Understanding the impact of climate change on debris-flow risk in a managed torrent: expected future damage versus maintenance costs

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ABSTRACT

In this communication, we evaluate the role of maintenance costs of hydraulic infrastructures in the risk analysis of torrential channels under the impact of process and/or climate changes. We combine stochastic life-cycle analysis (LCA), debris-flow modelling and risk assessments to understand the cumulative effects of extreme debris-flow events and potential progressive degradation of infrastructure on mitigation structures. We compare two scenarios to assess the reliability of check dams in reducing debris flow risks, with a focus on their performance and maintainability. We detect that maintenance works will play an important role in the next decades to maintain the reliability of infrastructure at a high level of confidence, which will however result in high economic costs.

KEYWORDS

Debris flow, risk assessment, stochastic life-cycle analysis, cost-benefit

INTRODUCTION

Debris flows are categorized as one of the costliest natural hazard in mountain environments, causing repeated damage to infrastructures, urban development and even loss of life (Jakob and Hungr, 2005). In mountain areas, debris flows risk assessment is an important issue for practitioners and it could even become more crucial in the next decades due to (i) the expected changes in magnitude-frequency of processes due to climate, and (ii) the rapid socio-economic development of such environments (Totschnig and Fuchs, 2013).
Disaster risk managers aim to reduce the expected losses based on passive (i.e. land-use management, hazard mapping) as well as active mitigation strategies (i.e. structural measurement, protection forest) (Holub and Fuchs, 2008). Active-based structural measures, such as retention basins, check dams and channel canalization are therefore common in Central

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Europe (Mazzorana et al., 2012) and they have played an important role in vulnerability reduction. However, the reliability of these structures can be affected by their previous state. Given that major investments in active measures were realized over the last decades, it is hypothesized that structures may soon lose or may already have lost performance of hydraulic function due to attrition. Consequently, some of them may no longer present optimal states (Romang et al., 2003), which would however be crucial for efficient risk reduction (Sánchez-Silva, 2004). Under this premise, two main factors will be therefore critical in the next decades: (i) the possible increase in frequency and magnitude of debris-flow hazards related to more frequent extreme climatic conditions (precipitation, snowmelt events) and/or changes in land cover and land use; and (ii) the current and future state of reliability of existing infrastructures depending on their maintenance, repair, and potential system failures.

In this communication, we present a coupled framework based on a time-dependent performance analysis of infrastructures in managed torrents affected by recurrent debris flow, their maintenance and operability and classical risk assessment procedures. By combining stochastic life-cycle analysis (LCA, Sanchez-Silva et al., 2011), debris flow modelling and risk assessment, we aim at understanding the cumulative effects of extreme events and progressive degradation on the design capacity of structures. We also aim at exploring the applicability of stochastic LCA to debris-flow risk assessment in a managed torrent watershed located in the southern part of the Austrian Alps where severe debris flows have been recorded in 1997. By comparing two alternatives ('pre- and post-1997 event'), we assess the reliability and sustainability of check dams in reducing debris-flow risks, with a focus on their performance and maintainability.

METHODS

Study site: The study site is the Wartschenbach torrent, located in the southern Austrian Alps (Lienz district, province of East Tyrol). This torrent is characterized by a catchment area of 2.7 km^2, with altitudes ranging from 670 to 2113 m a.s.l. The main channel is 3.6 km long and has an average slope gradient of 0.18 m/m, and maximum values up to 0.4 m/m in the central part (Melton index = 1,01). The apex of the sediment fan is located at 1460 m a.s.l and it has an average slope of 16°. The two villages of Nußdorf-Debant and Gaiming, located on the fan of the Wartschenbach torrent, have suffered severe damage from debris-flow activity in the past (Hübl et al., 2002). To achieve more effective protection of the exposed community, local authorities adopted a protection strategy focused on the successive implementation of a range of active measures (i.e. three open-slit check dams in the upper part of the fan). The historical record of events suggests that deposition heavily reduced the capacity of the dams between 1995 and 2000, requiring maintenance and cleaning work with an annual average cost of about 280,000 €.

Methodological steps: We quantify expected losses due to debris-flow activity by using a coupled stochastic LCA risk assessment model (Figure 1; Ballesteros-Cánovas et al., in review). Expected losses were estimated as the sum of the costs related to (i) regular maintenance work of check dams to keep their original retention capacity after a debris-flow event; and (ii) damage downstream of the structure in case that a debris flow exceeds the maximum capacity of the dams. We considered two different alternatives for the development of infrastructures: i) pre-1997 event and, ii) post-1997 event. Additionally, we also considered three climate change (CC) scenarios (i.e. S1, S2 and S3) integrating expected changes in debris-flow frequency as a result of the expected increase in temperatures and extreme precipitation events (Gobiet et al., 2014).

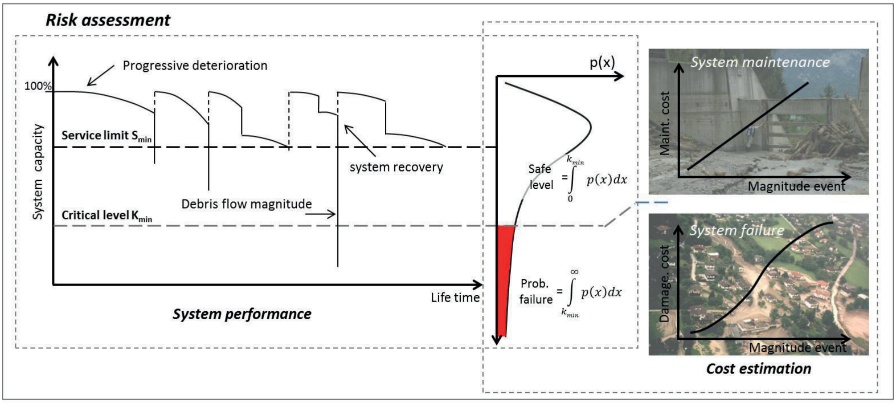

Figure 1: General description of the proposed method (Ballesteros-Cánovas et al., in review).

We used the catalogue of historical natural disasters from the Lienz region (Hübl et al., 2011) to characterize the occurrence of debris-flow events. Then, we determined daily rainfall intensities prior to and at the day of occurrence of each event based on the Iselsberg-Penzelberg meteorological series. Debris-flow frequencies (i.e. number of events per decade) were then analyzed in terms of threshold exceedance (from 10 to 100 mm) by using the distribution of past daily rainfall triggers as a guide and basis for the assessment of how these thresholds could be exceeded in the future (Guzzetti et al., 2008). Finally, debris-flow frequencies were connected to statistically downscaled station data and error-corrected climate change scenarios available for fixed daily precipitation thresholds (comprised between 10 to 100 mm) averaged over two months until the mid-21st century. For the purpose of this study, we used three contrasting climate scenarios derived from regional climate model.
In the subsequent step, a stochastic LCA model (Sánchez-Silva et al., 2011) was implemented to determine the performance of existing dams during their life time (t=80 yrs). Two different alternatives (A) were considered:

– (i) A1 (past situation, pre-1997 event): one dam (maximum retention capacity: 25,000 m^3).
– (ii) A2 (current situation, post-1997 event): three check dams (maximum retention capacity: 77,000 m^3).

Exponential distributions were used to characterize the average recurrence time of events for each scenario. In addition, LogNormal (LN) distributions were used to model expected magnitudes of events (i.e. the volume of deposition; m^3) based on historical information. Age-related degradation of check dam capacity was assessed with a monotonous-decrease time-dependent function by using observations from other torrents (Romang et al., 2003). During the LCA, two different check dam capacity limits can be taken into account namely Smin and Kmin. . Here, we have considered Smin as the average event capacity > 10,000 m^3 resulting in a capacity loss requiring system maintenance according to historical records (Hübl et al., 2002), and Kmin as the maximum designed retention capacity volume for A1 = 25,000 m^3 and A2 = 77,000m^3 .Building cost was assessed at 1 million € per dam and clearance (i.e. maintenance costs) at 5 € per m^3 sediment retained behind the dam. This average value includes the cleaning of the dam as well as the transport, and further deposition of sediments; however other costs related with technical works during maintenance are not explicitly here considered (i.e. condition assessment, attendance, corrective maintenance). The stochastic LCA analysis has been performed using Monte-Carlo simulations with 1,000 iterations and takes account of a subsequent recovery of retention capacity up to 100 % when retention capacity of the check dams D[t] falls below Smin. In addition, the impact of performing periodic maintenance works was analyzed and different maintenance periods have been implemented in the model (i.e. each 2, 5, or 10 years). Their impact on the reliability of check dams has been evaluated in terms of number of recoveries, time to recovery, and average recovery cost. Here it was assumed that periodic maintenance works can improve check dam capacity by up to 10%.

In case that Kmin is exceeded, deposition outside the channel causes damage to properties located on the fan. To estimate related cost with this scenario, we quantified damage functions based on available vulnerability curves (Fuchs et al., 2007; Totschnig and Fuchs, 2013), intensity of the event (deposition depth in m), and economic value of houses. We then used the numerical simulation model Flo-2D to estimate expected debris-flow deposition (m) to each expected volume. Flo-2D is a bi-dimensional quadratic shear stress model describing regimes from viscous to turbulent/dispersive flow. The model was based on a 1-m digital elevation model and previously calibrated based on the well-documented event in August 1997. ArcGis was used to determine the exposure degree of each building, whereas vulnerability curves and average economic properties values were used to define damage functions.

Finally, a cost-based debris-flow risk assessment was based on the expected total annual cost incurred by the entire system, i.e. the sum of expected maintaining costs of check dams throughout the life cycle of works, and expected annual costs of debris-flow damage in terms of fatalities after a potential failure of the retention system was carried out. We compared the reliability of the entire system (different alternatives) under different scenarios based on the expected annual cost. In order to include all uncertainties from all modelling steps, we performed Monte Carlo simulations based on 5,000 iterations.

RESULTS

Analysis of the historical database suggests that more than 121 debris-flow and related events occurred in the Lienz region between 1950 and 2000 (mean: 21 events per decade). Threshold intensities extracted from the database for debris-flow initiation vary between 0 mm and 123.3 mm day–1. Mean rainfall intensity for debris-flow triggering is 59 mm day–1. Maximum debris flow frequency was observed in the past during summer (S1: 5.2 events per decade in June-July) for daily rainfall intensities comprised between 10 and 20 mm. In the future, according to scenarios S2 (S3), the frequency of 10-20 mm rainfall will decrease (increase) by 30% (5%). As a consequence, the expected frequency of debris-flow events per decade will change accordingly:

– i. S1 (reference scenario): 21 events/decade,
– ii. S2 (best scenario): 14 events/decade (-33 %)
– iii. S3 (worst scenario): 29 events/decade (+38 %).

Figure 2 provides a graphical example of check dam performance as a result of debris-flow occurrences and ageing degradation along structure life (example of 1 and 10 simulations for A2). Results indicate that the expected damage resulting from debris flows in the Wartschenbach in A1 is almost 98 % lower than in A2. The mean expected annual damage for the scenarios were 56,955 € (S1), 78,653 € (S2) and 37,970 € (S3) for A1, and 1,236,753 € (S1), 1,659,085 € (S2) and 790,179 € (S3) for A2. Changes in debris-flow frequency as a result of climate change are predicted to induce a range of variations in expected annual costs which are comprised between +38 % (S2) and -33 % (S3).

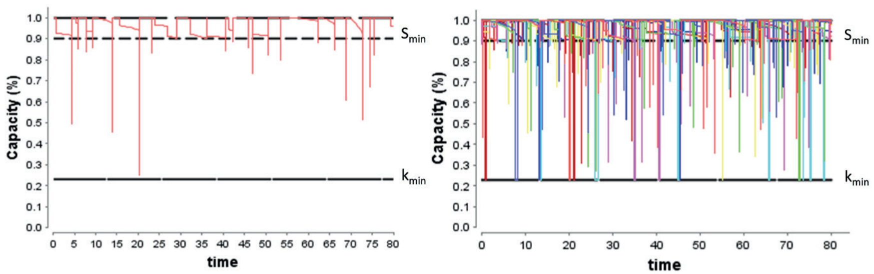

Figure 2: Example of check dam performance analysis. Left (right) panel represents 1 (10) simulations. In both cases, the evolution of check dam performance has been evaluated for the mitigation scenario A1 (3 check dams) and the climate change scenario S1 (current situation, 21 debris flow per decade (Ballesteros-Cánovas et al., in review).

The cost related with system performance under climate change forcing vary between 2,336,988 € (3,126,953 €) and 3,423,836 € (5,988,019 €) for A1 (A2), respectively.
The total expected annual costs (expected damage including expected maintenance costs) are on average lower in A1 (S1=82,690 €; S2=114,459 €; S3=59,227 €) as compared to A2 (S1 = 1,236,753 €; S2 = 1,659,085 €; S3 = 790,179 €) regardless of the scenario considered. As a consequence, we interpret that the performance of A1 is more economical than A2. However, when the initial installation cost of each check dam (estimated at 1 million € per dam) is weighted against the recovery factor (80-yr lifetime with a 5 % interest rate), the expected annual cost for A1 will vary between 212,315 and 267,547 €; whereas for A2 it is ranked between 1,710,114 € and 841,208 €. As a consequence (Figure 3), the annual net benefit without considering the installation cost is optimal for the current alternative (+14 % vs -9.5 %), however, if the installation cost is included in the analysis, the current alternative seems much less cost-effective (-185 % versus -9.5 %).

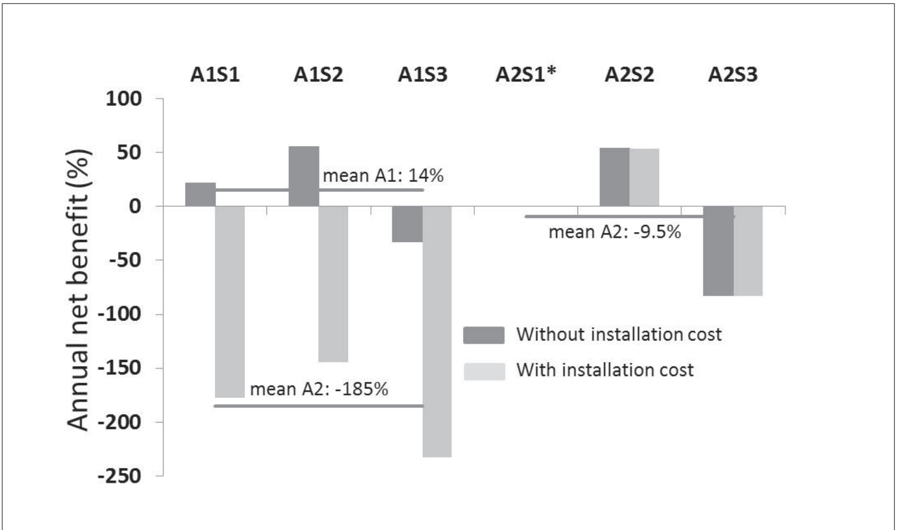

Figure 3: Annual net benefit comparison (in %) taking account of or ignoring the installation cost of the check dams. (*) indicates the reference level at which the appraisal was performed (Ballesteros-Cánovas et al., in review).

CONCLUSIONS

The coupled stochastic LCA risk analysis allowed for an estimation of expected annual costs related to debris-flow hazards in a managed torrent catchment under future climate change conditions. Through the use of a stochastic analysis, uncertainties related to the performance of the existing infrastructures and the quantification of damage have been considered. Despite the large and uncertainties step involve in the risk system analysis, the coupled stochastic LCA risk analysis has been demonstrated as being a powerful tool to integrate most of processes involved in the economic analysis. We conclude that integrated analysis incorporating deterioration and maintenance operation cost should be included in future analysis of debris flow on managed torrents. Therefore, the modeling approaches clearly highlighted the prominent role of maintenance operation works needed to maintain the reliability of infrastructure at a high level of confidence for our case study site.

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