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Debris-flow risk analysis in a managed torrent based on a stochastic life-cycle performance

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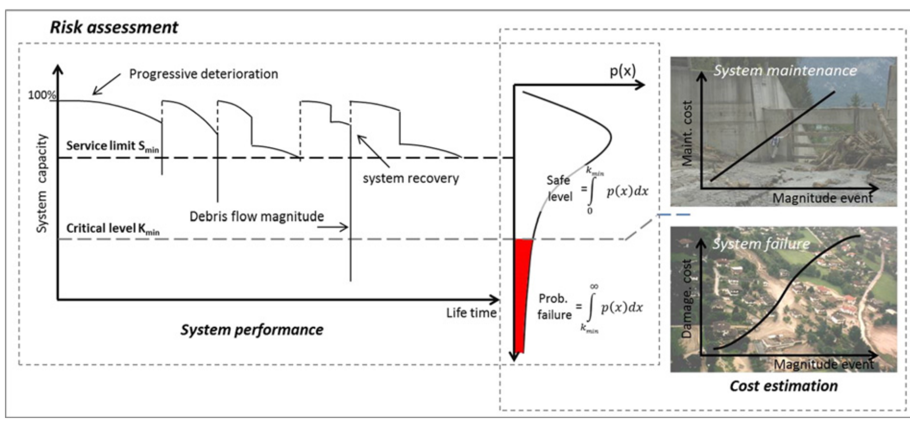
HIGHLIGHTS

- Debris flows are considered as one of the most common hazards in Alpine areas
- Reliable countermeasures are needed to prevent damage under CC scenarios
- We present a stochastic life-cycle assessment for risk analysis assessment
- We include maintenance costs into account in risk assessments in managed torrents

GRAPHICAL ABSTRACT



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ABSTRACT

Two key factors can affect the functional ability of protection structures in mountains torrents, namely (i) infrastructure maintenance of existing infrastructures (as a majority of existing works is in the second half of their life cycle), and (ii) changes in debris-flow activity as a result of ongoing and expected future climatic changes. Here, we explore the applicability of a stochastic life-cycle performance to assess debris-flow risk in the heavily managed Wartschenbach torrent (Lienz region, Austria) and to quantify associated, expected economic losses. We do so by considering maintenance costs to restore infrastructure in the aftermath of debris-flow events as well as by assessing the probability of check dam failure (e.g., as a result of overload). Our analysis comprises two different management strategies as well as three scenarios defining future changes in debris-flow activity resulting from climatic changes. At the study site, an average debris-flow frequency of 21 events per decade was observed for the period 1950–2000; activity at the site is projected to change by +38% to −33%,

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Check dams
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Wartschenbach

according to the climate scenario used. Comparison of the different management alternatives suggests that the current mitigation strategy will allow to reduce expected damage to infrastructure and population almost fully (89%). However, to guarantee a comparable level of safety, maintenance costs is expected to increase by 57–63%, with an increase of maintenance costs by ca. 50% for each intervention. Our analysis therefore also highlights the importance of taking maintenance costs into account for risk assessments realized in managed torrent systems, as they result both from progressive and event-related deteriorations. We conclude that the stochastic life-cycle performance adopted in this study represents indeed an integrated approach to assess the long-term effects and costs of prevention structures in managed torrents.

1. Introduction

Debris flows are fast-flowing mass movements composed of a mixture of water, mud and debris, discharging through steep and confined channels (Iverson, 1997). This natural process is supposed to be 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; Fuchs et al., 2013). Dealing with debris flows is an important issue for land managers in mountain areas and could even become more crucial over the next decades as a result of the rapid socio-economic development of such environments (Totschnig and Fuchs, 2013).

In order to protect elements at risk and to reduce expected losses, different passive (e.g. land-use management, hazard delimitation) as well as active (e.g. structural measurement, protection forest) mitigation strategies are available (Holub and Fuchs, 2008). In particular active structural measures, such as retention basins, check dams and channel canalization are established in the management of mountain hazards in Central Europe (Vischer, 2003; Mazzorana et al., 2012). Several studies suggest that active structural measures significantly reduce vulnerability and the subsequent risk level of exposed communities (Hübl and Fiebiger, 2005; Fuchs et al., 2007). It has also been demonstrated that the efficiency of these structures can be affected by aging (Romang et al., 2003; Dell'Agnese et al., 2013). As a consequence, two factors are likely to affect the reliability of existing infrastructures over the next decades, namely (i) the postulated increase in the frequency and magnitude of debris-flow hazards related to more frequent extreme climatic conditions (precipitation, snowmelt events; Keiler et al., 2010; Stoffel and Huggel, 2012; Stoffel et al., 2014a, 2014b) or changes in land cover and land use (e.g., IPCC, 2012, on the global level; and, Cammerer and Thieken, 2013, for the Eastern Alps); as well as (ii) the current and future state of reliability of existing infrastructures depending on their maintenance, repair and potential system failures (Mazzorana et al., 2009). Moreover, structural measures built over the last decades may have lost performance of hydraulic function due to attrition. Consequently they may no longer present optimal states (Romang et al., 2003), which are, however, crucial for efficient risk reduction (Sánchez-Silva and Leondes, 2004).

A coupled framework based on a performance analysis of infrastructures in torrents and classical risk assessment procedures can be applied to integrate both climate change impacts and the reliability of infrastructure so as to provide more accurate values of expected economic losses which is needed to allocate public financial resources efficiently (Weck-Hannemann, 2006). Such an analysis involves a large range of uncertainties, which is mostly inherent to (i) our limited understanding of processes as well as (ii) difficulties to perform a proper characterization of the studied system (Mazzorana et al., 2009). With respect to the latter it has been demonstrated that these sources of uncertainties may have significant impacts on derived cost quantification (Merz et al., 2010).

From a statistical perspective, the stochastic life-cycle performance integrates the time-dependent behavior of structural systems affected by external shocks, their maintenance and operability (Sanchez-Silva et al., 2011). Such an approach may be used to combine the cumulative effects of extreme events and progressive degradation affecting the design capacity of structures. Moreover, the approach can be used to represent the occurrence of debris flows stochastically and to consider them as independent shocks with a certain frequency (Xi[t]) independently of their magnitude (defined here by the size of each shock). It enables inclusion of uncertainties inherent to debris-flow processes throughout the analysis (Sanchez-Silva et al., 2011). Similar analyses have been widely used in engineering to support decision-making processes based on reliability concepts (Sherif and Smith, 1981; Rackwitz et al., 2005). By contrast, and despite their potential in mountain hazard assessment, life-cycle performance models have not been used in mass-movement research so far but were only implemented in a fairly limited number of earthquake engineering cases (Sánchez-Silva and Leondes, 2004; Padgett and Tapia, 2013).

This paper therefore aims at exploring the applicability of stochastic life-cycle performance to debris-flow risk assessment and to quantify expected economic losses related to debris-flow occurrence exemplarily in a managed torrent watershed located in the southern part of the Austrian Alps. Here a very severe debris flow has been recorded in 1997. More recent events in the catchment occurred in 1999 and 2000 (Hübl et al., 2002; see Table 1) but were of much more limited magnitude. As a result of major and intensive mitigation works at the study site, debris flows have not been recorded after the year 2000. For the purpose of model calibration, we (i) analyzed available technical data to determine the future performance of existing check dams; (ii) combined the information with chronical, meteorological, as well as Regional Climatic Model (RCM) data to define potential future hazards; and (iii) calibrated hydraulic models and vulnerability curves to estimate the expected losses at the community level. By comparing two scenarios ('pre- and post-1997 event'), we assessed the reliability and sustainability of check dams in reducing debris flow risks, with a focus on their performance and maintainability. Noteworthy, the current study has to be regarded as a simplified, multi-disciplinary test case for a wider investigation of the applicability of a stochastic life cycle performance in times of climate change. We here explore the effects of differing engineering mitigation measures and climate change scenarios on expected risks and costs in the longer term. In this context and in view of uncertainties, several simplifications had to be made; these are detailed in the following sections.

2. Study site

The Wartschenbach torrent is located in the southern Austrian Alps (Fig. 1; Lienz district, province of East Tyrol). The catchment area is almost 2.7 km^2 at altitudes between 670 m and 2113 m asl. The apex of the sediment fan is located at 1460 m asl with an average slope of 16°. At this altitude, the main channel is 3.6 km long (Melton index = 1.01; Totschnig et al., 2011), with an average slope gradient of 0.18 m/m, and maximum values up to 0.4 m/m in the central part of the channel. Geologically, the catchment is comprised of para-gneisses and mica schists covered by unconsolidated Quaternary deposits (Fuchs et al., 2007). The terrain conditions present at the catchment can be described as highly prone for debris-flow initiation in the case of intense rainfalls.

The two villages of Nussdorf-Debant and Gaiming, located on the fan of the Wartschenbach torrent, have repeatedly suffered severe damage as a result of past debris-flow activity (Hübl et al., 2002). Recent event