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Natural Hazards and Earth System Sciences
Discussions

Multi-hazard risk assessment for roads: Probabilistic versus deterministic approaches

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Abstract. Mountain hazard risk analysis for transport infrastructure is regularly based on deterministic approaches. Due to a variety of variables and data needed for risk computation, a considerable degree of epistemic uncertainty results. Consequently, input data needed for risk assessment is normally processed as mean values with or without scatter, or as an individual deterministic value from expert judgement if no statistical data is available. To overcome this gap, we used a probabilistic approach to express the potential bandwidth of input data with two different distribution functions, taking a mountain road in the Eastern European Alps as case study. The risk assessment included the damage potential of road infrastructure and traffic exposed to a multi-hazard environment (torrent processes, snow avalanches, rock fall). Reliable quantiles of the calculated probability density distributions attributed to the aggregated road risk due to the impact of multiple-mountain hazards were compared to the deterministic results from the standard guidelines on road safety. The results demonstrate that with common deterministic approaches risk is underestimated in comparison to a probabilistic risk modelling setup, mainly due to epistemic uncertainties of the input data. The study provides added value to further develop standardized road safety guidelines and may therefore be of particular importance for road authorities and political decision-makers.

1 Introduction

Mountain roads are particularly prone to natural hazards, and consequently, risk assessment for road infrastructure focused on a range of different hazard processes, such as landslides (Benn, 2005; Schlögl et al., 2019), rockfall (Bunce et al., 1997; Hungr and Beckie, 1998; Roberds, 2005; Ferlisi et al., 2012; Michoud et al., 2012; Unterrader et al., 2018) and snow avalanches (Schaerer, 1989; Kristensen et al., 2003; Margreth et al., 2003; Zischg et al., 2005; Hendrikx and Owens, 2008; Wastl et al., 2011). These studies have in common that they exclusively address the negative interaction of individual hazards with values at risk of the built environment and/or of society and use qualitative, semi-quantitative and/or quantitative approaches. In contrast, there is still a gap in multi-hazard risk assessments for road infrastructure.

Multi-hazard risk assessment

According to Kappes et al. (2012a), two approaches to multi-hazard risk analysis can be distinguished, a spatially-oriented and a thematically-defined method. While the first aims to include all relevant hazards and associated loss in

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

an area, the latter deals with the influence or interaction of one hazard process on another hazard, frequently addressed as hazards chain or cascading hazards, meaning that the occurrence of one hazard is triggering one or several second-order (successive) hazards. One of the major issues in multi-hazard risk analysis – see Kappes et al. (2012a) for a comprehensive overview – lies in the different process characteristics which lead to challenges for a sound comparison of the resulting risk level among different hazard types due to different reference units. Standardization by a classification scheme for frequency and intensity thresholds of different hazard types resulting in semi-quantitative classes or ranges allows for a comparison among different hazard types, such as shown in Table 2. Therefore, the analysis of risk for transport infrastructure is often focused on an assessment of different hazard types affecting a defined road section rather than on hazard chains or cascades (Schlögl et al., 2019). Following this approach, hazard-specific vulnerability can be assessed either in terms of loss estimates (e.g., Papathoma-Köhle et al., 2011; Fuchs et al., 2019) or in terms of other socioeconomic variables, such as limited access in case of road blockage or interruption (Schlögl et al., 2019). Focusing on the first and neglecting any type of hazard chains, our study demonstrates the application of risk to a specific road section in the Eastern European Alps and shows the sensitivity of the results using deterministic and probabilistic risk approaches.

Deterministic risk concept

Quantitative risk analyses for natural hazards are regularly based on deterministic approaches, and the temporal and spatial occurrence probability of a hazard process with a given magnitude is multiplied by the expected consequences, the latter defined by values at risk times vulnerability (Varnes, 1984; International Organisation for Standardisation, 2009). A universal definition of risk relates the likelihood of an event with the expected consequences, thus manifests risk as a function of hazard times consequences (UNISDR, 2004; ISO, 2009). Depending on the spatial and temporal scale, values at risk include exposed elements, such as buildings (Fuchs et al., 2015), infrastructure systems (Guikema et al., 2015) and people at risk (Fuchs et al., 2013). These elements at risk are linked to potential loss using vulnerability functions, indices or indicators (Papathoma-Köhle, 2017), and can be expressed in terms of direct and indirect, as well as tangible and intangible loss (Markantonis et al., 2012; Meyer et al., 2013). While direct loss occurs immediately due to the physical impact of the hazard, indirect loss occurs with a certain time lag after an event (Merz et al., 2004, 2010). Furthermore, the distinction between tangible or intangible loss is depending on whether or not the consequences can be assessed in monetary terms. In this context, vulnerability is defined as the degree of loss given to an element of risk as a result from the occurrence of a natural phenomenon of a given intensity, ranging between 0 (no damage) and 1 (total loss) (UNDRO, 1979; Fell et al., 2008; Fuchs, 2009). This definition highlights a physical approach to vulnerability within the domain of natural sciences, neglecting any societal dimension of risk. However, the expression of vulnerability due to the impact of a threat on the element at risk considerably differs among hazard types (Papathoma-Köhle et al., 2011).

Using a deterministic approach, the calculation of risk has repeatedly been conceptualised by Eq. (1) (e.g. Fuchs et al. 2007; Oberndorfer et al. 2007; Bründl et al. 2009) and is dependent on a variety of variables all of which being subject to uncertainties (Grêt-Regamey and Straub, 2006).

$$R_{i,j} = f\left(p_j,\ p_{i,j},\ A_i,\ v_{i,j}\right) \tag{1}$$

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

Where $R_{i,j}$ = risk dependent of object i and scenario j; p_j = probability of defined scenario j; $p_{i,j}$ probability of exposure of object i to scenario j; A_i = value of the object i (the value at risk affected by scenario j); $v_{i,j}$ = vulnerability of the object i in dependence on scenario j.

With respect to mountain hazard risk assessment, standardised approaches are available, such as IUGS (1997), Dai et al. (2002), Bell and Glade (2004), and Fell et al. (2008a, b) for landslides, Bründl et al. (2010) for snow avalanches, and Bründl (2009) or ASTRA (2012) for a multi-hazard environment. These approaches, however, usually neglect the inherent uncertainties of involved variables. In particular, they ignore the probability distributions of the variables (Grêt-Regamey and Straub, 2006) by obtaining the results with constant input parameters, which may lead to inconsistencies in the results. Therefore, loss assessment for natural hazard risk is associated with high uncertainty (Špačková et al., 2014 and Špačková, 2016) and studies quantifying uncertainties of the expected consequences are underrepresented (Grêt-Regamey and Straub, 2006). In our study, we bridge this gap by quantifying the potential uncertainties within road risk assessment using a stochastic risk assessment approach.

Uncertainties within risk assessment

Since the computation of risk for roads requires a variety of auxiliary calculations, a broad range of input data are used, such as the spatial and temporal probability of occurrence of specific design events. These auxiliary calculations subsequently provide variables necessary for risk computation of the respective system under investigation. Individual contributing variables are often characterized either as the mean value of the potential spectrum from a statistical dataset or, as a consequence of incomplete data, as a single value form expert judgement. Expert information is frequently processed with semi-quantitative probability classes and therefore subjected to considerable uncertainties. Consequently, they serve as rough qualitative appraisals encompassing a high degree of uncertainty.

The use of vulnerability parameters or lethality values as a function of process-specific intensities is often based on incomplete or insufficient statistical data resulting from missing event documentation (Fuchs et al., 2013). As discussed in Kappes et al. (2012a), Papathoma-Köhle et al. (2011, 2017) and Ciurean et al. (2017) with respect to mountain hazards, potential sources of uncertainty in vulnerability assessment are independent of the applied assessment method. The amplitude in data is considerably high in continuous vulnerability curves or functions, but also in discrete (minimum and maximum) vulnerability values referred to as matrices (coefficients), and in indicator-/index-based methods used to calculate the cumulative probability of loss. Associated with the uncertainty in vulnerability matrices, Ciurean et al. (2017) suggested a fully probabilistic simulation in order to quantify the propagation of errors between the different stages of analysis by substituting the range of minimum-maximum values with a probability distribution for each variable in the model.

Grêt-Regamey and Straub (2006) listed potential sources of uncertainties in risk assessment models and classified uncertainties into aleatory and epistemic uncertainties. The first is considered as inherent to a system associated to the natural variability over space and time (Winter et al., 2018) and the variability of underlying random or stochastic processes (Merz and Thieken, 2005, 2009), which cannot be further reduced by an increase in knowledge, information or data. The latter results from incomplete knowledge and can be reduced with an increase of cognition or better information of the system under investigation (Merz and Thieken, 2004, 2009; Grêt-Regamey and Straub, 2006). Particularly referring to deterministic risk analysis, epistemic uncertainty is associated with a lack of

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

knowledge about quantities of fixed but poorly known values (Merz and Thieken, 2009). Špačková (2016) pointed out the importance of interactions (correlations) between uncertainties which may affect the final results, an issue that was also discussed in the framework of multi-hazard risk assessments (Kappes, 2012a, b). Therefore, uncertainties should be included in the analysis by their upper and lower credible limits or by integrating confidence intervals reflecting the incertitude of input data, for an in-depth discussion see e.g. Apel et al. (2004), Merz and Thieken (2004, 2009), Bründl et al. (2009) and Winter et al. (2018).

Deterministic vs. probabilistic risk

In contrast to the well-established deterministic approach for mountain hazard risk assessment, probabilistic methods are underrepresented as a standard procedure to cope with the uncertainties of complex safety-relevant surroundings. To overcome this gap, we present an probabilistic design for loss calculation in order to compute the potential spectrum of input data with simple distribution functions and further aggregate the intermediate data of exposure situations, hazard- and scenario-related modules to the probability density function (PDF) of the total collective risk R_C by means of stochastic simulation (Fig. 1). Consequently, damage induced by natural hazards impact to road infrastructure as well as to traffic are represented by a range of monetary values as a prognostic distribution of the expected annual average loss instead of an individual amount.

Deterministic and probabilistic methods for risk analysis differ significantly in approach. Deterministic methods generally use a defined value (point value) for probability and for the impact (consequence) and consider risk by multiplying the probability of occurrence and potential consequences. The result is an “expected value” of risk. If multiple risks e.g. with varying frequencies are addressed, the total risk is expressed as the simple sum of individual risks resulting in an expected annual average loss. However, information about probability or best and/or worst-case scenarios are often excluded. In particular, the following shortcomings of deterministic approaches can be summarized (Tecklenburg 2003), which in turn leads us to a recommendation of probability-based risk approaches:

- A deterministic method gives equal weight to those risks that have a low probability of occurrence and high impact and to those risks that have a high probability of occurrence and low impact by using a simple multiplication of probability and impact.
- By multiplying the two elements of probability and impact, these values are no longer independent. Therefore, this method is not adequate for aggregation of risks where both probability and impact information need to remain available. Due to multiplication, the only information that remains is the mean value.
- The actual impact will definitely deviate from the deterministic value (i.e., the mean).
- Without the Value at Risk information, there is no way to determine how reliable the mean value is and how likely it might be exceeded.

In this context, deterministic systems are perfectly predictable, and the state of the parameters to describe the system behavior are fixed (single) values associated with total determinization following an entirely known rule, whereas probabilistic systems include some degree of uncertainty and the variables/parameters to describe the state of the system are therefore random (Kirchsteiger, 1999). The variables/parameters in probabilistic systems are described with probability distributions due to incomplete knowledge, rather than with a discrete single or point value which is assumed to be totally certain. Probabilistic risk modelling uses stochastic simulation with a defined distribution

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

function to generate random results within the setting of the boundary conditions. The deterministic variable is usually included within the input distribution. In Table 1 the two different methods are compared.

Table 1. Deterministic versus probabilistic method for risk analysis adjusted and compiled from Sander et al. (2015) and Kirchsteiger (1999).

	Deterministic method	**Probabilistic method**
Input	Definition of a single number for consequence as descriptive statements including conservative assumptions expressed by the probability of occurrence multiplied by the impact of the particular hazard.	The probabilistic assessment of risk requires one number for the probability of occurrence and several values for the impact (e.g., minimum, most likely and maximum) expressed as distribution functions, therefore including uncertainty.
Result	A simple mathematical addition to give the aggregated consequence for all risks (point value calculation). This results in an expected consequence for the aggregated risks but does not adequately represent the bandwidth (range) of the aggregated consequences.	Simulation methods e.g. Monte Carlo simulation produce a bandwidth (range) of aggregated natural hazards risks as probability distribution based on thousands of coincidental but realistic scenarios (depiction of realistic risk combinations). The method allows an explicit consideration and treatment of all types of reducible uncertainty.
Qualification	Results are displayed as a single sharp number, which, in itself, does not have an associated probability.	Results are displayed using probability distributions, which allow Value at Risk (VaR) interpretation for each value within the bandwidth (range).

Objective

The objective of this paper is a comparison between two fundamentally different approaches to assess risks due to natural hazard impacts on roads. Using the standardized framework from ASTRA (2012) for operational risk assessment for roads and transportation networks, we supplement the well-established deterministic method with a probabilistic framework for risk calculation (Fig. 1). While the former calculates risk with constant or discrete values, ignoring the epistemic uncertainty of the variables, the latter enables the consideration of the potential range of parameter value by using different distributions to characterize the input data uncertainty. Even though the presented methodology in this study focuses on a road segment exposed to a multi-hazard environment on a local-scale, the approach can easily be transferred to other risk-oriented purposes.

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

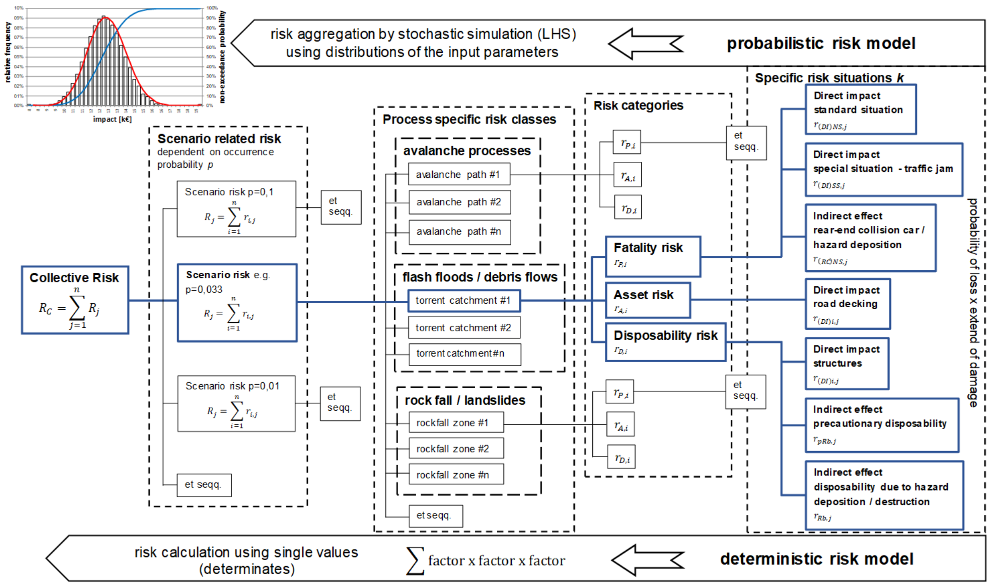

Figure 1. Flow chart for the risk assessment method following the standard approach (deterministic risk model) from ASTRA (2012) which was supplemented with the probabilistic risk model in present study.

2. Case study

The study area is located in the Eastern European Alps, within the Federal State of Salzburg, Austria (Fig. 2). The case study is a road segment of the federal highway B99 with an overall length of two kilometers ranging from km 52.8 to km 54.8 and is endangered by multiple types of natural hazards. The road segment was chosen to demonstrate the advantages of using probabilistic risk approaches in comparison to traditional deterministic methods. The mountain road under examination is part of a north-south traverse over the main ridge of the Eastern European Alps and is therefore an important regional transit route. Furthermore, the road provides access to the ski resort of Obertauern.

The road is frequently used for individual traffic from both sides of the alpine pass. Hence, a mean daily traffic (MDT) of 3,600 cars is observed. This constant frequency represents the standard situation for the potentially exposed elements at risk. However, especially in the winter months the average daily traffic can considerably increase up to an amount of about 7,000 cars. Thus, the traffic data underlies short-term daily and longer-term seasonal fluctuations with peaks up to the double of the mean value. The importance of dynamic risk computation needed for traffic corridors was also discussed earlier by Zischg et al. (2005) and Fuchs et al. (2013) with respect to the spatial-temporal shifts in elements at risk. Besides of the use as a regional transit route, the road is also a central bypass for one of the main transit routes through the Eastern European Alps. Hence, any closure of this main transit route (A10 Tauern motorway) results in a significant increase of daily traffic frequency up to a total of 19,650 cars. The evaluation of the dataset in terms of the bandwidth of the traffic data is shown in Table A6.

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

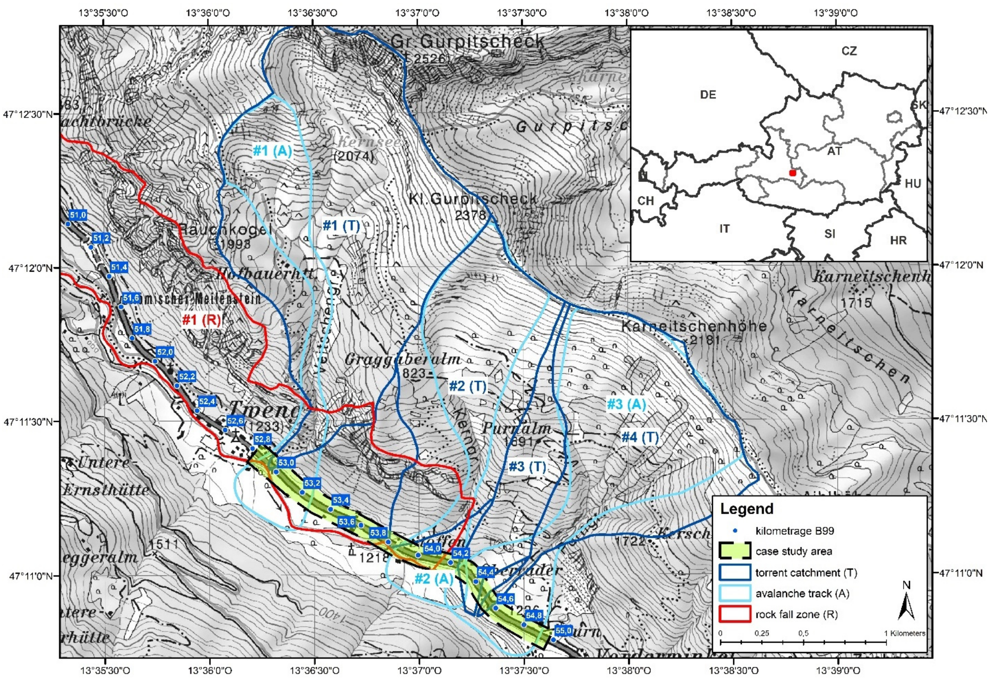

Figure 2. Overview of the case study area and location of the natural hazards along the road segment (Source base map: © BEV 2020 – Federal Office of Metrology and Surveying, Austria, with permission N2020/69708).

3. Methods

3.1 Hazard analysis

The hazard analysis was conducted in technical studies undertaken for the road authority of the Federal State of Salzburg (Geoconsult, 2016; Oberndorfer, 2016). The results regarding the spatial impact of the hazard processes on the elements at risk and the corresponding hazard intensities were used for the loss assessment in this research. The hazard assessment included the steps of hazard disposition analysis to detect potential hazards within the perimeter of the road followed by a detailed numerical hazard analysis. Therefore, these analyses considered approaches for hazard-specific impact assessment according to the engineering guidelines of e.g. Bründl (2009), ASTRA (2012) and Bründl et al. (2015) and relevant engineering standards and technical regulations (Austrian Standards Organisation, 2009, 2010, 2017). The physical impact parameters of the hazard processes were calculated using numerical simulation software, such as Flow-2D for flash floods and debris flows (Flow-2D Software, 2017), SamosAT for dense and powder snow avalanches (Sampl, 2007) and Rockyfor3D for rock fall (Dorren, 2012). The hazard analyses were executed without probabilistic calculations, thus the generated results were integrated as constant input in the risk analysis.

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

For the multi-hazard purpose three hazard types were evaluated, (1) hydrological hazards (torrential floods, flash floods, debris flows), (2) geological hazards (rock fall, landslides), and (3) snow avalanches (dense and powder snow avalanches). For each hazard type, intensity maps for the affected road segment were computed. The intensity maps specify for a specific hazard scenario the spatial expression of a certain physical impact (e.g., pressure, velocity or inundation depth) during a reference period (Bründl et al., 2009). In order to transfer the physical impact to object-specific vulnerability values for further use in the risk assessment, three process-specific intensity classes were distinguished (Table 2). These intensity classes were based on the underlying technical guidelines (Bründl, 2009; ASTRA, 2012; Bründl et al., 2015) and were slightly adapted to comply with the regulatory framework in Austria (Republik Österreich, 1975, 1976; BMLFUW, 2011). Table 2 represents the intensity classes which correspond to the affiliated object-specific vulnerability and lethality values (mean damage values) in Tables A7 and A8.

Table 2. Process-specific intensity classes with p = pressure, h = height (suffix h_{ws} refers to water and solids), v = velocity, d = depth and E = energy (compiled and adapted from Bründl (2009), ASTRA (2012) and Republik Österreich (1975) in conjunction with Republik Österreich (1976) and BMLFUW (2011). The low intensity class for debris flow has the same intensity indicators than for inundation because it was assumed that low intensity debris flow events have equal characteristics than hydrological processes.

Hazard type	Low intensity	Medium intensity	High intensity
Snow avalanche	$1 < p < 3$ kN/m²	$3 < p < 10$ kN/m²	$p > 10$ kN/m²
Inundation	$h < 0.5$ m or $v \times h < 0.5$ m²/s	$0.5 < h_{ws} < 1.5$ m or $0.5 < v \times h < 1.5$ m²/s	$h_{ws} > 1.5$ m or $v \times h > 1.5$ m²/s
Debris (bed load) deposit	$h_{ws} < 0.5$ m or $v \times h < 0.5$ m²/s	$0.5 < h_s < 0.7$ m or $v < 1$ m/s	$h_s > 0.7$ m and $v > 1.0$ m/s
Erosion	--	$d < 1.5$ m or top edge of the erosion	$d > 1.5$ m or top edge of the erosion
Rockfall	$E < 30$ kJ	$30 < E < 300$ kJ	$E > 300$ kJ

To determine the intensities of individual hazard processes, two different return periods were selected, a 1-in-10-year and a 1-in-30-year event (probability of occurrence $p_{10} = 0.1$ and $p_{30} = 0.033$). As shown in Fig. 2, the road segment is affected by three avalanche paths, four torrent catchments and one rockfall area. All three snow avalanches can either develop as powder snow avalanches or as dense flow avalanches, depending on the meteorological and/or snowpack conditions. Due to the catchment characteristics of the torrents two different indicator processes were assigned for assessing the hazard effect, depending on the two occurrence intervals. Therefore, the occurrence interval served as a proxy for the process type. For the frequently occurring events ($p = 0.1$) flash floods with sediment transport and for the medium scale recurrence intervals ($p = 0.033$) debris flow processes were assumed. The four torrent catchments have steep alluvial fans on the valley basin. The road segment is located at the base of these fans or the road is slightly notched in the torrential cone and passes the channels either with bridges or with culverts. The rockfall area is situated in the west district of the road segment (Fig. 2). Approximately two third of the study area is affected from rock fall processes either as single blocks or by multiple blocks.

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences Discussions

3.2 Standard guideline for risk assessment

The method to calculate road risk for our case study followed the deterministic standard framework of the ASTRA (2012) guideline for operational road risk assessment. The identification of elements at risk regarding their quantity, characteristics and value as well as their temporal and spatial variability was assessed through an exposure analysis. The assessment of the vulnerability of objects and the lethality of persons was carried out by a consequence analysis to characterize the extent of potential losses. The finally resulting collective risk R_C (Eqn. 2) as a sum of all hazard types over all object classes and scenarios – under the assumption that the occurrence of the individual hazards are independent from each other – was expressed in monetary terms per year as a prognostic value. R_C is therefore defined as the expected annual damage caused by certain hazards and is frequently used as a risk indicator (Merz et al., 2009; Špačková et al., 2014). Hence, R_C was calculated based on Eqn. (1) by summing up the partial risk over all scenarios j and objects i (Bründl et al., 2009, Bründl, 2009, ASTRA, 2012, Bründl et al., 2015):

$$R_C = \sum_{j=1}^{n} R_{C,j} \quad (2)$$

Where $R_{C,j}$ = the total collective risk of scenario j and objects i, $R_{C,j} = \sum_{i=1}^{n} r_{i,j}$.

According to the ASTRA (2012) guideline, the collective risk R_C is divided into three main risk groups, (1) risk for persons R_P, (2) property or asset risk R_A, and (3) risk of non-operational availability or disposability R_D.

3.2.1 Risk for persons R_P

The risk characterization for persons in terms of the direct impact of a natural hazard on cars was distinguished in a standard situation for flowing traffic and a situation during a traffic jam, which was seen as specific situation leading to a significant increase of potentially endangered persons. Additionally, another specific case was also included representing the rear-end collision either on stagnant cars or on the process depositions on the road in case of the standard situation. The probability for a rear-end collision depends on the characteristics of the road and is influenced by a factor of e.g. the visual range, the winding and steepness of the road, the velocity, and traffic density (ASTRA, 2012). Furthermore, an additional specific scenario was explicitly considered in the case of the road closure of the main transit route (A10 Tauern motorway) due to the resulting temporal peak of the mean daily traffic. The statistical mean daily traffic (MDT) was used as mean quantity of persons N_p travelling along the road (Table A7).

In order to compute R_P, the expected annual losses of a person i traveling along the road segment under a defined hazard scenario j was calculated as a combination of the specific damage potential or potential damage extent of a person i and the damage probability of the exposure situation k for persons using the road under investigation. The potential losses for persons were monetized by the cost for a statistical human life as published by the Austrian Federal Ministry of Transportation, Innovation and Technology (BMVIT, 2014). Thus, road risk for persons was calculated with three road-specific exposure situations k (Bründl et al., 2009):

1. Direct impact of the hazard event – standard situation (Eqn. 1A; Table A1)
2. Direct impact of the hazard event – specific situation due to traffic jam (Eqn. 2A; Table A2)
3. Indirect effect – Rear-end collision (Eqn. 3A; Table A3)

The risk variables to assess R_P are stated in Table A6 for the exposure situations and in Table A7 in the Appendix.

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Discussions

3.2.2 Property risk R_A

The property risk due to the direct impacts of the hazard process on physical assets of the road infrastructure was calculated for each object *i* and scenario *j* using Eqn. (4A) with Table A4 under consideration of risk variables in Table A8. The damage probability was assumed to be equal to the frequency of the scenario *j*.

With respect to the potential direct tangible losses within the study area, the physical assets including e.g. the road decking of the street segment, culverts and bridges were expressed by the building costs of the assets calculated from a reference price per unit (Table A8). The physical assets of affected cars were not addressed as this damage type is not included in the standard guideline due to the assumption of an obligatory insurance coverage. The monetized costs refer to replacement costs and reconstruction costs, respectively, instead of depreciated values, which is strongly recommended in risk analysis by Merz et al. (2010) due to the fact that replacement cost systematically overestimates the damage. Since there is a limitation of reliable or even available data on replacement costs, the usage of reconstruction costs is a pragmatic procedure to calculate damage.

3.2.3 Risk due to non-operational availability R_D

The risk due to non-operational availability can be generally separated into economic losses due to (1) road closure after a hazard event or (2) as a result of precautionary measures for road blockage. The former addresses the mandatory reconditioning of the road and interruption time is depending on the severity of the damage. For our case study, only the precautionary non-operational availability was calculated with Eqn. (5A), Table A5 and variables in Table A9 because the village of Obertauern can be accessed from both directions of the mountain passroad. Therefore, a general accessibility of the village was supposed because it was assumed that events only lead to a road closure on one site of the pass. Potential costs resulting from time delays for necessary detours or e.g. from an increase of environmental or other stresses were neglected. The maximum intensity of the process served as a proxy for the duration of the road closure.

The direct intangible costs for non-operational availability of the road were approximated from statistical data accounting for the business interruption and the loss of profits of the tourism sector in the village of Obertauern due to road closure (see Table A9). The village of Obertauern is a major regional tourism hot spot and therefore the predominant income revenues are based on tourism, thus other business divisions have been neglected. Regarding the precautionary expected losses only snow avalanches were included, due to the obligatory legal implementation of a monitoring of a reginal avalanche commission. Thus, a reliable procedure for a road closure could be assumed.

3.3 Risk computation

For purpose of computing road risk, the risk Equations 1A to 5A from the standard guideline (ASTRA, 2012), stated in the Appendix in conjunction with Tables A1 to A5, were used without further modification both for the deterministic and for the probabilistic calculation. Hence, the probabilistic setup is based on the same equations as the standard approach, but the variables were addressed with probability distributions instead of single values. In a first step, the deterministic result was computed as a base value for comparison with the results (probability density functions PDFs) of the two diverging probabilistic setups. In a second step, a probabilistic model was integrated into the same calculation setup to consider the band width of the risk-contributing variables. Using this probabilistic

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

model, the individual risk variables were addressed with two separate probability distributions. The flow chart in Fig. 1 illustrates the risk assessment method and distinguishes between the deterministic and the probabilistic risk model. The diagram exemplarily demonstrates the calculation steps for both model setups. Whereas only the single value of the input data was processed within the standard (deterministic) setup, the probabilistic risk model utilized the bandwidth of each variable denoted in Tables A6 to A9 in the Appendix. These values were either defined from statistical data, expert judgement or from existing literature. The range represents the expected potential scatter of the variables including a minimum (lower bound *l)*, an expected or most likely value (*m)* and a maximum value (upper bund *u)*. The deterministic setup was calculated with the expected value, which corresponds in most cases to the recommended input value of the guideline.

3.3.1 Probabilistic framework

Within the probabilistic risk modelling setup, the contributing variables for computing the prognostic annual loss were calculated in a stochastic way using their potential range. The probabilistic risk calculation was conducted with the software package RIAAT – Risk Administration and Analysis Tool (RiskConsult, 2016). The probabilistic setup comprised two different and independent calculation runs each with two different distribution functions to characterize the uncertainty of the input variables. Hence, each variable was modelled using either (1) a triangular or three-point distribution (TPD) or (2) a beta-PERT distribution (BPD) within the probabilistic model, which generated two independent probabilistic setups and results. The discrete risk calculation with two different approaches of probability distributions facilitated a comparison of the applicability and the sensitivity of the simple distribution functions on the results. The expected annual monetary losses induced by the three hazard types were aggregated and further compacted to the probability density function (PDF) of the total risk caused by multi-hazard impact. Finally, the two different PDFs from the stochastic risk assessment were compared with the result from the deterministic method to show the potential dynamics in the results.

1. Triangular distribution (TPD)

The triangular distribution derives its statistical properties from the geometry: it is defined by three parameters *l* for lower bound, *m* for most likely value (the mode) and *u* for upper bound. Whereas lower and upper bounds define on both edges the limited bandwidth, the most likely value indicates that values in the middle are more probable than the boundary values, and also allows for the representation of skewness. The TPD is a popular distribution in the risk analysis field (Cottin and Döhler, 2013) for example to reproduce expert estimates. Especially if little or no information about the actual distribution of the parameter or only an estimate of the additional variables to fit the theoretical distribution is feasible, a best possible approximation can be achieved using the TPD. If there is no representative empirical data available as a basis for risk prediction, complex analytical (theoretical) distributions, which are harder to model and communicate, may not represent the reality better than a simple triangular distribution (Sander, 2012).

2. Beta-PERT distribution (BPD)

The beta-PERT distribution (Program Evaluation and Review Technique) is a simplification of the Beta distribution with the advantage of an easier modelling and application (Sander, 2012). It requires the same three

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Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
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EGU
Discussions

parameters as a triangular distribution: *l* for lower bound, *m* for most likely value (mode) and *u* for upper bound. In contrast to the two parametric normal distribution N(μ,σ) – μ for average and σ for standard deviation – the beta-PERT distribution is limited on the edges and it allows for modelling asymmetric situations. In reality, risk parameters commonly have a natural boundary. Therefore, estimating min/max values instead of standard deviation is more realistic or feasible as there is in most cases no data available to express the mean variation. Moreover, BPD allows for smoother shapes, making it suitable to model a distribution that is actually an aggregation of several other distributions.

For a given number of risks, each with a probability of occurrence and an individual probability distribution, the potential number of combinations (scenarios) escalates nonlinear. Especially if dependencies or correlations between different risks are included and/or numerous partial risks are aggregated to an overall risk the application of analytical methods have computational restrictions. Stochastic simulations are better suited to work on such complex models (Tecklenburg, 2003). Therefore, the aggregation of the distributions were calculated by means of Latin Hybercube sampling (LHS) which is a comparable stochastic simulation technique to Monte-Carlo simulation (MCS) with the advantage of a faster data processing, a better fitting on the theoretical input distribution and a more efficiently calculation as fewer iterations are needed to get equally good results (Sander, 2012). LHS consistently produces values for the distribution's statistics that are nearer to the theoretical values of the input distribution than MCS. These advantages are possible because the real random numbers used to select samples for the MCS tend to have local clusters, which are only averaged out for a very large number of draws. Addressing this issue using LHS can immediately improve the quality of the result by splitting the probability distribution into *n* intervals of equal probability, where *n* is the number of iterations that are to be performed on the model. In the present study, 1,000,000 iterations where performed for every single simulation to get consistent results.

4. Results and discussion

In Table 3 the results for each risk group (R_P, R_A, R_D) as well as for the total multi-hazard risk R_C calculated with the standard deterministic risk approach are shown and compared to those obtained by the two probabilistic setups using two different probability distributions (TPD and BPD). The results associated with the two distribution functions are displayed as median value of the PDF to show their deviation to the outcome of the standard approach. Based on our case study, the road risk over all hazards types and scenarios (multi-hazard risk) with the deterministic approach results in 76.0 k€/y. The results with the probabilistic approach referring to the median of the PDFs amounts to a monetary risk of 105.6 k€/y (TPD) and 90.9 k€/y (BPD), respectively. Compared to the standard approach the median of the PDFs equals an increase of 38 % (BPD) and 19 % (TPD), depending on the choice of probability distribution to model the uncertainties of the input variables. Focusing on the 95% percentile (P95) of the results – non-exceedance probability of 95%, shown in Fig. 3 – an increase of 79 % (TPD) and 46 % (BDP) to the deterministic result can be observed. Fig. 3 illustrates, based on the Lorenz curves for the two distributions (TPD and BPD), the scale of deviation of the total multi-hazard risk R_C within the probabilistic risk modelling and compared to the standard outcome. The graphs show the potential uncertainties of the risk computation, which can be covered by a suitable choice of a Value at Risk (VaR) level. For example, with a benchmark of the 95 % quantile (P95), 95 % of the potential uncertainties within the risk calculation can be covered by using a probabilistic risk assessment

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Discussions

approach. However, a suitable VaR level is depended on the general safety requirement of the system as well as on the degree of uncertainty of the input variables.

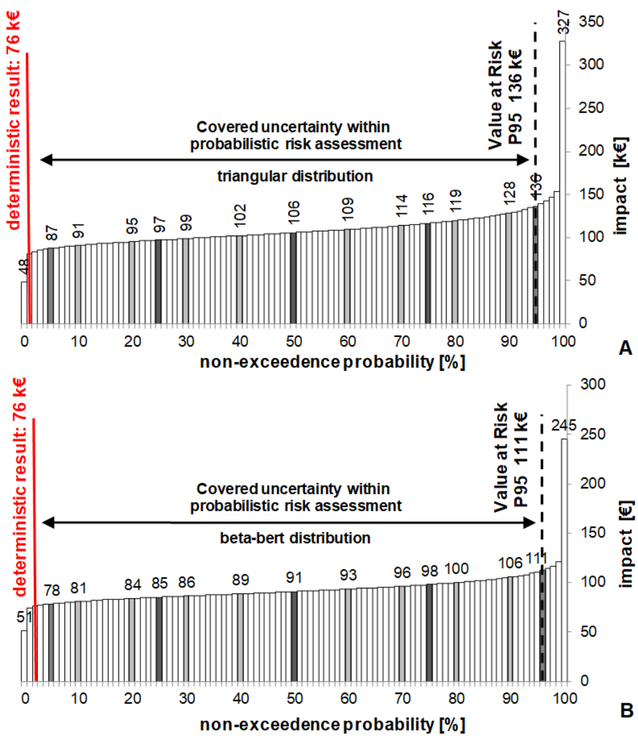

Figure 3. Lorenz curves for (A) triangular distribution and (B) beta-PERT distribution showing the scale of deviation of the total multi-hazard risk R_C within the probabilistic risk modelling and compared to the deterministic result in k€/y.

Geological hazards (rockfall) contribute with a fraction of 7.8 % to the total risk (or, in absolute numbers, 5.9 k€, see Table 3) based on the deterministic model, which can be attributed to the relatively small importance in comparison to the other hazard types in the study area. Hydrological hazards pose the highest risk (50.5 %, or, in absolute numbers, 38.4 k€/y) previous to avalanche hazards (41.7 %, or, in absolute numbers, 31.7 k€/y). Overall, R_P (44.9 %; 34.1 k€/y) has the highest share on the total multi-hazard risk narrowly followed by R_A (38.9 %; 29.6 k€/y), both associated to direct damage. The hydrological hazards (predominantly debris flow processes) with a portion of 76.5 % or 26.1 k€/y have a disproportionate high share on R_P due to the high-intensity hazard impact. Similarly, the semi-empirical lethality factors shown in Table A7 have high values (λ_D = 0.8) just like the impact of rock fall on cars with a probability of death of λ_R = 1.0. Thus, these event types yield in high monetary losses in contrast to snow avalanches with a lethality factor for high intensity of λ_A = 0.2. By modelling the hazard-specific lethality with probability functions a wider scatter can be achieved but the effect still remains due to the heavy weight around the

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Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

most likely value *m*. The indirect losses related to R_D with a fraction of 16.3 %, or, in absolute numbers 12.4 k€/y has a minor portion because this risk group is only relevant for snow avalanches.

Table 3. Comparison of the deterministic versus probabilistic results for the three risk categories depending on the three hazard types and the total collective risk with R_P = risk for persons, R_A asset risk, R_D= disposability risk and R_C = total collective risk with absolute values in k€/y in the first row and as percentage in the second row. For the probabilistic data the median value of the triangular △ and the beta-PERT ⌒ distribution functions are displayed. Note that, risk-based aggregated losses do not equal the sum of the sub-components because probabilistic metrics such as P50 are not additive.

Risk category		**R_P**			**R_A**			**R_D**			**R_C**		
Hazard type	**Unit**	**Det.**	△	⌒	**Det.**	△	⌒	**Det.**	△	⌒	**Det.**	△	⌒
Geological hazards	k€/y	5.4	10.5	7.8	0.47	0.43	0.44	0	0	0	5.9	10.9	8.3
	%	15.8	17.0	16.3	1.6	1.4	1.5	0	0	0	7.8	10.3	9.1
Hydrological hazards	k€/y	26.1	42.3	34.5	12.3	13.9	13.1	0	0	0	38.4	56.2	47.6
	%	76.5	68.3	71.9	41.6	45.6	43.5	0	0	0	50.5	53.2	52.4
Avalanche hazards	k€/y	2.6	8.4	5.3	16.8	16.2	16.6	12.4	13.1	12.7	31.7	37.9	34.7
	%	7.6	13.6	11.0	56.8	53.1	55.1	100	100	100	41.7	35.9	38.2
Total	k€/y	**34.1**	**61.9**	**48.0**	**29.6**	**30.5**	**30.1**	**12.4**	**13.1**	**12.7**	**76.0**	**105.6**	**90.9**
	%	**44.9**	**58.6**	**52.8**	**38.9**	**28.9**	**33.1**	**16.3**	**12.4**	**14.0**	**100**	**100**	**100**

The results related to our case study (Table 3 and Fig. 4) show that due to the shape and the mathematical definition of the distribution the TPD leads to the highest variation in the monetary losses. The boxplots in Fig. 4 display the results from the probabilistic simulation for the three risk categories (R_P, R_A, R_D) and for the total hazard-specific risk (R_C) relating to the three hazard types (Figs. 3 A – C) and for the total multi-hazard collective risk (Fig. 4 D) in respect of the measures of the central tendency of the PDF. The boxplot diagrams are thereby plotted against the deterministic value to show its position. The wide range of the distribution in R_C is markedly caused by R_P, which exhibits a broad bandwidth and a right-skewed distribution. Hence, unlike to R_A and R_D, the physical injuries expressed as the economic losses of persons (R_P) are responsible for the highest divergence to the standard approach and show a considerable scatter. The main causes for the striking deviations can be associated to the relatively high monetary value of persons which was modeled as discrete point value in combination with the fluctuations of the MDT and the variations of the hazard specific lethality. The monetized costs for a statistical human life equal 3 M€ (Table A7) and is based on a statistical survey of the economic expenses for a road accident in Austria (BMVIT, 2014). Although we ascribe this value to a high degree of uncertainty the valuation of the expenses for a statistical human life was not attributed to a probability distribution due to the case study-specific fixed governmental requirements in Austria. The discussion of a monetarily evaluation of a human life is still ongoing across scientific disciplines using different economic approaches (e.g. Hood, 2017). Furthermore, the lethality factors also correspond to the high variation of R_P which are seen as very sensitive parameters. Therefore, we encourage further research on hazard-specific lethality functions for road risk management either based on comprehensive empirical datasets or on

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

representative hazard impact modelling. Due to the strong effect of R_P on R_C the results have to be carefully interpreted as they are sensitive to the input variables. Therefore, the values on our case study especially the cost for human life cannot be directly transferred to other application without a detailed validation and verification of national regulations.

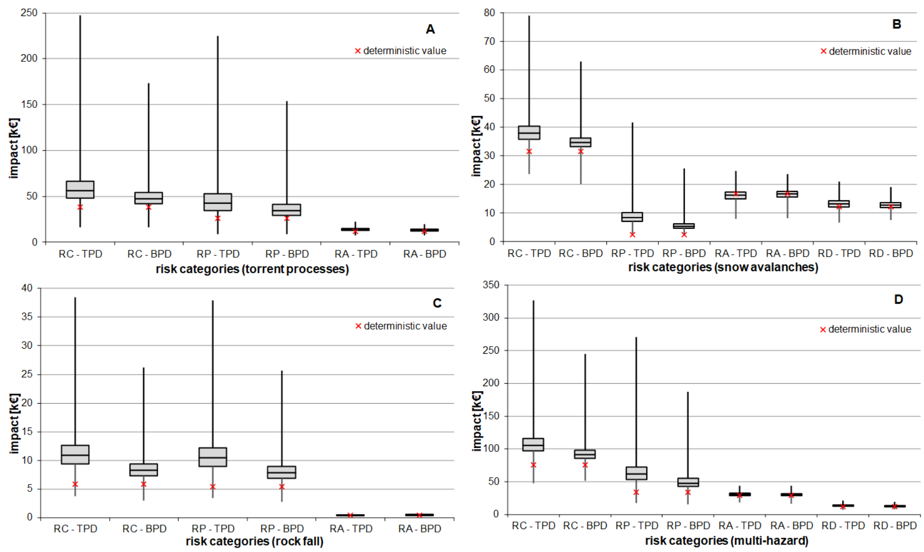

Figure 4. Probabilistic results for the three risk categories per hazard type (A = torrent processes, B = snow avalanches, C = rockfall) and for the total collective risk (D) based on the two distribution functions triangular or three-point distribution (TPD) and the beta-PERT distribution (BPD) with R_P = risk for persons, R_A asset risk, R_D = disposability risk and R_C = total collective risk in k€/year.

Apart from R_P where the deterministic result is located below or near the 5 % percentile of both PDFs, R_A and R_D are mostly within the interquartile range between the 25 % quartile and the median compared to the standard approach (Fig. 4). In this context, R_A for snow avalanche exceeds the median and is situated between the median and the 75 % quartile. The effect can be traced back to the left-skewed distribution of the vulnerability factor $v_{B,A}$ for medium avalanche hazard intensities regarding the object class structures (bridges and culverts) in Table A8. In general, due to the shape and the mathematical characteristics of the distribution, the BPD leads to a stronger compaction around the median than the TPD which can be well explained by the properties of the BPD which has, in comparison to the TPD, a larger weight around the most likely value m.

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Preprint. Discussion started: 10 March 2020

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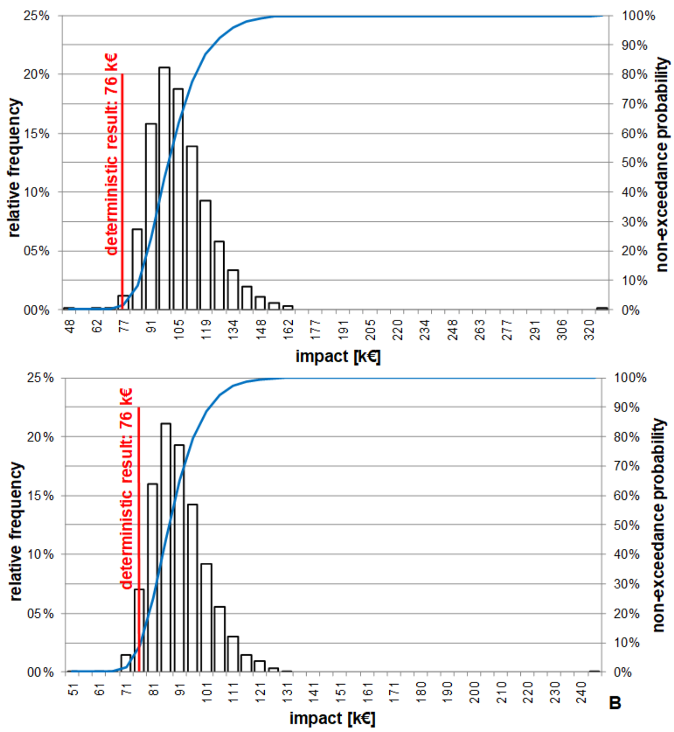

Figure 5. Probability density function (PDF) and cumulative distribution function (CDF) for (A) triangular distribution, (B) beta-PERT distribution in k€/y.

In Fig. 5, the PDF and the cumulative distribution function (CDF) are shown for R_C with the two probabilistic model results and the deterministic result. In both cases (TPD and BPD), the deterministic result is situated at the lower edge of the PDF near or under the 5 % percentile. Thus, the deterministic result of our case study covers approximately less than 5 % of the potential band-with of the probability distribution. The TPD has a wide range, whereas the BPD is considerably flattened on the boundary of the amplitude. The results of the two distributions have in common that they are allocated right-skewed. In contrast to the location of the median, the deterministic result is on the far-left side of both distribution and is exceeded of more than 95 % of the potential outcome.

5 Conclusion

The results based on our case study provide evidence that the monetary risk calculated with a standard deterministic method following the conventional guidelines is lower than applying a probabilistic approach. Thus, without consideration of uncertainty of the input variables risk might be underestimated using the operational standard risk assessment approach for road infrastructure. The mathematical product of the frequency of occurrence and the potential consequences and, in a narrower sense, the multiplication of the partial risk factors in the second part of the

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

risk equation may lead to a bias in the risk magnitude because the multiplication of the ancillary calculations generates a theoretical value ignoring the full scope of the total risk. The deterministic risk value is expressed as a theoretical mean value neglecting the potential distribution functions of the input data. Thus, the compression of the input values to a single deterministic risk value with total determination prevents an actual prognosis of reliability that would have been achieved by specifying bandwidths (Sander, 2012). Furthermore, the simple summation of the scenario related and the object-based risk to receive the cumulative risk level instead of using probabilistic risk aggregation leads to an underestimation of the final risk. Hence, the full spectrum of risk cannot be represented with deterministic risk assessment, which may further lead to biased decisions on risk mitigation. The Value at Risk (VaR) approach by considering a reliable percentile of the non-exceedance probability e.g. P95 as shown in Fig. 3 – depending on the desired covering of the risk potential form society, authorities or organizations – might be an appropriate concept to tackle this challenge. However, within a probabilistic approach the scale of deviation is dependent on the choice of distribution for modelling the bandwidth of the variables and the results are sensitive to the defined spectrum of input information stated in Tables A6 - A9. These variables are case study specific and cannot be directly transferred to other road risk assessments without careful validation. However, probabilistic risk assessment (PRA) enables a transparent representation of potential losses due to the explicit consideration of the entire potential bandwidth of the variables contributing to risk. Since comparable results can be achieved based on predefined values (Bründl et al., 2009), we still recommend the consideration of the deterministic value as a comparative value to the probabilistic method.

Road risk assessment is usually afflicted to data scarcity; thus, risk operators and practitioners are often dependent on expert appraisals, which are subject to uncertainties. In order to improve data quality, upper and lower values and the expected value can be easily estimated for fitting a simple distribution of the input variables. Even though empirical values such as statistical data are available, a certain degree of uncertainty remains. Therefore, simple distribution functions such as TPD or BPD can adjust the shape of the distribution more conveniently than complex probability distributions, since the required additional parameters to adjust a complex distribution are simple not available. Hence, for a prognostic prediction, risk modelling with complex distributions in contrast to simple techniques cannot be justified if there is a lack of empirical data.

A limitation of our study is that the performance of the probabilistic approach cannot be verified and validated with empirical data, but the results show that the explicit inclusion of epistemic uncertainty leads to a bias in risk magnitude. The probabilistic approach allows quantification of uncertainty, and thus enables decision makers to better assess the quality and validity of the results from road risk assessments. This can facilitate the improvement of road-safety guidelines, and thus is of particular importance for authorities responsible for operational road-safety, for design engineers and for policy makers due to a general increase of information for optimal decision-making under budget constraints. Furthermore, the paper addresses the second part of the risk concept in terms of the consequence analysis. The results of the hazard analysis serve thereby as a constant input using the physical modelling of the hazard processes without the consideration of probabilistic methods. Therefore, we expect a considerable source of epistemic uncertainty within the hazard analysis which emphasises the necessity for an additional inclusion of probabilistic based hazard analyses in a holistic multi-hazard risk environment.

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Competing interests: Sven Fuchs is member of the Editorial Board of Natural Hazards and Earth System Sciences.

Author contribution: SO initiated the research, was responsible for data collection, literature research, preparation of the manuscript, visualization of the results and performed the risk simulations with additional contribution by PS. PS contributed to additional information on probabilistic risk calculation. SF compiled the background on risk assessment and helped to shape the research, analysis and the manuscript. All authors discussed the results and contributed to the final manuscript.

Data availability: All risk related data are publicly available (see references throughout the paper as well as in the Appendix).

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Appendix

Risk equations according to ASTRA (2012) guideline:

A. Risk for persons R_P

1. Direct impact of the hazard event – standard situation

$$r_{(DI)NS,j} = p_j \times (1 - p_{Rb}) \times (1 - p_{RbE}) \times p_N \times N_P \times \lambda \times p_{So,j} \times f_L \tag{1A}$$

Table A1. Risk variables and their derivation for the calculation of R_P – direct impact standard situation.

Variable	Description	Derivation
$r_{(DI)NS,j}$	risk of a person i in scenario j (normal situation)	
p_j	probability of occurrence of an event (frequency of a scenario j)	$p_j = f_j - f_{j+1};\ f_j = \frac{1}{T_j}$ p_j = probability of occurrence of scenario j f_j = frequency of occurrence T_j= return period of scenario j
p_{Rb}	probability of precautionary road blockage	
p_{RbE}	probability of a road blockage due to an event (road closure due to a previous event of the same hazard type along the road)	$p_{RbE} = \alpha \times \left(1 - \frac{1}{n_H}\right)$ α = reduction factor [1] n_H= number of hazard areas with the same[2] hazard process and triggering mechanism
p_N	probability of the standard (normal) situation	$p_N = 1 - p_C$
p_C	probability of a traffic jam (congestion)	$p_C = \left(\frac{n}{365}\right) \times \left(\frac{D}{24}\right)$ n = number of traffic jams per year D = average duration of a traffic jam [h]
N_p	number of affected persons	$N_P = N_V \times \beta$ $N_{VN} = \frac{MDT}{v \times 24000} \times l$ = number of vehicles in the standard situation $N_{VS} = \frac{(\rho_{max} \times l)}{1000}$ = number of vehicles in case of a traffic jam MDT = mean daily traffic v = signalized velocity for cars [km/h] l = length of the street segment [m][3] ρ_{max} = maximum traffic density per lane and kilometer in case of a traffic jam β = mean degree of passengers
λ	lethality factor	Hazard-process and intensity related variable ($\lambda_D, \lambda_F, \lambda_R, \lambda_A$ in table A6)

[1] The reduction factor considers that not all hazard areas get simultaneously released by the same triggering event.
[2] The number of hazard areas for the three hazard types was calculated as discrete values based on field surveys according to the release probability as a function of the event frequency (avalanches n_{A10} = 6, n_{A30} = 7; torrent processes n_{T10} = 7, n_{T30} = 8; rockfall p_{RbE} = 0 not relevant).
[3] The length of the affected street segment is a discrete (single) value according to the results of the hazard analyses.

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

$p_{So,j}$	spatial occurrence probability of the process in the scenario j as proportion of the mean width or area of the process domain in scenario j to the maximum width or area of the potential hazard domain	for rockfall processes $p_{So,j} = ET \times \frac{d}{w_{HD}}$ ET = event type d = mean diameter of the block [m] w_{HD} = width or amplitude of the hazard domain in scenario j
f_L	factor to differentiate the affected lane	0,5 = one lane affected 1 = whole road (both lanes) affected

2. Direct impact of the hazard event – special situation due to traffic jam

$$r_{(DI)SS,j} = p_j \times (1 - p_{Rb}) \times (1 - p_{RbE}) \times p_C \times N_P \times \lambda \times p_{So,j} \times f_L \quad (2A)$$

Table A2. Risk of a person i in scenario j for the calculation of R_P – direct impact traffic jam. The calculation of the variables is according to Table A1.

Variable	Description
$r_{(DI)SS,j}$	risk of a person i in scenario j in case of a traffic jam (special situation)

3. Indirect effect – Rear-end collision

$$r_{(RC)NS,j} = p_j \times (1 - p_{Rb}) \times (1 - p_{RbE}) \times p_{Rc} \times f_L \times (1 - p_C) \times N_P \times \lambda_{\mathrm{Rc}} \quad (3A)$$

Table A3. Risk variables and their description for the calculation of R_P – rear-end collision. The calculation of the residual variables is according to Table A1.

Variable	Description
$r_{(RC)NS,j}$	risk of a person i in scenario j for a rear-end collision in the normal situation[4]
p_{Rc}	probability of rear-end collision
λ_{Rc}	probability of fatality in the case of a rear-end collision

B. Property risk R_A

$$r_{(DI)i,j} = p_j \times l \times A_i \times v_{i,j} \times p_{So,j} \times f_L \quad (4A)$$

Table A4. Risk variables and their description for the calculation of R_A – direct impact. The calculation of the residual variables is according to Table A1.

Variable	Description
$r_{(DI)i,j}$	risk of object i in scenario j in terms of a direct impact of the hazard
A_i	asset value
$v_{i,j}$	hazard-specific vulnerability of object i in scenario j (in table A7)

[4] A rear-end collision is only valid in case of a standard situation (no traffic jam). The scenario is not relevant for low intensity hazard events with deposition heights < 0,15 m.

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

C. Risk due to non-operational availability R_D

$$r_{Rb,j} = \left(p_i \times f_{Rb} \times \frac{1}{n_H}\right) \times D_{Rb} \times C_{Rb} \qquad (5A)$$

Table A5. Risk variables and their description for the calculation of R_D. The calculation of the residual variables is according to Table A1.

Variable	Description
$r_{Rb,j}$	risk of a roadblock in scenario j
f_{Rb}	frequency of road blockage
D_{Rb}	duration of road blockage depended on the hazard type
C_{Rb}	costs of a road blockage
n_H	number of hazard areas which are responsible for road closure

Risk variables:

A. Probability of loss – exposure

Table A6. Band width (credible intervals with *l* - lower bound, *m* – most likely value and *u* – upper bound) of the variables within the probabilistic risk analysis for calculating exposure situations.

Variable	Description	Specific-ation	Unit	*l* lower bound	*m* – most likely value	*u* – upper bound	Source
p_{Rb}	probability of a roadblock	not probable	-		0		ASTRA (2012)
		sparse probable		0.05	0.1	0.5	
		probable		0.1	0.5	0.9	
		most likely		0.5	0.9	0.95	
α	reduction factor for p_{RbE}	--	-	0.5	0.75	1	ASTRA (2012)
n_{B99}	number of traffic jams per year	--	n/y	0	1	2	Expert judgement icw. surveyor of highways (Federal State of Salzburg)
D	duration of a traffic jam	--	h	0.083	0.5	2.0	Expert judgement icw. surveyor of highways (Federal State of Salzburg)

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

f_{A10}	frequency of occurrence special situation A10	--	n/y	5	22	30	Statistical evaluation traffic jam database ASFINAG for the year 2015
D_{A10}	duration of special situation A10	--	h	0.5	2.65	5.0[5]	Statistical evaluation traffic jam database ASFINAG for the year 2015
n_{SS}	number of traffic jams in case of a special situation A10	--	n	0	4	11[6]	Statistical evaluation traffic jam database ASFINAG for the year 2015 n > 0.5h
D_{A10}	duration of traffic jam special situation A10	--	h	0.083	1	2	Statistical evaluation traffic jam database ASFINAG for the year 2015
p_{Rc}	Probability of a rear-end collision	improbable	-	0	0.05	0.15	ASTRA (2012)
		medium probable		0.05	0.15	0.25	
		frequent		0.15	0.25	0.35	
ET	event type of rock fall[7]	--	-	1	5	5	ASTRA (2012)

D. Degree of damage – Risk for persons R_P

Table A7. Band width (credible intervals *l* - lower bound, *m* – most likely value and *u* – upper bound) of the variables within the probabilistic risk analysis for calculating R_P.

Variable	Description	Specific-ation	Unit	*l* lower bound	*m* – most likely value	*u* – upper bound	Source
λ_{Rc}	probability of fatality in the case of a rear-end collision	--	-	0	0.0066	0.05	ASTRA (2012)
λ_D	lethality for debris flow	low intensity	-	0			ASTRA (2012) and Bründl (2009)
		medium intensity		0	0.5005	0.7995	
		strong intensity		0.5005	0.7995	1	
λ_F	lethality for dynamic	low intensity	-	0			ASTRA (2012) and Bründl (2009)

[5] Max. value according to traffic jam database from ASFINAG 2015
[6] Traffic jam database from ASFINAG 2015 - traffic jam events > 0.5 h
[7] Event type 1|5|10 equates to single stone| multiple stones | small scale rockslide

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

	flooding	medium intensity		0	0.0025	0.108	
		strong intensity		0.025	0.108	0.20	
λ_R	lethality for rock fall	low intensity	-	0	0.1	0.8	ASTRA (2012) and Bründl (2009)
		medium intensity		0.1	0.8	1	
		strong intensity		0.8	1	1	
λ_A	lethality for avalanche	low intensity	-	0	0.00025	0.1	ASTRA (2012) and Bründl (2009)
		medium intensity		0.0002 5	0.1	0.2	
		strong intensity		0.1	0.2	1	
MDT_{B99}	Average daily traffic B99	--	n	3.000	3.600	7.000	Traffic counting for the year 2016 (Federal State of Salzburg)
MDT_{A10}	average daily traffic A10	--	n	10.000	19.638	62.000	Permanent automatic traffic counting ASFINAG for the year 2016
v	signalized velocity for cars	free land zone	km/h	80	100	120	Expert judgement icw. surveyor of highway (Federal State of Salzburg)
		municipality zone	km/h	45	50	60	
		acceleration / deceleration	km/h	70	80	110	
ρ_{max}	maximum traffic density per lane and kilometer in case of a traffic jam	--	n	120	140	145	ASTRA (2012)
β	mean degree of passengers	--	n	1	1.76	5	ASTRA (2012)
C_P	value (cost) of a person	--	€	3,016,194[8]			BMVIT (2014) for the period 2014-2016

526

[8] The monetary value of person was used as single (point) value as this value is recommended from the Austrian government.

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

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Discussions

E. Extent of damage – Risk for material assets R_A

Table A8. Band width (credible intervals *l* - lower bound, *m* – most likely value and *u* – upper bound) of the variables within the probabilistic risk analysis for calculating R_A.

Variable	Description	Specific-ation	Unit	*l* lower bound	*m* – most likely value	*u* – upper bound	Source
A_R	asset value– construction costs road	--	€/m	800	850	1,000	Statistical data from Federal State of Salzburg
A_B	asset value– construction costs bridges (span with 8-10m)	--	€/m²	1,350	2,200	2,400	Statistical data from Federal State of Salzburg
A_C	asset value– construction costs pipe culverts DN 500-1200	--	k€	52	65	71.5[9]	Statistical data from Federal State of Salzburg
$v_{R,F}$	vulnerability road dynamic flooding	low intensity	-	0	0.05	0.1	ASTRA (2012)
		medium intensity		0.05	0.1	0.45	
		strong intensity		0.1	0.45	0.80	
$v_{B,F}$	vulnerability structures (bridges) dynamic	low intensity	-	0	0.025	0.05	ASTRA (2012) and Bründl (2009)
		medium intensity		0.025	0.05	0.65	
		strong intensity		0.05	0.65	1	
$v_{R,D}$	vulnerability road debris flow	low intensity	-	0	0.05	0.35	ASTRA (2012) and Bründl (2009)
		medium intensity		0.05	0.35	0.65	
		strong intensity		0.35	0.65	1	
$v_{B,D}$	vulnerability structures (bridges, culvert) debris flow	low intensity	-	0	0.025	0.25	ASTRA (2012) and Bründl (2009)
		medium intensity		0.025	0.25	0.95	
		strong intensity		0.25	0.95	1	
$v_{R,A}$	vulnerability road avalanche	low intensity	-	0	0.005	0.1	ASTRA (2012) and Bründl (2009)
		medium intensity		0.005	0.1	0.2	
		strong intensity		0.1	0.2	0.30	

[9] Base value according to the Federal State of Salzburg – min – -20% / max + 10% (right-skewed distribution)

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Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

$v_{B,\mathrm{A}}$	vulnerability structures (bridges, culvert) avalanche	low intensity	-	0	0.005	0.7	ASTRA (2012) and Bründl (2009)
		medium intensity		0.005	0.7	1	
		strong intensity		0.7	1	1	
$v_{R,\mathrm{R}}$	vulnerability road rock fall	low intensity	-	0	0.1	0.5	ASTRA (2012) and Bründl (2009)
		medium intensity		0.1	0.5	1	
		strong intensity		0.5	1	1	
$v_{B,\mathrm{R}}$	vulnerability structures (bridges, culvert) rock fall	low intensity	-	0	0.1	0.5	ASTRA (2012) and Bründl (2009)
		medium intensity		0.1	0.5	1	
		strong intensity		0.5	1	1	

B. Degree of damage – Risk for operational availability R_D

Table A9. Band width (credible intervals *l* - lower bound, *m* – most likely value and *u* – upper bound) of the variables within the probabilistic risk analysis for calculating R_D.

Variable	**Description**	**Specific-ation**	**Unit**	***l* lower bound**	***m* – most likely value**	***u* – upper bound**	**Source**
f_{Rb}	frequency of road blockage	--	n/y	1	2	4	ASTRA (2012) icw. expert judgement
$D_{Rb,A10}$	duration of a precautionary roadblock for avalanche with return interval T_{10}	--	d	0.33	1	2	ASTRA (2012) icw. expert judgement
$D_{Rb,A30}$	duration of a precautionary roadblock for avalanches with return interval T_{30}	--	d	1	2	3	ASTRA (2012) icw. expert judgement
$C_{Rb,W}$	expanses of a roadblock during winter season	--	M€	1.245	1.557	1.868[10]	BMNT (2015)
$C_{Rb,S}$	expanses of a roadblock during summer season	--	k€	200	343.4	500	BMNT (2015)

[10] Range of fluctuation +/- 20%

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Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Discussions

References

Apel, H., Thieken, A. H., Merz, B., Blöschl, G.: Flood risk assessment and associated uncertainty, Nat. Hazards and Earth Syst. Sci. 4, 295–308, https://doi.org/10.5194/nhess-4-295-2004, 2004.

Austrian Standards International: Protection works for torrent control – Terms and their definitions as well as classification, ONR 24800:2009 02 15, Vienna, 2009.

Austrian Standards International: Permanent technical avalanche protection – Terms, definition, static and dynamic load assumptions, ONR 24805:2010 06 01, Vienna, 2010.

Austrian Standards International: Technical protection against rockfall – Terms and definitions, effects of actions, design, monitoring and maintenance, ONR 24810:2017 02 15, Vienna, 2010.

ASTRA: Naturgefahren auf Nationalstraßen: Risikokonzept, Methodik für eine risikobasierende Beurteilung, Prävention und Bewältigung von gravitativen Naturgefahren auf Nationalstraßen, Bundesamt für Straßen ASTRA, Bern, 2012.

Bell, R., Glade, T.: Quantitative risk analysis for landslides – Examples from Bíldudalur, NW-Iceland, Nat. Hazards and Earth Syst. Sci. 4, 117-131, https://doi.org/10.5194/nhess-4-117-2004, 2004.

Benn, J. L.: Landlide events on the West Coast, South Island, 1867-2002, New Zealand Geographer 61, 3-13, https://doi.org/10.1111/j.1745-7939.2005.00001.x, 2005.

BMLFUW: Richtlinie für Gefahrenzonenplanung, 2011.

BMNT: Richtlinien für die Wirtschaftlichkeitsuntersuchung und Priorisierung von Maßnahmen der Wildbach- und Lawinenverbauung (Kosten-Nutzen-Untersuchung), Vienna, available at: https://www.bmnt.gv.at/forst/wildbach-lawinenverbauung/richtliniensammlung/Richtlinien.html, (last access: 01 June 2016), 2015.

BMVIT: Durchschnittliche Unfallkosten Preisstand 2011, Bundesministerium für Verkehr, Innovation und Technologie BMVIT, Vienna, available at: https://www.bmvit.gv.at/verkehr/strasse/sicherheit/strassenverkehrsunfaelle/ukr2012.html. (last access: 01 June 2016), 2014.

Bründl M. (Ed.): Risikokonzept für Naturgefahren – Leitfaden. Nationale Plattform für Naturgefahren PLANAT, Bern, 2009.

Bründl, M., Romang, H. E., Bischof, N., Rheinberger, C. M.: The risk concept and its application in natural hazard risk management in Switzerland, Nat. Hazards Earth Syst. Sci., 9, 801–813, https://doi.org/10.5194/nhess-9-801-2009, 2009.

Bründl, M., Bartelt, P., Schweizer, J., Keiler, M., Glade, T.: Review and future challenges in snow avalanche risk analysis, In: Alcántara-Ayala, I., Goudie, A. S. (Eds.), Geomorphological Hazards and Disaster Prevention, Cambridge University Press 2010, pp 49-61, 2010.

Bründl, M., Ettlin, L., Burkard, A., Oggier, N., Dolf, F. und Gutwein, P.: EconoMe – Wirksamkeit und Wirtschaftlichkeit von Schutzmaßnahmen gegen Naturgefahren, Formelsammlung, 2015.

Bunce, C., Cruden, D., Morgenstern, N.: Assessment of the hazard from rock fall on a highway, Canadian Geotechnical Journal 34, 344-356, https://doi.org/10.1139/t97-009, 1997.

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Ciurean, R. L., Hussin, H., van Westen, C. J., Jaboyedoff, M., Nicolet, P., Chen, L., Frigerio, S., Glade, T.: Multi-scale debris flow vulnerability assessment and direct loss estimation of buildings in the Eastern Italian Alps, Nat. Hazards, 85, 929-957, https://doi.org/10.1007/s11069-016-2612-6, 2017.

Cottin, C., Döhler, S.: Risikoanalyse. Modellierung, Beurteilung und Management von Risiken mit Praxisbeispielen, Studienbücher Wirtschaftsmathematik, 2. Auflage, Springer Spektrum, Wiesbaden, https://doi.org.10.1007/978-3-658-00830-7, 2013.

Dai, E.C., Lee, C.F., Ngai, Y.Y.: Landslide risk assessment and management: an overview, Eng. Geol. 64, 65-87, https://doi.org/10.1016/S0013-7952(01)00093-X, 2002.

Dorren, L. K. A.: Rockyfor3D (V5.1) Transparent description of the complete 3D rockfall model, ecorisQ Paper, https://www.ecorisq.com, 2012.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.: Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning, Eng. Geol. 102 (3-4), 85-98, https://doi.org/10.1016/j.enggeo.2008.03.022, 2008a.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.: Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning – Commentary, Eng. Geol. 102 (3-4), 99-111, https://doi.org/10.1016/j.enggeo.2008.03.014, 2008b.

Ferlisi, S., Cascini, L., Corominas, J., Matano, F.: Rockfall risk assessment to persons travelling in vehicles along a road: the case study of the Amalfi coastal road (southern Italy), Nat. Hazards 62, 691-721, https://doi.org/10.1111/nzg.12170, 2012.

Flow-2D Software: Flow-2D Reference Manual, Nutrioso, 2017.

Fuchs, S., Heiss, K., Hübl, J.: Towards an empirical vulnerability function for use in debris flow risk assessment, Nat. Hazards and Earth Syst. Sci., 7, 495–506, https://doi.org/10.5194/nhess-7-495-2007, 2007.

Fuchs, S.: Susceptibility versus resilience to mountain hazards in Austria – paradigms of vulnerability revisited, Nat. Hazards and Earth Syst. Sci. 9, 337-352, https://doi.org/10.5194/nhess-9-337-2009, 2009.

Fuchs, S., Keiler, M., Sokratov, S., Shnyparkov, A.: Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management, Nat. Hazards 68, 1217-1241, https://doi.org/10.1007/s11069-012-0508-7, 2013.

Fuchs, S., Keiler, M., Zischg, A.: A spatiotemporal multi hazard exposure assessment based on property data, Nat. Hazards and Earth Syst. Sci. 15, 2127-2142, https:/doi.org/ 10.5194/nhess-15-2127-2015, 2015.

Fuchs, S., Keiler, M., Ortlepp, R., Schinke, R., Papathoma-Köhle, M.: Recent advances in vulnerability assessment for the built environment exposed to torrential hazards: Challenges and the way forward, J. Hydrol. 575, 587-595, https://doi.org/10.1016/j.jhydrol.2019.05.067, 2019.

Geoconsult ZT GmbH: Gefahrenanalyse B99, Technischer Bericht Sturzprozesse, Salzburg, 2016.

Grêt-Regamey, A., Straub, D.: Spatially explicit avalanche risk assessment linking Bayesian networks to a GIS, Nat. Hazards Earth Syst. Sci., 6, 911–926, https://doi.org/10.5194/nhess-6-911-2006, 2006.

Guikema, S., McLay, L., Lambert, J. H.: Infrastructure Systems, Risk Analysis, and Resilience - Research Gaps and Opportunities, Risk Analysis, 35 (4), 560-561, https://doi.org/10.1111/risa.12416, 2015.

Hendrikx, J., Owens, I.: Modified avalanche risk equations to account for waiting traffic on avalanche prone roads, Cold Reg. Sci. and Technol., 51, 214-218, https://doi.org/10.1016/j.coldregions.2007.04.011, 2008.

Hood K.: The science of value: Economic expertise and the valuation of human life in US federal regulatory agencies, Soc. Stud. Sci. 47 (4), 441-465. https://doi.org/10.1177/0306312717693465, 2017.

Hungr, O., Beckie, R.: Assessment of the hazard from rock fall on a highway: Discussion, Canadian Geotechnical Journal 35, 409, https://doi.org/10.1139/t98-002, 1998.

International Organisation for Standardisation: Risk management – Principles and guidelines on implementation, ISO 31000, Geneva, 2009.

IUGS Committee on Risk Assessment: Quantitative risk assessment for slopes and landslides – The state of the art, In: Cruden, E.M., Fell, R. (Eds.), Proceedings of the International Workshop of Landslide Risk Assessment, Honolulu, pp 3-12, 1997.

Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T.: Challenges of analyzing multi-hazard risk: a review, Nat. Hazards 64, 1925-1958, https://doi.org/10.1007/s11069-012-0294-2, 2012a.

Kappes, M.S., Gruber, K., Frigerio, S., Bell, R., Keiler, M., Glade, T.: The MultiRISK platform: The technical concept and application of a regional-scale multihazard exposure analysis tool, Geomorphology 151-152, 139-155, https://doi.org/10.1016/j.geomorph.2012.01.024, 2012b.

Kirchsteiger, C.: On the use of probabilistic and deterministic methods in risk analysis, Journal of Loss Prevention in the Process Industries, 12, 399–419, https://doi.org/10.1016/S0950-4230(99)00012-1, 1999.

Kristensen, K., Harbitz, C., Harbitz, A.: Road traffic and avalanches - methods for risk evaluation and risk management, Surveys in Geophysics 24, 603-616, https://doi.org/10.1023/B:GEOP.0000006085.10702.cf, 2003.

Margreth, S., Stoffel, L., Wilhelm, C.: Winter opening of high alpine pass roads - analysis and case studies from the Swiss Alps, Cold Reg. Sci. and Technol. 37, 467-482, https://doi.org/10.1016/S0165-232X(03)00085-5, 2003.

Markantonis, V., Meyer, V., Schwarze, R.: Valuating the intangible effects of natural hazards – review and analysis of the costing methods, Nat. Hazards Earth Syst. Sci., 12, 1633–1640, https://doi.org/ 10.5194/nhess-12-1633-2012, 2012.

Merz, B., Kreibich, H., Thieken, A. H., Schmidke, R.: Estimation uncertainty of direct monetary flood damage to buildings, Nat. Hazards Earth Syst. Sci., 4, 153–163, https://doi.org/10.5194/nhess-4-153-2004, 2004.

Merz, B., Elmer, F., Thieken, A. H.: Significance of “high probability/low damage” versus “low probability/high damage” flood events, Nat. Hazards Earth Syst. Sci., 9, 1033–1046, https://doi.org/10.5194/nhess-9-1033-2009, 2009.

Merz, B., Thieken, A. H.: Flood risk curves and associated uncertainty bounds, Nat. Hazards, 51, 437–458, https://doi.org/10.1007/s11069-009-9452-6, 2009.

Merz, B., Thieken, A. H.: Separating natural and epistemic uncertainty in flood frequency analysis, Journal of Hydrology, 309, 114–132, https://doi.org/10.1016/j.jhydrol.2004.11.015, 2005.

Merz, B., Kreibich, H., Schwarze, R., Thieken, A. H.: Assessment of economic flood damage, Nat. Hazards Earth Syst. Sci., 10, 1697–1724, https://doi.org/10.5194/nhess-10-1697-2010, 2010.

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E.,

https://doi.org/10.5194/nhess-2020-66
Preprint. Discussion started: 10 March 2020

Natural Hazards and Earth System Sciences
Discussions

Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A. A., Viavattene, C.: Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps, Nat. Hazards Earth Syst. Sci., 13, 1351-1373, https://doi.org/ 10.5194/nhess-13-1351-2013, 2013.

Michoud, C., Derron, M., Horton, P.: Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps, Nat. Hazards and Earth Syst. Sci. 12, 615-629, https://doi.org/10.5194/nhess-12-615-2012, 2012.

Oberndorfer, S., Fuchs, S., Rickenmann, D., Andrecs, P.: Vulnerabilitätsanalyse und monetäre Schadensbewertung von Wildbachereignissen in Österreich, Bundesforschung- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft, BFW-Berichte 139/2007, Wien, 2007.

Oberndorfer, S.: Technischer Bericht – Gefahrenanalyse Wildbach- & Lawinengefahren B99 Katschberg Straße, Radstadt – Obertauern – Mauterndorf, km 24,70 – km 62,60, Leogang, 2016.

Republik Österreich: Forstgesetz 1975, BGBl 440/1975, Republik Österreich, Vienna, 1975.

Republik Österreich: Verordnung des Bundesministeriums für Land- und Forstwirtschaft vom 30. Juli1976 über die Gefahrenzonenpläne, BGBl 436/1975, Republik Österreich, Vienna, 1976.

Roberds, W.: Estimating temporal and spatial variability and vulnerability, In: Hungr, O., Fell, R., Couture, R. and Eberhardt, E., (Eds.), Landslide risk management, Taylor and Francis Group, London, pp 129-157, 2005.

Schaerer, P.: The avalanche-hazard index, Annals of Glaciology 13, 241-247, 1989.

Papathoma-Köhle, M., Kappes, M., Keiler, M., Glade, T.: Physical vulnerability assessment for alpine hazards: state of the art and future needs, Nat. Hazards 58, 645-680, https://doi.org/ 10.1007/s11069-010-9632-4, 2011.

Papathoma-Köhle, M., Gems, B., Sturm, M., Fuchs, S.: Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flow, Earth-Sci. Rev. 171, 272-288, https://doi.org/10.1016/j.earscirev.2017.06.007, 2017.

RiskConsult GmbH: RIAAT Risk Administration and Analysis Tools, Manual, Version 28-F01, Innsbruck, 2015.

Sander, P.: Probabilistische Risiko-Analyse für Bauprojekte. Entwicklung eines branchenorientierten softwaregestützten Risiko-Analyse-Systems, University of Innsbruck, ISBN 978-3-902811-75-2, 2012.

Sander, P., Reilly, J.J. & Moergeli, A.: Quantitative Risk Analysis – Fallacy of the Single Number, ITA World Tunnel Congress, 2015, Dubrovnik, 2015.

Sampl, P.: SamosAT – Beschreibung der Modelltheorie und Numerik, AVL List GmbH, Graz, 2007.

Schlögl, M., Richter, G., Avian, M., Thaler, T., Heiss, G., Lenz, G., Fuchs, S.: On the nexus between landslide susceptibility and transport infrastructure – an agent-based approach, Nat. Hazards and Earth Syst. Sci. 19 (1), 201-219, https://doi.org/10.5194/nhess-19-201-2019, 2019.

Straub, D., Grêt-Regamey, A.: A Bayesian probabilistic framework for avalanche modelling based on observation, Cold Regions Science and Technology, 46, 192–203, https://doi.org/10.1007/978-3-319-09054-2_90, 2006.

Špačková, O., Rimböck, A., Straub, D.: Risk management in Bavarian Alpine torrents: a framework for flood risk quantification accounting for subscenarios, in: Proc. of the IAEG Congress 2014, IAEG XII congress, Torino, Italy, 2014.

Špačková, O.: RAT Risk Analysis Tool. Risk assessment and cost benefit analysis of risk mitigation strategies – Methodology, Engineering Risk Analysis Group, Technical University of Munich, 2016.

Tecklenburg, T.: Risikomanagement bei der Akquisition von Großprojekten in der Bauwirtschaft, Dissertation, TU Braunschweig, Schüling Verlag, Münster, 2003.

UNDRO: Natural disasters and vulnerability analysis, Department of Humanitarian Affairs/United Nations Disaster Relief Office, Geneva, 1979.

UNISDR: Living with risk: A global review of disaster reduction initiatives, United Nations Publication, Geneva, 2004.

Unterrader, S., Almond, P., Fuchs, S.: Rockfall in the Port Hills of Christchurch: Seismic and non-seismic fatality risk on roads. New Zealand Geographer 74 (1), 3-14, https://doi.org/10.1111/nzg.12170, 2018.

Varnes, D.: Landslide hazard zonation: a review of principles and practice. UNESCO, Paris, 1984.

Wastl, M., Stötter, J., Kleindienst, H.: Avalanche risk assessment for mountain roads: a case study from Iceland, Nat. Hazards 56, 465-480, https://doi.org/10.1007/s11069-010-9703-6, 2011.

Winter, B., Schneeberger, K., Huttenlau, M., Stötter, J.: Sources of uncertainty in a probabilistic flood risk model, Nat. Hazards 91, 431–446, https://doi.org/10.1007/s11069-017-3135-5, 2018.

Zischg, A., Fuchs, S., Keiler, M., Meissl, G.: Modelling the system behaviour of wet snow avalanches using an expert system approach for risk management on high alpine traffic roads, Nat. Hazards and Earth Syst. Sci. 5, 821-832, https://doi.org/10.5194/nhess-5-821-2005, 2005.