 A.D., during the reign of Alfonso XII (1874–1885), the construction of a railway line to link France with Spain through the Somport tunnel was planned. The works started in 1882, although the perforation of the tunnel started several decades later (in 1908) after several discussions about the convenience of the project. These works included the construction of an International Railway station in the south exit of the tunnel, in a flat place called *Los Arañones* within the municipality of Canfranc. The works ended in 1928, and the International Railway of Canfranc quickly became an important spot for international trading. In parallel, the village of *Los Arañones* grew significantly, becoming an important population center at that time. After the Spanish Civil War (1936–1939), this infrastructure experienced a golden age, especially during the 1950s and 1960s. However, a train accident in 1970 on the French side affected a bridge seriously and since then the communication has not been re-established. Without a willingness to solve this issue between both countries in the following years, the infrastructures have seen their aging and progressive deterioration. Currently, the existing International Railway of Canfranc (and related infrastructures) forms part of the tourist attraction and only works on the Spanish side, while the international communication has been changed to road transportation.

The planning of the International Railway of Canfranc supposed a real scientific-technical challenge due to the intrinsic complexity of works in mountain terrains and the existing hazards related to the occurrence of natural disasters [25]. The engineers in charge understood that the feasibility of the infrastructures was linked to their protection against frequent floods and snow avalanches, enhanced by the intense deforestation by the end of nineteenth century [25]. Innovatively, Spanish forest engineers (Benito Ayerbe—1872–1917—and followers, see [22]) designed and planned nature-based solutions to improve the hydrologic and forest ecosystem functioning, aimed at reducing the risk of natural hazards. Overall, these measurements consisted in (i) the design and implementation of small dikes to consolidate and contain erosive processes, rockfall activity, and intense flood-like processes, as well as the innovative design of empty dikes (non seen so far in other mountain regions worldwide) to retain mainly dense or non-inertial snow avalanches; and (ii) the intensive hillslope reforestation of more than 600 ha in the triggering zones to control the occurrence of phenomena with natives species such as *Pinus sylvestris* L., *Pinus uncinata* Ramond ex DC., *Abies alba* Mill., *Picea abies* (L.) Karsten, *Larix decidua* Mill. and *Fagus sylvatica* L. While measurements described in (i) were considered measures to protect a highly degraded zone in the short term, reforestation measures described in (ii) were planning to work in the long term. Interestingly, such strategy of combining structural and non-structural measures, which was planned more than one hundred years ago, is seen now as “a flexible, effective, and efficient solution to reducing impacts in the mountains” [i.e., 26]. Recognizing the innovative Eco-DRR approach and contribution realized in this and analog places and learning from their performance during the entire twentieth century would bring light about future and reliable strategies on DRR.

The study site is placed in the public forest (MUP n° 406) with an extension of 760 ha (Fig. 28.2). This area is formed by different torrents and valleys located in a north-south direction mountain chain, which favors north winds (higher humidity, lower temperature). The climate is defined as type D according to Köppen-Geiger [27] characterized by a cold and wet winter season and a mild summer. The annual

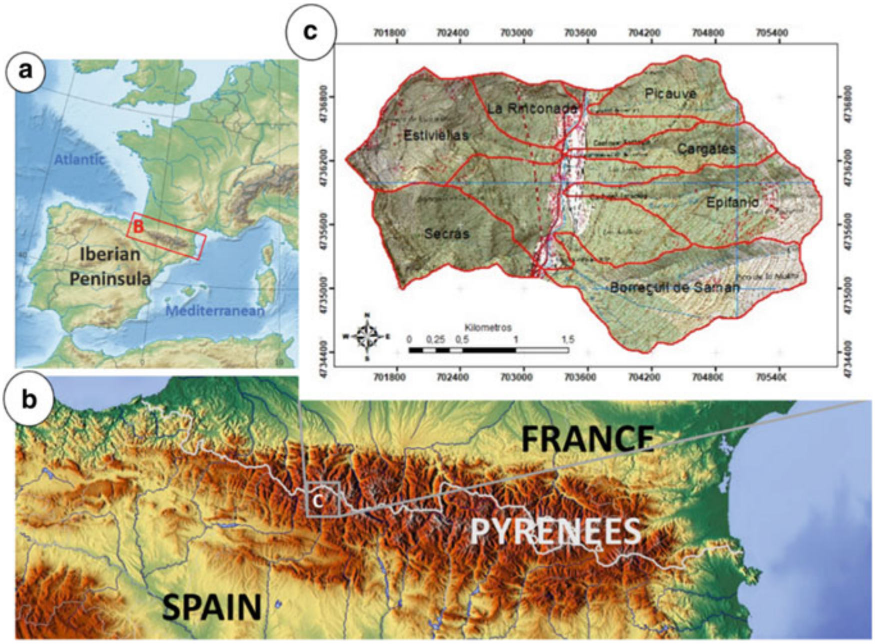

Fig. 28.2 Location of the Pyrenees in the Iberian Peninsula (**a**), the Canfranc valley between the Spanish-France border (**b**) and the torrent system of *Los Arañones* (**c**). *Source* **a** and **b** from available files under public domain (CC0), and **c** from [29]

mean precipitation is 1664 mm while the average annual temperature stands at 7.9 °C. *Los Arañones* is composed by seven torrential systems (Fig. 28.2), from which four represent a threat to the existing infrastructure. Overall, the torrent system called Picauvé and Borreguil de Samán does not affect current infrastructures. The torrent Rinconada is relatively smaller and much more inactive. The torrent Secras may affect the south exit of the current tunnel, while the torrent system called Cargates, San Epifanio, and Estiviellas represent a serious threat to the entire complex infrastructures. Table 28.1 represents the main physical characteristics of these torrential systems, including the Melton index M_{i}, as an indicator of the torrentiality defined as Eq. (28.1), as well as the fraction of covered canopy (fcc).

Table 28.1 Main physical characteristic of the most danger torrents

Torrent	Max. altitude (m)	Relief (m)	Length (m)	Slope (%)	Area (km^2)	Melton index	Fcc
Estiviellas	2358	743	1.771	41.9	~ 1.15	0.69	0.65
Cargates	2328	974	1.862	52.3	~0.53	1.33	0.87
Epifanio	2477	1050	2.25	46.7	~1.26	0.93	0.71

$$M_{\mathrm{i}} = \frac{\mathrm{WR}}{\sqrt{A}} \tag{28.1}$$

where WR is the watershed relief; and A represents the area of the watershed.

Over the last centuries, the landscape evolution of Canfranc valley has followed an analog tendency than the Pyrenees, which clearly is linked to human activities [27]. Thus, this evolution has been characterized by a progressive abandonment of crops and pasture lands from the late nineteenth century that continued until the 1980s. Since this moment, this tendency has been established or even slightly increased [27], including the livestock densities [28]. As a consequence, a progressive increase in vegetation cover can be observed in these regions. This simplified view of recent land-use changes (see [27] for more details about environmental and socio-economic factors related to these changes) was similar in *Los Arañones*, where, moreover, the reforestation practices and soil erosion control in the context of the implemented Eco-DRR have contributed to establishing dense and mature forest stands.

28.3 Natural Hazards and Infrastructures in Los Arañones

Among all processes, snow avalanches and torrential floods are especially common in Los Arañones. At the beginning of the twentieth century, powder (inertial flow) and wet/slab snow avalanches (non-inertial flow) were recurrent in Estivielles, San Epifanio, Secras, and Cargates catchments. Examples of such events took place on January 24th, 1915, when an intense snow avalanche reached the bottom valley affecting housing and other assets. Torrential floods were also recurrent, especially during summertime. The forest service recorded such events, as the torrential flood that took place on August 16th, 1916; when an intense thunderstorm triggered intense floods in all torrents, but especially in Estivielles.

The first Eco-DRR project was designed by Benito Ayerbe. The initial project was only focused on the San Epifanio catchment, but it was extended to surrounding torrents after checking the reliability of the works against snow avalanches during the winter of 1915. The final project was finished in 1919, defining measurements against rockfall, snow avalanches, and torrential floods. These measurements were:

(i) to protect against rockfall, the government bought and reforested the cropland (up to 235 ha) located in the lower parts of the torrents;

(ii) to protect against torrential floods, measurements were carried out in the catchment, at the channel, and on the debris flow cones. At the catchment level, reforestation practices were carried out with the aim of controlling erosion processes (Fig. 28.3). Innovatively, bands of *Salix eleagnos* were planted along contour lines. At channel level, transversal dikes were built to laminate the peak flow, control remontant erosion and retain sediments. At cone level, longitudinal dikes and channelization were built to direct the flood directly to the Aragon river (Fig. 28.4).

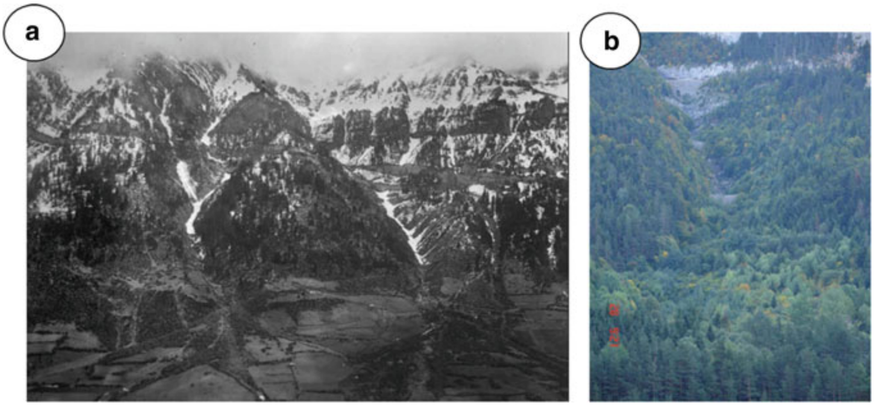

Fig. 28.3 **a** View of the *Los Arañones* landscape in early twentieth century. **b** View of the forested torrents in early twenty-first century. Pictures from Arrazola-Herreros et al. [30]

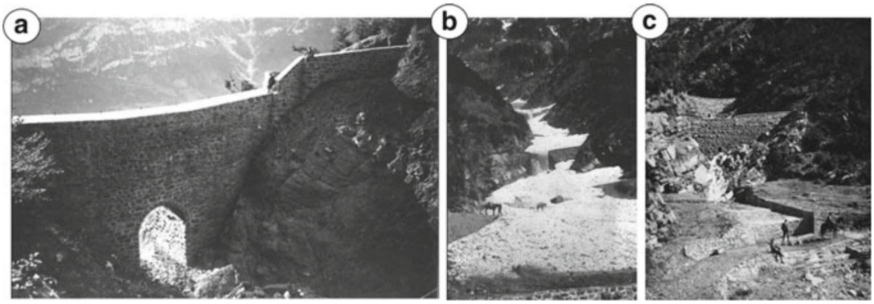

Fig. 28.4 **a** View of an empty dike designed and implemented in *Los Arañones*. **b** Example of snow-avalanche retention by the dikes. **c** Example of channelization at cone level. Pictures from Arrazola-Herreros et al. [30]

(iii) to protect against snow avalanches, measurements were carried out in the starting zone to prevent triggering and in the transport zone to limit the runout of events. In the starting zone, different snowpack stabilizers such as small walls or stakes were implemented, but also the reforestation of 360 ha with native species. In the transport zone different masonry walls, dikes, or reforestation were implemented. Innovatively, large empty dikes (up to 20 m height) were built with a large central culvert to retain the non-inertial snow avalanches but allow the flow of water-like events (Fig. 28.4).

After the implementation of the project, several studies were performed to evaluate the performance of the measures and for maintenance purposes. Yet, in 1933, the first extension of the initial project was designed which mainly consisted of the construction of a new empty dike in the Epifanio catchment. The Spanish Civil War reduced investment in the area, and only a few works technical reviews were done afterward. Over the last decades, the tourism presence has steadily increased, augmenting the elements-at-risk. This new situation has triggered the realization of several studies and projects, such as (1) repair project existing works; (2) built new measures in the Torrente Estiviellas; and (3) the publication of new scientific-technical studies.

Since the implementation of the first Eco-DRR project in Canfranc, the impact of snow avalanches and torrential floods seems to be changed. Thus, while the impact of snow avalanches still has been present during the entire twentieth century and last decades, the impact of torrential floods seems to be reduced. Thus, during the last extreme flood event in 2015, the measures in the torrents were able to reduce damages in Canfranc station, while large damages were reported downvalley in the Aragon river. However, although the impact of minor and moderate snow avalanches events seems to be significantly reduced, yet large snow avalanches have had the potential to reach the bottom valley. For instance, during winter 1954, a massive snow avalanche was triggered in Estiviellas, causing large damages to the vegetation along the transport zone and runout. On 1st February 1963, a refuge in Estiviellas was destroyed, while in 1970 the snow avalanches reached the railway installation. The largest snow avalanches occurred in the winter of 1986 when a snow avalanche caused important damages to the church of Canfranc; and more recently in 2013, when the snow reached the village.

28.4 Current and Future Performance of *Los Arañones*

As previously mentioned, the steady increase in tourism has attracted a larger socio-economic activity in the region. This has resulted in newer urban developments in the bottom valley, leading to an important increase in the elements-at-risk. The situation is worrisome since the records suggest that extreme events still eventually take place. Besides, the aging of the infrastructures could reduce their reliability [23] (Fig. 28.5), and the forest stands could have reached their mature state. On the other hand, climate change may modify the hydrological response of the catchments in *Los Arañones*, as seen in analog zones [31]. Overall, climate change scenarios are expected to have an impact on temperature trends, specifically with an increase in maximum temperatures [32], while the uncertainties related to the projected precipitation avoid to see any clear tendency [33]. Yet, intense precipitation events due to convective processes could increase in the region, probably favored by the provided moisture from the ocean at this latitude [34]. As result, the snowpack in the Pyrenees may be strongly affected, especially in low-mid altitudes [32] as well as the soil moisture, which is expected to be reduced.

All these abovementioned issues have opened the question about the reliability of the implemented Eco-DRR actions to protect the existing and new settlements and infrastructure. Specifically, questions about the changes in the frequency and type of snow avalanches processes due to climate change [5], as well as the impact of soil moisture on soil erosion (i.e., sediment laden) under torrential precipitation, are

Fig. 28.5 Current state reveals the aging of the transversal dikes in San Epifanio torrent

on the table. As a first analytical step, an analysis of the reliability of the Eco-DRR approach under current conditions has been performed. Particularly, a classical risk assessment was implemented to evaluate the feasibility of the current scenario (implemented Eco-DRR) and scenario defined without any implementation (Fig. 28.6). To this end, hydraulic (i.e., IBER model) and snow-avalanche numerical models (RAMMS::AVALANCHE) have been calibrated based on more than a hundred year' records from the Forest Service. Additionally, losses from current exposed elements have been analyzed, by including local and national vulnerability curves. The risk analyses of each scenario have been evaluated based on Avoided Costs Method (ACM) as well as the use of the Human Capital Method (HCM), the calculation of Replacement Costs (RC), and the revision of market prices (RMP). Finally, the economic indicators related to the implementation of a hypothetical analog original project with current costs and an approach to the maintenance costs were also evaluated. A detailed methodological description can be found on Esteban-Muñoz et al. [29].

Overall, results show that the Eco-DRR works and the designed maintenance actions (which included check dams reconstruction) are economically and socially justified. Maintenance costs reach up to € 1.089.848 during works lifetime. Thus, the approach developed to provide evidence that the Net Present Value (NPV), which corresponds to the protective effect of the Eco-DRR is € 606.79 per year and ha; while the estimated risk reduction reaches up to € 1,522,188/year. These indicators demonstrate the economic and social viability of the Eco-DRR. Furthermore, the values of the indicators are high due, in part, to the age of the works and the local development that has allowed the defensive nature of the works. Thus, the long-term cost-benefit ratio of the project was 0.31, with an investment return period of 19 years.

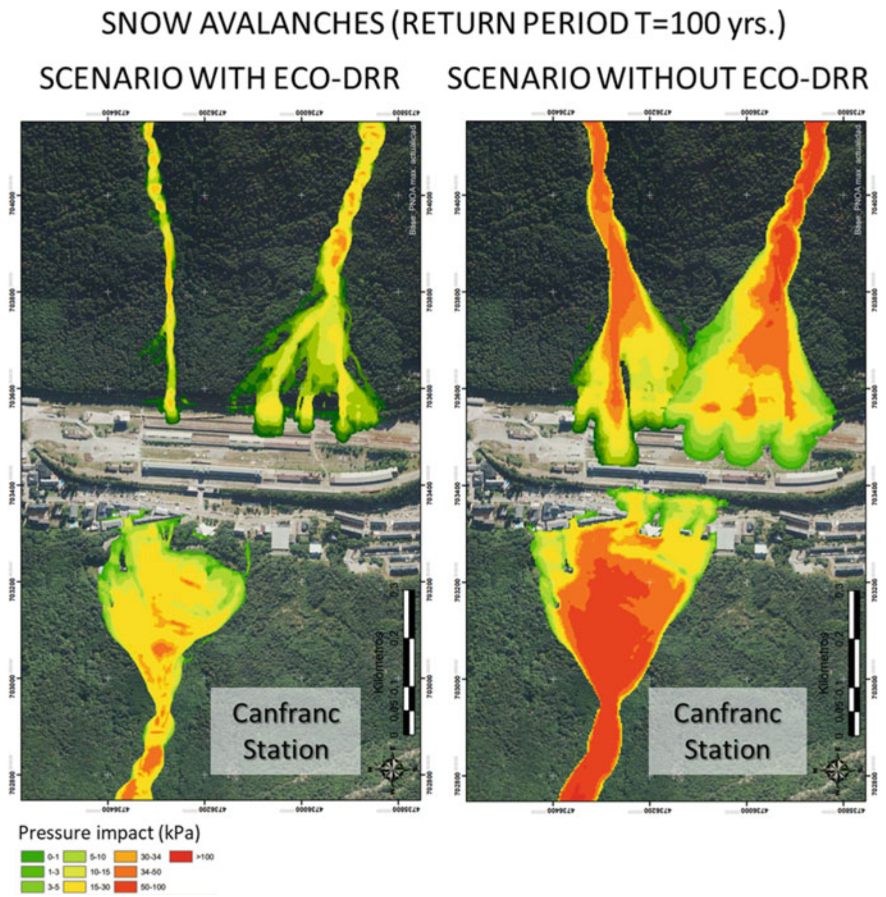

Fig. 28.6 Comparison between the impact of snow avalanches ($T = 100$ yrs) considering the Eco-DRR (left) and without Eco-DRR (right)

It was also estimated that carrying out the same works with current material costs would be 37% more expensive, thereby reducing economic indicators such as NPV.

28.5 Conclusions

With more than one hundred years old, the Eco-DRR implemented in Los Arañones constitutes physical evidence on how the combination of soft and hard measurements can be implemented to reduce the risk in mountain areas. The updated risk analyses suggest that such an approach still is still functioning, and is willing to be effective at reduce reducing the risk. Yet, the passing of time has resulted in a loss of functionality, and cost of maintenance is increasing. Under climate change conditions, and given the ongoing urbanization of the bottom valley, studies focused on the deterioration of the protective elements and their reliability will be required. In this sense, we call for in-depth analyses of the structure and infrastructures, as well as the implementation of a monitoring an evaluation plan that allows to anticipate potential failures.

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