Quantitative assessment of landslide risk: how well are we doing?

Jordi Corominas

Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain

jordi.corominas@upc.edu

Abstract

This paper presents an overview of the methods for the quantitative assessment of landslide risk, based largely in the author's experience. It first revisits some basic landslide hazard and risk concepts from the quantitative point of view. Special emphasis is placed on the spatially distributed nature of the risk components. The issues addressed focus on the outputs and quality of landslide susceptibility analysis and on the steps to evaluate hazard. The combined effect of both climate and anthropogenic changes, though complex and geographically dissimilar, can no longer be ignored. Empirical evidence suggests the existence of a maximum finite regional landslide magnitude although additional research is needed to identify the factors controlling it at a regional level. The quantitative risk analysis facilitates the evaluation of the performance of each risk component, its relevance in the final result, and provides criteria for risk acceptability assessment and risk mitigation plans. Risk may be quantified by the aggregation of scenarios of different probability of occurrence. Nevertheless, performing complete multi-hazard risk analysis is more demanding. It requires the use of a common metrics and the appropriate identification of scenarios in which the interaction between potential hazardous processes may occur.

1. INTRODUCTION

Landslides cause a high toll of deaths and damage to society (Petley, 2012). However, landslide occurrence is difficult to forecast. Forecasting implies the specification of the time, location, and magnitude of a future event within stated limits. It must be accurate and reliable, without false alarms or missing events. In spite of recent advances in monitoring and some successful experiences (i.e. Loëw, 2017), we are not yet ready for a trustworthy forecasting of the landslide occurrence. This task requires the understanding of the, often complex, mechanisms driving the instability (Crosta et al. 2013) and it is particularly challenging when considering landslide occurrence at a regional scale (Canli et al. 2018; Segoni et al. 2018). As alternative, we may anticipate future scenarios of risk and evaluate their consequences.

Risk assessment is a procedure designed to support the management of the landslide threat. Its ultimate goal is deciding whether the risk level is acceptable or not (Ho et al., 2000), and provide criteria to implement strategies to avoid or at least, minimize the consequences of future events. Evaluation of landslide hazard is still challenging. Despite the experience accumulated over more than 40 years, there are no widely accepted standards for the assessment and mapping of landslide hazard. The diversity of approaches developed makes it difficult to compare the results and implement the advances efficiently. Standards are necessary to help local authorities, who often have to manage the landside threat with limited resources.

There is an extensive scientific literature describing methods for landslide susceptibility and hazard assessment (e.g. Chacón et al. 2006; Reichenbach et al. 2018 and references therein). Some methodologies allow quantifying risk directly, but most do not. It is therefore necessary to select the most suitable approach, which must be tailored to the object of the analysis. All approaches have benefited from the development of new data acquisition and treatment techniques (Van Westen et al. 2008). This includes data capture tools such as hyper-spectral imagery, digital photogrammetry, radar interferometry, lidar (Jaboyedoff et al. 2012; Scaioni et al. 2014; Casagli et al. 2017) as well as both statistical and deterministic models integrated in GIS platforms (Baum et al. 2005; Godt et al. 2008).

The quantitative analysis of risk (QRA) is a formal and structured framework to calculate the probability and consequences of hazard scenarios (Ho, 2004; Fell et al. 2008). It is recommended because the procedures can be replicated while gaps in input data and weaknesses of the analysis can be identified. QRA is useful for decision-makers because risk from different locations can be directly compared and cost–benefit analysis is facilitated. It helps governmental agencies in making rational decisions on the allocation of resources, and prioritize risk mitigation actions. Last but not least, risk quantification increases the awareness of the existing risk levels by defining risk acceptability criteria (Corominas et al. 2014b). However, it must be warned that the reliability of the quantitative analysis is strongly dependent on the quality of the data used and on the strength of the methods. QRA cannot replace missing information or amend incorrect assumptions.

The work carried out during the last few decades on landslide hazard and risk analysis cannot be summarized in this contribution. The reader will find extensive reviews in Dai et al. (2002), Glade et al. (2005), AGS (2007), Fell et al. (2005, 2008), Lee and Jones (2013), or Corominas et al. (2014b). The aim here is to discuss some critical issues and challenges in landslide risk research. A brief description of concepts related to risk is included. A discussion follows on the steps, the diversity of approaches to assess risk, and on the challenges we face in the future. This review builds upon previous work published by the author on landslide susceptibility, hazard and risk analysis as well as on the experience gained in its application to land use planning and civil engineering works.

In the text, we use the nomenclature for landslides collected by Hungr et al. (2014), which includes fall, slide, debris flow, and slope deformation. Unless otherwise specified, the term landslide will we used generically to refer any type of slope failure. The state of activity and type of movement follows nomenclature of WP/WLI, 1993).

2 LANDSLIDE HAZARD AND RISK CONCEPTS

The study of landslides has some specificities. Unlike other natural hazards such as sea storms, forest fires, or hurricanes, which are not site-discriminant, landslides only occur in discrete susceptible portions of land. Their analysis requires the application of the earth science technology (Hansen, 1984). Other natural hazards are characterized by well-defined sources (e.g. volcanos), or potentially affected areas (e.g. floods). The occurrence of landslides usually involves multiple scattered sources throughout the territory, small to large magnitude events, different propagation mechanisms, and affected areas.

A number institutions and scientific committees have proposed guidelines for the preparation of landslide hazard maps and the assessment of risk (e.g. Lateltin, 1997; GEO 2006; AGS 2007; Fell et al. 2008a, 2008b; Jackson et al. 2012). Their common goal is the use of a unified terminology, to pinpoint the data needed to prepare the maps, and provide guidance to the practitioners in their approaches. Stressing on terminology in the documents may seem like an academic debate but terms have obvious contractual implications and their inappropriate use can generate misunderstanding. A selection of landslide risk-related terms as used in this text, are included in Table 1.

The term "landslide" generally designates both the process and the event that results in a displaced mass or debris. Here, "landslide susceptibility" and "landslide hazard" refer to the process only. The most commonly used definition of landslide risk was introduced by Varnes (1984), and formally defined by Einstein (1988). Risk is a measure of the probability and severity of an adverse effect (the landslide) to health, property or the environment. Mathematically it is defined as the probability of occurrence of the landslide event multiplied by the consequences.

The assessment of risk encompasses the identification and characterization of the hazard with reference to a time frame, the exposure of the elements at risk, their vulnerability, and the estimation of the consequences. All these components are defined by both spatial and non-spatial attributes. The characterization of the landslide hazard implies determining the probability of occurrence of a given magnitude event, the distance traveled and the intensity along the path. The latter expresses the severity of the hazard. As different types of landslides and triggering factors may occur within the study area, the analysis of landslide risk often requires a multi-hazard approach. The elements at risk have spatial and non-spatial attributes since they can be either static or moving.

Once the landslide event has occurred, the exposure and vulnerability of the elements at risk determine the consequences. The exposure indicates whether or not the element at risk is actually located in the path of the landslide. Vulnerability is the measure of the degree of loss to a given element or set of exposed elements in case of being reached by the landslide. Losses may be described with different metrics according to the goal of the assessment and the nature of the exposed elements. They can be either a conditional probability of loss, loss exceedance probability, or cumulative losses within a period of time. For further details on hazard and risk analysis the reader is referred to textbooks such as Glade et al. (2005), or Lee and Jones (2013).

It is interesting to note that although hazard is defined as the probability of a future landslide event of a given magnitude (Varnes, 1984), it is the consequences that determine the hazard level. This is illustrated in Table 2, in which hazard levels are ranked based on the probability of the expected consequences (risk) and not directly by the magnitude of the potential event.

Table 2. Transposition of hazard levels for land use planning. Each level has associated pairs of frequency-intensity values (modified from Lateltin et al. 2005)

High hazard	People at risk both inside and outside of buildings. A rapid destruction of buildings is possible
	Events occurring with a lower intensity, but with a higher probability of occurrence. People are mainly at risk outside the buildings, or buildings can no longer house people
Moderate hazard	People at risk or injury outside of buildings. Risk considerably lower inside of buildings.
	Damage to buildings should be expected but not a rapid destruction, as long as the construction type has been adapted to the present conditions
Low hazard	People at low risk or injury. Slight damage to buildings is possible.
	Damage might occur inside the building but not at the structure
Residual hazard	Very low probability of a high-intensity event
No danger	or negligible hazard, according to currently available information

The magnitude refers to the size of the landslide that is quantitatively described by its volume. It should not be mistaken with "landslide-event magnitude" (Malamud et al. 2004), that designates the multiple occurrence of slope failures. In this paper, the latter is termed as "landsliding event".

Table 1. Selected landslide susceptibility, hazard and risk-related terms (modified from TC32, 2004; Corominas et al. 2014a)

Term	Definition	Comment
Consequence	The outcome or result of a hazard being realized.	
Danger (threat)	The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics	It can be an existing one (i.e. a creeping slope) or a potential one
Event	The realization of the hazard	Slope failure, reactivation or surge
Exposure	For a given element, the probability of being located in the landslide path at the time of its occurrence	Spatio-temporal probability of the element at risk
Hazard	A condition with the potential of causing an undesirable consequence. Matematically, the probability of a particular threat occurring in an area within a defined time period	It is expressed by pairs of probability of occurrence (or frequency) and intensity
Hazard Assessment	The use of available information to estimate the zones where landslides of a particular type, volume, velocity and runout may occur within a given period of time	The slope failure (or the reactivation) is the event
Hazard Level	A measure of the intensity and probability of occurrence of a hazardous event.	
Hazard Map	A map in which different areas are related to particular landslide hazard level	
Hazard Matrix	Tool for ranking and displaying hazard by defining ranges for landslide intensity and likelihood (probability)	
Hazard zoning	Mapping of an area in which particular zones correspond to different hazard levels	Often used as a basis for land use planning (see hazard map)
Landslide Intensity	A set of spatially distributed parameters related to the destructive potential of a landslide	It expresses the severity of the hazard
Landslide magnitude	The measure of the landslide size	It may be quantitatively described by its volume
Multi-hazard Analysis	Analysis of all possible and relevant potentially hazardous events, and their interactions, in a given area and within a defined time period	
Scenario	The realization of an event (or a sequence of events) having a given probability of occurrence	
Susceptibility	The assessment of the volume (or area) and spatial distribution of landslides, which exist or potentially may occur in an area.	Measure of the propensity of certain locations to initiate landslides of a given type (Hungr, 2016)
Vulnerability	The degree of loss of a given element or set of elements exposed to a landslide of a given intensity.	interaction between intensity and the elements at risk, can be synthesized as fragility curves
Zoning	The division of land into homogeneous areas or domains and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk.	It does not necessarily implies legal restriction or regulation by zoning ordinances or laws

The magnitude per se does not render the potential for damage. A large creeping landslide with displacements of mm/yr may be less damaging than a small-size debris flow (Corominas et al. 2014b). The parameter expressing the destructive potential of landslides is the intensity. Hungr (1997) characterized landslide intensity with descriptors such as maximum velocity, thickness of flow or deposits, potential impact forces, or differential displacement. Intensity is not an intrinsic property of a landslide. It is a spatially distributed function (Figure 1) and, for a fixed magnitude, it may take different values along the path. Intensity has to be calculated either empirically, analytically, or modelled considering the landslide mechanism, volume, material properties, and local slope conditions (Hungr et al. 2005).

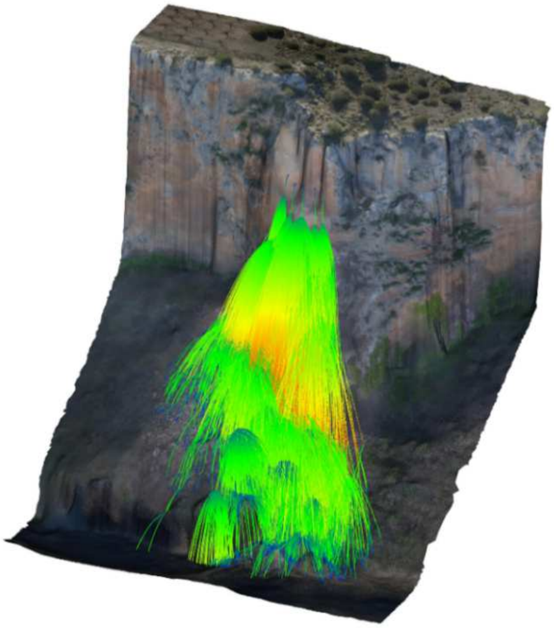


Figure 1. Spatial distribution of rockfall fragments' velocities. The velocity increases from blue to green, yellow, orange and red.

The implication of the spatial distribution of the intensity is that the evaluation of risk must be spatially explicit. Otherwise, the impact probability, impact energy, and vulnerability cannot be determined. In fact, all the elements involved in the analysis of risk own distributed attributes: the landslide source, the travel distance, the landslide intensity, the exposure and the vulnerability of the elements at risk.

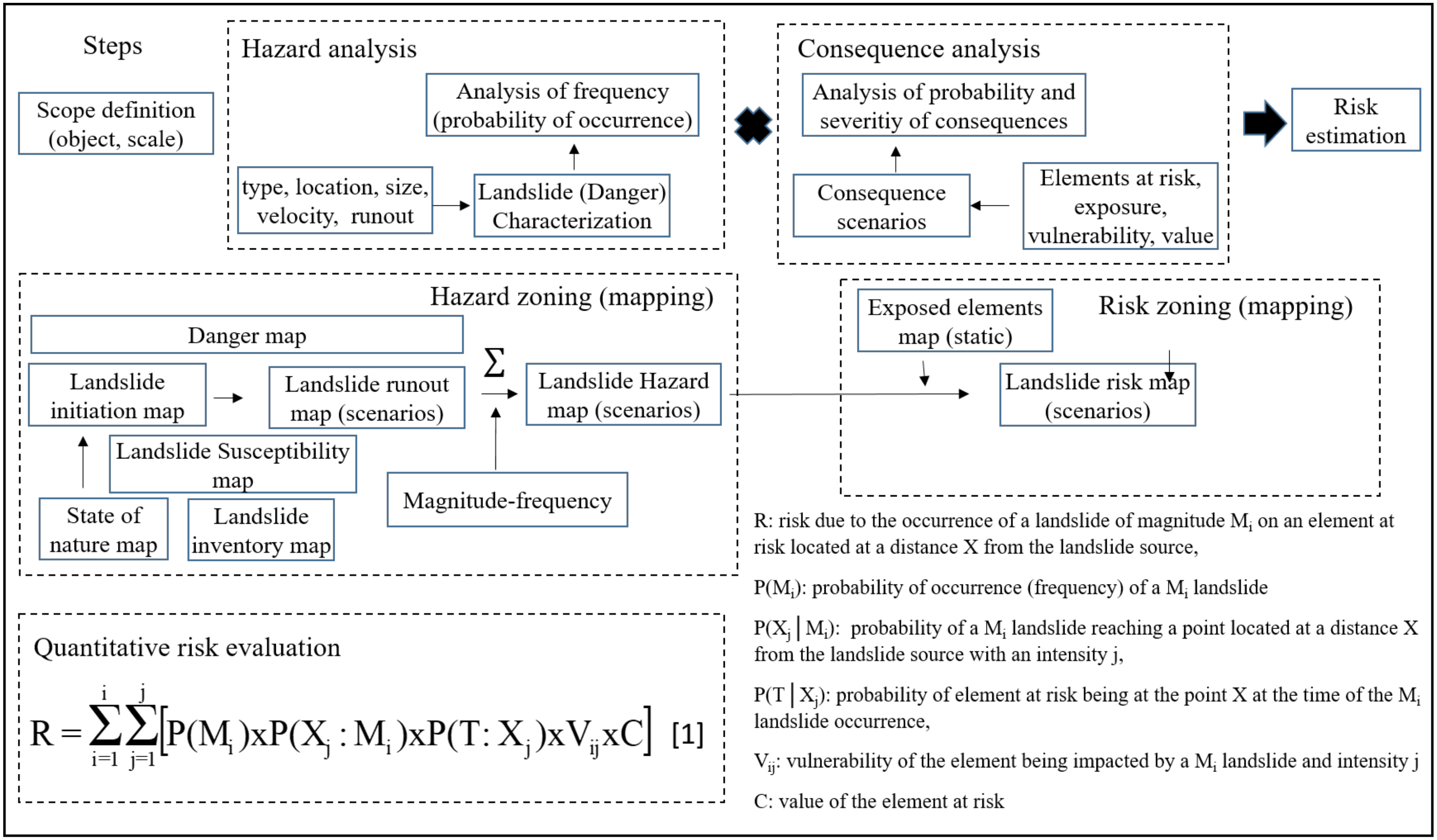
The analysis of risk generally implies the disaggregation into its fundamental parts. It contains the following steps: definition of the scope (object of the analysis, scale, nature of the end product); hazard evaluation, which includes the characterization of the threat (type of existing or potential landslide, location and volume, anticipated travel distance and intensity); its probability of occurrence (or frequency); and the evaluation of the consequences (considering the exposed elements, their vulnerability and estimation of expected damages). Usually, different scenarios have to be considered because potential landslides of different types and magnitude occur with different probabilities of occurrence, travel distances, intensities, and consequences. The assessment of risk consists of comparing the value of risk, as determined from the risk analysis, against risk acceptance criteria to decide whether the existing risk is acceptable or not.

It is recommended to define the scope of the risk analysis from the very beginning to ensure that scale, input data, and all relevant issues are taken into account (Fell et al. 2008). The object of analysis (whether point like, linear or areal) will determine the risk metrics, the hazard model, and the methods to be used. Figure 2 presents the framework for the quantitative analysis of landslide risk. The outputs of the analysis can be presented in the form of a set of maps, or risk values. The steps of the framework may be displayed with maps that corresponds to each of the factors of the risk equation in Figure 2.

3 LANDSLIDE HAZARD AND RISK MAPPING

Maps are the most efficient way to show the spatial attributes of landslides. Irrespective of the scale of work, the assessment of hazard must specify the time frame for the occurrence of all potential landslide types and intensities. This is the most difficult part of the assessment because: (a) different landslide types usually occur with different timespan; (b) there are locations that may be affected by landslides originating from different sources; (c) frequency of landslides varies with the distance from the source (Figure 3). To display all these features, maps must be spatially explicit.

Einstein (1988) proposed the following sequence of landslide hazard and risk maps: (1) state of nature maps, that present the basic information describing topography, geology, hydrology, geotechnical properties, land use and other predisposing factors; (2) danger maps which display the potential and existing landslides, also the potentially affected



$$R=\sum_{i=1}^{i}\sum_{j=1}^{j}\left[P(M_i)xP(X_j:M_i)xP(T:X_j)xV_{ij}xC\right] \quad [1]$$

R: risk due to the occurrence of a landslide of magnitude M_i on an element at risk located at a distance X from the landslide source,

$P(M_i)$: probability of occurrence (frequency) of a M_i landslide

$P(X_j|M_i)$: probability of a M_i landslide reaching a point located at a distance X from the landslide source with an intensity j,

$P(T|X_j)$: probability of element at risk being at the point X at the time of the M_i landslide occurrence,

V_{ij}: vulnerability of the element being impacted by a M_i landslide and intensity j

C: value of the element at risk

Figure 2. Framework for the quantitative analysis of landslide risk

zones such as runout zones and velocity; (3) hazard maps is which the danger (potential event) and its probability of occurrence are combined; (4) risk maps where hazard and its potential consequences are presented. In practice, several risk maps are necessary in the same area.

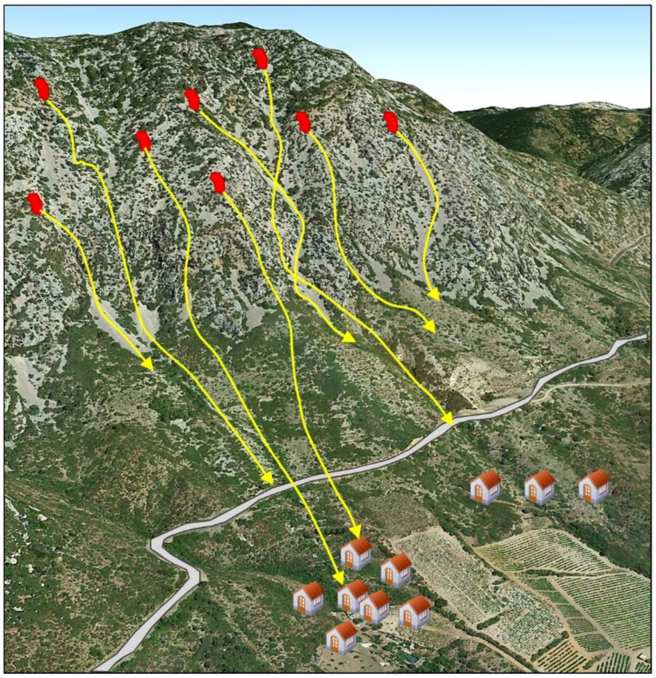


Figure 3. The slope in the figure has experienced several landslide events over a given period of time. In the event that the object of the risk analysis be the entire slope, the road, or the village, note that the frequency recorded in each one is different.

3.1 Landslide susceptibility maps

In the analysis of landslide hazard, Varnes (1988) distinguished between: (a) the inherent conditions of the slopes that predispose them to landsliding without actually initiating it; and (b) the factors that produce changes in the slope, usually transient, that lead to failure (triggering factors). The propensity of an area to undergo landsliding is the landslide susceptibility (LS) (Brabb, 1984; Hansen, 1984). The landslide susceptibility map is a synthetic document that depicts areas likely to have landslides in the future by correlating some of the principal factors that contribute to failure with the past distribution of landslides (Brabb, 1988, Hansen, 1984). First landslide susceptibility (LS) maps were variants of geomorphological maps in which the expert identified active and dormant landslides and evaluated the potential for reactivation or further instability considering heuristic criteria (e.g. Humbert, 1976). The quality of these maps relied on the criterion and experience of the expert. More elaborated maps were those displaying the relative slope stability, in which landslide density is associated to prominent predisposing parameters, such as lithology and slope gradient (Brabb et al. 1972; Nilsen et al. 1979). The basic assumption is that terrain units having similar predisposing factors than those that failed in the past are likely to fail in the future. Extensive reviews of the methods used to prepare landslide susceptibility maps are found in Carrara et al. (1999), Guzzetti et al. (1999), Chacón et al. (2006), van Westen et al. 2008, Reichenbach et al (2018), and several others.

The preparation of LS maps normally requires a complete inventory of landslides, whose spatial distribution is analysed versus a set of independent topographical and geoenvironmental variables (e.g. slope angle, lithology, and land use). The relation is established heuristically, statistically, or deterministically with slope stability models. More recently, soft computing methods based on machine learning algorithms and hybrid methods have appeared (Chen et al. 2018). The analysis is performed on a variety of terrain units such as pixels, grids, slope units, unique condition units, which are eventually ranked according to their propensity to failure. The results are presented in the form of either relative or quantitative estimates. In the quantitative approach, susceptibility is typically given as probability in a continuous scale of the spatial occurrence of slope failures (Chung and Fabbri, 2003).

The ultimate goal of LS maps is the evaluation of hazard. LS maps are considered the initial step of the hazard analysis but they can also be a product in themselves (Crozier and Glade, 2005; Greiving et al, 2014) with direct application for land use planning purposes. It is therefore fundamental check and validate LS maps. The applicability of LS maps relies on their quality and reliability. It is not acceptable develop areas threatened by landslides but overestimating hazard should be avoided as much as possible. A terrain which is classified as stable can be used without restrictions, keeping its economic value, whereas unstable terrain may loss its value as development and activities are often restricted. Misclassification has therefore economic and social consequences.

Several studies reveal biases and errors that affect the accuracy and reliability of LS models. Errors may originate in the landslide inventories (Galli et al. 2008; Sterger et al. 2016; Marc and Hovius, 2015), the selection of conditioning factors (Constanzo et al. 2012; Catani et al. 2013; Jebur et al. 2014;), sampling strategy (Baeza et al. 2010; Petschko et al. 2014), due to the spatial resolution of the DEM (Crosta and Agliardi, 2004; Schögel et al. 2018; Žabota et al. 2019), or in the selected model (Yilmaz, 2009; Sciarra et al. 2017).

Guzzetti et al. (2006) and Frattini et al. (2010) presented a set of procedures to test the quality and performance of the LS models. A complete validation analysis should address the following issues: the robustness or sensitivity of the model to changes in the input data; the degree of fit and the predictive skill by means of contingency tables and model performance plots; and determine the errors or uncertainty affecting the reliability of the probabilistic estimate of each mapping unit. Ideally, the model is prepared using a training set of landslides that occurred in a period and validated with landslides that occurred in a different period (Irigaray et al. 1999; Remondo et al. 2003; Zêrere et al. 2004). Validation can be also carried out using a multi-temporal landslide inventory which is split into two subsets, one to construct the model and the other to verify its predictive performance (Chung and Fabbri 2003; Von Ruette et al. 2011). The latter approach is less recommended as it may lead to overestimation of the predictive capability of the map (Brenning, 2005; Guzzetti et al. 2006).

A review of the LS literature indicates the most prevalent validation procedures for assessing the quality of susceptibility models rely on the indexes derived from contingency tables (i.e. sensitivity and specificity), the performance and prediction rate curves (Chung and Fabbri, 1999, 2003), and the area under the curve (AUC) in receiver operating characteristics plots (Fawcett, 2006). Typically, the model with higher AUC is deemed as the most appropriate one and threshold values are proposed with the support of optimization procedures. For AUC values > 80%, the classifier is considered very satisfactory and >90% indicates a highly accurate model (Swets 1988). However, a number of subjects are hidden behind AUC plots. Thus, LS models with similar performance rate may show low spatial agreement between susceptibility classes and, consequently, may not have the same meaning in terms of predicted results (Sterlacchini et al. 2011). On the other hand, misclassification is a very important piece of information for the LS quality assessment (Beguería, 2006). The applicability of the LS maps for land use planning and their reliability depend on the absence of "missing events" and "false alarms". In that respect, the latter are less conflictive than the former. Cells predicted as to fail that did not (false alarm) could fail in future landsliding events. On the contrary, cells classified as to remain stable but that really fail (missing events) are relevant when they occur in low susceptibility classes.

In the literature, many LS models that are evaluated as satisfactory, show landslides spreading across all susceptibility classes, although with different probability or density. As the validation curves and indices evaluate the overall performance of the LS model and are not spatially explicit, the interpretation is not simple. The results of the LS analysis could be argued if misclassification affects low LS classes. Misclassification may be visualized with plots of percentage of area, ranked from most to least susceptible (x-axis), against the cumulative number of landslides (y-axis) (Chung and Fabbri, 2003; Remondo et al. 2003). Ideally, low LS classes should be free of landslides.

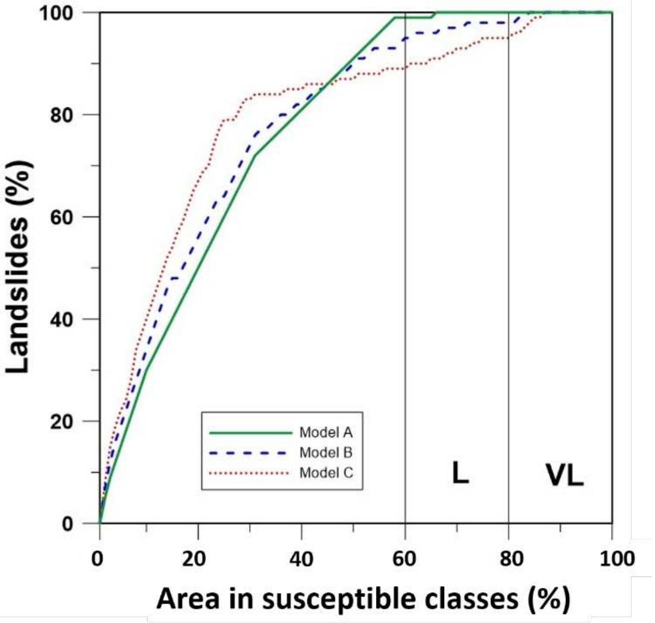


Figure 4. Synthetic case. Cumulative percentage of landslides and cumulative percentage of study area ranked from highest to lowest susceptibility. L and VL mean low and very low susceptibility, respectively.

Figure 4 is a synthetic example of the performance of three LS models. In the example, a cut-off value of P<0.45 is stablished for stable cells, while the AUC for models A, B and C is respectively, 0.772, 0.780 and 0.794. Based on the AUC, model C seems outperform over the other models. However, the distribution of landslides per susceptibility classes indicates that the percentage of missing events (unexpected landslides) for the three models in the two lowest susceptible classes (P<0.4) is 1, 5, and 11%, respectively. The fact that none of the LS classes are potentially free of landslides in the study area may generate uncertainty to decision makers and lack of confidence on the LS analysis.

The question that emerges is what the rate of landslide misclassification can be for an acceptable risk level. Chung and Fabbri (2003) proposed an effectiveness ratio defined as the proportion of landslide area (AL) over the proportion of the susceptibility class (AS) in the study area. They estimated that a ratio of less than 0.1 for units classified as stable areas is significantly effective. For instance, 10, 2 and 1% of landslide area occurring in a low susceptibility class representing 20% of the study area gives a ratio of effectiveness of 0.5, 0.1 and 0.05, respectively. These values may be hard to match when working in complex areas with considerable geomorphological variability (Guzzetti et al. 2006).

The real impact of the landslide misclassification may be evaluated by quantifying the consequences. The probability of landslides affecting a built pixel (terrain unit) in the synthetic example of Figure 4 is calculated next. The scenario evaluated is a landsliding event of a 20-yr return period (0.05 annual probability) that generates slope failures affecting 5% of the study area (Table 3). Each of the two lowest susceptibility classes cover 20% of the study area. Prediction rate curves generated with the three susceptibility models (A, B, C) yield 1, 3, and 6% and 0, 2 and 5% of the landslides located in the low and very low susceptibility classes, respectively. The probability of landslides affecting a built cell (pixel) is calculated with the following expression (Chung, 2006):

$$P_b = 1 - [1 - P_c]^{\frac{n_l}{n_c}k} \qquad (2)$$

Where

P_b is the probability that a landslide affects a built cell

P_c is the portion (probability) of the susceptibility class in the prediction rate curve

n_l the number of pixels in the susceptibility class expected as future landslides

n_c the number of pixels in the susceptibility class

k the number of pixels in the susceptibility class that have been built

One may expect that lowest landslide susceptibility classes will concentrate most of the development in the area. The simulation consider three scenarios with 5, 10, and 20% of the area of the low ($0.2 \leq P < 0.4$) and very low ($P < 0.2$) susceptibility classes being developed. The results are shown in Table 3. It illustrates that despite landslide density in the two lowest susceptibility classes is small, the consequences (landslides affecting a built cell) largely depends on the exposure. Thus, for a 20% of development in the low LS class, the probability that a built cell be affected by landslides is $6x10^{-2}$ for model C and 10^{-2} for model A. These values could be unacceptable for high-intensity (or large magnitude) landslides with the capacity to heavily damage or destroy buildings. Therefore, considerable caution should be exercised before using LS for land used planning, since a small landslide density in the low susceptibility classes cannot always guarantee acceptable levels of risk. Note that in the example of Table 3, runout is not considered. In the event that landslides move far away from the source, hazard may increase significantly.

Table 3. Probability of a landslide affecting a built cell (Pbc) of low and very low susceptibility classes of models A, B, and C (figure 4) and its annual probability (Pabc). All scenarios refer to a 20yr return period landsliding event affecting 5% of the study area. Built area ranges between 5 and 20%. Pls: probability of landslides in the susceptibility class.

	Model	Pls	% cells built	Pbc	Pabc
Low ($0.2 \leq P < 0.4$)	A	0.01	5	0,003	$1.3x10^{-4}$
			10	0,005	$2.5x10^{-4}$
			20	0,010	$5.0x10^{-4}$
	B	0.03	5	0,008	$3.8x10^{-4}$
			10	0,015	$7.6x10^{-4}$
			20	0,031	$1.5x10^{-3}$
	C	0.06	5	0,015	$7.7x10^{-4}$
			10	0,030	$1.5x10^{-3}$
			20	0,060	$3.0x10^{-3}$
Very low ($P<0.2$)	A	0	5	0	0
			10	0	0
			20	0	0
	B	0.02	5	0.005	$2.5x10^{-4}$
			10	0.010	$5.0x10^{-4}$
			20	0.020	$1.0x10^{-3}$
	C	0.05	5	0.013	$6.4x10^{-4}$
			10	0.025	$1.3x10^{-3}$
			20	0.050	$2.5x10^{-3}$

3.2 From landslide susceptibility to hazard

The evaluation of hazard requires the estimation of the runout and the intensity (e.g. impact energy). In the literature, the spatial distribution of the landslide magnitude at regional scale has been rarely been considered. Most LS maps do not resolve the magnitude. According to Reichenbach et al. 2018, pixel is the most popular unit used in LS analysis (86.4% of the published studies). LS calculated based on the probability of pixel-failure often shows a mismatch between the landslide size and that of the pixel. A way to overcome this restriction is performing the susceptibility analysis in terrain units containing the physical boundaries of the slope where the potential failure may develop. A terrain unit is characterized with a set of attributes that differ from the adjacent units across distinct boundaries, such as drainage and a divide lines (Hansen, 1984; Carrara et al. 1991). To calculate hazard, the failure probability of the unit is first calculated and the result multiplied by the size probability obtained from the magnitude-frequency relation (Guzzetti et al. 2006). Alternatively, Domènech et al. (2019) determined the size of the potential failures by aggregation of unstable pixels, within defined physiographic boundaries (Figure 5). In case of geographically-contained and/or slow-moving landslides, the magnitude may be used as a proxy for the landslide intensity to estimate hazard.

For long runout landslides, the analysis can be carried out either within the frame of the landslide susceptibility assessment (Fell et al. 2008; Greiving et al. 2012), or in a subsequent step (Reichenbach et al. 2018). Whatever the approach a set of maps has to be prepared. Each represents a scenario of potential landslides and the affected zones, with a given probability of occurrence (or return period). To generate the scenarios, the total number of landslides and their size distribution have to be known. They can be estimated from the magnitude and frequency (M-F) of past landslides or from the triggering events. A summary of the steps based on the latter is shown in Figure 6. First, the LS map (landslide initiation map) is prepared. Then, the probability (or return period) of the landslide triggering event scenarios have to be defined. The number and size distribution of landslides is calculated from the magnitude of the trigger (e.g. Malamud et al. 2004), and then split among different susceptibility classes according to their relative probability. Finally, the landslide runout is determined from either diffuse or discrete sources, considering the mechanism and size.

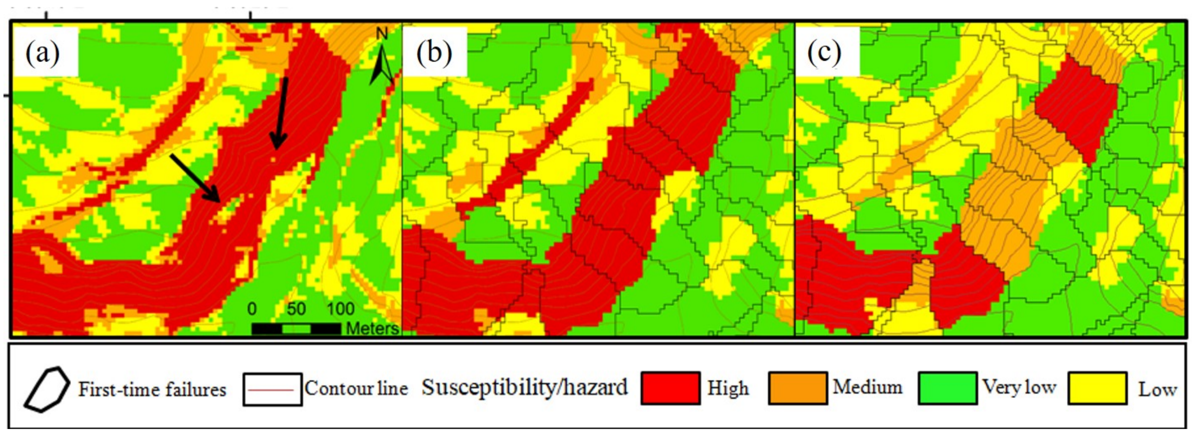


Figure 5. a) reclassified (black arrows) susceptibility map obtained from SINMAP; b) susceptibility map after the pixel clustering within each SU; c) Hazard map obtained after the application of the MF matrix for each cluster of pixels. Note that a high susceptibility class in (a) may yield either a high or a medium hazard class depending on the size of the expected slope failure (modified from Domenech et al. 2019).

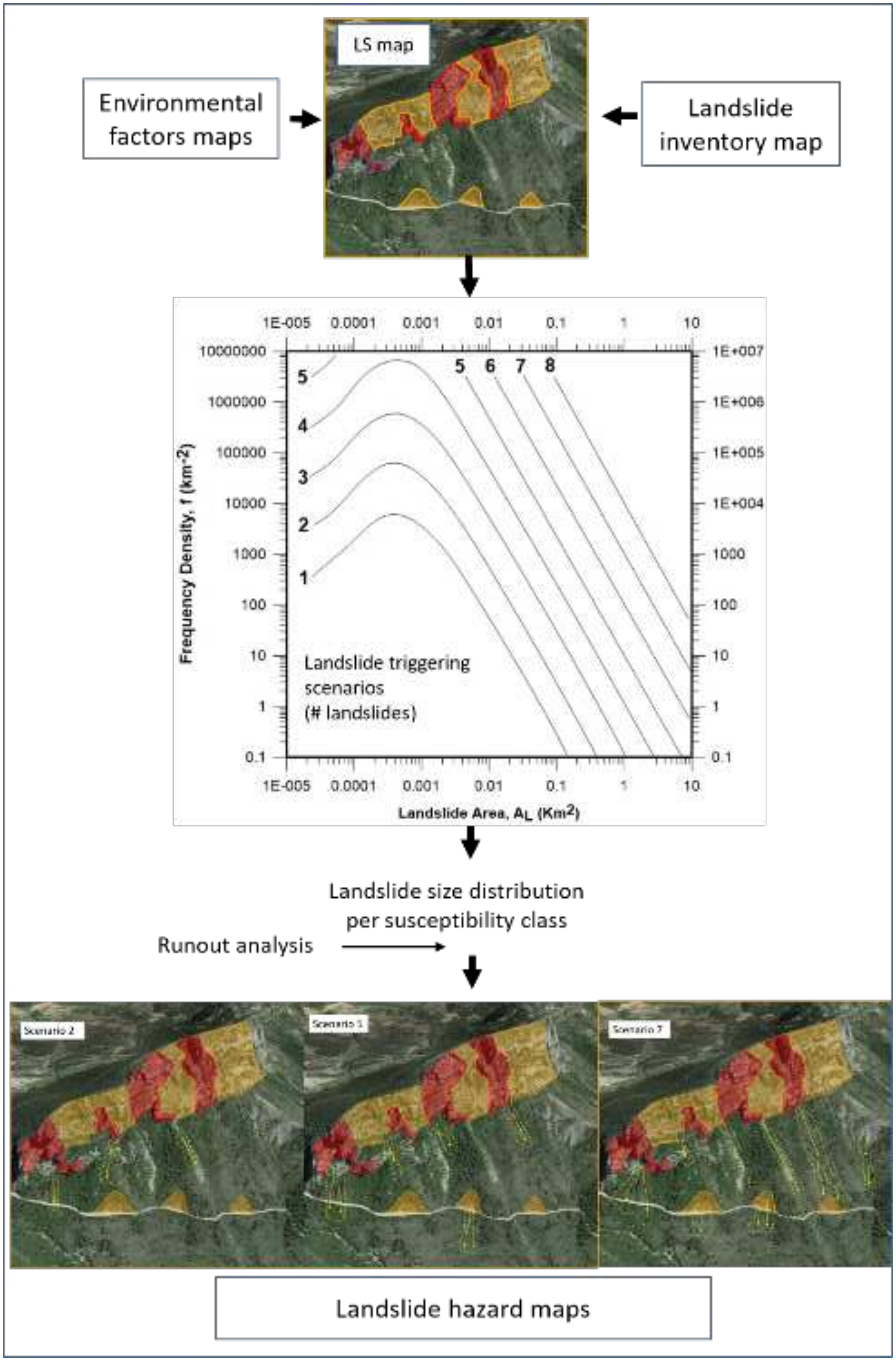


Figure 6. Framework for preparing landslide hazard scenario maps from the frequency of the triggers.

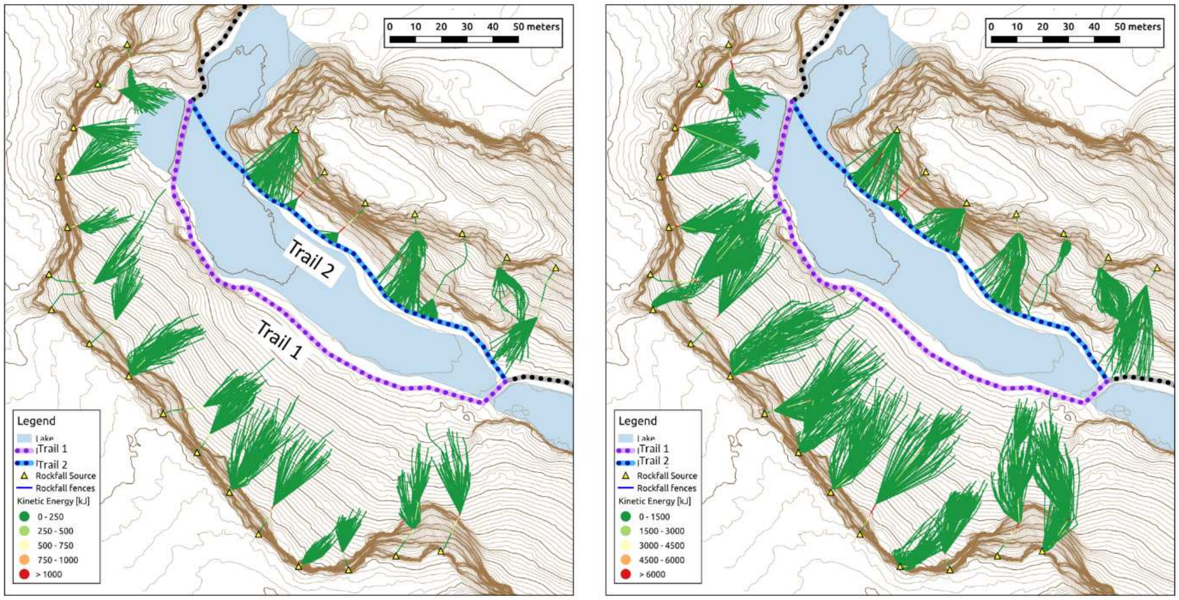


Figure. 7. Hazard scenarios for 1m^3 and 10 m^3 fragmental rockfall events in Monasterio de Piedra, Spain. Each rockfall magnitude has an associated probability of occurrence and generates trajectories with different runout probability and spatially distributed intensity. A discussion based on this figure is included in section 4.1.

A critical step of this approach is obtaining the landslide size distribution from the triggering event magnitude. Several relations have been established between the number of landslides and the magnitude of the earthquake (Keefer, 1988) or rainfall events (Reid and Page, 2003). This step however, contains a high degree of uncertainty as the relation between triggers and landslides is complex (Gorum et al. 2014) and both overprediction and under prediction can expected (Marc et al. 2016). Moreover, too close landsliding events generally produce different number of slope failures, following the process known as event resistance (Glade and Crozier, 2005).

Hazard scenarios of different probability may also be prepared assuming diffuse hazard sources (Hantz, 2011). Events initiate randomly over time from the sources (Figure 7). The distribution of the runout probabilities and intensities is calculated for each magnitude range, which has a probability (frequency) given by the frequency-magnitude relation (Corominas et al. 2005; Agliardi et al 2009; Stock et al. 2012). This approach assumes homogeneous landslide sources and it has been also applied in the analysis of linear infrastructures (Hungr et al. 1999; Ferlisi et al. 2012; Macciotta et al. 2016). An application example of this approach is presented in section 4.1.

Both empirical or numerical methods are used to analyze landslide runout (Hungr et al. 2005). Most prevalent empirical methods relate the landslide volume to the distance travelled by the landslide debris. Although these correlations tend to be highly scattered, they have the advantage of being easily incorporated into GIS-platforms to delineate the affected areas (Jaboyedoff, 2003; Scheidl and Rickenmann, 2010; Horton et al. 2013) and can be treated probabilistically (Copons et al. 2009; Jaboyedoff and Labiouse, 2011). The main limitation for risk quantification is that velocity (impact energy) is not obtained. A significant step forward comes from the integration of the runout numerical models into the GIS-platforms. Codes have been developed for debris flows and debris avalanches (McDougall and Hungr, 2004; Pastor et al. 2009; McDougall, 2017) and rockfalls (Guzzetti et al. 2002a; Crosta and Agliardi, 2003; Dorren et al. 2006; Lan et al. 2007; Matas et al. 2017).

It has to be noticed that the prediction of post-failure behavior for natural slopes requires the understanding of the instability process and of the propagation mechanism. For example, a substantial strength loss is observed in flow slides due to the collapse of the soil structure (Hungr, 2003; Picarelli et al. 2008) or in rock slides due to the brittle behavior of the rock mass (Glastonbury and Fell 2010), which leads to an extremely rapid failure and greater runout than expected. On the other hand, processes such as debris flows and debris avalanches are able to entrain large amounts of sediments, thus modifying the dynamic parameters of the displaced materials (McDougall and Hungr, 2005; Crosta et al. 2009). Keeping this in mind, the definition of credible runout scenarios requires the calibration using real landslide events, for the full spectrum of landslide types.

3.3 Trend of the magnitude-frequency (M-F) distributions and Maximum Credible Event

A typical feature of the M-F distributions is the decay following an inverse power law over several orders of magnitude, with deviations at both high and low magnitudes (Brardinoni and Church, 2004; Guthrie and Evans, 2004). The rollover observed for small-size landslides and its interpretation has been a matter of debate. Although sampling bias and/or mapping resolution has been claimed as potential cause (Stark and Hovius, 2001), analysis of complete landslide inventories indicates that rollover is real (Guzzetti et al. 2002b; Guthrie and Evans, 2004; Malamud et al. 2004: Frattini and Crosta, 2013) and that physical causes inhibiting failure size exist (Pelletier et al. 1997; Martin et al. 2002). Satisfactory approximation to the observed M-F is obtained by fitting double Pareto distribution (Stark and Hovius, 2001), inverse gamma distribution (Malamud et al. 2004), or both (Hurst et al. 2013). The tail of the distributions for mid to large landslides follow power laws whose exponents reflect the diversity of landslide mechanisms and physiographical settings.

The value of the exponent of the power law is relevant because it expresses the relative dominance of landslide sizes. A high exponent implies that small-size landslides dominate the distribution and vice versa. Malamud et al. (2004) and Brunetti et al (2009) observed that rockfalls show exponent values smaller than other types of landslides. They attribute the difference to the fact that rockfalls involve the disintegration of the rock mass. This particular behavior of rockfalls has to be confirmed with more data sets as other studies suggest a wider range for the exponent values (Barlow et al. 2012; Van Veen et al. 2017; D’Amato 2019). Several causes are identified which affect the slope of the volume distribution, giving an incorrect appearance of their scaling properties. Van Veen et al. (2017) and Williams et al. (2019) observed the increase in the exponent of the power law as the monitoring interval of the evens is reduced. In addition, superimposition and amalgamation may overestimate the number of large events (Barlow et al. 2012; Marc and Hovius, 2015; Williams et al. 2019) and the underestimation of small events. The latter effect may increase significantly risk in locations where loss of life is directly associated to the occurrence of frequent small-size events as it happens in high traffic intensity roads or railways.

A fundamental question in risk evaluation is whether the rate of occurrence of small and mid-size landslides in a region can be extrapolated to predict the rate of occurrence of large landslides and vice versa. The occurrence of large events has significant influence in the calculated value of both hazard and risk of the urbanized areas.

Extrapolation of the M-F relation has been proposed to estimate the size of large unseen landslide events (e.g. Picarelli et a. 2005). Nevertheless, in the author’s opinion, the range of validity of the M-F relations should be bounded at each location or region. Consideration of a maximum credible event (MCE) is routinely performed in the analysis of other natural hazards such as earthquakes or floods to define worst case scenarios. The estimation of the largest hypothetical earthquake takes into account the characteristics seismic source and the current tectonic setting (Cosentino et al. 1977; US Bureau of Reclamation, 2015). Truncated magnitude-frequency relations are defined for earthquakes using either deterministic (Wells and Coppersmith 1994; Anderson et al. 1996; Wheeler 2009) or probabilistic approaches (Cosentino et al. 1977; Kijko and Singh, 2011, and references therein). Similarly for floods, different procedures have been developed to obtain the upper bound of magnitudes and the return periods (Swain et al. 2006).

In the case of landslides, the use of statistics based upon unbounded random variable models is arguable. Hungr et al. (2008), considered that M-F curves of debris flows and debris avalanches, derived from a region would underestimate the magnitudes if applied to a smaller sub-region of relatively tall slopes and overestimate them in a nearby sub-region with lower relief. Regional landslide inventories show deviations from the relationship at the high magnitude range and empirical evidence suggests a finite maximum regional magnitude (Corominas et al. 2018). Power law volume distributions prepared from complete (more than 150 years) rockfall inventories show oversteepening of the relation at large volumes and specific cut off values can be obtained (Zhang et al. 2019). Guzzetti et al. (2002b), Guthrie and Evans (2004), Parry (2016) argue that the power law portion of the curve describes inherent landscape limitations. Landslides cannot be bigger than the slope itself and the larger the landslide, the lesser the number of slopes that can nest them.

The physiographic setting is therefore one the main controls of the maximum landslide size. The analysis of the landslide magnitude–frequency distributions in Fiordland and Southern Alps in New Zealand (Clarke and Burbank, 2010), reveal order-of-magnitude differences between regions. These authors suggest that the depth of bedrock fracturing affects the magnitude and frequency of landslides. Jarman et al. (2014) observed that large-scale rock slope failures in the Pyrenees are sparse compared to other mountain ranges. In this case, low mean rates of later Neogene tectonic uplift, combined with weak fluvial and glacial erosion may have been insufficient to destabilise the slopes. Corominas et al. (2018) observed that neither geomorphological evidences of past events nor the size of the potentially unstable rock masses identified in the slopes can support the occurrence of the large rockfall/rock avalanche volumes in the slopes of Andorra. There, the fracture pattern is considered to constraint the maximum size of the potential failures (Mavrouli & Corominas, 2017). On the contrary, triggering mechanisms seem not have any influence, as deduced from the similar exponents and cutt-off values of the landslide volume distributions generated by earthquakes and rainfall in the same region of Central Himalaya (Zhang et al. 2019).

The challenge that arise is how to quantify the relation between morpho-structural parameters and MCE and stablish criteria to extrapolate the M-F relations beyond the range of observations. Even though the analysis of the MCE for landslides is not a standardized procedure, two possible models may be envisaged (Figure 8):

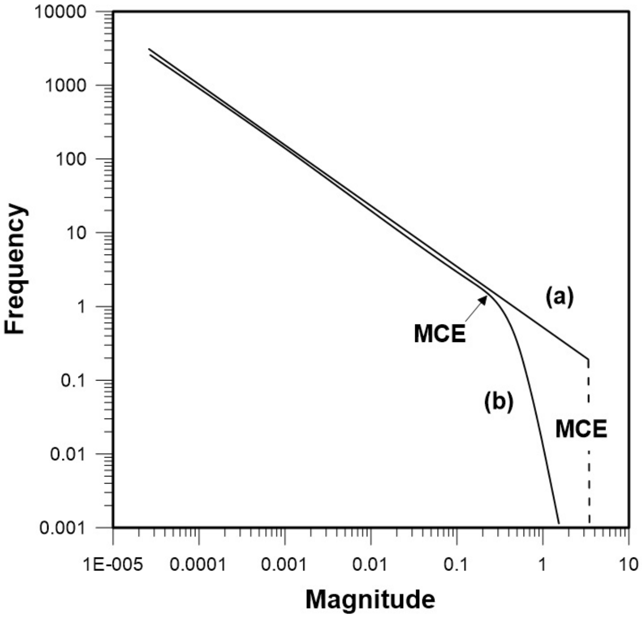


Figure 8. Cut-off of the M-F relation: (a) sharp cut-off; (b) soft cut-off

(a) Sharp cut-off magnitude at a maximum magnitude, so that by definition, no landslides are possible with a magnitude exceeding m_{max} (e.g. De Biaggi et al. 2017a)
(b) Soft cut-off maximum, using non-scale invariant models. The distribution decays beyond the maximum much faster than the power law distribution (e.g. Hergarten, 2012). Such cut-off implies that landslides larger than the maximum defined are not necessarily excluded.

An appropriate understanding of the geological and geomorphological conditions of slopes is therefore required to define the MCE and additional work remains to be done for deciphering its local and regional controls. Meanwhile, the MCE may be reasonably approached considering the rate of small landslides (Guzzetti et al. 2005), the largest morphological depression in the landscape (Parry and Ng, 2010), or the largest kinematically detachable rock mass (Corominas et al. 2018), provided that the range of sizes is not extrapolated much beyond the largest observed historical and pre-historical regional landslide events.

3.3 Stationarity of landslide frequency

It is currently feasible to estimate of probabilities of extreme events without understanding of the causal structure that controls the stability of slopes. Klemes (2000) complained that the historical or geological record it is often assumed as a random sample drawn from the postulated distribution and that frequencies are transformed in probabilities, without proper consideration of the hydrology, meteorology or climatology.

Landslide susceptibility and hazard models rely on the principle of uniformity that future landslides will likely occur in slopes having similar geo-environmental conditions than the slopes that experienced failures in the past (Varnes 1984). Based on this principle, the probability of occurrence may be calculated from a list of both historic and prehistoric landslide events. The practical implementation of this approach assumes stationarity of the landslide record (i.e. statistical properties such as the mean or variance are constant over time) although this does not hold for landslides (Guzzetti et al. 2005; Corominas and Moya, 2008; Hungr, 2016). Slope failures change the local morphology and the stability conditions for both new and reactivated landslides differ. Very large landslides cannot physically repeat, or at least not with the same probability. In addition, natural (e.g. river erosion) and human-induced slope modifications (e.g. logging, burning) may take place in the short term while other processes such as weathering, strength decay, or uplift may develop in the long term (hundreds or thousands of years). In the current practice, the stationarity assumption is accepted to make the problem tractable mathematically (Guzzetti et al. 2005) but in the scenario of the global change (both climate and human change) it should be reconsidered (Meusburger and Alewell, 2009).

The assumption of stationarity is a serious limitation to the reliability of hazard analysis. For instance, once a dense cluster of landslides removes a large proportion of soil cover from steep slopes of an area, another cluster may not be possible for a considerable period of time until the slopes are again refilled (Jakob et al. 2005; Corominas and Moya, 2008). An illustrative example is found in the Campania Region, Italy. There, shallow failures entrain the pyroclastic mantle that overlies the bedrock, deposited by successive eruptions of the Vesuvius volcano. As the mantle is progressively reduced over time so does the frequency of the events, until it is refilled again with new eruptions (Ferlisi et al. 2016).

Other potential limitation is that landslides do not occur at a constant rate. Many of them tend to occur in clusters, both in space and time. Clustering may be associated to the temporal pattern of the climatic triggers (Berrisford and Mathews, 1997; Corominas and Moya, 1999) or to seismicity (Schuster et al. 1992; Bull, 1996; Crosta et al. 2017). Clusters and changes in frequency may also occur if predisposing factors are modified. Intense shaking from strong earthquakes may disturb rock masses and weaken slopes thus favoring delayed failures (Parker et al. 2015; Fan et al. 2018) and the supply of sediments which are subsequently mobilized as debris flows (Lin et al. 2006; Tang et al. 2011; Zhang et al. 2012).

Climate is one main driver of landslide occurrence (Corominas, 2000; Borgatti and Soldati, 2010). Nowadays, climate change is undisputable. It have significant effects on the slopes and existing landslides (Dijkstra and Dixon, 2010) while the consequences are exacerbated by human actions (Crozier, 2010), and population increase (Petley, 2010). However, climate and landslides operate at different geographical and temporal scales. The attribution of a climatic effect to a given set of landslides requires that the non-climatic and anthropogenic causes be eliminated (Huggel et al. 2012). Temperature and rainfall are key climatic variables governing the response of the slopes (Crozier, 2010). Glacierized regions are highly sensitive to the increase of temperature and ice-cover shrinkage and permafrost degradation is a global process (Bottino et al. 2002; Patton et al. 2019), with consequences on the geometry of the slopes, on physical properties of the newly exposed soils and rocks as well as on the hydrological conditions (Johnson et al. 2017). Outside the mountain ranges, coastal cliffs emerge as highly vulnerable locations in front of the widespread sea-level rise (Bray and Hooke, 1999).

A list of both anthropogenic and climate-induced processes affecting the slope instability is presented in Table 4. Several works (Geertsema et al 2006; Petley et al. 2007; Keiler et al. 2010; Ravanel and Deline, 2011; Dietrich and Krautblatter, 2017; Patton et al. 2019), argue that frequency and magnitude of landslides increases in high mountain regions. It is due to a combination of factors such as the raise of air temperature, permafrost thawing (Ravanel and Deline, 2011; Gruber et al. 2004), and sediment availability (Zimmermann and Haeberli, 1992). However, the intensification of landslide activity cannot be generalized. One should expect that the response of the slopes to the climate forcing be geographically uneven, nonlinear, and with a variable time lag. The increase will probably be less evident in the slopes of valleys already deglaciated during Late Pleistocene and Early Holocene times (Messenzehl et al. 2017) and in mid latitude regions. There, it has been observed that the high initial landslide activity has declined following an exhaustion model (Berrisford and Matthews, 1997; Ballantyne et al. 2014), particularly in locations where sediment has been progressively washed away (Jomelli et al. 2004; Glade 2005). This process is known as “event resistance” (Glade and Crozier, 2005). Improved stability conditions are also achieved in places where large unstable rock masses slid down over discontinuity surfaces leaving more stable topographic profiles (Cruden and Hu, 1993; Ballantyne 2002).

Simulations based on current climate projections and slope stability models yield diverging results (Gariano and Guzzetti, 2016). Some models confirm the increase of landslide events, particularly shallow slides and debris flows chiefly due to the increase of rainfall intensity (Chiang and Chang, 2011). In contrast, a number of cases predict the reduction of landslide occurrence and decrease of rate of movement in the existing ones as the result of a greater evapotranspiration and lesser precipitation. Other models show that the increase of precipitation is counterbalanced by the increase of evapotranspiration (Collison et al. 2000). Care in needed with the projections as the results depend largely on the climate models, the downscaling methods, and weather generators selected to obtain temperature and rainfall time series (Gariano and Guzzetti, 2016) and on the inherent limiting stability factors of the slopes which ultimately govern the response to the changing climate (Crozier, 2010). The lack of reliable relations between climate projections and slope stability at this time, poses some limit to the consideration of the climate change in the QRA.

Table 4. Changes in landslide occurrence in response to climatically and anthropogenically-driven modifications of the slopes

		Predisposing factors	Triggering factors
Increase landslide occurrence and/or magnitude	Hydrology	Wetter antecedent conditions in the slopes (Crozier, 2010)	Increase of rainfall duration and/or intensity (Chiang and Chang, 2011)
		Water impoundment: e.g. landslide dams (Richardson and Reynolds, 2000)	Excess of pore water pressures due to permafrost thawing (Harris et al. 2009)
	Slope geometry	Redistribution of stresses in response to changes of slope geometry (e.g. oversteppening) by glacier erosion or wave actions on shorelines and cliffs (Crozier, 2010).	
		Cracking and bulging of the slopes as result of the unloading and debuttressing (Evans and Clague, 1994; Holm et al. 2004; Geertsema et al 2006)	Melting of ice-bonds in rock joints (Davies et al. 2001; Gruber and Haeberli, 2007)
	Soil/rock Strength	Rock deterioration/ weathering - Segregation ice growth and joint widening (Gruber and Haeberli, 2007)	
		Unprotected soil cover as result of wildfires and/or logging (Cannon et al. 2008; Glade, 2003)	
	New exposures	New susceptible landforms: e.g. moraines and moraine-dammed lakes(Clague and Evans, 2000; Kääb and Reichmuth, 2005),	
		Increase of available unconsolidated sediment Gruber and Haeberli, 2007; Frank et al. 2019)	
Decrease landslide occurrence		Dryer antecedent conditions: reduction of the mean annual precipitation associated to an increase of evapotranspiration (Gariano and Guzzetti, 2016)	Reduction of the rainfall intensity and /or duration (Comegna et al. 2013; Rianna et al. 2014)
		Long term evolution towards more stable slope profiles (Cruden and Hu, 1993)	
		Sediment exhaustion (Corominas and Moya, 2008)	
		Increase of forest (abandonment) (Houet et al. 2017)	

A critical issue behind the climate change is whether it will modify the magnitude/intensity of future events. This possibility will depend on the sediment availability and the weathering rate in the affected basins (Jakob et al. 2005; Corominas and Moya, 2008). Mitigation measures such as debris flow channels are designed for specified returns periods. They may become undersized if magnitude of the mobilized materials is bigger than the design event (Keiler et al. 2010). Increase of magnitude is feasible in locations having unlimited sediment source as it occurs in slopes composed of weak volcanic materials (Yano et al. 2019) or where the strength of the slope materials deteriorate quickly as for example, deepening of the active layer by thawing permafrost (Harris et al. 2009). The magnitude increase might occur despite the fact that the overall frequency suffer only slight changes (Stoffel et al. 2014).

4 LANDSLIDE RISK ANALYSIS

4.1 Quantifying risk

QRA is routinely performed to evaluate industrial risks and it is increasingly applied to landslides. Recent experience show that some administrations base certain landslide risk management decisions (e.g. land use planning, mitigation measures) on either qualitative or quantitative hazard matrices (e.g. Lateltin, 1997, 2005). Risk, however, depends on the nature and location (vulnerability and exposure) of the threatened elements.

Different disciplines work with multiple definitions for vulnerability. From our perspective, vulnerability may be defined as the degree of loss of a given element (or set of elements) exposed to a landslide of a given intensity (Table 1). A review of vulnerability terms and approaches is found in Fuchs et al. (2012). The assessment of vulnerability to landslides and its integration in QRA, is recent. Vulnerability is a distributed function in which the scenarios have to be defined beforehand. It is not an intrinsic attribute of the exposed element as damage and loss also depend on both the landslide mechanism, intensity, and impact location (Leroi, 1996; Van Westen et al. 2006). There are three dominant methods for assessing and assign vulnerability values to the exposed elements (Fuchs et al. 2015): matrices, indicators, and curves. As vulnerability is a conditional probability, the use fragility curves facilitates quantitative risk analysis. Vulnerability curves display the probability of reaching or exceeding a certain damage state, due to the interaction with a landslide event of a given type and intensity. They are built based on either empirical or analytical data. The use of vulnerability curves has several advantages: (a) a quantitative relation is established between intensity of the landslide and damage of the element; (b) curves can explicitly include both epistemic and aleatory uncertainties; (c) the vulnerability value can be used directly to calculate risk; (d) the feasibility of protection measures can be assessed by means of cost-benefit analysis. Vulnerability curves have been prepared for debris flows (Quan Luna et al. 2011; Papathoma-Köhle et al. 2012; Totschnig and Fuchs, 2013), rock falls (Mavrouli and Corominas, 2010), or slow moving landslides (Mavrouli et al. 2014; Peduto et al. 2017). Examples of QRA in which vulnerability curves are integrated in the analysis, may be found in Mavrouli and Corominas (2010) and Agliardi et al. (2009).

Risk is an aggregated function. Loss due to a particular landslide in a single or a set of exposed elements corresponds to the specific risk defined by Varnes (1984). Total cumulative risk quantifies the losses of the scenarios defined by all potential landslide events, and elements at risk. A particular concern is the risk estimation posed by large infrequent events. Catastrophic events produce strong impact on societies and it is believed that few large landslides dominate most of fatalities. Several overview reports support this finding in Europe (Haque et al. 2016), Latin America (Sepúlveda and Petley, 2015), or the Caribbean (Haque et al. 2016). A study of the damage of landslides in Switzerland reveals that a large amount of the monetary costs is due to a few major events only (Hilker et al. 2009). On the contrary, Zhang and Huang 2018 observed that a large number of fatalities are caused by the occurrence of numerous small landslides, each affecting few people. Other examples, in which rockfall risk is quantified by segregating the analysis in block size classes, show that highest risk is associated to small or medium-sized events (Corominas et al. 2005; Farvacque et al. 2019). These figures raise an interesting debate on, for example, whether the largest events in a region are those that generate unacceptable levels of risk, or what is the size of the event that should be considered in the design of the remedial measures in order to achieve a reasonable level of safety. The analyses on the relative contribution of different landslide magnitudes to risk are scarce but these type of questions can be resolved with QRA.

Table 4 presents the results of a rockfall QRA in the Monasterio de Piedra, Spain (Corominas et al. 2019). Two trails below steep limestone cliffs are analyzed (Figure 7). Trail 1 runs along the end of a gentle slope topped by the cliff. Trail 2 runs directly below the rock cliff. The results show that highest risk is associated to frequent small events and that the rockfall fragmentation has contrasting effects. Fragmentation reduces the annual probability of loss of life from $1.2\cdot10^{-2}$ to $3.5\cdot10^{-4}$, that is, almost two orders of magnitude, provided that the slope is sufficiently long and gentle. This is because the new fragments generated travel shorter distanceswith lesser kinetic energy. The effect disappears in case of large rockfalls (>50m^3) because most of them reach the trail despite the fragmentation. Conversely, the risk increases when rock fragments propagate over steep slopes. In this case, few blocks stop along the way and the generation of a cone of fragments increases the exposure. The probability of impact for fragmental rockfalls in trail 2 increases substantially, typically by a factor of 2 or 3.

4.2 Multi-hazard risk analysis

Human settlements and infrastructures may be exposed to different hazards. The term multi-hazard refers to all possible and relevant hazards, and their interactions in a given region (Gill and Malamud, 2014). International agencies have called for a multi-hazard approach in order to lower risks and reduce the effects of natural disasters (Kappes et al. 2012b and references therein). Performing quantitative risk analysis from multiple hazards is challenging (Marzocchi et al. 2012; Mignan et al. 2014; Terzi et al. 2019) but for a meaningful and complete risk evaluation, the combined effects of hazards have to be accounted for. Otherwise, risk may be underestimated. The diversity of multi-hazard interactions has been reviewed by Gill and Malamud (2014), Tilloy et al. (2019), among others.

Landslide hazard and risk are usually assessed independently from other hazards despite the fact that landslides are often the consequence of the occurrence of a primary event, such as rainfall or earthquake. A number of contexts involving landslides require a multi-hazard risk analysis:

a) Source-dependent coeval hazardous events. The events are genetically linked and share the same source (location). Processes having the potential to generate multiple simultaneous (quasi simultaneous) damaging-events as in volcanic eruptions that may result in lava flows, ash or lapilli fallout, lahars, volcano flank collapse, or earthquakes (Pierson et al. 1990; Zuccaro et al. 2008).
b) Source-independent coeval hazardous events. Genetically linked by the trigger, which initiates multiple hazardous events from different sources. This is typically the scenario generated by heavy rainfall triggering a number of individual events such as debris flows, landslides, rockfalls and river floods (Borga et al. 2014). The events occur (almost) simultaneously and most of them independently although interaction, such as erosion/undercutting of the slopes by river floods and subsequent destabilization (Corominas & Alonso, 1990), can also take place.
c) Compound hazardous processes in which intensity and consequences are greater than the sum of the effects of each event separately. This can be observed in concurrent events (temporal and spatial overlapping) such as short-lived landslide dams that form and fail during the rainfall event thus worsening the effects of river floods (Catane et al. 2012); or rain falling onto fresh deposited pyroclastic material generating lahars (Self, 2006). The events may have a common trigger or not.
d) Cascading (or domino) effects. Hazardous events follow one another either immediately as in the case of rock avalanches falling in lakes generating displacement waves (Korup and Tweed, 2007; Huggel et al. 2012) or after some delay as shown in the collapse of landslide-dams emptied catastrophically (e.g. Dunning et al. 2006; Cui et al. 2009). Secondary events subsequent to a primary event (e.g. the slope failure) may become more damaging than the initial event.
e) Spatially overlapped independent hazardous events. The events may affect the same elements at risk but the events are triggered by different mechanisms and their occurrence usually follow different temporal scales such as in the case of snow avalanches and landslides (Bell and Glade, 2004).

Risk quantification of scenarios (a), (b), and (e), can be performed separately for each process and then aggregated, under the assumption that interaction does not exist (Zêrere et al. 2008; Mavrouli et al. 2019). This approach is known as multi-layer risk assessment (Terzi et al. 2019) Assessment of (c) and (d) contexts require first defining scenarios of specified primary event-magnitude that can be either modelled or analyzed with probabilistic tools such as event trees (Neri et al. 2008; Sandri et al. 2014). One main difficulty of the combined analysis over a given time period of hazardous events such as volcanic eruptions, landslides, floods, or earthquakes is that generally, each one is founded upon different methodologies leading to the results not being comparable (Marzocchi et al. 2012). This also applies to landslides. Regions affected by a diversity of landslide mechanisms (i.e. rockfalls, debris flows,

Table 4. Individual risk (annual probability of loss of life) for unfragmented (U) and fragmental (F) rockfalls at two trail sections of Monasterio de Piedra, Spain: 1 (top) and 2 (bottom). A uniformly distributed flow of visitors (700 visitors/day) is assumed (Corominas et al. 2019). Risk components are those shown in the equation of figure 4, in which the probability of occurrence of an event of magnitude M_i is replaced by the annual frequency (N_i).

Trail 1 - long gentle slope

Volume	Frequency	Unfragmented rockfalls			Fragmented rockfalls		
M_i (m^3)	Ni	P(X:M)	P(T:X)	Risk - U	P(X:M)	P(T:X)	Risk- F
<0.05	16.32	0.119	0.010	9.9x10^{-3}	0.000	0.000	0.000
0.05 < x <0.5	0.25	0.328	0.019	1.4x10^{-3}	0.000	0.000	0.000
0.5 < x <5	3.3x10^{-2}	0.590	0.022	4.3x10^{-4}	0.043	0.034	4.7x10^{-5}
5 < x <50	4.3x10^{-3}	0.765	0.066	2.2x10^{-4}	0.233	0.120	1.2x10^{-4}
50 < x <500	5.7x10^{-4}	0.832	0.124	5.9x10^{-5}	0.631	0.374	1.4x10^{-4}
>500	8.0x10^{-5}	0.874	0.153	1.0x10^{-5}	0.800	0.678	4.2x10^{-5}
Cumulated annual probability of loss of life				**0.012**			**3.5x10^{-4}**

Trail 2– steep slope

Volume	Frequency	Unfragmented rockfalls			Fragmented rockfalls		
M_i (m^3)	Ni	P(X:M)	P(T:X)	Risk	P(X:M)	P(T:X)	Risk
<0.05	7.324	0.611	0.010	2.3 x10^{-2}	0.2940	0.0401	4.4 x10^{-2}
0.05 < x <0.5	0.112	0.839	0.019	1.6 x10^{-3}	0.5700	0.062	3.6 x10^{-3}
0.5 < x <5	0.015	0.945	0.022	3.1 x10^{-4}	0.7908	0.156	1.8 x10^{-3}
5 < x <50	2.0 x10^{-3}	0.970	0.066	1.2 x10^{-4}	0.9507	0.244	4.5 x10^{-4}
50 < x <500	2.6 x10^{-4}	0.979	0.124	3.1 x10^{-5}	0.9886	0.367	9.4 x10^{-5}
>500	3.0 x10^{-5}	0.982	0.153	5.0 x10^{-6}	0.9917	0.472	1.6 x10^{-5}
Cumulated annual probability of loss of life				**0.025**			**0.050**

rotational slides), requires a multi-hazard approach. Despite different landslide types can be triggered by the same trigger (i.e. rainfall, earthquake), researchers are aware that each type of slope failure needs specific predictive model based on a set of factors that are either common to other models or unique (Carrara et al. 1999). Different landslide types have distinctive M-F relations, travel distances and produce different impacts. Separate hazard map and risk scenarios are therefore required for each landslide type, which are eventually combined. If concurrence and interrelation between events is foreseen, then the scenario of compound hazard and/or cascading effects has to be considered.

Primary hazardous events may also affect the predisposing factors of other secondary hazards, normally increasing the probability of occurrence as discussed in section 3.5 (e.g. wild fires increasing frequency and magnitude of shallow landslides; earthquake-induced slope weakening favors future instability). The effects may show up shortly in the aftermath (e.g. Lin et al. 2006) or in the long term.

The challenge of multi-hazard QRA is therefore bringing all these phenomena under a common metric to produce comparable risk levels and results on a common and meaningful scale (Kappes et al. 2012a). This may be attempted using quantitative risk descriptors for each of the hazards, such as the expected annual monetary loss, the probability of a given loss scenario, the probability of one or more fatalities, or others mentioned at Corominas et al. (2014b). In that respect, a key point is establishing criteria to relate hazard levels to vulnerability and costs (Schmidt et al., 2011, Kappes et al., 2012b).

Examples of quantitative landslide multi-hazard risk analysis within a given time period are limited in number. To make the problem manageable, the analysis usually includes simplifications. Zêzere et al. (2008) quantified direct risk from the occurrence of translational, rotational, and shallow landslides on roads and buildings in the north of Lisbon, Portugal, for a defined rainfall scenario of a given return period. In this particular case, landslide magnitude is assumed the pixel size and both constant vulnerability and damage was estimated based on the landslide type regardless its intensity.

Mavrouli et al. (2019) presented the quantification of risk in a road network due to multiple independent hazardous events. The study analyse a number of locations of a road network that may be potentially affected by landslides, rock falls, debris flows, and the failure of retaining structures. The comparison and quantification of the risk levels is achieved by estimating the loss on different exposed elements (persons, vehicles, infrastructure, and indirect economical loss), for each hazard scenario. Hazard is expressed in terms of annual probability of failure of either a natural or cut slope, or retaining structure,of a given magnitude. For dormant landslides, hazard is given by the probability of a sudden reactivation. Magnitude or intensity descriptors are assigned to each hazard type, whose levels are associated to a degree of damage and its consequent loss. In the example of Mavrouli et al (2019), the consequences include the costs related to removal of rubble, repair and/or replacement of the road pavement, scaling of the slopes (removal of loose undetached rock or debris), slope stabilization and traffic detours. In case that more than one type of hazard is present on a given location, total risk is the sum of risks.

The overall methodology for the quantification of the risk consists in the application of the general equation:

$$\mathrm{R_T} = \sum_{\mathrm{j}}^{\mathrm{k}} \mathrm{P_{rk}} * C_k \qquad (2)$$

Where:

j: magnitude (volume) or intensity (velocity) class

k: hazardous event type (rockfall; failure of an anchored retaining wall; slow moving landslide; failure of a sea wall)

$\mathrm{R_T}$: Average annual risk in terms of UC per year

$\mathrm{P_{rk}}$: Annual probability/frequency of occurrence of a k-type event of magnitude j

$\mathrm{C_k}$: Consequences of the failure/rupture caused by a hazardous k-type event, of magnitude j in terms of (as multiples of) the cost units.

4.3 Risk assessment

To date, few jurisdictions around the world have set legislated or administrative guidelines for risk-to-life acceptability for landslide hazards as for instance, Hong Kong (GEO 1998) or Australia (AGS 2007). The scarcity of reliable data, the complexity of the landslide processes and the lack of well-established methodologies, are reasons that difficult the implementation of QRA studies. Compared to other natural hazards such as floods and earthquakes, the public awareness in front of landslides is generally low (Landeros-Mugica et al. 2016). Despite all the efforts of the administrations, landslide damages are steadily increasing worldwide (Petley, 2012; Haque et al. 2016; Zhang and Huang, 2018). Instead, the number of fatalities appears to be falling (Kron, 2000; United Nations, 2009) except for some specific regions (Petley et al. 2007). These figures most probably reflect the population growth and the increase of exposure.

Landslide risk assessment is the process of making a decision recommendation on whether the existing risk, considering existing mitigation measures, is tolerable or not (Fell et al. 2005). It involves the risk analysis and risk evaluation phases. The latter is the stage at which values and judgement enter the decision process, explicitly, to consider risk acceptance criteria and identify a range of alternatives for managing the risks. Risk may be acceptable, tolerable or unacceptable. Acceptable risk refers to the level of risk that requires no further reduction, while risk can be tolerated if certain benefits are achieved. The latter option usually requires the implementation of risk mitigation measures according to principle as low as reasonably practicable (ALARP). It is therefore the society's decision whether to accept or tolerate the risk (Duzgun and Lacasse, 2005).

Where only material losses are concerned, risk acceptability can be assessed by a routine cost-benefit analysis, comparing the total annual risk cost with the annualized cost of prevention or protection. However, when humans are in danger acceptability standards has to be set by other stakeholders (Hungr, 2016). A common criterion for risk acceptance is that the incremental risk from landslides should not be significant compared to other risks to which a person is exposed in everyday life (Leroi et al. 2005). Although "significant" is not defined, the maximum allowable risk for individuals in terms of annual probability of loss of life, for existing and new developments is set respectively as 10^{-4} and 10^{-5} in Hong Kong (Ho et al. 2000) and Australia (AGS, 2007), while in Canada is 10^{-5} (Porter and Morgenstern, 2013). Societal risk is commonly evaluated with cumulative frequency-number of fatalities (F-N) plots, which are subdivided in regions of unacceptable, ALARP, and broadly acceptable

(Fell and Hartford, 1997). To scale F-N plots of societal risk, a reference toe length of the natural hillside of 500 m is considered (Ho et al. 2000).

As noted by Hungr et al. (2016), actual applications of the acceptance criteria are based on either hazard or risk. Hazard-based acceptance establishes an acceptable maximum probability and intensity levels of potential landslides, with specific consideration for sensitive elements such as schools or hospitals, or less sensitive ones such as storage houses (e.g. Lateltin, 1997; Corominas et al 2003). Risk-based acceptance typically establishes a maximum probability of loss of life (Ho et al. 2000; AGS, 2007) or specified economic losses.

In the context of the hazard-based approach, the literature review indicates that LS maps are often proposed, as the acceptability criterion for land use planning, without consideration of present and projected exposed population and/or property. This leads again to the discussion of section 3.1, on whether planned development in LS classes potentially affected by a percentage of landslides ensures the minimum level of security required for the population, particularly if landslide runout is not considered. In the author's opinion this is a critical issue. Exposure is a dynamic component of risk and population growth stimulated by planning can lead to an unwanted scenario. This has been already highlighted in relation to other natural hazards. Projections of future impacts of floods by the end of this century indicate that damages may increase more than one order of magnitude in built areas. Although climate change plays a role, the increase is mostly due to the socio-economic growth and particularly, to the exposure (Winsemius et al. 2016; Tanoue et al. 2016).

The application of hazard-based acceptance approach may be contemplated in situations where it can be demonstrated that landslides do not pose a credible threat to an existing or proposed development, or in locations outside of the run-out zone of the maximum credible landslide event (Porter et al. 2009). For all other situations it is more appropriate to conduct the quantitative assessment of potential scenarios.

Within the ALARP region, cost benefit calculations should demonstrate that all cost-effective and practicable risk mitigation measures are undertaken (Ho et al. 2000). Mitigation works, are often costly, may have a significant impact upon the environment, and considered too conservative (Ho and Roberts, 2016). The ALARP principle requires a delicate balance between, risk perception, the willingness to accept risk and the willingness to pay (Winter and Bromhead, 2012).

5 FINAL REMARKS

Carrara et al. (1999) warned that the diffusion of the GIS technology was hampered by high digitation costs, bottlenecks in hardware capabilities, efforts in tuning-up hazard models and the lack of appropriate data. Since then, significant progress have been made. Hazard and risk analysis have nowadays benefited from new and improved remote data capture equipment (e.g. lidar, digital photogrammetry) which provide products at an increasingly higher resolution over wide regions as well as from the development of codes integrated in GIS platforms run by powerful computers.

Quantitative landslide hazard and risk analyses and mapping must ensure repeatability and transparency of the procedures used. Despite the wide spectrum of landslide types, newly developed step-by-step analytical and numerical techniques should facilitate standardization. To account for the intensity and probability of impact, the analysis must be spatially explicit otherwise quantification of risk will be limited.

Uncertainty is a central feature of risk analysis and models must be checked and validated. In that respect, several challenges still remain on the interpretation of indexes and validation curves. Validation of LS maps focus mainly on the overall performance of the models (i.e. AUC, contingency tables). However, errors are not equally relevant. Validation must pay attention on the impact of misclassification in the low landslide susceptibility classes before integrating LS analysis and maps in land use planning. Unfortunately, despite the accumulated experience, no requirements have been proposed so far on the number and nature of the input parameters (factors), the DEM resolution, the data treatment methods, or the quantitative quality indicators that must be met for generating reliable LS models. In any case, application of LS maps for land use planning without consideration of the magnitude and landslide runout should not be recommended.

Landslide inventories in some regions show strong scale-invariant M-F relation over several orders of magnitude. The relation, however, has not been tested in all instances and the extrapolation of the relation to both low and high magnitude ranges may give unrealistic hazard scenarios. Bounds to the landslide volume distributions must be defined. Empirical evidence suggests the existence of a maximum regional/local finite landslide magnitude, which depends on the geomechanical and morpho-structural attributes of the slopes present in the region. However, it is necessary to develop procedures based on the actual regional physiographic context to determine it. Meanwhile, the largest inventoried landslide volume as well as the largest kinematically detachable rock mass (or movable sediment deposit) could be used as a proxy of the MCE.

Increasing evidence indicates that global change (both climate and anthropogenic) affect the stability of slopes worldwide and this fact can no longer be omitted in landslide hazard assessment and in QRA. A main restriction is that the quantitative relation between the global change and the landslide occurrence is not entirely reliable. The response of the slopes is complex, geographically dissimilar and non-linear. It may involve late responses that can be delayed from a few decades to millennia. Analysis of future scenarios has to consider several opposing effects: (i) shift of potential landslide sources towards receding glacial and periglacial environments, which release large amount of sediments, exposing degraded rock mass and overstepped slopes. In contrast, the reduction of both the activity and frequency may be expected following sediment exhaustion and evolution towards more stable slope profiles; (ii) the increase of both temperature and precipitation in high latitude regions will favor the increase of landslide frequency. Conversely, substantial reduction of precipitation is expected in other regions (i.e. Mediterranean region) with the subsequent reduction of landslides (Orlowsky and Seneviratne, 2012). Special concern is required in locations where landslide activity was hitherto minimal or where existing remedial/protective measures can be undersized.

Regional analyses often involve a diversity of geomorphological processes (muti-hazard) that are amenable to different methods of assessment. The risk analysis for multi-hazards remains a challenge due to the diversity in the nature of the phenomena, diversity of timeframes, and variability of the consequences. It also requires matching metrics of different hazardous process. A number of approaches have been proposed to aggregate risk from multiple independent hazardous processes. However, further effort has to be directed towards the analysis of compound hazardous events and cascading effects initiated by the landslide occurrence, which require anticipating the potential scenarios.

Despite the increase of knowledge and the awareness of the administrations, the economic losses are steadily increasing worldwide. It most probably reflects a sustained increase of the exposure and the inability of local authorities to cope with a scientifically complex problem. Hazard maps are legally binding in a few countries only while in other, maps are simply recommendations with the delimitation of hazard zones lacking of official statutory regulation. Risk acceptance based on hazard-approach has to be checked. In that respect, the evaluation of the risk scenarios resulting from the development of the study area should help authorities to decide on the enforcement of the maps.

6 ACKNOWLEDGEMENTS

The author is indebted to Dr. Roger Ruiz-Carulla and Gerard Matas for their support preparing this contribution. This work has benefited from the results of the Rockmodels research project (BIA2016-75668-P), funded by the Spanish Ministry of Economy and Competitiveness and the European Regional Development's Funds (FEDER).

7 REFERENCES¡

Agliardi, F., Crosta, G.B., Frattini, P. (2009). *“Integrating rockfall risk assessment and countermeasure design by 3D modelling techniques.* Nat. Hazards Earth System Sci. 9:1059–1073.

AGS (2007). *“Guidelines for landslide susceptibility, hazard and risk zoning for land use management”.* Australian geomechanics society landslide taskforce landslide zoning working group. Australian Geomechanics, 42(1): 13-36

Anderson, J.G., Wesnousky, S.G., Stirling, M.W. (1996). *“Earthquake Size as a Function of Slip Rate”.* Bull. Seismol. Soc. Am., 86: 683–690.

Baeza, C., Lantada, N., Moya, J. (2010). *“Influence of sample and terrain unit on landslide susceptibility assessment at La Pobla de Lillet, Eastern Pyrenees, Spain”.* Environ. Earth Sci., 60:155–167.

Ballantyne, C.K. (2002). *“Paraglacial geomorphology”.* Quat. Sci. Rev., 21: 1935-2017.

Ballantyne, C.K., Sandeman, G.F., Stone, J.O., Wilson, P., (2014). *“Rock-slope failure following Late Pleistocene deglaciation on tectonically stable mountainous terrain”.* Quat. Sci. Rev., 86: 144–157.

Barlow, J., Lim, M., Rosser, N., Petley, D., Brain, M., Norman, E., and Geer, M. (2012). *“Modeling cliff erosion using negative power law scaling of rockfalls”.* Geomorphology, 139: 416-424.

Baum, R.L., Coe, J.A., Godt, J.W., et al (2005). *“Regional landslide-hazard assessment for Seattle, Washington, USA”.* Landslides, 2: 266–279.

Beguería, S. (2006). *"Validation and Evaluation of Predictive Models in Hazard Assessment and Risk Management"*. Nat. Hazards, 37: 315-329

Bell, R., Glade, T. (2004). "*Quantitative risk analysis for landslides—examples from Bíldudalur, NW-Iceland".* Nat. Hazards Earth System Sci., 4:117–131.

Berrisford, M.S., Matthews, J.A. (1997). "*Phases of enhanced mass movement and climatic variation during the Holocene: a synthesis".* Palaeoclimate Research, 19: 409-440.

Borga, M., Stoffel, M., Marchi, L., Marra, F., Jakob, M. (2014). *"Hydrogeomorphic response to extreme rainfall in headwater systems: flash floods and debris flows".* J. Hydrol., 518: 194-205.

Borgatti, L., Soldati, M. (2010). *"Landslides as a geomorphological proxy for climate change: a record from the Dolomites (northern Italy)".* Geomorphology 120, 56–64.

Bottino, G., Chiarle, M., Joly, A., Mortara, G. (2002). *"Modelling rock avalanches and their relation to permafrost degradation in glacial environments".* Permafrost and Periglacial Processes, 13: 283 – 288.

Brabb, E.E., Pampeyan E.H., Bonilla, M.G. (1972). *"Landslide susceptibility in San Mateo County, California".* U.S. Geol. Surv., Misc. Field Studies, Map MF-360. https://doi.org/10.3133/mf360

Brabb, E.E. (1984). *"Innovative approaches to landslide hazard mapping".* In: Proc. 4th Int. Symp. Landslides, Toronto. 1. pp. 307–324.

Brardinoni, F., Church, M. (2004). *"Representing the landslide magnitude–frequency relation, Capilano River Basin, British Columbia".* Earth Surface Processes and Landforms 29: 115–124.

Bray, M.J., Hooke, J.M. (1997). *"Prediction of soft-cliff retreat with accelerating sea-level rise".* J. Coastal Research, 13: 453-467.

Brenning, A. (2005). *"Spatial prediction models for landslide hazards: review, comparison and evaluation".* Nat. Hazards Earth System Sci., 5: 853–862.

Brunetti, M.T., Guzzetti, F., Rossi, M. (2009). *"Probability distributions of landslide volumes".* Nonlin. Processes Geophys 16: 179–188.

Bull, W.B. (1996). *"Prehistorical earthquakes on the Alpine fault, New Zealand".* J. Geophys. Res., 101(B3): 6037-6050.

Canli, E., Mergili, M., Glade, T. (2018). *"Probabilistic landslide ensemble prediction systems: Lessons to be learned from hydrology".* Nat. Hazards Earth Syst. Sci.,18: 2183–2202

Cannon, S.H., Gartner, J.E., Wilson, R.C., Bowers, J.C., Laber, J.L. (2008). *"Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California".* Geomorphology, 96: 250–269.

Carrara, A., Cardinali, M., Detti, R. (1991). *"GIS techniques and statistical models in evaluating landslides hazard".* Earth Surf Process Landforms, 16: 427–445.

Carrara, A., Guzzetti, F., Cardinali, M., Reichenbach, P. (1999). *"Use of GIS technology in the prediction and monitoring of landslide hazard".* Nat. Hazards, 20: 117–135.

Casagli, N., Frodella, W., Morelli, S., Tofani, V., Ciampalini, A., et al. (2017). *"Spaceborne, UAV and ground-based remote sensing techniques for landslide mapping, monitoring and early warning".* Geoenvironmental Disasters, 4, 1–23.

Catane, S.G., Abon, C.C., Saturay, R.M., Mendoza, E.P.P., Futalan, K.M. (2012). *"Landslide-amplified flash floods—the June 2008 Panay Island flooding, Philippines".* Geomorphology, 169–170: 55–63.

Catani, F., Lagomarsino, D., Segoni, S., Tofani, V. (2013). "Landslide susceptibility estimation by random forests technique: sensitivity and scaling issues". Nat. Hazards Earth System Sci., 13: 2815-2831.

Chacón, J., Irigaray, C., Fernández, T., El Hamdouni, R. (2006). "*Engineering geology maps: landslides and geographical information systems".* Bulletin of Engineering Geology & Environment 65, 341–411.

Chen, W., Xie, X., Peng, J., Shahabi, H., Hong, H., Tien Bui, D. et al. (2018). *"GIS-based landslide susceptibility evaluation using a novel hybrid integration approach of bivariate statistical based random forest method".* Catena 164, 135–149.

Chiang, S.H., Chang, K.T. (2011). *"The potential impact of climate change on typhoon-triggered landslides in Taiwan, 2010–2099".* Geomorphology 133: 143–151.

Chung, C-J. (2006). *"Using likelihood ratio functions for modeling the conditional probability of occurrence of future landslides for risk assessment".* Computers & Geosciences, 32: 1052–1068.

Chung, C.-J., Fabbri, A.G. (1999). *"Probabilistic prediction models for landslide hazard mapping".* Photogrammetric Engineering & Remote Sensing, 65: 1389–1399.

Chung, C.-J., Fabbri, A.G. (2003). *"Validation of spatial prediction models for landslide hazard mapping".* Nat. Hazards, 30: 451–472.

Clague, J.J., Evans, S.C., (2000). *"A review of catastrophic drainage of moraine-dammed lakes in British Columbia".* Quat. Sci. Rev., 19: 1763–1783.

Clarke, B.A., Burbank, D.W. (2010). *"Bedrock fracturing, threshold hillslopes and limit to the magnitude of landslides".* Earth and Planetary Science Letters, 297: 577-586.

Collison, A., Wade, S., Griffiths, J., Dehn, M. (2000). *"Modelling the impact of predicted climate change on landslide frequency and magnitude".* Engineering Geology, 55: 205–218.

Comegna, L., Picarelli, L., Bucchignani, E., Mercogliano, P. (2013.) *"Potential effects of incoming climate change on the behaviour of slow active landslides in clay".* Landslides, 10 (4): 373–391.

Costanzo, D., Rotigliano, E., Irigaray, C., Jiménez-Perálvarez, J. D., Chacón, J. (2012). *"Factors selection in landslide susceptibility modelling on large scale following the gis matrix method: application to* *the river Beiro basin (Spain)".* Nat. Hazards Earth Syst. Sci., 12: 327–340.

Copons R., Vilaplana, J.M., Linares, R. (2009). *"Rockfall travel distance analysis by using empirical models (Solà d'Andorra la Vella, Central Pyrenees)".* Nat. Hazards Earth System Sci. 9: 2107–2118.

Corominas, J. (2000). *"Landslides and climate".* Keynote lecture- In Bromhead E, Dixon N, Ibsen ML (eds).: Proceedings 8th International Symposium on Landslides, Cardiff, UK; A.A. Balkema, CD-ROM vol. 4: 1–33.

Corominas, J., Alonso E.E. (1990). *"Geomorphological effects of extreme floods (november 1982) in the Southern Pyrenees".* Hydrology in Mountainous Regions. IAHS publ. 194: 295-302.

Corominas, J., Moya, J. (1999*). "Reconstructing recent landslide activity in relation to rainfall in the Llobregat River basin, Eastern Pyrenees, Spain".* Geomorphology, 30: 79-93

Corominas, J., Moya, J. (2008). *"A review of assessing landslide frequency for hazard zoning purposes".* Engineering Geology, 102: 193-213.

Corominas, J., Copons, R., Moya, J., Vilaplana, J.M., Altimir, J., Amigo, J. (2005). *"Quantitative assessment of the residual risk in a rockfall protected area".* Landslides, 2: 343–357.

Corominas, J., Einstein, H., Davis, T., Strom, A., Zuccaro, G., Nadim, F., Verdel, T. (2014a). *"Glossary of Terms on Landslide Hazard and Risk".* Engineering Geology for Society and Territory. Volume 2, 1775-1779

Corominas, J., Van Westen, C., Frattini, P., Cascini, L., Malet, J. P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M. G., et al. (2014b). *"Recommendations for the quantitative analysis of landslide risk".* Bull. Eng. Geol. Environ., 73, 209–263.

Corominas, J., Mavrouli, O., Ruiz-Carulla, R. (2018). *"Magnitude and frequency relations: are there geological constraints to the rockfall size?"* Landslides, 15: 829-845

Corominas, J., Matas, G., Ruiz-Carulla, R. (2019). *"Quantitative analysis of risk from fragmental rockfalls".* Landslides, 16: 5–21

Cosentino, P., Ficarra, V., Luzio, D. (1977). *"Truncated exponential frequency-magnitude relationship in earthquake statistics".* Bull. Seismological Society of America, 67: 1615-1623

Costanzo, D., Rotigliano, E., Irigaray, C., Jiménez-Perálvarez, J.D., Chacón, J. (2012). *"Factors selection in landslide susceptibility modelling on large scale following the GIS matrix method: application to the River Beiro Basin (Spain)".* Nat. Hazards Earth System Sci. 12:327–340

Crosta, G., Agliardi, F. (2003). *"A methodology for physically based rockfall hazard assessment".* Nat. Hazards Earth System Sci. 3: 407-422

Crosta, G., Agliardi, F. (2004). *"Parametric evaluation of 3D dispersion of rockfall trajectories".* Nat. Hazards Earth System Sci. 4: 583–598

Crosta, G. B., Imposimato, S.; Roddeman, D. (2009). *"Numerical modeling entrainment/deposition in rock and debris-avalanches".* Eng. Geol., 109, 135– 145.

Crosta, G.B., di Prisco, C., Frattini, P., Frigerio, G., Castellanza, R., Agliardi, F. (2013). *"Chasing a complete understanding of the triggering mechanisms of a large rapidly evolving rockslide".* Landslides, 11: 747-764

Crosta, G.B., Hermanns, R.L., Dehls, J., Lari, S. Sepulveda, S. (2017). *"Rock avalanches clusters along the northern Chile coastal scarp".* Geomorphology, 289: 27–43.

Crozier, M.J., Glade T., (2005). *"Landslide hazard and risk: Issues, Concepts and approach".* In: T. Glade, M. Anderson and M. J. Crozier (Eds). Landslide Hazard and Risk. Wiley, pp. 2-40.

Crozier, M. (2010). *"Deciphering the effect of climate change on landslide activity: A review".* Geomorphology, 124: 260-267

Cruden, D.M., Hu, X.Q. (1993). "*Exhaustion and steady state models for predicting landslide hazards in the Canadian Rocky Mountains".* Geomorphology, 8: 279-285

Cui, P., Zhu, Y., Han, Y., Chen, X., Zhuang, J. (2009). *"The 12 May Wenchuan earthquake-induced landslide lakes: distribution and preliminary risk evaluation".* Landslides, 6: 209-223

Dai, F.C., Lee, C.F., Ngai, Y.Y. (2002). *"Landslide risk assessment and management: an overview".* Engineering Geology 64: 65-87

Davies, M.C.R., Hamza, O., Harris, C. (2001*). "The effect of rise in mean annual temperature on the stability of rock slopes containing ice-filled discontinuities"*. Permafrost and Periglacial Processes,12: 137–144

D'Amato, J. (2019). *"Apport d'une base de donneés d'éboulements rocheux obtenue par scanner laser dans la caractérisation des conditions de rupture et processus associés".* Bull Eng Geol Environ, 78: 653–668

De Biagi, V., Napoli, M.L., Barbero, M., Peila, D. (2017). *"Estimation of the return period of rockfalls according to their size".* Nat. Hazards Earth System Sci. 17: 103-113

Dietrich, A., Krautblatter, M. (2017). *"Evidence for enhanced debris-flow activity in the Northern Calcareous Alps since the 1980s (Plansee, Austria)".* Geomorphology, 287: 144–158

Dijkstra, T.A., Dixon, N., (2010). *"Climate change and slope stability: Challenges and approaches".* Q. J. Eng. Geol. Hydrogeol., 43 (4), 371–385.

Domènech, G., Alvioli M., Corominas, J. (2019). *"Preparing first-time slope failures hazard maps: from pixel-based to slope unit-based".* Landslides, DOI 10.1007/s10346-019-01279-4

Dorren, L.K.A., Berger, F., Putters, U.S. (2006). *"Real size experiments and 3D simulation of rockfall on forested and non-forested slopes".* Nat. Hazards Earth System Sci., 6: 145–153

Dunning, S.A., Rosser, N.J., Petley, D.N., Massey, C.R. (2006). *"Formation and failure of the Tsatichhu landslide dam, Bhutan".* Landslides, 3:107–113

Duzgun, H. S. B., Lacasse, S. (2005). *"Vulnerability and acceptable risk in integrated risk assessment framework".* In: Landslide risk management, edited by: Hungr, O., Fell, R., Couture, R., and Eberhardt, E., Balkema, Rotterdam, 505–515

Einstein, H.H. (1988). *"Special lecture, landslide risk assessment".* Proc. 5th Int. Symp. On Landslides, Lausanne, Switzerland. A.A. Balkema, Rotterdam, The Netherlands, 2: 1075-1090

Evans, S.G., Clague, J.J. (1994). *"Recent climatic change and catastrophic geomorphic processes in mountain environments".* Geomorphology, 10: 107-128

Fan, X., Juang, C. H., Wasowski, J., Huang, R., Xu, Q., Scaringi, G., van Westen, C. J., Havenith, H.B. (2018). *"What we have learned from the 2008 Wenchuan Earthquake and its aftermath: A decade of research and challenges"*. Eng. Geol., 241: 25–32,

Farvacque, M., Lopez-Saez, J., Corona, C., Toe, D., Bourrier, F., Eckert, N. (2019). *"Quantitative risk assessment in a rockfall-prone area: the case study of the Crolles municipality (Massif de la Chartreuse, French Alps)"*. Géomorphologie, 25: 7-19.

Fawcett, T. (2006). *"An introduction to ROC analysis".* Pattern Recognition Letters, 27: 861-874

Fell, R., Hartford, D. (1997). *"Landslide Risk Management".* In Cruden and Fell (eds.), "Landslide Risk Assessment", Balkema, Rotterdam, 51-110.

Fell, R., Ho, K.K.S., Lacasse, S., Leroi, E. (2005). *"A framework for landslide risk assessment and management".* Proceedings Int. Conference on Landslide Risk Management, London, Taylor & Francis, 3-25.

Fell, R., Corominas, J., Bonnard, Ch., Cascini, L., Leroi, E., Savage, W.Z. on behalf of the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes. (2008a). *"Guidelines for landslide susceptibility, hazard and risk zoning for land use planning"*. Eng. Geology, 102: 85-98

Fell, R., Corominas, J., Bonnard, Ch., Cascini, L., Leroi, E., Savage, W.Z. on behalf of the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes. (2008b). *"Guidelines for landslide susceptibility, hazard and risk zoning for land use planning Commentary.* Eng. Geology, 102: 99-111

Ferlisi, S., Cascini, L., Corominas, J., Matano, F. (2012) *"Rockfall risk assessment to persons travelling in vehicles along a road: the case study of the Amalfi coastal road (southern Italy)".* Nat. Hazards, 62(2): 691–721

Ferlisi, S., De Chiara, G., Cascini, L. (2016). *"Quantitative risk analysis for hyperconcentrated flows in Nocera Inferiore (southern Italy)"*. Nat. Hazards, 81 (Suppl. 1): 89–115.

Frank, F., Huggel, C., McArdell, B.W., Vieli, A. (2019). *"Landslides and increased debris-flow activity: A systematic comparison of six catchments in Switzerland".* Earth Surf. Process. Landforms 44, 699–712

Frattini, P., Crosta, G.B., Carrara, A. (2010). *"Techniques for evaluating the performance of landslide susceptibility models".* Eng. Geology, 111: 62-72

Frattini, P., Crosta, G.B. (2013). *"The role of material properties and landscape morphology on landslide size distributions".* Earth and Planetary Science Letters, 361: 310-319

Fuchs, S., Birkmann, J., Glade, T., (2012). *"Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges".* Nat. Hazards, 64 (3): 1969-1975.

Galli, M., Ardizzone, F., Cardinali, M., Guzzetti, F., Reichenbach, P. (2008). *"Comparing landslide inventory maps".* Geomorphology, 94: 268–289.

Gariano, S.L., Guzzetti, F. (2016). *"Landslides in a changing climate".* Earth Sci. Rev. 162: 227–252

GEO (2006). *"Assessment of landslide risk in natural hillsides in Hong Kong".* GEO Report nº 191, Hong Kong Geotechnical Engineering Office, 117 pp

Geertsema, M., Clague, J.J., Schwab, J.W., Evans, S.G. (2006). *"An overview of recent large catastrophic landslides in northern British Columbia, Canada".* Eng Geol., 83:120–143

Gill, J.C., Malamud, B.D. (2017). *"Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework".* Earth-Science Reviews, 166: 246–269

Glade, T. (2005). *"Landslide occurrence as a response to land use change: a review of evidence from New Zealand".* Catena, 51: 297-314

Glade, T., Anderson, M., Crozier, M.J. (2005). *"Landslide Hazard and Risk".* John Wiley & Sons, Ltd, Chichester, England. 802 pp.

Glade, T., Crozier, M. (2005). *"The nature of landslide hazard impact".* In: Glade T, Anderson M, Crozier M (eds) Landslide hazard and risk. Wiley, Chichester, pp 43–74

Godt, J.W., Baum, R.L., Savage, W.Z., Salciarini, D., Schulz, W.H., et al. (2008). *"Transient deterministic shallow landside modelling: requirements for susceptibility and hazard assessment in a GIS framework".* Eng. Geol., 102: 214–226

Glastonbury, J., Fell, R. (2010). *"Geotechnical characteristics of large rapid rock slides".* Can. Geotech. J. 47: 116–132

Gorum, T., O. Korup, C. J. van Westen, M. van der Meijde, C. Xu, van der Meer, F.D. (2014). *"Why so few? Landslides triggered by the 2002 Denali earthquake, Alaska".* Quat. Sci. Rev., 95, 80–94

Greiving, S., van Westen, C., Corominas, J., Glade, T., Malet, J.P., van Asch, T. (2014). *"Introduction: The components of Risk Governance".* In: T. Van Asch, J. Corominas, S. Greiving, J.P. Malet, S. Sterlacchini (Eds). Mountain Risks: From Prediction to Management and Governance, Springer Netherlands, pp. 1-27

Gruber, S., Haeberli, W. (2007). *“Permafrost in steep bedrock slopes and its temperature- related destabilization following climate change”.* Journal of Geophysical Research 112, F02S18

Guthrie, R.H., Evans S.G. (2004). *“Magnitude and frequency of landslides triggered by a storm event, Loughborough Inlet, British Columbia”.* Nat. Hazards Earth System Sci., 4: 475–483

Guzzetti, F., Carrara, A., Cardinali, M., Reichenbach, P., (1999). *“Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy”.* Geomorphology 31, 181–216.

Guzzetti, F., Crosta, G., Detti, R., Agliardi, F. (2002a) *“STONE: A computer program for the three-dimensional simulation of rock-falls”.* Computers & Geosciences 28: 1081-1095

Guzzetti, F., Malamud, B. D., Turcotte, D. L., Reichenbach, P. (2002b). *“Power-law correlations of landslide areas in Central Italy”.* Earth and Planet. Sc. Let., 195: 169–183

Guzzetti, F., Reichenbach, P., Wieczorek, G.F. (2003). *“Rockfall hazard and risk assessment in the Yosemite Valley, California, USA”.* Nat. Hazards Earth System Sci., 3: 491–503.

Guzzetti, F., Galli, M., Reichenbach, P., Ardizzone, F., Cardinali, M. (2005). *“Landslide hazard assessment in the Collazzone area, Umbria, Central Italy”.* Nat. Hazards Earth System Sci., 6: 115–131

Guzzetti, F., Reichenbach, P., Ardizzone, F., Cardinali, M., Galli, M. (2006). *“Estimating the quality of landslide susceptibility models”.* Geomorphology, 81: 166–184

Hansen, A. (1984). *“Landslide hazard analysis”.* In: D. Brunsden & D.B. Prior (eds) Slope Instability. John Wiley and Sons, New York, pp 523–602

Hantz, D. (2011). *“Quantitative assessment of diffuse rock fall hazard along a cliff foot”.* Nat. Hazards Earth Syst. Sci., 11: 1303–1309

Haque, U., Blum, P., da Silva, P. F., Andersen, P., Pilz, J., Chalov, S. R., Malet, J. P., et al. (2017). *“Fatal landslides in Europe”.* Landslides, 13, 1545–1554,

Harris, C., Arenson, L. U., Christiansen, H. H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hölzle, M., Humlum, O., Isaksen, K., Kääb, A., Kern-Lütschg, M. A., Lehning, M., Matsuoka, N., Murton, J. B., N¨otzli, J., Phillips, M., Ross, N., Seppälä, M., Springman, S. M., Mühll, D. V. (2009). *“Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses”.* Earth-Sci. Rev., 92, 117–171,

Hergarten, S. (2012). *“Topography-based modeling of large rockfalls and application to hazard assessment”.* Geophys. Res. Lett., 39, L13402, doi:10.1029/2012GL052090.

Hilker, N., Badoux, A., Hegg, C. (2009). *“The Swiss flood and landslide damage database 1972–2007”.* Nat Hazards Earth Syst Sci,. 9: 913–925

Ho, K.K.S. (2004). *“Recent advances in geotechnology for slope stabilization and landslide mitigation – perpective from Hong Kong”.* In: Lacerda, W.A., Ehrlich, M., Fontoura S.A.B., Sayao, A.S.F (eds) Landslides: Evaluation and Stabilization.. Taylor and Francis, London, UK. Vol. 2 pp. 1507-1560

Ho, K., Leroi, E., Roberts, B. (2000). *“Quantitative Risk Assessment : Application, Myths And Future Direction”.* Pro-ceedings of the International Conference on Geotechnical and Geological Engineering, GEOENG 2000, Melbourne, Australia, vol. 1. Technomic, Lancaster, pp. 236 – 312.

Ho, H.Y., Roberts, K.J. (2016). *“Guidelines for Natural Terrain Hazard Studies”.* GEO Report No. 138 (Second Edition). 173 pp.

Holm, K., Bovis, M.J., Jakob, M. (2004). *“The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia”.* Geomorphology, 57: 201 – 216.

Horton, P., Jaboyedoff, M., Rudaz, Zimmermann M. (2013). *“Flow-R, a model for susceptibility mapping of debris flows and other gravitational hazards at a regional scale”.* Nat. Hazards Earth Syst. Sci. 13, 869–885.

Houet, T., Grémont, M., Vacquié, L., Forget, Y., Bourrier, F., Peltier, A., Puissant, A., Bernardie, S., Grandjean, G. (2017). *“Downscaling scenarios of future land use and land cover changes using a participatory approach: An application to mountain risk assessment in the Pyrenees (France)”.* Reg. Environ. Chang., 17: 2293–2307.

Huggel, C., Clague, J.J., Korup, O. (2012). *“Is climate change responsible for changing landslide activity in high mountains?”*. Earth Surf. Processes Landforms, 37 :77–91.

Humbert, M., (1976). *“La cartographie en France des Zones Exposées à des Risques liés aux Mouvements du Sol. Cartes ZERMOS”.* IAEG Bull., 16, 80–82.

Hungr, O. (1997). *“Some methods of landslide hazard intensity mapping”.* Procs., Landslide Risk Workshop, R. Fell & D.M. Cruden, Eds., Balkema, Rotterdam , pp. 215-226.

Hungr, O., (2003). *“Flow slides and flows in granular soils”.* In: L. Picarelli (Ed.) FLOWS 2003, International Workshop, Sorrento, Italy. Patron pp. 37–44,

Hungr, O. (2016). *“A review of landslide hazard and risk assessment methodology”.* in – Aversa et al. (eds), Landslides and Engineered Slopes. Experience, Theory and Practice. CRC Press. pp. 3-27

Hungr, O., Clague, J., Morgenstern, N., VanDine, D., Stadel, D. (2016). *“A review of landslide risk acceptability practices in various countries”.* in – Aversa et al. (eds.), Landslides and Engineered Slopes. Experience, Theory and Practice, CRC Press. pp. 1121-1128.

Hungr, O., Corominas, J. Eberhardt, E. (2005). *“Estimating landslide motion mechanism, travel distance and velocity”.* In: O. Hungr, R. Fell, R. Couture and E. Eberhardt (Editors), Landslide risk management. Taylor & Francis Group, Vancouver, pp. 99-128.

Hungr, O., Evans, S.G., Hazzard, J. (1999). *“Magnitude and frequency of rock falls and rock slides along the main transportation corridors of south-western British Columbia”.* Canadian Geotechnical Journal 36: 224-238.

Hungr, O., Leroueil, S., Picarelli, L. (2014). *“The Varnes classification of landslide types, an update”.* Landslides, 11: 167-194.

Hungr, O., McDougall, S., Wise, M., Cullen, M. (2008) *“Magnitude–frequency relationships of debris flows and debris avalanches in relation to slope relief”.* Geomorphology 96: 355–365.

Hungr, O., Wong, H.H. (2007). *“Landslide risk acceptability criteria: Are F-N plots objective?”* Geotechnical News, 25 (4): 47-50.

Hurst, M.D., Ellis, M.A., Royse, K.R., Lee, K.A. Freeborough K. (2013). “*Controls on the magnitude-frequency scaling of an inventory of secular landslides”.* Earth Surf. Dyn., 1 :67–78.

Irigaray, C., Fernández, T., El Hamdouni, R., Chacón, J. (1999). *“Verification of landslide susceptibility mapping. A case study”.* Earth Surf Proc Land., 24: 537–544.

Jaboyedoff, M. (2003). *“CONEFALL 1.0 : A program to estimate propagation zones of rockfall based on cone method”.* Quanterra, www. quanterra.ch.

Jaboyedoff, M., Dudt, J.P., Labiouse, V. (2005). *“An attempt to refine rockfall hazard zoning based on the kinetic energy, frequency and fragmentation degree”.* Nat. Hazards Earth Syst. Sci., 5: 621–632.

Jaboyedoff, M., Labiouse, V. (2011). *“Preliminary estimation of rockfall runout zones”.* Nat. Hazards Earth Syst. Sci., 11, 819–828.

Jaboyedoff, M., Oppikofer, T., Abellán, A., Derron, M.H., Loye, A., Metzger, R., Pedrazzini, A. (2012*). “Use of LIDAR in landslide investigations: A review”.* Natural Hazards, 61: 5–28.

Jackson, L.E., Bobrowsky, P.T., Bichler, A. (2012). *“Identification, maps and mapping”.* – Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction; Geological Survey of Canada, Open File 7059, doi:10.4095/292122

Jaiswal, P., van. Westen, C.J., V. Jetten, V. (2010). *“Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India”.* Nat. Hazards Earth Syst. Sci., 10, 1253–1267.

Jakob, M., Bovis, M., Oden, M., (2005). *“Estimating debris flow magnitude and frequency from channel recharge rates”.* Earth surf. Processes Land,. 30, 755–766.

Jarman, D., Calvet, M., Corominas, J., Delmas, M., Gunnell, Y. (2014). *”Large-scale rock slope failures in the eastern Pyrenees: identifying a sparse but significant population in paraglacial and parafluvial contexts”.* Geograf. Ann. Ser. A Phys. Geogr. 96, 357–391.

Jebur, M.N., Pradhan, B., Tehrany, M.S. (2014). *“Optimization of landslide conditioning factors using very high-resolution airborne laser scanning (LiDAR) data at catchment scale”.* Remote Sens Environ., 152: 150–165.

Johnson, B.G., Smith, J.A., Diemer, J.A. (2017). *“A chronology of post-glacial landslides suggests that slight increases in precipitation could trigger a disproportionate geomorphic response”.* Earth Surface Processes and Landforms, 42: 2223-2239.

Jomelli, V., Pech, V.P., Chochillon, C., Brunstein, D., (2004). *“Geomorphic variations of debris flows and recent climatic change in the French Alps”.* Climatic Change 64, 77–102.

Kääb, A., Reichmuth, T. (2005). *“Advance mechanisms of rockglaciers”.* Permafrost and Periglacial Processes 16 (2), 187–193.

Kappes, M. S., Gruber, K., Frigerio, S., Bell, R., Keiler, M., Glade, T. (2012a). *“The MultiRISK platform: The technical concept and application of a regional-scale multihazard exposure analysis tool”.* Geomorphology, 151–152: 139–155.

Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T., (2012b). *“Challenges of analyzing multi-hazard risk: a review”.* Nat. Hazards, 64: 1925–1958.

Keefer, D.K. (1984). *“Landslides caused by earthquakes”.* Geological Society of America Bulletin 95: 406–421.

Keiler, M., Knight, J., Harrison, S. (2010). *“Climate change and geomorphoogical hazards in the eastern European Alps”.* Philosophical Transactions of the Royal Society A 368: 2461–2479.

Kijko, A., Singh, M. (2011). *“Statistical tools for maximum possible earthquake magnitude estimation”.* Acta Geohysica, 59, 4, 674-700.

Klemes, V. (2000). *“Tall tales about tails of hydrological distributions”.* J. Hydrol. Eng. 5: 227-231

Korup, O., Tweed, F. (2007). *“Ice, moraine, and landslide dams in mountainous terrain”.* Quat. Sci. Rev., 26: 3406-3422.

Kron, W. (2000). *“Natural Disasters: Lessons from the Past – Concerns for the Future”.* The Geneva Papers on Risk and Insurance - Issues and Practice, 25 (4): 570–581 https://doi.org/10.1111/1468-0440.00083

Lan, H., Martin, C.D., Lim, C.H. (2007). *“RockFall analyst: a GIS extension for three-dimensional and spatially distributed rockfall hazard modeling”.* Comput. & Geosci., 33:262–279

Landeros-Mugica, K., Urbina-Soria, J., & Alcántara-Ayala, I. (2016). *“The good, the bad and the ugly: on the interactions among experience, exposure and commitment with reference to landslide risk perception in México”*. Nat. Hazards, 80 : 1515–1537

Lateltin, O. (1997). *“Recommandations: prise en compte des dangers dus aux mouvements de terrain dans le cadre des activités de l'aménagement du territoire”.* OFAT, OFEE, OFEFP, Berne, Switzerland, pp 42

Lateltin, O., Haemmig, C., Raetzo, H., Bonnard, C. (2005). *“Landslide risk management in Switzerland*”. Landslides, 2: 313–320,

Lee, E.M., Jones, D.K.C. (2013). *“Landslide Risk Assessment”*. ICE publishing, London, 428 pp.

Leroi, E. (1996). *“Landslide hazard – risk maps at different scales: objectives, tools and developments”.* In Landslides Proc. Int. Symp. On Landslides, Trondheim, 17-21 June, K. Senneset (ed), 35-52.

Leroi, E., Bonnard, C., Fell, R., McInnes, R. (2005). *“Risk assessment and management”.* In: O. Hungr, R. Fell, R. Couture and E. Eberhardt (Editors), Landslide risk management. Taylor & Francis Group, Vancouver,. pp. 159-198

Lin, C.W., Liu, S.H., Lee, S.Y., Liu, C.C. (2006). *“Impacts of the Chi-Chi earthquake on subsequent rainfall-induced landslides in central Taiwan”.* Eng. Geol. 86: 87–101.

Loew, S., Gischig, V., Glueer, F., Seifert, R., Moore, J. R. (2017). *“Multidisciplinary monitoring of progressive failure processes in brittle rock slopes”.* in: Rock Mechanics and Engineering Volume 4: Excavation, Support and Monitoring, CRC Press, London, 4, 629–662.

Macciotta, R., Martin, C. D., Morgenstern, N. R., Cruden, D. M. (2016). *“Quantitative risk assessment of slope hazards along a section of railway in the Canadian Cordillera – a methodology considering the uncertainty in the results”.* Landslides, 13: 115-127

Malamud, B.D., Turcotte, D.L., Guzzetti, F., Reichenbach, P. (2004) *“Landslide inventories and their statistical properties”.* Earth Surface Processes and Landforms, 29: 687–711

Marc, O., Hovius, N. (2015*). “Amalgamation in landslide maps: effects and automatic detection”.* Nat. Hazards Earth Syst. Sci., 15: 723-733,

Marc, O., Hovius, N. Meunier, P., Gorum, T., Uchida, T. (2016). *“A seismologically consistent expression for the total area and volume of earthquake-triggered landsliding”.* Journal Geophysical Research Earth Surface, 121: 640-663

Martha, T., van Westen, C., Kerle, N., Jetten, V., Kumar, K.V. (2013). *“Landslide hazard and risk assessment using semi-automatically created landslide inventories”*. Geomorphology, 184: 139-150.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M.L., Di Ruocco, A. (2012). *“Basic principles of multi-risk assessment: a case study in Italy”.* Nat. Hazards, 62, 551–573.

Matas, G., Lantada, N., Corominas, J., Gili, J.A., Ruiz-Carulla, R., Prades, A. (2017). “*RockGIS: a GIS-based model for the analysis of fragmentation in rockfalls”.* Landslides, 14: 1565–1578

Mavrouli, O., Corominas, J. (2010). *“Vulnerability of simple reinforced concrete buildings to damage by rockfalls”.* Landslides, 7:169–180

Mavrouli, O., Corominas, J. (2017*). “Comparing rockfall scar volumes and kinematically detachable rock masses”.* Eng. Geology, 219: 64-73

Mavrouli, O., Fotopoulou, S., Pitilakis, K., Zuccaro, G., Corominas, J., Santo, A., Cacace, F., De Gregorio, D., Di Crescenzo, G., Foerster, E., Ulrich, T. (2014) *“Vulnerability assessment for reinforced concrete buildings exposed to landslides”.* Bull Eng Geol Environ., 73: 265– 289

Mavrouli, O., Corominas, J., Ibarbia, I., Alonso, N., Jugo, J., Ruiz, J., Luzuriaga, S., Navarro, J.A. (2019). *“Integrated risk assessment due to slope instabilities in the roadway network of Gipuzkoa, Basque Country”.* Nat. Hazards Earth Syst. Sci., 19: 399–419

McDougall, S. (2017). *“Canadian Geotechnical Colloquium: Landslide runout analysis - current practice and challenges”.* Canadian Geotechnical Journal, 54: 605–620,

McDougall, S., Hungr, O. (2004). *“A model for the analysis of rapid landslide run out motion across three dimensional terrain”.* Canadian Geotechnical Journal 41: 1084-1097

McDougall, S., Hungr, O. (2005). *“Dynamic modelling of entrainment in rapid landslides”.* Can. Geotech. J. 42: 1437–1448

Messenzehl, K., Meyer, H., Otto, J.C., Hoffmann, T., Dikau, R. (2017). *“Regional-scale controls on the spatial activity of rockfalls (Turtmann Valley, Swiss Alps) - A multivariate modeling approach”.* Geomorphology, 287: 29–45.

Meusburger, K., Alewell, C. (2009). *“On the influence of temporal change on the validity of landslide susceptibility maps in an alpine catchment, Switzerland”.* Nat. Hazards Earth Syst. Sci. 9, 1495–1507.

Mignan, A., Wiemer, S., Giardini, D. (2014). *“The quantification of low-probability–high- consequences events: part I. a generic multi-risk approach”.* Nat. Hazards 73, 1999–2022

Neri, A., Aspinall, W.P., Cioni, R., Bertagnini, A., et al. (2008). *“Developing an event tree for probabilistic hazard and risk assessment at Vesuvius”.* J. Volcanol. Geoth. Res., 178(3), 397–415.

Nilsen, T.H., Wright, R.H., Vlasic, T.C., Spangle, W.E., (1979). *“Relative slope stability and land-use planning in the San Francisco Bay region, California”.* U.S. Geological Survey Professional Paper 944: 96.

Orlowsky, B., Seneviratne, S.I. (2012). *“Global changes in extreme events: regional and seasonal dimension”.* Clim. Chang. 110, 669–696.

Papathoma-Köhle, M., Keiler, M., Totschnig, R., Glade, T. (2012). *“Improvement of vulnerability curves using data from extreme events: debris flow event in South Tyrol”*. Nat. Hazards, 64: 2083-2105.

Parker, R.N., Hancox, G.T., Petley, D.N., Massey, C.I., Densmore, A.L. and N.J. Rosser (2015). *“Spatial distributions of earthquake-induced landslides and hillslope preconditioning in the northwest South Island, New Zealand”*. Earth Surface Dynamics, 3: 501-525.

Parry, S. (2016). *“Quantification of landslide hazards: example from Hong Kong. Landslides and Engineered Slopes*”. Experience, Theory and

Practice- Aversa et al. (Eds). CRC Press. pp. 1567-1573.

Parry, S., Ng, K.C. (2010). *"The assessment of landslide risk from natural slopes in Hong Kong: an engineering geological perspective".* Quarterly Journal of Engineering Geology and Hydrogeology, 43, 307–32.

Pastor, M., Haddad, B., Sorbino, G., Cuomo, S. & Drempetic, V. (2009). *"A depth-integrated, coupled SPH model for flow-like landslides and related phenomena".* Int. J. Numer. Analyt. Methods Geomech. 33: 143–172.

Patton, A.I., Rathburn S.L., Capps, D.M. (2019). *"Landslide response to climate change in permafrost regions".* Geomorphology, 340: 116–128.

Peduto, D., Ferlisi, S., Nicodemo, G., Reale, D., Pisciotta, G., Gullà, G. (2017). *"Empirical fragility and vulnerability curves for buildings exposed to slow-moving landslides at medium and large scales".* Landslides, 14:1993–2007.

Pelletier, J.D., Malamud, B.D., Blodgett, T., Turcotte, D.L. (1997). *"Scale-invariance of soil moisture variability and its implications for the frequency-size distribution of landslides"*. Eng. Geol., 48: 255-268.

Petley, D.N., Hearn, G.J., Hart, A., Rosser, N.J., Dunning, S.A., Oven, K., Mitchell, W.A. (2007). *"Trends in landslide occurrence in Nepal".* Nat Hazards, 43:23–44.

Petley, D.N., Hearn, G.J., Hart, A., Rosser, N.J., Dunning, S.A., Oven, K., Mitchell, W.A. (2007) "*Trends in landslide occurrence in Nepal".* Nat Hazards, 43:23–44.

Petley, D.N. (2010). *"On the impact of climate change and population growth on the occurrence of fatal landslides in South, East and SE Asia".* Q J Eng Geol Hydrogeol, 43:487–496.

Petley, D.N. (2012a). *"Global patterns of loss of life from landslides".* Geology, 40: 927-930

Petley, D.N. (2010b). *"On the impact of climate change and population growth on the occurrence of fatal landslides in South, East and SE Asia".* Q. J. Engineering Geology and Hydrogeology, 43: 487–496.

Petschko H, Brenning A, Bell R et al (2014). *"Assessing the quality of landslide susceptibility maps—case study Lower Austria"*. Nat. Hazards Earth Syst. Sci., 14: 95–118.

Picarelli, L., Oboni, F., Evans, S.G., Mostyn, G., Fell, R., (2005). *"Hazard characterization and quantification".* In O. Hungr, R. Fell, R. Couture and E. Eberthardt (eds.) Landslide Risk Management. Taylor and Francis, London. pp. 27-61

Picarelli, L., Olivares, L., Avolio, B. (2008). *"Zoning for flowslide and debris flow in pyroclastic soils of Campania Region based on infinite slope analysis".* Eng Geol., 102:132–141

Pierson, T. C., Janda, R. J., Thouret, J. C., Borrero, C. A. (1990). *"Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Columbia, and consequent mobilization, flow and deposition of lahars".* J. Volcanology Geothermal Res. 41: 17–66.

Porter, M., Jakob, M., Holm, K. (2009). *"Proposed landslide risk tolerance criteria".* 62nd Canadian Geotechnical Conference and 10th Joint CGS/IAH-CNC Groundwater Conference, Halifax, pp 533–541

Porter, M., Morgenstern, N. (2013). *"Landslide Risk Evaluation"* – Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction; Geological Survey of Canada, Open File 7312, 21 p. doi:10.4095/292234

Quan Luna, B., Blahut, J., Van Westen, C.J., Sterlacchini, S., Van Asch, T.W.J., Akbas, S.O. (2011). *"The application of numerical debris flow modelling for the generation of physical vulnerability curves".* Nat Hazards Earth Syst Sci., 11: 2047–2060

Ravanel, L., Deline P. (2010). "*Climate influence on rockfalls in high-Alpine steep rockwalls: the north side of the Aiguilles de Chamonix (Mont Blanc massif) since the end of the Little Ice Age".* The Holocene, 21: 357-365

Reichenbach, P., Rossi, M., Malamud, B.D., Mihir, M., Guzzetti, F. (2018). *"A review of statistically-based landslide susceptibility models".* Earth Science Reviews 180: 60–91

Reid, L.M., Page, M.J. (2003). *"Magnitude and frequency of landsliding in a large New Zealand catchment"*. Geomorphology, 49: 71-88.

Remondo, J., Gonzalez, A., Diaz De Teran, J.R., Cendrero, A., Fabbri, A., Chung, C.F. (2003). *"Validation of landslide susceptibility maps; examples and applications from a case study in Northern Spain"*. Natural Hazards 30, 437 – 449.

Remondo, J., Bonachea, J., Cendrero, A. (2005). *"A statistical approach to landslide risk modelling at basin scale: from landslide susceptibility to quantitative risk assessment"*. Landslides, 2: 321-328.

Rianna, G., Zollo, A.L., Tommasi, P., Paciucci, M., Comegna, L., Mercogliano, P. (2014). *"Evaluation of the effects of climate changes on landslide activity of Orvieto clayey slope"*. Procedia Earth Plan. Sci., 9: 54–63.

Richardson, S.D., Reynolds, J.M. (2000). *"An overview of glacial hazards in the Himalayas"*. Quat. Int., 66: 31–47.

Rossi, M., Witt, A., Guzzetti, F., Malamud, B., Peruccacci, S. (2010). *"Analysis of historical landslide time series in the Emilia-Romagna region, northern Italy"*. Earth Surface Processes and Landforms 35, 1123–1137.

Sandri, L., Thouret, J-C., Constantinescu, R., Biass, S., Tonini R. (2014). *"Long-term multi-hazard assessment for El Misti volcano (Peru)".* Bull Volcanol 2014, 76: 771-797.

Scaioni, M., Longoni, L., Melillo, V., Papini, M. (2014). *"Remote sensing for landslide investigations: An overview of recent achievements and perspectives".* Remote Sens., 6: 9600–9652.

Scheidl, C., Rickenmann, D. (2010). *"Empirical prediction of debris-flow mobility and deposition on fans".* Earth Surf Process Landforms, 35: 157–173

Schlögel, R., Marchesini, I., Alvioli, M., Reichenbach, P., Rossi, M., Malet, J. P. (2018). *"Optimizing landslide susceptibility zonation: Effects of DEM spatial resolution and slope unit delineation on logistic regression models".* Geomorphology, 301, 10– 20

Schmidt, J., Matcham, I., Reese, S., King, A., Bell, R., Henderson, R., Smart, G., Cousins, J., Smith, W., and Heron, D. (2011). *"Quantitative multi-risk analysis for natural hazards: a frame-work for multi-risk modelling"*. Nat. Hazards, 58, 1169–1192

Schuster, R.L., Logan, R.L., Pringle, P.T. (1992). *"Prehistoric rock avalanches in the Olympic Mountains, Washington"*. Science, 258: 1620-1621.

Sciarra, M., Coco, L., Urbano, T. (2017). *"Assessment and validation of GIS-based landslide susceptibility maps: a case study from Feltrino stream basin (Central Italy)"*. Bull Eng Geol Environ, 76:437–456.

Segoni, S., Piciullo, L., Gariano, S.L. (2018). *"A review of the recent literature on rainfall thresholds for landslide occurrence."* Landslides, 15:1483–1501

Self, S. (2006). *"The effects and consequences of very large explosive volcanic eruptions".* Phil. T. Roy. Soc. A, 364: 2073–2097.

Sepúlveda, S.A., Petley, D. N., (2015). *"Regional trends and controlling factors of fatal landslides in Latin America and the Caribbean"*. Nat. Hazards Earth Syst. Sci., 15:1821–1833.

Stark, C.P., Hovius, N. (2001). *"The characterization of landslide size distributions".* Geophysical Research Letters 28: 1091–1094.

Steger, S., Brenning, A., Bell, R. S., Glade, T. (2016). *"The propagation of inventory-based positional errors into statistical landslide susceptibility models".* Nat. Hazards Earth Syst. Sci., 16: 2729–2745.

Sterlacchini, S., Ballabio, C., Blahut, J., Masetti, M., Sorichetta, A. (2011). *"Spatial agreement of predicted patterns in landslide susceptibility maps".* Geomorphology, 125, 51–61.

Stock, G.M., Luco, N., Collins, B.D., Harp, E.L., Reichenbach, P., Frankel, K.L. (2012). *"Quantitative rock-fall hazard and risk assessment for Yosemite Valley, Yosemite National Park, California".* USGS Scientific Investigations Report 2014–5129. Available from: http://pubs.usgs.gov/sir/2014/5129/

Stoffel, M., Mendlik, T., Schneuwly-Bollschweiler, M., Gobiet, A. (2014). *"Possible impacts of climate change on debris-flow activity in the Swiss Alps".* Climatic Change 122, 141–155.

Swain, R.E., England, J.F.Jr., Bullard, K.L., Raff, D.A. (2006). *"Guidelines for evaluating hydrologic hazards".* U.S. Department of Interior, Bureau of Reclamation, Denver, CO, 83 pp.

Swets, J. (1988). *"Measuring the accuracy of diagnostic systems".* Science, 240: 1285-1293.

Tang, C., Zhu, J., Qi, X., Ding, J. (2011). *"Landslides induced by the Wenchuan earthquake and the subsequent strong rainfall event: a case study in the Beichuan area of China"*. Eng. Geol. 122: 22–33.

Tanoue, M., Hirabayashi, Y., and Ikeuchi, H. (2016). *"Global-scale river flood vulnerability in the last 50 years".* Scientific Reports, 6, 36021

TC32-Technical Committee 32 ISSMGE (2004). *"Risk assessment – Glossary of terms".* www.engmath.dal.ca/tc32/2004Glossary_Draft1.pdf

Terzi, S., Torresan, S., Schneiderbauer, S., Critto, A., Zebisch, M., Marcomini, A. (2019). *"Multi-risk assessment in mountain regions: a review of modelling approaches for climate change adaptation".* J. Environ. Manag. 232, 759–771.

Tilloy, A., Malamud, B.D., Winter, H., Joly-Laugel, A. (2019). *"A Review of Quantification Methodologies for Multi-Hazard Interrelationships".* Earth-Science Reviews, 196, doi:j.earscirev.2019.102881

Totschnig, R., Fuchs, S. (2013). *"Mountain torrents: quantifying vulnerability and assessing uncertainties".* Eng. Geol., 155: 31-44.

Trigila, A., Carla, I., Carlo, E., Gabriele, S.M. (2015). *"Comparison of logistic regression and random forests techniques for shallow landslide susceptibility assessment in Giampilieri (NE Sicily, Italy)".* Geomorphology, 249: 119-136.

United Nations (2009). *"Global assessment report on disaster risk reduction: Risk and poverty in a changing climate".* Geneva: UNISDR.

USBR. (2015). *"Best practices in dam and levee safety risk analysis".* Version 4.0 USBR, USACE. https://www.usbr.gov/ssle/damsafety/risk/BestPractices

Van Veen, M., Hutchinson, D.J., Bonneau, D.A., Sala, Z., Ondercin, M., Lato, M. (2017). *"Combining temporal 3D remote sensing data with spatial rockfall simulations for improved understanding of hazardous slopes within rail corridors".* Nat. Hazards Earth Syst. Sci. 18, 2295–2308.

Van Westen, C.J., Van Asch, T.W., Soeters, R. (2006). *"Landslide hazard and risk zonation-why is it still so difficult?".* Bull. Eng. Geol. Environ., 65: 167–184.

Van Westen, C.J., Castellanos Abella, E.A., Sekhar, L.K. (2008). *"Spatial data for landslide susceptibility, hazards and vulnerability assessment: an overview".* Engineering Geology, 102: 112–131.

Van Westen, C. J., Kappes, M.S., Luna, B. Q. Frigerio, S., Glade, T., Malet, J.P. (2014). *"Medium-scale multi-hazard risk assessment of gravitational processes".* In T. Van Asch et al. (eds.) Mountain Risks: From Prediction to Management and Governance, pp. 201–231, Springer, Netherlands.

Varnes, D.J. (1984). *"Landslide hazard zonation: A review of principles and practice".* Natural Hazards, vol.3, Paris, France. UNESCO, 63p.

Von Ruette, J., Papritz, A., Lehmann, P., Rickli, C. D. (2011). *"Spatial statistical modeling of shallow landslides—validating predictions for different landslide inventories and rainfall events".* Geomorphology, 133: 11–22.

Wells, D.L., Coppersmith, K.J. (1994). "*New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement".* Bull. Seism. Soc. Am. 84, 4, 974-1002.

Wheeler, R.L. (2009). *"Methods of Mmax estimation east of the Rocky Mountains".* U.S. Geological Survey Open-File Report 2009-1018, 44 pp.

Williams, J.G., Rosser, N.J., Hardy, R.J., Brain, M.J. (2019). *"The Importance of Monitoring Interval for Rockfall Magnitude-Frequency Estimation".* Journal of Geophysical Research. Earth Surface. doi: 10.1029/2019JF005225

Winsemius, H. C., Aerts, J. C. J. H., van Beek, L. P. H., Bierkens, M. F. P., Bouwman, A., Jongman, B., Kwadijk, J. C. J., Ligtvoet, W., Lucas, P. L., van Vuuren, D. P., Ward, P. J. (2016). *"Global drivers of future river flood risk".* Nat. Clim. Change, 6: 381–385.

Winter, M.G., Bromhead, E.N. (2012). *"Landslide risk: some issues that determine societal acceptance".* Nat. Hazards, 62:169–187

WP/ WLI (1993). *"A suggested method for describing the activity of a landslide".* Bulletin of the International Association of Engineering Geology 47: 53-57

Yano, A., Shinohara, Y., Tsunetaka, H., Mizuno, H., Kubota, T. (2019). *"Distribution of landslides caused by heavy rainfall events and an earthquake in northern Aso Volcano, Japan from 1955 to 2016".* Geomorphology, 327: 533–541.

Yilmaz, I. (2009). *"Landslide susceptibility mapping using frequency ratio, logistic regression, artificial neural networks and their comparison: a case study from Kat landslides (Tokat—Turkey)".* Comput Geosci., 35:1125–1138.

Žabota, B., Repe, B., Kobal, M. (2019). *"Influence of digital elevation model resolution on rockfall modelling".* Geomorphology, 328: 183–195.

Zêzere, J.L., Reis, E., Garcia, R., Oliveira, S., Rodrigues, M.L., Vieira, G., Ferreira, A.B. (2004). *"Integration of spatial and temporal data for the definition of different landslide hazard scenarios in the area north of Lisbon (Portugal)".* Nat. Hazards Earth Syst. Sci., 4: 133–146.

Zêzere, J. L., Garcia, R. A. C., Oliveira, S. C., Reis, E. (2008). *"Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal)".* Geomorphology, 94: 467–495.

Zhang, F., Huang, X. (2018). *"Trend and spatiotemporal distribution of fatal landslides triggered by non-seismic effects in China".* Landslides, 15: 1663–1674.

Zhang, S., Zhang, L.M., Peng, M., Zhang, L.L., Zhao, H.F., Chen, H.X. (2012). *"Assessment of risks of loose landslide deposits formed by the 2008 Wenchuan earthquake".* Nat. Hazards Earth Syst. Sci., 12: 1381–1392.

Zhang, S., Zhang, L.M., Glade, T. (2014). *"Characteristics of earthquake- and rain-induced landslides near the epicenter of Wenchuan earthquake".* Eng. Geol., 175: 58-73

Zhang, J., van Westen, C., Tanyas, H., Mavrouli, O., Ge,Y., Bajrachary, S., Gurung, D.R., Dhital, M.R., and Khana, N.R. (2019). *"How size and trigger matter: analyzing rainfall- and earthquake-triggered landslide inventories and their causal relation in the Koshi River basin, Central Himalaya".* Nat. Hazards Earth Syst. Sci., 19: 1789-1805.

Zimmermann, MN., Haeberli, W. (1992). *"Climatic change and debris flow activity in high-mountain areas. A case study in the Swiss Alps".* In: Greenhouse-Impact on Cold-Climate Ecosystems and Landscapes. Catena supplement, 22: 59-72.

Zuccaro, G., Cacace, F., Spence, R., Baxter, P. (2008). *"Impact of explosive eruption scenarios at Vesuvius".* J Volcanol Geoth Res .,178: 416–453.