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

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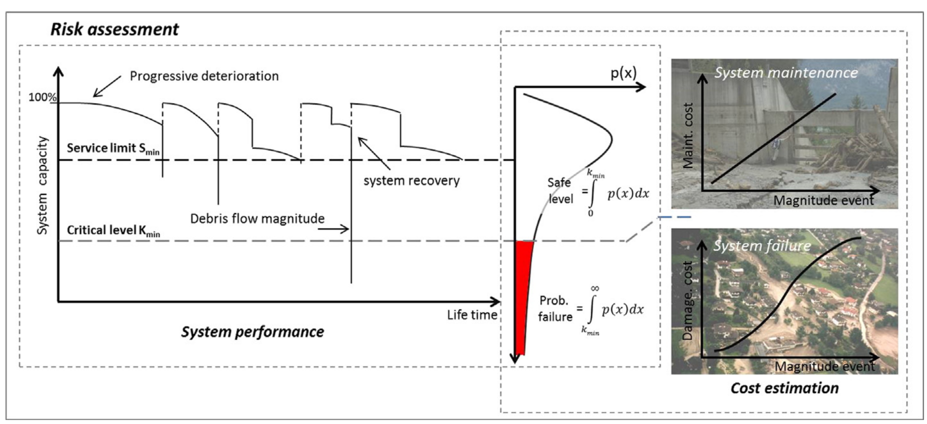
HIGHLIGHTS

- 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
Deterioration
Debris flow
Natural hazard
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

Table 1
Available historical information on debris-flow activity, including event volumes reaching the fan, triggers, and damage in the communities of Nussdorf-Debant and Gaiming (Hübl et al., 2002). Values are inflation-adjusted to the year 2014 based on values reported by Totschnig and Fuchs (2013). Inflation over the period is 44.55%, the index used is ATCPI2013 (initial index: 71.06, end index: 102.72).

Date	Vol (m^3)	Trigger	Damage	Economic loss [€]
1879	–	Frontal system	–	–
1882	–	Frontal system	–	–
1966	–	–	3 buildings damaged and debris deposition on roads and agricultural land	–
12 June 1972	–	–		–
18 October 1980	–	–		–
19 July 1981	–	–		–
06 August 1995	35,000	Storm (1.5 h)	~14 buildings damaged	593,956
27 June 1996	2000	Storm	Roads damaged	–
25 July 1997	5000			–
16 August 1997	45,000	Storm (1 h) 40 mm/20 min at Zettersfeld	~16 buildings damaged	1,738,984
06 Sept. 1997	35000	Storm + cold front (west)		–
25 July1998	7500	Storm (18 h)	Roads damaged	–
07 October 1998	5000	–		–
27 July 1999	35,000	Storm (2 h)	Roads damaged	–
21 Sept. 2000	20,000	Rainfall (6.5 h)	Roads damaged	–

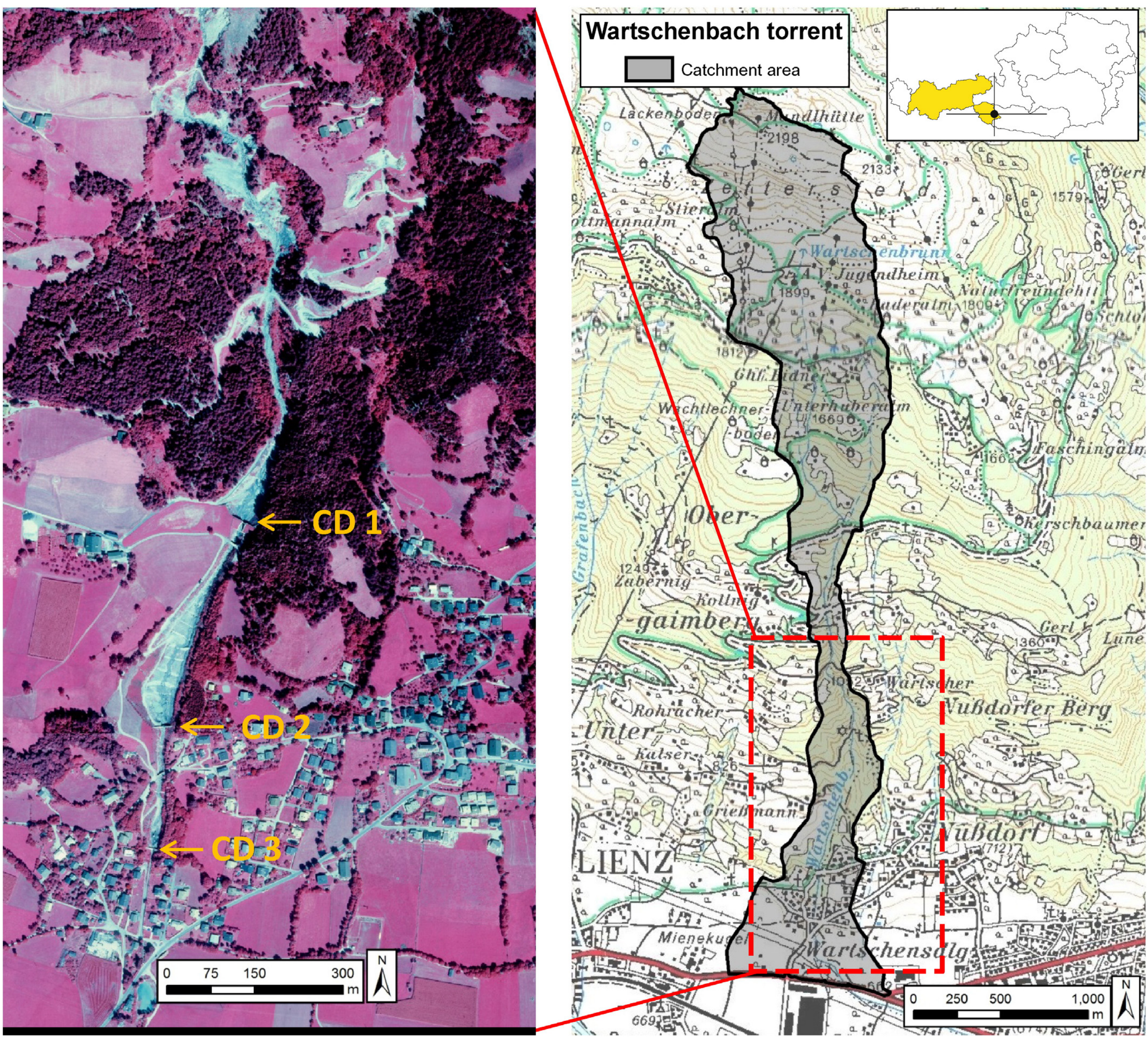

Fig. 1. Overview of the Wartschenbach torrent. The lower part of the catchment including the location of the three check dams is presented on an aerial picture from 2000 (modified from Hübl et al., 2002).

documentation (Hübl et al., 2002) revealed that at least nine well-documented debris flows occurred at the site between 1995 and 2000 (which is 1.5 events/year on average). Additionally, incomplete historical chronicles mention six damaging events between 1879 and 1981 (Table 1). The most recent harmful event took place on August 16, 1997, when an intense storm (40 mm of rainfall in 20 min) mobilized approximately 45,000 m^3 of debris from the upper part of the catchment (Fuchs et al., 2007).

To achieve more effective protection of the exposed communities, local authorities adopted a protection strategy focused on the successive implementation of a range of active measures (Hübl et al., 2002). These measures included the construction of three open-slit check dams in the upper part of the fan. The first check dam was built in 1985 (CD 3) with a maximum retention capacity of 25,000 m^3. Following damage caused by the 1997 debris flow, two additional check dams were built upstream of CD3 in 1999 with a respective maximum retention capacity of 30,000m^3 (CD 2) and 22,000m^3 (CD 1). Technical reports highlight that debris-flow deposition heavily reduced the capacity of the dams between 1995 and 2000, leading to maintenance and cleaning works with an annual average cost of about 280,000 € (Table 2). Over the last decades, several other mitigation measures have been implemented, including three small retention basins in the upper parts of the catchment, which have so far effectively reduced channel runoff and therefore the probability of debris flow initiation during intensive rainfall events (Hübl et al., 2002). We did neither take these additional engineering activities, nor other natural processes (e.g. bedload transport during minor rainfall events) into account.

3. Method

The proposed method is based on the quantification of expected losses as a result of debris-flow risk by considering a stochastic life-cycle performance to a risk assessment (Fig. 2). 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 to (ii) damage downstream if a debris flow exceeds the maximum capacity of the dams. We considered two alternatives for the development of infrastructures (here referred to as pre- and post-1997 event scenarios) and three climate change (CC) scenarios integrating expected changes in debris-flow frequency as a result of the expected increase in temperatures and extreme precipitation events (Gobiet et al., 2014).

3.1. Possible impacts of climate change on debris-flow frequency

Changes in rainfall intensity and duration, in combination with higher temperatures, will presumably lead to a local increase in frequency – and possibly magnitude – of debris flows (e.g., Stoffel and Huggel, 2012; Stoffel et al., 2011, 2014a, 2014b), provided that sediment is not limited and that the occurrence of events is driven primarily by water input above a certain meteorological threshold (e.g., Borga et al., 2014; Gobiet et al., 2014).

Table 2
Cost related with the clearing works after debris-flow event for the period 1995–2000. (average: 281,140 €/year; adapted from Hübl et al., 2002). Values inflation-adjusted to the year 2014 (inflation over the period: 44.55%, used index: ATCPI2013, initial Index: 71.06, end index: 102.72).

Year	Nature of work	Cost (€)	Adjusted-cost (€)
1995	Clearing of concrete channel and CD 3	145,000	209,600
1996	Clearing channel reach	22,000	31,200
1997	Clearing of concrete channel and CD 3	432,500	602,600
1999	Clearing channel reach	317,500	434,900
2000	Clearing CD 1	93,000	127,400
		1,010,000	1,405,700

To estimate possible impacts of future CC on debris-flow frequency in the Wartschenbach torrent, a regional debris-flow assessment has been carried out for the entire Lienz region. The idea behind this approach is that averaging the record of past events over a large number of torrents should be fairly free of local artefacts and therefore more representative of a regional forcing (such as climate change) on a process than one single time series of events from an individual torrent (Bollschweiler and Stoffel, 2010; Schneuwly-Bollschweiler and Stoffel, 2012; Nikolopoulos et al., 2014a, 2014b).

The approach has also been preferred over a local assessment since a large and unusually dense catalogue of historical landslides exists for Austria (Hübl et al., 2011). The province of East Tyrol has an area of around 12,000 km^2, and the event database contains daily resolved data on 251 debris flows (May-October) that occurred in 121 torrents between 1950 and 2000. Each event was associated to the closest meteorological station of this network. As on days with temperatures below 5 °C, the amount of water provided by precipitation is temporarily stored as snow in the upper part of the catchments, the events that occurred during snowy days were removed from the analysis.

Daily rainfall intensities recorded prior to and at the day of occurrence of historical events were extracted from the Iselsberg-Penzelberg meteorological series, available with a daily resolution since 1896. In a subsequent step, 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., 2007, 2008; Brunetti et al., 2010). We are aware that such an approach based on a local rain gauge is probably less precise than on weather radar series, but available over at our study site. This limitation can (i) potentially lead to increased underestimation and increased estimation variance of debris-flow triggering rainfall (Nikolopoulos et al., 2014a, 2015) and (ii) blur local differences in rainfall intensity–duration thresholds as evidenced e.g. in the eastern Italian Alps (Nikolopoulos et al., 2014b). Furthermore, we acknowledge that the use of daily precipitation data may not always represent the properties of debris-flow triggering storms well and thus represent an additional source of underestimation in debris-flow triggering rainfall thresholds (Nikolopoulos et al., 2014b).

Finally, debris-flow frequencies derived from the retrospective (historical) analysis were connected to statistically downscaled station data and error-corrected climate change scenarios available for fixed daily precipitation thresholds (comprised between 10 and 100 mm) averaged over two months until the mid-21st century.

For the purpose of this study, the initial set of 24 IPCC A1B available for the Iselberg-Penzelberg meteorological station was used to define three scenarios:

(i) Frequency as observed in the past (scenario S1),
(ii) Minor changes in debris-flow frequency as a result of moderate climatic changes (best CC scenario or S2; WEGC-CCLM_ECHAM5-A1Br2_DS_10km_1955–2050),
(iii) Large changes in debris-flow frequency as a result of major CC (worst CC scenario or S3; CNRMRM5.1_SCN_ARPEGE_DM_25km_1951–2050).

3.2. Performance of check dam capacity under different hazard definitions

The stochastic life-cycle performance (Sanchez-Silva et al., 2011) was implemented to determine the performance of existing dams during their life time (t), estimated at 80 years, and by using the different hazard scenarios defined above. We considered two different alternatives:

(i) Alternative 1 (A1) reelecting the current, post-1997 event situation: the three check dams (maximum retention capacity: 77,000 m^3) ensure the protection of the village located on the fan;

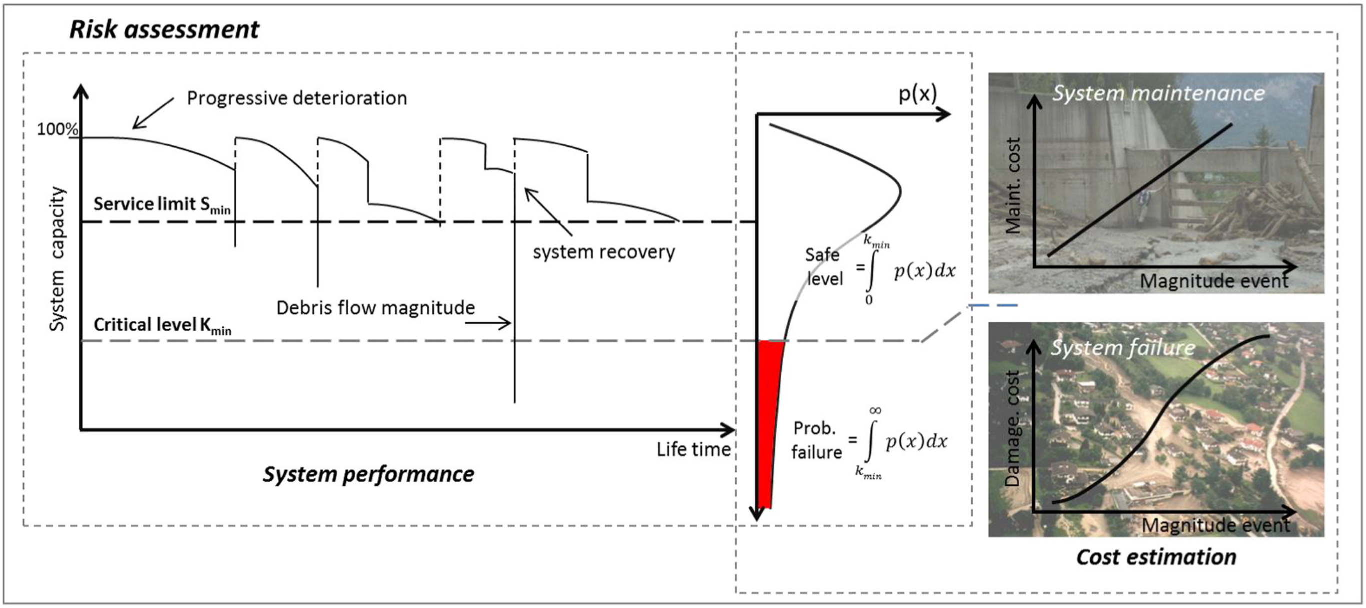

Fig. 2. General description of the proposed method (inspired on Sanchez-Silva et al., 2011). System capacity, which is given by the retention capacity of the check dam, can decrease as a result of (i) progressive deterioration of the infrastructure, and, (ii) infilling of dams during specific debris-flow events. The service limit (S_{min}) indicates the periodicity at which system recovery (e.g., clearance and maintenance) should be realized. Within these levels, annual costs will be related to system maintenance. If system capacity drops below the critical level (K_{min}), which indicates the maximum infrastructure capacity, annual cost will be reflect system failure and consequently damage in the communities of Nussdorf-Debant and Gaiming (image source: Hübl et al., 2002).

(ii) Alternative 2 (A2), presenting the past or pre-1997 event situation where only one dam (with a maximum retention capacity: 25,000 m^3) existed in the channel.

Exponential distributions were used to characterize average recurrence times of events for each scenario defined in Section 3.1. These distributions describe the time between two consecutive, but independent events following a Poisson distribution. Distributions are characterized by a rate parameter lambda (λ = frequency^{-1}; i.e. May and Gresswell, 2004). In addition, LogNormal (LN) distributions (μ = mean; σ = standard deviation) were used to model expected magnitudes of events (i.e. the volume of deposition; m^3) based on the estimation shown in Table 1. Age-related degradation of check dam capacity was assessed with the following equation (Vallippan et al., 2009):

$$AD(t) = R_0 \times PD(t)$$

where R_0 is the initial capacity and PD(t) is the time dependent degradation function defining the fraction of initial capacity remaining at time t. Due to the lack of quantitative values specific to the study site.

AD(t) has been assessed according to qualitative observations provided by Romang et al. (2003), who defined the expected states of reinforced concrete check dams as a function of the nature of events; and quantitative results from empirical vulnerability assessments realized before and after events northern of Italy (Dell'Agnese et al., 2013). Based on an extensive survey performed in Switzerland, Romang et al. (2003) observed (i) slight to moderate damage to check dam structural stability (due to scouring) and capacity (due to sedimentation) in approximately 80% of the cases after 20 years of operation; (ii) moderate to severe damage in those cases where the design event took place (this was the case for >80% of the structures inventoried) and (iii) severe damage or destruction in those cases where debris-flow overload occurred (i.e. in approx. 60% of the cases). Dell'Agnese et al. (2013) conclude that (i) check dams older than 20 years presented larger damage indices after an event; (ii) a significant abrupt decrease in structural capacity was widespread in check dams older than 40 years; and that (iii) the functionality of check dam can become critical if an event with a volume exceeding half of the design discharge structure occurred. Even if the authors suggest that these observations may suffer from uncertainties due to the scarcity of data on very old check dams, they nevertheless recommend the use of these observations for the assessment of check dam vulnerability (Dell'Agnese et al., 2013). We therefore used the values provided by Dell'Agnese et al. (2013) to define a continuous t-dependent degradation function with an increase in capacity losses and an increase in uncertainties after 40 years. We also included the expert judgment (in %) provided by Romang et al. (2003), with a weighted state of damage, as follows: (i) no or only minor damage (loss of capacity < 5%), (ii) moderate damage (loss of capacity < 30%), (iii) severe damage (loss of capacity < 70%), (iv) partly or completely destroyed (loss of capacity < 85%). This combined approach allows ranking of expected losses of capacity to between 0.14 and 0.075% for a time horizon of 20 years. Consequently, the dependent degradation function (in %) was defined as a family of monotonous, increasing, and continuous stochastic functions of a given time, and satisfies this premise as follows:

$$PD(t) = 0.002 \times X \times t^2$$

with X representing a LN distribution (0.3, 0.5). During the stochastic life-cycle performance, two different check dam capacity limits were taken into account, namely (i) S_{min} where an event with >10,000 m^3 will result in a capacity loss requiring system maintenance according to historical records (Table 2), and (ii) K_{min} where the maximum retention volume for A1 = 25,000 m^3 and A2 = 77,000 m^3 is attained. According to the available technical documentation, the building cost has been set to 1 million € per dam and typical clearance costs to 5 €/m^3 sediment retained behind the dam. This value includes the cleaning of the dam as well as the transport, and further deposition of sediments. The stochastic life-cycle performance analysis has been performed using Monte-Carlo simulations with 1000 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 S_{min}. In addition, the impact of performing periodic maintenance works was analyzed and different maintenance periods have been implemented in the model (i.e. 2, 5, or 10 years). Their impact on the reliability of check dams

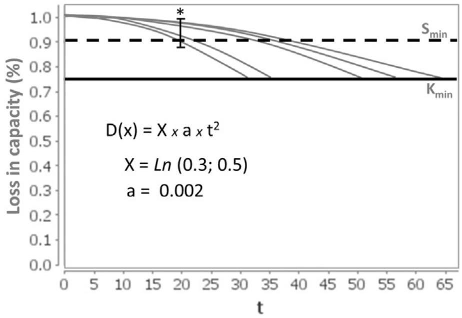

Fig. 3. Progressive deterioration function used in the stochastic life-cycle performance. The curves indicate the stochastic modeling of the progressive loss in capacity during the lifetime of the infrastructure. (*) indicates a slight to moderate loss of infrastructure capacity based on observations from Romang et al. (2003).

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 the check dam capacity by up to 10% (Fig. 3).

3.3. Estimating damage functions

In case of K_{min} exceedance, deposition outside the channel may cause damage to properties located on the fan. The expected costs of events were quantified with damage functions and vulnerability curves available for the study site (Fuchs et al., 2007, Fuchs, 2008; Totschnig and Fuchs, 2013) in terms of the degree of economic losses in the village (in %) in relation to the intensity of the event (deposition depth in m).

Information on debris flow deposition pattern (distribution and height) has been obtained using the numerical simulation model Flo-2D, which is frequently applied for debris flows hazard assessment. The Flo-2D model uses classic depth averaged shallow water equations and an equivalent fluid approach based on a modified Bingham-type rheology to model two-dimensional flow and deposition behavior of debris flows (O'Brien et al., 1993). To minimize calculation time and avoid numerical instabilities, which often occurs when using a calculation grid <3 m, our 1-m digital elevation model (DEM) was converted to a 3-m grid. In a first step, we calibrated the model, to the observed event in August 1997. Here, event documentation showed that 45,000 m^3 out of a total of 50,000 m^3 of mobilized sediment and water were transported to the fan of the Wartschenbach. Of these, about 25,000 m^3 were retained by CD 3 (the only dam existing at that time, representing our alternative A2) and approximately 20,000 m^3 inundated the settled area downstream. In Flo-2D we only modelled the volume passing CD 3 and focused on matching observed deposition pattern in the village. The simulated deposition area (>0.1 m) below CD 3 was calculated with 19,200 m^2 whereas the reported depositional area was estimated at 15,800 m^2. In a subsequent step we fed the calibrated model with scenarios of different event volumes, increasing total event magnitudes to 25,000 m^3, 30,000 m^3 and 40,000 m^3 (equivalent to an increase of 25%, 50% and 100% of volume passing CD 3), while keeping boundary conditions constant (Fig. 4). Based on the coupling of maps showing the distribution and depths of debris flow deposits and cadastral information, the exposure of residential homes was evaluated using ArcGIS 9.3 (Kang et al., 2005). At the level of each exposed building, the mean, maximum and minimum depositional depths were used as input parameters to derive vulnerability. Economic losses were quantified on the basis of a loss assessment model (average cost of housing is estimated from census data is 327,776 ± 43,422 € after removal of values belonging to the first and fourth quartiles (n = 626). The median of the full dataset (n = 1246) is 311,465 €; see Keiler et al., 2006 and Fuchs et al., 2007, 2015 for details). In order to include property losses, we assume a weighted rate above 30%, which corresponds approximately to the estimated property insurance value. Finally, in order to incorporate the quantified variability of the entire dataset, we again used Monte-Carlo simulations (5000 iterations) to derive a damage-magnitude function for the Wartschenbach fan. Since the retention capacity of the current situation with three check dams is larger than future event magnitudes of all scenarios evaluated in this study, no additional Flo-2D simulation runs were carried out for alternative A1.

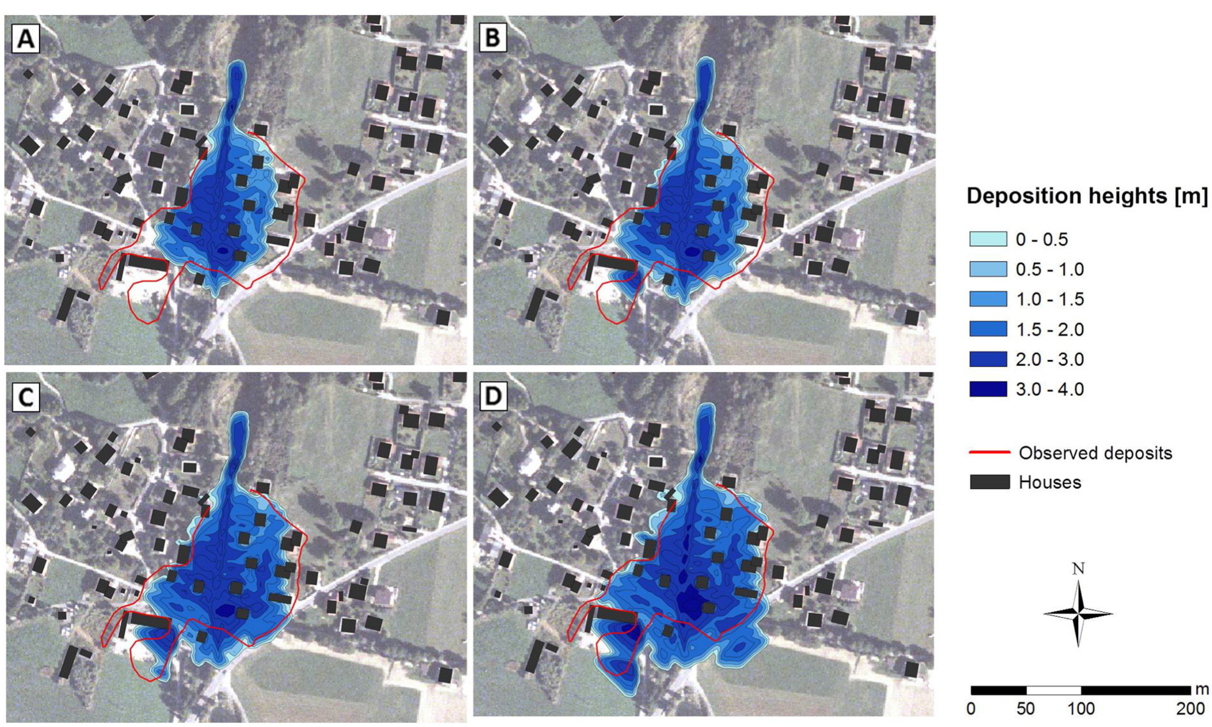

Fig. 4. Simulation results obtained with Flo-2D for alternative A2 with a volume of 25,000 m^3 of debris-flow material deposited behind check dam (CD 3). In this run, 20,000 m^3 inundated the settled area (A). In addition, scenarios with an increased total event volume of 25,000 m^3 (B), 30,000 m^3 (C) and 40,000 m^3 (D) are shown. The solid line indicates observed limits of debris-flow deposits, whereas fluvial deposits are represented with a dashed line.

3.4. Assessment of expected losses

The 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 after a potential failure of the retention system (Tung, 2002). By contrast, potential costs associated to dam destruction and reconstructions after an extreme event have not been taken into account for this study. Based on this approach, the expected annual cost C_T was computed for each considered scenario as:

$$C_T = Ic \times CRF + NPV_{(MC)} + E(D|x)$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$NPV_{(MC)} = \frac{1}{n} \sum_{j=1}^{n} C\left(t_j(x)\right) \times e^{-it_{j(x)}}$$

$$E(D|x) = \frac{1}{n} \int_{x_{K_{\min}}}^{\infty} D\left(x|x_{K_{\min}}\right) f(x) dx$$

where Ic is the installation cost of A1 and A2 and CRF is the capital recovery factor for the service life T (n years) including interest rate i; NPV_{MC} represents the net present value of the maintenance cost incurred for the recovery of a certain capacity (j) in the system along the time of the life cycle (t) which in turn depends on the magnitude and frequency of a potential event (x) in each scenario. The $E(D|x)$ term represents the expected annual damage cost associated with a system failure, where $x_{K_{\min}}$ is the maximum deterministic dam storage capacity, $D(x|x_{K_{\min}})$ is the damage function for a debris flow magnitude of x exceeding the maximum capacity, and $f(x)$ is the probability density function describing event occurrence. The computation of the $E(D|x)$ was based on the Monte-Carlo method with 5000 simulations. Results were, consequently, given as mean expected costs and associated statistics characterizing their distribution function. Finally, comparison of alternatives has been conducted through the annual net benefit (ANB, %) which compares the benefit generated by an alternative (% reduction of damage) with increasing costs in the form of new infrastructure.

4. Results

4.1. Changes in debris flow events under CC

Analysis of the historical database of past debris-flow events of the Lienz region shows that 14, 52, and 34% of past debris flows occurred in May–June (MJ), July–August (JA), September–October (SO), respectively. Depending on event location and date, the precipitation threshold intensities extracted from the database for debris-flow initiation vary between 0 mm and 123.3 mm day^{-1} (09 February 1965). Amongst the 121 events listed in historical archives, 105 were triggered by rainfall intensities > 10 mm day^{-1} during the period 1950–2000 (which contains an average of 21 events per decade).

Mean rainfall intensity for debris-flow triggering is 59 mm day^{-1}. Fig. 5 shows the evolution of debris-flow frequencies (i.e. the number of events per decade) as a function of threshold (from 10 to 100 mm) for the past (S1) and accordingly also for future climate scenarios (S2, S3).

The maximum debris-flow frequency was observed during summer (5.2 events per decade in June–July) and for daily rainfall intensities comprised between 10 and 20 mm. In the future, according to 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 will likely decrease (increase) to 3.59 (5.45) events per decade. In the same way, future debris-flow frequencies were computed for each threshold and pairs of two-month periods (MJ, JA, SO).

Results are synthetized in Table 3. According to S2, the frequency of debris flows is expected to decrease from 21 (S1) to 14 events/decade (−33%) by 2050, with a marked decrease in process activity in JA (−60%). Conversely, the CNRMRM5.1_SCN_ARPEGE_DM_25km_1951–2050 simulation (S3) predicts more frequent rainfalls in spring and fall, such that the number of events would rather increase from 21 to 29 events/decade (+38%) under this scenario, mainly as a result of higher frequencies in 40–50 mm rainfall in MJ (+40%) and 10–40 mm rainfall in SO (+77%). Consequently, the exponential lambda rates for each scenario were defined as: $\lambda = 0.47$, $\lambda = 0.71$ and $\lambda = 0.34$ for S1, S2, and S3, respectively.

4.2. Check dam performance

Fig. 6 provides a graphical example of check dam performance as a result of debris-flow occurrences and aging degradation along structure life (example of 1 and 10 simulations for A2). System capacity is shown to reduce until it reaches the S_{min} threshold, where maintenance work will again be increased to initial capacity. Costs related with this performance are shown in the Table 4.

For A1, the expected NPV_{MC} for S1 is 2.51 ± 0.52 M€. The costs increased by almost 32% in S3 and decrease by almost 20% in S2. The average cost (COST, €) for each system repair is determined as 0.15 ± 0.10 M€ with little variation between scenarios (below ±6%). The expected no. REP (average amount of repairs along the structure lifetime) needed to keep the capacity of the system > K_{min} is almost 27.4 ± 4.6 (−26% and +47% for S2 and S3, respectively), with a time between repairs (TMR) calculated to 2.8 ± 2.4 years (+36% and −32%).

For A2, NPV_{MC} is lower with 1.45 ± 0.24 €, with a comparable evolution of costs as in A1 for S2 (−20%) for S3 (+44%). Consequently, the related COST is 0.10 ± 0.03 € (deviation between scenarios is ±3%). For this alternative, the expected no. REP (26.6 ± 3.9) and TMR (2.8 ± 2.5) are comparable to the values obtained in A1.

The influence of additional maintenance to the planned scheme suggests that intervention efforts every 2 years could reduce the NPV by almost 10% (Fig. 7). The sensitivity analysis of the defined capacity threshold S_{min} also reveals the slight impact of this parameter on NPV. Conversely, sensitivity analysis of K_{min} suggests a trend change of around $K_{min} = 0.4$. This inflection point can be interpreted as an efficiently designed structure capacity in terms of NPV, since below this threshold, the impact of system performance on NPV is less pronounced than in the upper section (Fig. 8).

4.3. Risk assessment and alternative comparison

Table 5 presents the vulnerability values for property damage based on modelled debris-flow magnitudes. The damage magnitude function obtained for the Wartschenbach fan is based on a stochastically averaged value of affected properties of 0.32 ± 0.04 M€ and multiplied by a 1.3 (30%) to include indirect costs, and is defined as a LN function with:

$$\text{Mean values}: f(\bar{x}) = 931.13 \times X^{0.3605}$$

and

$$\text{STDEV}: (x) = 6.9216 \times X^{0.8191}$$

where X is the magnitude of the modelled event (m^3).

Results indicate that the expected damage resulting from debris flows in the Wartschenbach in A1 is almost 89% lower than in A2.

The mean expected annual damage in the town for the scenarios were 0.005 (S1), 0.007 (S2), and 0.003 M€ (S3) for A1; and 0.04 (S1),

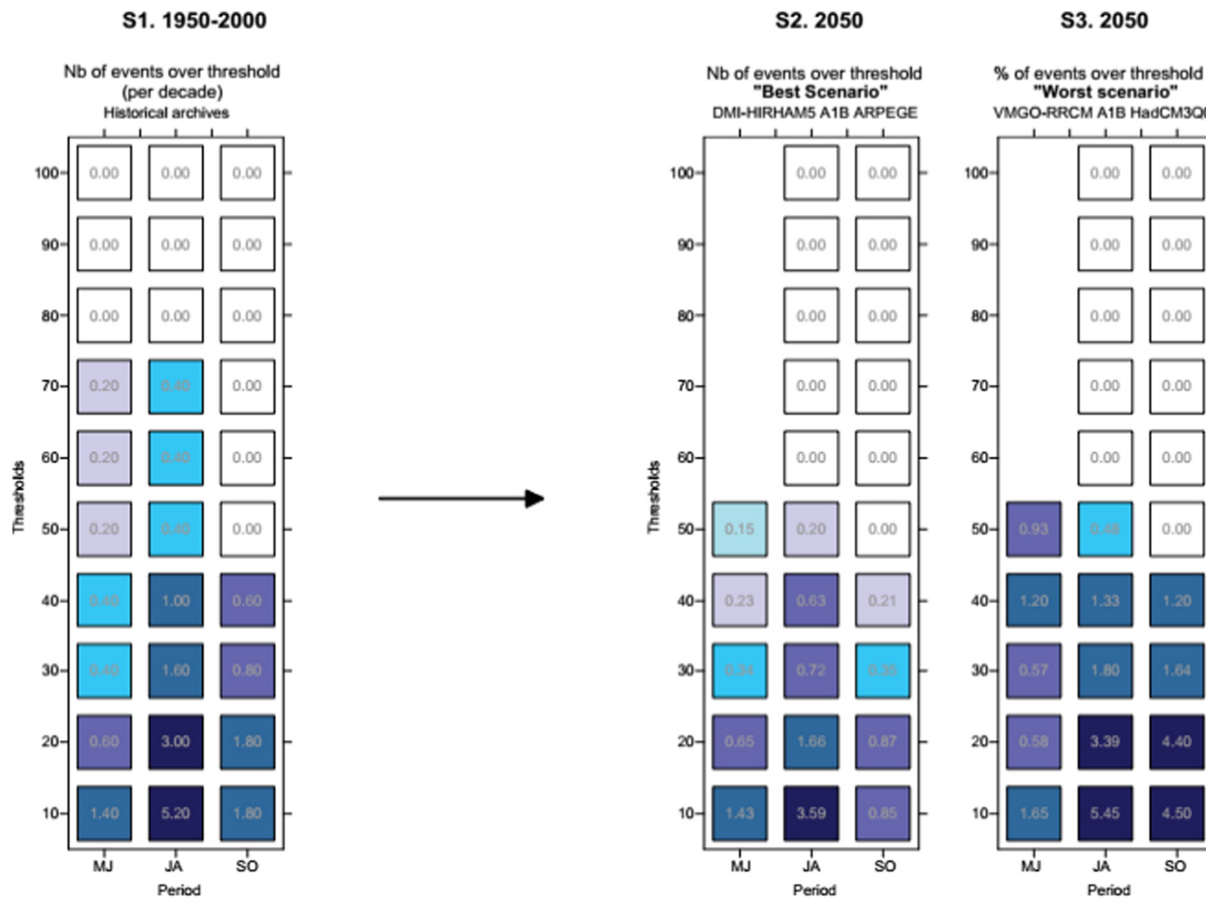

Fig. 5. Potential number of debris-flow events based on rainfall threshold exceedances for July–August and the period 1950–2000 and 2000–2050. The illustration includes the "best" and "worst" scenarios. For details see text.

0.06 (S2), and 0.03 M€ (S3) for A2, which reflect the efficiency of the existing check dams (A1) in reducing debris-flow risk at the town level.

Changes in debris-flow frequency as a result of CC induce a range of variations in expected annual costs which are comprised between −33% (S2) and +38% (S3). Table 6 shows the system performance and expected annual damage costs as a result of debris-flow impacts in the village. As can be seen in Table 6, scenario A2 is characterized by large variability which is above all reflective of the large variability in the estimation of expected costs of debris-flow damage on the fan. Comparison between the cost components shows a transfer of costs associated with damage to population costs related to an adequate and optimal maintenance of hydraulic infrastructure (Tables 4 and 6).

The total expected annual costs (expected damage plus expected maintenance costs) are on average lower in A1 (S1 = 0.036 M€; S2 = 0.028 M€; S3 = 0.047 M€) than in A2 (S1 = 0.064 M€; S2 = 0.045 M€; S3 = 0.89 M€), regardless of the scenario considered (average decrease by almost 42%).

Table 3
Expected number of debris-flow events based on future rainfall threshold exceedances.

	Period (months)	Number of events/decade (past)	Expected number of events/decade (best scenario)	Expected number of events/decade (worst scenario)
1 day	May–Jun	3	2.8	4.9
1 day	Jul–Aug	11.2	6.8	12.5
1 day	Sept–Oct	6.8	4.4	12.1
		21	14	29.5

As a consequence, we interpret that the performance of A1 is more economical than A2. However, when initial installation cost of each check dam (calculated at 1 million € per dam) is weighted against the recovery factor (80 years lifetime with a 5% interest rate), the expected annual cost for A1 will vary between 181,328 and 201,060 €; and between 140,852€ and 96,088€ for A2. As a consequence, the annual net benefit without considering the installation cost is optimal for the current alternative (+41% vs −3.5%). Conversely, when installation cost is included in the analysis, the current situation (A1) seems much less cost-effective (−65% versus −2%) (Fig. 9).

5. Discussion and conclusion

The coupled risk analysis assessment considering the stochastic life-cycle performance allowed for an estimation of expected annual costs related to debris-flow hazards in a managed torrent catchment under climate change. Through the use of a stochastic analysis, both uncertainties related to the performance of existing infrastructure and the quantification of damage were taken into consideration. This study focused on costs associated with the maintenance of the retention capacity at a reliable level after an event and demonstrated that the maintenance and reliability of works will become an economic challenge for affected communities in the next decades.

The stochastic approach used in this paper also accounted for the epistemic nature of risk analyses. From a methodological perspective, frequency and magnitude of past debris-flow events were integrated independently to a Poisson and Lognormal distribution on the basis of incomplete and short historical chronicles. In the future, these distributions could be assessed by the use of proxies such as tree rings that permitted in the past (i) to derive chronicles of past debris-flow events

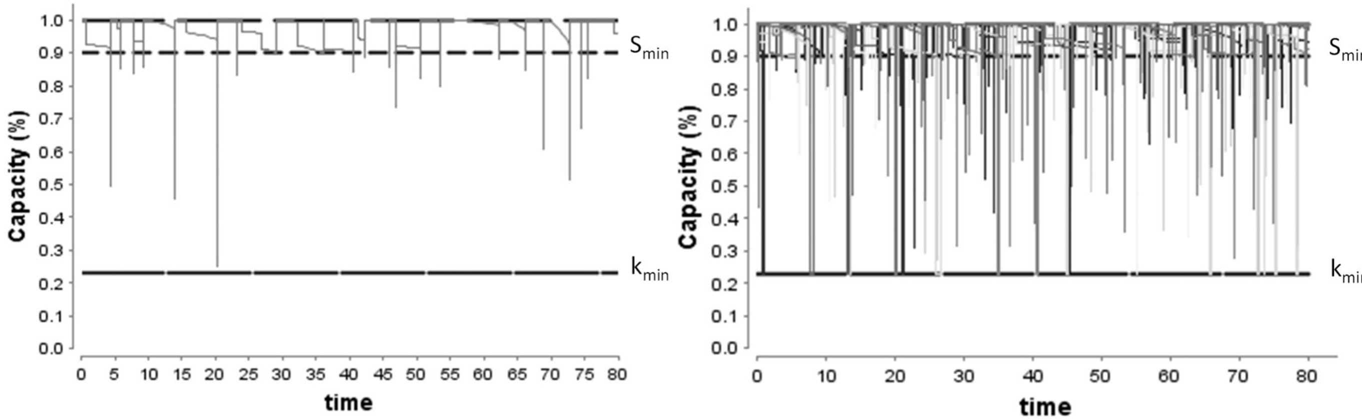

Fig. 6. Example of check dam performance analysis. Left (right) panel represents 1 (10) simulations. In both cases, the evolution of check dam performance has been evaluated for the mitigation scenario A1 (3 check dams) and the climate change scenario S1 (current situation, 21 debris flow per decade).

with a yearly resolution, and (ii) to obtain information about the magnitude (extension, volume) of past debris flow events (Stoffel, 2010).

The analysis of historical chronicles enables (i) determination of event frequencies in case that predefined thresholds have been exceeded; and (ii) definition of future scenarios for debris-flow occurrence by comparing the frequency of precipitation thresholds typically leading to debris flows in observational records and in climate change projections. Despite potential shortcomings related to (i) the regional approach used for the analysis, (ii) the lack of a rain gauge networks inside the catchment (Wieczorek and Glade, 2005; Nikolopoulos et al., 2014b), (iii) the absence of radar-derived rainfall series and (iv) the daily resolution of precipitation data which can potentially lead to a significant underestimation of debris-flow triggering rainfall thresholds (Nikolopoulos et al., 2014a, 2014b, 2015), similar approaches – as the one suggested here – have been successfully used in different poorly gauged mountain areas to define daily rainfall thresholds (Schneuwly-Bollschweiler and Stoffel, 2012) and to detect changes in debris-flow trends under climate change (e.g., Stoffel et al., 2011, 2014a, 2014b). Results of our study indicate an average frequency of 21 events per decade for the period 1950–2000. According to climate projections derived from scenario S2, this frequency is likely to decrease by approximately 33%. Conversely, an increase of 38% is expected in the debris-flow occurrence for the best (or most optimistic) scenario S3. In both cases, drier conditions in future summers and the wetting of springs, falls, and early winters are likely to have significant impacts on the behavior of debris flows. These evolutions are in agreement with Stoffel et al. (2014a, 2014b) who concluded for the Valais Alps (Switzerland) that the anticipated increase of rainfalls in MA and ND will likely initiate more frequent debris flows during this season in the future, whereas the absolute number of days with conditions favorable for the release of debris flows will likely decrease in JA.

Table 4
Quantitative results obtained from the life cycle performance analysis. NPV = average net present value of costs (€) associated with system performance, COST = average cost (€) of system repair, no. REP = average amount of reconstruction along the structure lifetime, TMR = expected time between two consecutive capacity reconstructions (years). KS indicate the Kolmogorov-Smirnov statistic to test the fit of the distribution function. See text for further details.

		NPV LN(μ, σ) [€]	KS	COST LN(μ, σ) [€]	no. REP LN(μ, σ)	TMR LN(μ, σ) [years]
A1	S1	2.51 ± 0.51	0.12	0.15 ± 0.10	27.4 ± 4.6	2.8 ± 2.4
	S2	2.01 ± 0.40	0.09	0.15 ± 0.10	20.1 ± 3.7	3.8 ± 3.2
	S3	3.33 ± 0.67	0.08	0.14 ± 0.09	40.4 ± 5.3	1.9 ± 1.7
A2	S1	1.45 ± 0.24	0.09	0.10 ± 0.03	26.6 ± 3.9	2.8 ± 2.5
	S2	1.15 ± 0.22	0.10	0.10 ± 0.03	19.3 ± 3.3	3.9 ± 3.1
	S3	2.10 ± 0.33	0.09	0.10 ± 0.03	38.3 ± 4.5	1.9 ± 1.7

The expected damage caused to the population can be reduced almost fully (89%) in A1 (current alternative) as compared to A2 (pre-1997 situation). On the other hand, check dam maintenance costs are expected to increase by almost 63%. These results clearly demonstrate that the reliability of the current infrastructure in terms of vulnerability reduction of the villages located on the fan. However, the net benefit analysis also showed that A1 induces larger total costs to the managers (−63%) than A2, and this is mainly due to the high installation costs of the check dams. One possible explanation for the implementation of such a decision, which might apparently seem imbalanced despite higher annual costs, may be related to an underestimation of costs related to the failure of infrastructure (i.e., damage due to dam destruction during an extreme event and/or loss of check dam functionality for reasons which were not considered here) in model simulations. The modeling approach was only based on damage to housing and properties (assumed as 30% of house value), but did not take account of other indirect losses such as the interruption and/or damage of traffic lines, other linear infrastructure, agricultural and forest areas or other externalities. The expected damage costs may therefore increase by up to 50% once that such indirect losses are also included (Pfurtscheller and Thieken, 2013).

Furthermore, several unknowns that may affect the estimation of damage costs still remain open. For instance, and despite the integration of different vulnerability functions recently published for the Austrian Alps and, specifically, for the study area (Fuchs et al., 2007; Totschnig et al., 2011; Totschnig and Fuchs, 2013), uncertainties remain with respect to vulnerability values involved in large magnitude events and in different building types (Hausmann, 1992), with potentially significant impacts on resulting estimations (Fuchs et al., 2007).

Another source of uncertainty stems from debris-flow modeling to derive the magnitude-damage function for alternative A2. Despite the fact that Flo-2D represents an often used engineering simulation tool

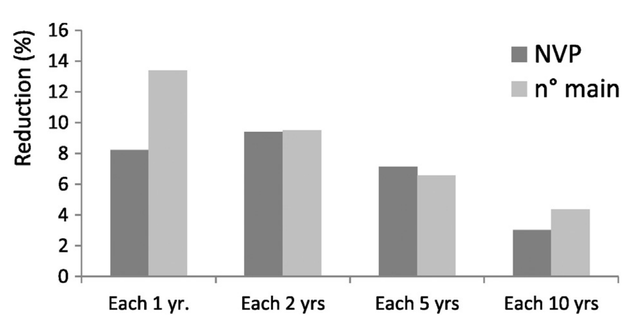

Fig. 7. Reduction (in %) in NVP_{MC} and number of maintenance interventions (no. main) under the assumption that additional regular cleaning works are carried out each 1, 2, 5, and 10 year(s).

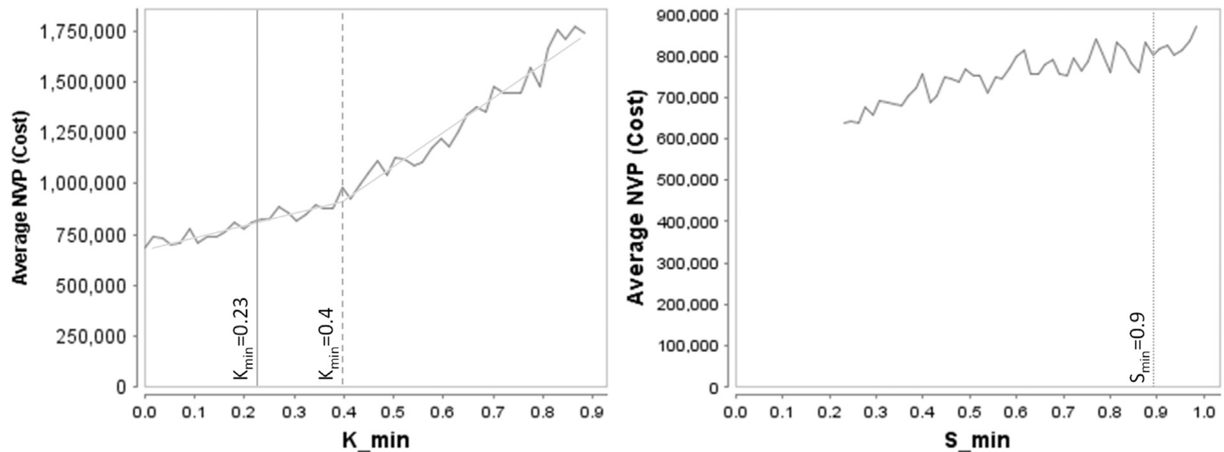

Fig. 8. Sensitivity analysis of NPV_{MC} with respect to changes in the K_{min} and S_{min} thresholds. The graph shows how the mean NPV_{MC} of costs varies in accordance with changes in these values. The right graph shows a change in trends related with a $K_{min} = 0.4$.

for debris-flow hazard assessment, several issues remain when it comes to the application of a simple one-phase depth averaged flow model to debris flows (e.g., Rickenmann et al., 2006; Beguería et al., 2009; Bühler et al., 2011). Specifically the suitability of a simple rheological flow law represents an ongoing matter of debate (Iverson, 1997). For our study, we argue that we focus only at the deposition pattern in the runout zone (without looking at dynamic parameters in the transit reach) and that we calibrate the model to a well-documented event. Although we independently carried out a sensitivity analysis of all input parameter, the main focus of this study was limited to the effect of magnitude variations. All scenarios show plausible results, in addition, their impact on the life-cycle performance have been shown to be too small compared to the effect of mitigation measures. Nevertheless, we would like to underline that the above-mentioned uncertainties may undoubtedly have an impact on the nature and amount of expected damage to elements at risk. The larger variability of damage costs resulting from A2 (Table 4), in which the villages are exposed to more frequent debris flows due to a lower protection level, clearly illustrates this concern and indirectly confirms the reliability of stochastic procedures in risk analysis. Beyond the quantitative data reported here, our study clearly shows that there is a need of maintenance works so as to preserve functional abilities of check dams at reliable thresholds.

Data also illustrates that the current maintenance costs are 57 to 63% higher in A1 (average S1 = 2.51 ± 0.51 M€), with each maintenance operation being approximately 50% more expensive than in A2 (average S1 = 1.45 ± 0.24 M€). Yet, a 2-year periodic maintenance could decrease these costs by around 10% (Fig. 7). The relative comparison between the variation in maintenance costs in the current situation (A1: 57 to 63%) with respect to the expected damage variation as a result of climate change in the previous situation (A2: +38% to −33%) suggests that maintenance of existing infrastructure may be more important than the effect that climate change will have on the occurrence of debris flow events such that maintenance will permit to compensate for or blur the impacts of climate change. The integration of the progressive deterioration of check dams owing to (i) the loss of retention capacities, (ii) the degradation of structural properties and/or (iii) the sudden debris-flow events allows determination of the respective influence of these parameters on the reliability of the defense structure. Similar approaches have been used previously to determine the reliability of large infrastructures (Sanchez-Silva et al., 2011). The approach has not been used so far in the analysis of mass movements, despite the fact that several studies have previously mentioned the potential contribution of this approach to the sizing of hydraulic infrastructures in torrents (Benito et al., 1998; Romang et al., 2003; Marchi et al., 2010). In Austria, Hübl and Fiebiger (2005) reported that function fulfillment of infrastructure is reached rapidly, mainly due to an underestimation of retention capacity, which could however be counterbalanced with (more) appropriate design criteria (Remaître et al., 2008).

This study assessed a progressive degradation function for the existing check dams in the Wartschenbach torrent, and addressed a topic for which homogenous data to characterize the structural behavior of check dams have not been available so far. As a consequence, we

Table 5
Vulnerability values obtained for the modelled debris-flow event according to existing references.

Volume	Estimator	Debris flow scenario									Average
		Fuchs, 2008			Totschnig and Fuchs, 2013			Fuchs et al., 2007			
		Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	
20,000 m^3	Average	0.043	0.152	0.025	0.106	0.198	0.021	0.040	0.114	0.014	0.08
	Std.	0.058	0.100	0.033	0.084	0.150	0.044	0.043	0.08	0.028	0.054
	Affected houses	~15									
25,000 m^3	Average	0.050	0.167	0.028	0.110	0.202	0.030	0.044	0.118	0.017	0.085
	Std.	0.058	0.120	0.038	0.094	0.165	0.054	0.053	0.095	0.033	0.065
	Affected houses	~17									
30,000 m^3	Average	0.069	0.182	0.032	0.114	0.207	0.033	00.048	0.112	0.019	0.091
	Std.	0.068	0.141	0.043	0.103	0.180	0.064	0.062	0.110	0.038	0.075
	Affected houses	~18									
40,000 m^3	Average	0.091	0.212	0.040	0.122	0.216	0.045	0.056	0.13	0.024	0.102
	Std.	0.088	0.180	0.054	0.124	0.210	0.084	0.083	0.140	0.048	0.095
	Affected houses	~21									

Table 6
Total expected annual costs related with the performance of the system and expected damage cost for both alternatives and all three scenarios. KS indicates the Kolmogorov-Smirnov statistics to test the fit of the distribution function.

		Total annual expected cost (LN)		K-S	Annual expected Damage cost (LN)	
		Mean	Std.		Mean	Std.
A1	S1	36,198	6749	0.02	4804	1597
	S2	28,240	5257	0.02	3203	1064
	S3	47,972	8283	0.02	6634	2205
A2	S1	64,051	29,330	0.04	46,007	32,896
	S2	45,059	20,020	0.05	30,671	21,930
	S3	89,825	38,998	0.05	63,533	45,427

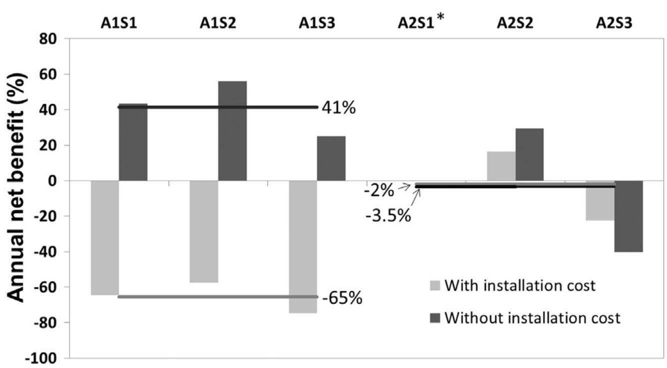

Fig. 9. Annual net benefit comparison (in %) taking account of/or ignoring the installation cost of the check dams. (*) indicates the reference level at which the appraisal was performed.

consider that the stochastic definition of the function taking account for a large range of likely infrastructure behavior – following the expert judgment provided by Romang et al. (2003) – was appropriate in the case of the present study. In the future, more quantitative analyses on this specific topic (i.e. Dell'Agnese et al., 2013) might needed in the future to further reduce model uncertainties. A prerequisite to include the progressive degradation function in system performance and risk assessment procedures more systematically would be through more frequent structure deterioration functions in risk assessment of managed mountain torrents. Both this lack of deterioration functions and the importance of maintenance work will become key issues in the following decades since (i) many infrastructures currently are in the second half of their life cycles (Sinabell, 2014) and (ii) paradigms in design criteria prevent debris flow damage to change over the last few decades (Marchi et al., 2010).

In conclusion, this study represents an exemplar of a successful implementation of an assessment of life-cycle performance of hydraulic infrastructures into a conventional debris-flow risk assessment. By including uncertainties inherent to the assumptions and different parameters used and their propagation throughout the different methodological step, we demonstrate that the current alternative (A1) reduces the cost of expected population and infrastructure damage significantly as compared to the protection strategy (A2) prior to the 1997 event. Nevertheless, reduced vulnerability is inevitably accompanied by increasing maintenance costs of the existing infrastructure (A1). The need for such maintenance works has been underlined by modeling approaches, with the latter clearly highlighting that safety of the local population and the reliability of infrastructure at a high level of confidence can only be guaranteed if maintenance operation works are performed at regular intervals at our study site. Therefore, we clearly recommend the inclusion of maintenance operations as well as the impact of progressive deterioration of existing infrastructures in risk analyses of managed torrents, so as to obtain more reliable cost-benefit ratios and to get a better idea of expected costs over longer time periods.

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