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## Recommendations for the quantitative assessment of landslide risk
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| **Abstract:** | This paper presents recommended methodologies for the quantitative assessment of the landslide hazard, vulnerability and risk at different scales (site specific, local, regional and national), as well as for the verification and validation of the results. The methodologies described focus on the evaluation of the probability of occurrence of different landslide types with certain characteristics. Methods to determine the spatial distribution of landslide intensity, the characterisation of the elements at risk, the assessment of the potential degree of damage and the quantification of the vulnerability of the elements at risk, and the quantitative risk assessment (QRA) are also described. The paper is intended to be used by scientists and practising engineers, geologists and other landslide experts. |

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# Recommendations for the quantitative assessment of landslide risk

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# Abstract

This paper presents recommended methodologies for the quantitative assessment of the landslide hazard, vulnerability and risk at different scales (site specific, local, regional and national), as well as for the verification and validation of the results. The methodologies described focus on the evaluation of the probability of occurrence of different landslide types with certain characteristics. Methods to determine the spatial distribution of landslide intensity, the characterisation of the elements at risk, the assessment of the potential degree of damage and the quantification of the vulnerability of the elements at risk, and the quantitative risk assessment (QRA) are also described. The paper is intended to be used by scientists and practising engineers, geologists and other landslide experts.


# 1. Introduction

Despite considerable improvements in our understanding of instability mechanisms and the availability of a wide range of mitigation techniques, landslides still cause a significant death toll and significant economic losses all over the world. Recent studies (Petley 2012) have shown that losses are concentrated in less developed countries in which there is relatively little investment in understanding the hazards and risks associated with landslides, associated with a lack of the appropriate resources. Cooperative research and greater capacity building efforts are required to support the local and regional administrations which are in charge of landslide risk management in most of the countries.

Authorities and decision makers need maps depicting the areas that may be affected by landslides in order that they are considered in development plans and/or that appropriate risk mitigation measures are implemented. A wide variety of methods for assessing landslide susceptibility, hazard and risk is available and to assist in risk management decisions, several institutions and scientific societies have proposed guidelines for the preparation of landslide hazard maps (i.e. OFAT, OFEE, OFEFP 1997; GEO 2006; AGS 2007; Fell et al. 2008a, 2008b) with the common goal of using a unified terminology, and highlighting the fundamental data needed for preparing the maps and guiding practitioners in their analyses. Some of them have become legislated standards. However, the methodologies implemented diverge significantly from country to country and even within the same country (Corominas et al. 2010).

To manage risk, it must be first analysed and evaluated. The landslide risk for an object or an area must be calculated with reference to a given time frame, for which the expected frequency or probability of occurrence of an event of intensity higher than a minimum established value is evaluated. In that respect, there is an increasing need to perform Quantitative Risk Assessment (QRA). QRA is distinguished from qualitative risk assessment by the input data, the procedures used in the analysis and the final risk output. In contrast with qualitative risk assessment that yields results in terms of weighted indices, relative ranks (e.g. low, moderate and high) or numerical classification, QRA quantifies the probability of a given level of loss and the associated uncertainties.

Performing a QRA is important for scientists and engineers because risk is quantified in an objective and reproducible manner and the results can be compared from one location (site, region, etc.) to another. Furthermore it helps with the identification of the gaps in the input data and the understanding of the weaknesses of the analyses used. For landslide risk managers it is also useful because it allows a cost-benefit analysis to be performed and it provides the basis for the prioritization of management and mitigation actions and the associated allocation of resources. For society in general, QRA helps to increase the awareness of existing risk levels and the appreciation of the efficacy of the actions undertaken.

For QRA, more accurate geological and geomechanical input data and a high-quality DEM are usually necessary to evaluate a range of possible scenarios, design events and return periods. Lee and Jones (2004) warned that the probability of landsliding and the value of adverse consequences are only estimates. Due to limitations in the available information, the use of numbers may conceal that the potential for error is great. In that respect, QRA is not necessarily more objective than the qualitative estimations as, for example, probability may be calculated based on personal judgment. It facilitates, however, clear and unambiguous communication between geoscience professionals and land owners and decision-makers.

Risk for a single landslide scenario may be expressed analytically as follows:

$$R = P(M_i)P\left(X_j \middle| M_i\right)P\left(T \middle| X_j\right)V_{ij}C \qquad (1)$$

where:

$R$ is the 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,

$P(M_i)$ is the probability of occurrence of a landslide of magnitude $M_{i,}$

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

$P(T \mid X_j)$ is the probability of the element being at the point $X$ at the time of the landslide occurrence,

$V_{ij}$ is the vulnerability of the element being impacted by a landslide of magnitude i and intensity j, and

$C$ is the value of the element at risk.

Three basic components appear in Equation (1) that must be specifically considered in the assessment: the hazard, the exposure of the elements at risk, and their vulnerability. They are characterized by both spatial and non-spatial attributes. Landslide hazard is characterized by its probability of occurrence and intensity (see section 6); the latter expresses the severity of the hazard. The elements at risk are the population, properties, economic activities, including public services, or any other defined entities exposed to hazards in a given area (UN-ISDR 2004). The elements at risk also have spatial and non-spatial characteristics. The interaction of hazard and the elements at risk involves the exposure and the vulnerability of the latter. Exposure indicates to what extent the elements at risk are actually located in the path of a particular landslide. Vulnerability refers to the conditions determined by physical, social, economic and environmental factors or processes, which makes a community susceptible to the impact of hazards (UN-ISDR 2004). Physical vulnerability is evaluated as the interaction between the intensity of the hazard and the type of elements at risk, making use of so-called vulnerability curves (see Section 7.1). For further explanations on hazard and risk assessment the reader is referred to textbooks such as Lee and Jones (2004), Glade et al. (2005) and Smith and Petley (2008).

Probably, the most critical issue is the determination of the temporal occurrence of landslides. In many regions the lack of data prevents the performance of a quantitative determination of the probability of slope failure or landslide reactivation within a defined time span. Despite this limitation, landslide risk management decisions are sometimes taken considering the spatial distribution of existing or potential landslides.

This is carried out by means of the analysis of the landslide predisposing factors or susceptibility analysis (see Section 5).

The goal of these recommendations is to present an overview of the existing methodologies for quantitative assessment and zoning of landslide susceptibility, hazard and risk at different scales and to provide guidance on how to implement them. They are not intended to become standards. They aim to provide a selection of quantitative tools to researchers and practitioners involved in landslide hazard and risk assessment, and mapping procedures. Users must be aware of the information and tasks required to characterize the landslide areas, to assess the hazard level, and to evaluate the potential risks as well as the associated uncertainties.

The paper is structured similarly to the JTC-1 Guidelines (Fell et al. 2008a,b), in the preparation of which some of the authors were deeply involved. However, all the sections have been updated. Sections 2 to 4 describe the framework of the QRA and its main components; the requirements associated with the scale of work as well as the hazard and risk descriptors; and the input data and their sources. Sections 5 to 7 discuss respectively the available methods for quantifying and mapping landslide susceptibility, hazard and risk. Finally, Section 8 presents procedures to check the reliability of the maps and validate the results. At the end of the document an Annex is included with the basic definitions of terms used.

These recommendations focus on quantitative approaches only. A significant effort has been devoted to topics that were only marginally treated in previously published guidelines, sometimes requiring novel developments: (a) the procedures for preparing landslide hazard maps from susceptibility maps; (b) the analysis of hazards multiple landslide types; (c) the assessment of the exposure of the elements at risk; (d) the assessment of the vulnerability, particularly the physical vulnerability and the construction of vulnerability curves; and (e) verification of the models and validation of the landslide maps.

# 2. QRA framework

The general framework involves the complete process of risk assessment and risk control (or risk treatment). Risk assessment includes the process of risk analysis and risk evaluation. Risk analysis uses available information to estimate the risk to individuals, population, property, or the environment, from hazards. Risk analysis generally contains the following steps: hazard identification, hazard assessment, inventory of elements at risk and exposure, vulnerability assessment and risk estimation. Since all of these steps have an important spatial component, risk analysis often requires the management of a set of spatial data, and the use of Geographic Information Systems. Risk evaluation is the stage at which values and judgments enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Landslide hazard assessment requires a multi-hazard approach as different types of landslides may occur, each with different characteristics and causal factors, and with different spatial, temporal and size probabilities. Also landslides hazards often occur in conjunction with other types of hazards (e.g. flooding or earthquakes). Fig. 1, based on Van Westen et al (2005), gives the framework of multi-hazard landslide risk assessment with an indication of the various steps (A to H). The first step (A) deals with the input data required for a multi-hazard risk assessment, focusing on the data needed to generate susceptibility maps for initiation and runout, triggering factors, multi-temporal inventories and elements at risk.

The second step (B) focuses on susceptibility assessment, and is divided into two components. The first, which is the most frequently used, deals with the modelling of potential initiation areas (initiation susceptibility), which can make use of a variety of different methods (inventory based, heuristic, statistical, deterministic), which will be discussed later in this document. The resulting maps will display the source areas for modelling of potential runout areas (reach probability).

The third step (C) deals with landslide hazard assessment, which heavily depends on the availability of so called event-based landslide inventories, which are inventories of landslides caused by the same triggering event. By linking landslide distributions to the temporal probability of the triggering event, it is possible to carry out a magnitude frequency analysis. Event-based landslide inventories in addition to other factors are also used to determine the spatial probability of landslide initiation and runout, and to determine the size probability of potential landslides for a given return period. The fourth step (D) is the exposure analysis, which involves the overlay of hazard maps and elements-at-risk maps in a GIS environment.

Step (E) focuses on vulnerability assessment and indicates the various types of vulnerability and approaches that can be used. The focus is on the use of expert opinion, empirical data and physically-based analytical or numerical models in defining vulnerability classes, and the application of available vulnerability curves or vulnerability matrices. Most of the focus is on determining the physical vulnerability of the elements at risk. Other types of vulnerability (e.g. social, environmental, and economic) are mostly analysed using a Spatial Multi-Criteria Evaluation, as part of a qualitative risk assessment (Step H) and are not discussed here.

Step (F) gives the concept of risk assessment which integrates the hazard, vulnerability and the both nature and quantity of the elements at risk (either as the number of people, number of buildings, or economic value). The risk for each specific element (specific risk) is calculated for many different situations, related to landslide type, volume, return period of the triggering event, and type of element at risk.

The integration of Step (G) presents the quantitative risk assessment approach in which the results are shown in risk curves plotting the expected losses against the probability of occurrence for each landslide type individually, and expressing also the uncertainty based on the uncertainties of the input components in the risk analysis.

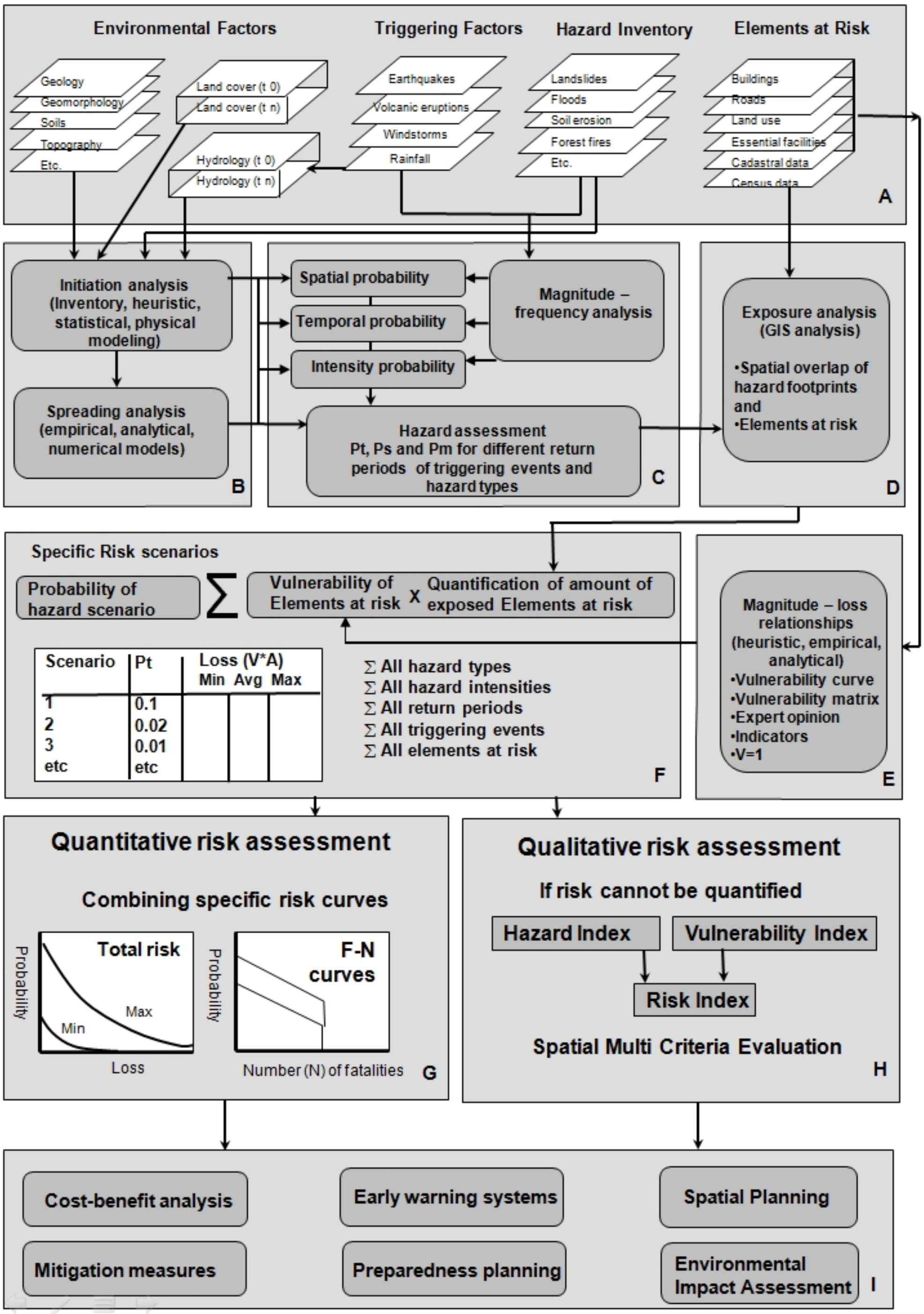


**Fig. 1**Framework of multi-hazard landslide risk assessment (based on Van Westen et al. 2005)

This could be illustrated by generating two loss curves expressing the minimum and maximum losses for each triggering event return period, or associated annual probability. The individual risk curves can be integrated into total risk curves for a particular area and the population loss can be expressed as F-N curves (IUGS, 1997).

The risk curves can be constructed for different basic units such as individual slopes, road sections, settlements, municipalities, regions or provinces.

Step (H) deals with methods for qualitative risk assessment, which are mostly based on integrating a hazard index and a vulnerability index, using Spatial Multi-Criteria Evaluation. The last step (I) deals with the use of risk information in various stages of Disaster Risk Management. Only steps A to G are discussed in this paper.

# 3. Landslide zoning at different scales

Landslide zoning is the division of land into homogeneous areas or domains and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk. The first formal applications of landslide zoning, based on qualitative approaches, date back to the 1970s (e.g. Brabb et al. 1972; Humbert 1972; Kienholz 1978), while quantitative methods were developed in the late 1980s (Brand 1988) and particularly in the 1990s for the risk management of individual slopes (Wong et al. 1997a; Hardingham et al. 1998) or a large number of slopes (OFAT, OFEE, OFEFP 1997; Wong and Ho 1998). These developments are described by Ho et al. (2000) and Wong (2005). Further significant developments of landslide zoning have been recorded during the last decade, as highlighted by

- the Guidelines developed by the Australian Geomechanics Society (AGS 2000; AGS 2007),
- the analysis of questions related to the scale of work (Cascini et al. 2005; Cascini 2008),
- the approaches adopted and the development trends in risk assessment practice from site-specific (Wong 2005) to global (Nadim et al. 2006, 2009; Hong et al. 2007) scale, and
- the JTC-1 Guidelines (Fell et al. 2008a).

Starting from these developments, this section introduces the different maps and goals as well as the zoning scales considering that both type and purpose of zoning should be determined by the end-users. The end users also need (Fell et al. 2008a) to:

i) understand the existing availability of potential input data,
ii) assess the implications for acquisition of new data, and
iii) define realistic goals for the zoning study taking into account timeframes, budgets and resources limitations.

## 3.1 Types and purposes of landslide zoning maps

Landslide zoning may be developed by preparing different maps that, according to the type of zoning, can be distinguished between:

- Landslide inventory map;
- Landslide susceptibility zoning map;
- Landslide hazard zoning map;
- Landslide risk zoning map.

Within the framework of landslide risk management (Fig. 1) the landslide zoning maps may pursue different purposes among those conventionally defined as (Fell et al. 2008a): information, advisory, statutory, design (see also Section 3.2).

Considering the number of stakeholders involved in the landslide risk management – owners, occupiers, affected public, regulatory authorities, geotechnical professionals and risk analyst (Fell et al. 2005) – as well as the different extension of the areas to be zoned, the landslide zoning maps must be prepared, via the use of suitable methods, at an appropriate scale. Suggestions and recommendations on these topics are furnished in the following sections.

## 3.2 Landslide zoning map scales

The current practice in Europe (Corominas et al. 2010) shows that the scale of the landslide zoning maps required by state or local authorities, varies significantly from country to country depending on the coverage, input data and methods that are used and the information provided (qualitative or quantitative).

On the basis of current practice and considering that landslide zoning may be also requested by land developers or those developing major infrastructure (such as highways and railways), the most common zoning map scales are hereafter described together with some considerations on the outputs and pursued purposes.

The scale of work strongly constraints the type of approach to be followed in order to achieve the zoning purposes. For instance, maps at national (<1:250,000) and regional (1:250,000 to 1:25,000) scales does not allow the mapping of individual small slope failures (up to few several thousands of cubic meters). Thus, landslides have to be treated collectively and neither the runout nor the intensity-frequency analyses can be performed at these scales. Similarly (see also Section 5.6), elements at risk must be identified and quantified for well-defined spatial units (administrative units or grid cells) or homogeneous units having similar characteristics (e.g. in terms of type and density of the elements at risk). As a consequence, susceptibility, hazard and risk approaches for national and regional zoning map scales are based on the following assumptions:

- geological conditions in the study area are homogeneous
- all slopes have similar probability of failure
- the exact location of the slope failure (landslide) is not required
- all landslides have similar size
- runout distance is not calculated and nor are the spatial distribution or the intensity
- elements at risk data are collected for given spatial/homogeneous units

On the contrary, at local (1:25,000 to 1:5,000) and site-specific (>1:5,000) scales, single landslides and single elements at risk must be taken into account in zoning-related activities. According to Soeters and van Westen (1996), zoning maps at national scale are intended to give a general overview of problem areas for an entire country. This can be used to inform national policy-makers and the general public; furthermore, they may be also used to specify and plan warning systems controlled by central authorities. The areas to be investigated are larger than tens of thousands of square kilometres.

Regional scale work is typically suited to the activities of planners in the early phases of regional development projects or for engineers evaluating possible constraints due to instability in the development of large engineering projects and regional development plans. Such work may also be used to specify and plan warning systems and urban emergency plans at a regional level. Typical areas to be investigated are larger than 1,000 $km^2$ up to tens of thousands of square kilometres.

Local scale maps have enough resolution to perform stability analyses or to assess the probability of the slope failure and combine the outputs with runout analyses. The local scale is usually used for statutory purposes and it is the reference scale for the planning and implementation of urban developments, warning systems and emergency plans at a local level. Moreover, this scale is absolutely relevant to rank the most at risk areas and to then prioritise those needing mitigation works to reduce the risk to elements at risk. Areas of zoning usually range from 10 to 1,000 $km^2$.

The main restriction of local scale maps is the uncertainty of landslide volumes, which should be the output of the susceptibility assessment, the uncertainty of rheological behaviour, and associated parameters such as entrainment of materials. If fixed (constant) landslide volume is assumed then the accuracy and reliability of the runout analysis might be low. Landslide magnitude-frequency relations are usually calculated through an independent process (i.e. from the analysis of past landslide records) making the hazard analysis de-coupled. Different landslide volumes are integrated into runout models or empirical relations to delineate the potentially affected area. Runout models are very sensitive to the resolution of the DEM and to the quality of the input parameters of the models such as details of the path or the material properties.

A site-specific zoning map scale may be used for statutory purposes and it is the only scale that can be adopted for site investigation for the design of control works (Soeters and van Westen 1996). The size of study areas may range up to tens of square kilometres.

Independently from the zoning methods and the adopted scale, the use of common descriptors to differentiate magnitude and intensity of landslides as well as to describe, in the zoning maps, the quantitative degree of landslide susceptibility, hazard and risk is strongly encouraged in order to have a common language, allowing the comparison among different homogeneous geo-environmental contexts (Fell et al. 2008a). In this regard, some suggestions are given in the following section.

### 3.3 Descriptors for landslide hazard and risk

Different descriptors are required depending upon the parameters of the analysis:

- The scale of analysis (being different from the reference territorial units passing from the national to the site-specific scale) and the related zoning purposes (information, advisory, statutory and design);
- The type of landslides (namely, potential or existing phenomena) and their characteristics (for instance, for rockfalls the hazard descriptors depend on the magnitude considering that the lowest frequencies are usually associated with the largest magnitudes);
- The characteristics of the exposed elements (e.g., linear infrastructures, urbanized areas, etc.);
- The adopted risk acceptability/tolerability criteria which may vary from country to country (Leroi et al. 2005).

Table 1 provides examples of landslide hazard descriptors to be considered in zoning activity.

**Table 1** Examples of hazard descriptors dealing with potential landslides for different scales of work

| Scale of work | Runout | I(M)/F* | Hazard descriptor |
|---|---|---|---|
| National <1:250,000 | Not included | Not considered | Number of landslides/administrative unit/yr |
| Regional 1:250,000-1:25,000 | Usually not included | Often fixed (constant) magnitude value | Number of landslides/km$^2$/yr |
| Local 1:25,000-1:5,000 | Included | Spatially distributed magnitude (intensity) | Annual probability of occurrence of a given magnitude or intensity |
| Site specific >1:5,000 | Included | Spatially distributed intensity | Annual probability of a given intensity |

*Intensity(Magnitude)/Frequency

# 4. Input data for landslide risk assessment

This section reviews the input data required for assessing landslide susceptibility, hazard and risk. Taking into account the huge amount of literature on this topic, a summary will be given related to the parameters that are most suitable for analysing the occurrence of, and the potential for, different landslide mechanisms (rockfalls, shallow landslides and debris flows, and slow moving large landslides). The main data layers required for landslide susceptibility, hazard and risk assessment can be subdivided into four groups: landslide inventory data, environmental factors, triggering factors, and elements at risk (Soeters and van Westen 1996; Van Westen et al. 2008). Of these, the landslide inventory is by far the most important, as it should give insight into the location of landslide phenomena, failure mechanisms, causal factors, frequency of occurrence, volumes and the damage that has been caused.

## 4.1 Parameters controlling the occurrence of landslides

Mass movements are controlled by a large number of factors, which can be subdivided into intrinsic, or predisposing, factors that contribute to the instability of the slope and the factors that actually trigger the event. These factors are different depending on the environmental setting (e.g. climatic conditions, internal relief, geological setting, geomorphological evolution) and may also differ substantially within a given area due to subtle differences in terrain conditions (e.g. soil properties and depth, density and orientation of discontinuities, local relief). Different combinations of factors may control different types of landslides within the same area. A recent overview of landslide mechanisms and triggers is given by Crosta et al (2012). They give a detailed description of the different landslide triggers, such as rainfall and changes in slope hydrology, changes in slope geometry due to excavation or erosion, earthquakes and related dynamic actions, snowmelt and permafrost degradation, deglaciation and related processes in the paraglacial environment, rock/soil weathering and related degradation, volcanic processes, and human activity.

The large diversity in predisposing and triggering factors makes the analysis of landslide susceptibility and hazard a complicated process, for which the methods and approaches, and the data required differ from case to case. Also the scale at which the analysis takes place plays an important role. Glade and Crozier (2005) present an interesting discussion on the relation between data availability, model complexity and predictive capacity. Therefore it is not possible to provide strict guidelines with respect to the type of data required for a landslide hazard and risk assessment, in the form of a prescribed uniform list of predisposing and triggering factors. The selection of causal factors differs, depending on the scale of analysis, the characteristics of the study area, the landslide type, and the failure mechanisms. A list of the possible factors controlling the occurrence of landslides is given in Table 2, differentiated for various landslide mechanisms. The list of factors is not exhaustive and it is important to make a selection of the specific factors that are related to the landslide types and failure mechanisms in each particular environment. However, it does give an idea of the type of factors related to topography, geology, soil types, hydrology, geomorphology, land use, earthquakes, volcanoes, weather and climatic conditions.

**Table 2** Overview of factors controlling the occurrence of landslides, and their relevance for landslide susceptibility and hazard assessment for different landslide mechanisms (R= rockfalls, S = shallow landslides and debris flows, L=large slow moving landslides). The relevance is indicated as: C= Crucial, H= Highly important, M= Moderately important, and L= Less important. Also the type of factor is indicated: C = conditioning factor, T = triggering factor

| Group | Parameters | Relevance for landslide susceptibility and hazard assessment | Type of Factor | | Landslide mechanisms | | |
|---|---|---|---|---|---|---|---|
| | | | C | T | R | S | L |
| Topography | Elevation, internal relief | Elevation differences result in potential energy for slope movements | ● | | H | C | H |
| | Slope gradient | Slope gradients are the predominant factor in landslides | ● | ● | C | C | C |
| | Slope direction | Might reflect differences in soil moisture and vegetation, and plays an important role in relation with discontinuities | ● | | C | M | M |
| | Slope length, shape, curvature, roughness | Indicator for slope hydrology, important for runout trajectory modelling | ● | | C | H | H |
| | Flow direction & accumulation | Used in slope hydrological modelling, e.g. for wetness index | ● | | M | C | H |
| Geology | Rock types | Determine the engineering properties of rock types | ● | | C | H | C |
| | Weathering | Types of weathering (physical/chemical), depth of weathering, individual weathering zones and age of cuts are important factors | ● | | C | H | H |
| | Discontinuities | Discontinuity sets and characteristics, relation with slope directions and inclination | ● | | C | M | H |
| | Structural aspects | Geological structure in relation with slope angle/direction | ● | | H | H | H |
| | Faults | Distance from active faults or width of fault zones | ● | | H | H | H |
| Soils | Soil types | Origin of soils determines their properties and geometry | ● | | L | C | H |
| | Soil depth | In superficial formations determines potentially movable volume | ● | | L | C | H |
| | Geotechnical properties | Grain size, cohesion, friction angle, bulk density | ● | | L | C | H |
| | Hydrological properties. | Pore volume, saturated conductivity, PF curve | ● | | L | H | H |
| Hydrology | Groundwater | Spatially and temporal depth to ground water table, perched ground water tables, wetting fronts, pore water pressure, soil suction | ● | ● | L | H | H |
| | Soil moisture | Spatially and temporal soil moisture content | ● | ● | L | H | H |
| | Hydrologic components | Interception, evapotranspiration, throughfall, overland flow, infiltration, percolation etc. | ● | ● | M | H | H |
| | Stream network& drainage density | Buffer zones around streams, in small scale assessment drainage density may be used as indicator for type of terrain | ● | | L | H | H |
| Geomorphology | Geomorphologic environment | Alpine, glacial, peri-glacial, denudational, coastal, tropical etc. | ● | | H | H | H |
| | Old landslides | Material and terrain characteristics have changed making these locations more prone to reactivations | ● | | M | H | C |
| | Past landslide activity | Historical information on landslide activity is often crucial for determining landslide hazards and risk | ● | | C | C | C |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Land use & anthropogenic factors | Current land use | Type of land use/ land cover, vegetation type, canopy cover, rooting depth, root cohesion, weight | ● | | H | H | H |
| | Land use changes | Temporal varying land use/ land cover | ● | ● | M | C | H |
| | Transportation infrastructure | Buffers around roads in sloping areas with road cuts | ● | | M | H | H |
| | Buildings | Slope cuts made for building construction | ● | ● | M | H | H |
| | Drainage and irrigation networks | Leakage from such networks may be an important cause for landslide occurrence. | ● | ● | L | H | H |
| | Quarrying and mining | They alter the geometry of slopes and stress distribution. Vibration due to blasting can trigger landslides. | ● | ● | H | H | H |
| | Dams and reservoirs | Reservoirs change the hydrological conditions. Tailing dams may fail. | ● | ● | L | H | H |
| Earthquakes & Volcanoes | Seismicity | Earthquake magnitude/frequency relations, historical intensity maps linked with co-seismic landslide inventories | | ● | C | C | C |
| | Fault mechanism | Fault locations, fault type, length of fault rupture, buried or exposed, distance from fault, hanging wall/footwalls | ● | ● | H | H | H |
| | Volcano type | Height and composition of volcanic edifice, magma chamber stability | ● | ● | M | H | H |
| | Volcanic eruption types | Lateral explosions, collapse of magma chambers, pyroclastic flows, lahars | ● | ● | M | H | H |
| Weather & climate | Precipitation | Daily or continuous data , weather patterns, magnitude/frequency relations, IDF curves, rainfall thresholds, antecedent rain, PADF curves | | ● | C | C | C |
| | Temperature | Important for hydrology and vegetation conditions. Rapid temperature changes, snowmelt, frost-thaw cycles, permafrost | ● | ● | H | H | H |

## 4.2 Sources of the input data

In order to consider the factors indicated in Table 2 in landslide hazard and risk assessment, for any of the spatial scales described in Section 3, they would have to be spatially represented in the form of maps. Table 3 gives an overview of the sources of input data together with an indication of the main types of data, their characteristics, the method used and the importance for the four types of landslide mechanisms considered. The sources of input data for landslide hazard and risk assessment can be subdivided into the following components: laboratory analysis, field measurements, monitoring networks, field mapping, archive studies and ancillary data, and remote sensing. There are relatively few publications that provide an overview of the sources of input data and data requirements for quantitative landslide hazard and risk assessment (e.g. Van Westen et al. 2008). Most textbooks on landslide hazard and risk assessment (e.g. Lee and Jones 2004; Glade et al. 2005) do not treat this topic separately. An overview of laboratory experiments, field mapping procedures, and monitoring techniques as input for quantitative landslide hazard assessment can be found in textbooks (e.g. Turner and Schuster 1996) and in more recent overviews such as Springman et al. (2011). Reviews on data collection related to individual components are more common. For example, Jongmans and Garambois (2007) provide a review of geophysical methods for landslide investigations, Corominas and Moya (2008) present an overview of dating methods used in landslide studies, and Cepeda et al. (2012) give a review of the methods for using meteorological data for analysing rainfall thresholds for quantitative landslide hazard assessment. Pitilakis et al. (2011) provide a comprehensive review of the data that needs to be collected for the characterization and physical vulnerability assessment of elements-at-risk such as buildings, roads, pipelines, etc. Good overviews of the use of remote sensing data for landslide hazard and risk assessment can be found in Soeters and van Westen (1996), Metternicht et al. (2005), Singhroy (2005), Kääb (2010), Michoud et al (2010) and Stumpf et al. (2011). Remote sensing is a field that has experienced very important developments over the last two decades, with satellites that are now orbiting the earth and have different characteristics with respect to their spatial, temporal and spectral resolution; for a recent overview see the comprehensive database hosted at http://gdsc.nlr.nl/FlexCatalog/catalog.html.

Table 3 indicates the method for spatial data collection for each of the data types. Many of the crucial input data are obtained as point information. These are either linked to specific features (e.g. landslides, buildings), or are sample points used to characterize spatial units (e.g. soil types, vegetation types). In the latter case they need to be converted into maps through spatial interpolation using environmental correlation with landscape attributes (e.g. geostatistical interpolation methods such as co-kriging). There are also points that provide information on regional variables (e.g. precipitation) that need to be interpolated as well. Many types of data are in the form of area-based features (e.g. landslide polygons, buildings) or are fully covering the study area (e.g. digital elevation models, vegetation, geology). As can be seen from the examples of data types listed in Table 3 there is a large amount of data needed in order to be able to carry out a quantitative landslide hazard and risk study. The availability of ancillary data, the size of the study area, the homogeneity of the terrain and the availability of resources will determine the type and quantity of data, which eventually will also govern the type of susceptibility method and the possibility for converting a susceptibility map into a quantitative hazard and risk map (Van Westen et al. 2008; Fell et al. 2008).

**Table 3** Overview of sources of input data and their relevance for quantitative landslide hazard and risk assessment for different landslide mechanisms (R= rockfalls, S = shallow landslides and debris flows, L= large slow moving landslides. The relevance is indicated as: C= Crucial , H= Highly important, M= Moderately important, and L= Less important. The suitability for collection this information at different scales is also indicated with: ● = possible, ○ = difficult, × = not possible. The scales are: N= National scale, R = Regional scale, L = Local scale and S = site specific scale.  M indicates the method for spatial data collection with Pf = point data linked to specific features (e.g. landslides), Ps= Sample points characterizing spatial units (e.g. soil types, vegetation types), Pn= points in a network which need to be interpolated, Af= area based feature data (e.g. landslide polygons, buildings), Ac= complete area coverage, L = line data

| Main source | Group of data | Examples | M | Scale | | | | Relevance | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | N | R | L | S | R | S | L |
| Laboratory analysis | Soil properties | Grainsize distribution, Saturated and unsaturated shear strength, soil water retention curves, saturated hydraulic conductivity, clay minerals, sensitivity, viscosity, bulk density | Ps | × | × | ○ | ● | L | C | H |
| | Rock properties | Unconfined compressive strength, shear strength, mineralogy | Ps | × | × | ○ | ● | C | L | C |
| | Vegetation prop. | Root tensile strength, root pullout strength, evapotranspiration, | Ps | × | × | ○ | ● | L | H | M |
| | Age dating | Radiocarbon C-14, pollen analysis, | Pf | ○ | ○ | ○ | ● | L | L | H |
| Field measurements | Landslide age | Dendrochronology, lichenometry, varves, tephrochronology, archeological artifacts. | Pf | ○ | ○ | ○ | ● | M | M | H |
| | Soil depth | Drillholes, trenches, pits, outcrops, auguring | Ps | × | × | ○ | ● | L | C | M |
| | Geophysics | Seismic refraction, microseismic monitoring, electrical resistivity, Electromagnetic method, Magnetic method, ground penetrating radar, borehole geophysical methods | Ps | × | × | ○ | ● | L | M | H |
| | Soil characteristics | standard penetration tests, field vane test | Ps | × | × | ○ | ● | L | C | M |
| | Rock characteristics | Lithology, Discontinuities (types, spacing, orientation, aperture, infilling), rock mass rating | Ps | × | × | ○ | ● | C | L | H |
| | Hydrological characteristics | Infiltration capacity, water table fluctuation, soil suction, pore water pressure. | Ps | × | × | ○ | ● | H | C | C |
| | Vegetation characteristics | Root depth, root density, vegetation species, crop factor, canopy storage, throughfall ratio, | Ps | × | × | ○ | ● | M | H | L |
| Monitoring networks | Landslide displacement | Electronic distance meters, Global Positing Systems, Theodolite, Terrestrial Laser Scanner, ground based interferometry etc. | Pf | × | × | ○ | ● | H | H | H |
| | Ground water | Piezometers, tensiometers, discharge stations. | P | × | × | ○ | ● | H | C | C |
| | Meteorological data | Precipitation, temperature, humidity, windspeed | Pn | ● | ● | ● | ● | H | H | H |
| | Seismic data | Seismic stations, strong motion stations, microseismic studies | Pn | ● | ● | ● | ● | H | H | H |
| Field mapping | Landslides | Type, (relative) age, speed of movement, state of activity, initiation, transport, runout zone, area, depth, volume, causes, development | Af | ○ | ● | ● | ● | C | C | C |
| | Geomorphology | Characterization of landforms, processes, and surface materials | Ac | ○ | ○ | ● | ● | L | H | H |
| | Soil types | Texture, soil classification, boundary mapping, conversion into engineering soil types | Ac | ○ | ○ | ● | ● | L | C | H |
| | Lithology | Lithological mapping, weathering zones, boundary mapping, formations, members, conversion into engineering rock types | Ac | ○ | ○ | ● | ● | C | H | H |
| | Structural geology | Strike and dip measurements of bedding planes, and | Ac | ○ | ○ | ● | ● | H | L | H |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | discontinuities, stratigraphic reconstruction, fault mapping, structural reconstruction | | | | | | | | |
| | Vegetation | Vegetation type, density, Leaf Area Index | Ac | ○ | ○ | ● | ● | L | H | M |
| | Land use | Land use types, characterization of vegetation per land use | Ac | ○ | ○ | ● | ● | H | H | H |
| | Elements-at-risk | Building typology, structural system, building height, foundation system, road classification, pipeline classification | Af L | ○ | ○ | ● | ● | H | H | H |
| Archive studies and ancillary data | Past landslide events | Historical information on location, date of occurrence, triggering mechanism, size, volume, runout length | Af Pf | ○ | ○ | ● | ● | H | H | C |
| | Damage data | Historical information on economic losses and population affected with dates, location and characterization | Pf | ○ | ○ | ○ | ○ | H | H | H |
| | Meteorological data | Precipitation (continuous or daily), temperature, windspeed, humidity | Pn | ● | ● | ● | ● | H | H | H |
| | Changes in land use | Historical maps of land use/land cover for different periods. | Ac | ● | ● | ● | ● | M | H | H |
| | Elements-at-risk | Historical maps of buildings, transportation infrastructure, economic activities and population characteristics | Af L | ● | ● | ● | ● | H | H | H |
| | Digital Elevation | Topographic maps with contour lines, Digital Elevation Models from existing catalogues. | Ac | ● | ● | ● | ● | H | H | H |
| | Thematic maps | Geological, geomorphological, drainage network and other existing thematic maps | Ac | ● | ● | ● | ● | H | H | H |
| Remote sensing | Aerial photographs and high resolution satellite images | Image interpretation for mapping and characterizing landslide locations, Geomorphology, faults and lineaments, land use/land cover, elements-at-risk mapping, | Af Ac | ○ | ● | ● | ● | C | C | C |
| | Multi-spectral imagery | Image classification methods for mapping of landslides, land use/land cover, Normalized Difference Vegetation Index, Leaf Area Index, | Af Ac | ● | ● | ● | ● | M | H | M |
| | Digital elevation data | Airborne stereophotogrammetry, Spaceborne stereo-photogrammetry, LiDAR, InSAR | Ac | ● | ● | ● | ● | C | C | C |

In the following sections some of the main types of input data are further explained.

## 4.3 Landslide inventories

Landslide inventory databases should display information on landslide activity, and therefore require multi-temporal landslide information over larger regions. For detailed mapping scales, activity analysis is often restricted to a single landslide and requires more landslide monitoring. In order to make a reliable map that predicts the landslide hazard and risk in a certain area, it is crucial to have insight into the spatial and temporal frequency of landslides, and therefore each landslide hazard or risk study should start by making a landslide inventory that is as complete as possible in both space and time, and that follows international nomenclature (IAEG Commission on Landslides 1990).

Landslide inventories can be carried out using a variety of techniques. A recent overview of the methods used for landslide inventory mapping is given by Guzzetti et al. (2012). Visual interpretation of stereoscopic imagery (either aerial photographs or very high resolution optical satellite images) remains the most widely used method, and results in the best inventories when carried out by expert interpreters (Cardinali et al. 2002). Nowadays for many areas the use of Google Earth data is a good alternative and many parts of the world are covered by high resolution imagery which can be downloaded, and combined in GIS with a Digital Elevation Model to generate stereoscopic images, that are essential in landslide interpretation. One of the most important developments is the use of shaded relief images produced from LiDAR DEMs, from which the objects (e.g. vegetation) on the earth surface have been removed, for the visual interpretation of landslide phenomena (Haugerud et al. 2003; Ardizzone et al. 2007; Van Den Eekhaut et al. 2009b; Razak et al. 2011).

Landslide inventory mapping using visual stereo image interpretation is a time-consuming task, and requires extensive skills, training and perseverance. In many cases such skilled interpreters are not available, or landslide inventories have to be produced within a short period of time after the occurrence of a triggering event, requiring the application of automated detection methods based on remote sensing. Michoud et al. (2010) and Stumpf et al. (2011) provide complete overviews of the various remote sensing methods and tools that can be used for (semi-) automated landslide mapping and monitoring. A large number of methods make use of passive optical remote sensing tools, such as pixel-based classification or change detection of spaceborne images (Hervás et al. 2003; Borghuis et al. 2007; Mondini et al. 2011), or object-oriented classification or change detection of spaceborne images (Martha et al. 2010a; Lu et al. 2011).

Many methods for landslide mapping and monitoring make use of digital elevation measurements that may be derived from a wide range of tools, such as terrestrial photographs (Travelletti et al. 2010), terrestrial videos, UAV-based aerial photographs (Niethammer et al. 2011), airborne stereo-photogrammetry and spaceborne stereo-photogrammetry (Martha et al. 2010b) Also the application of LiDAR data from both Airborne Laser Scanner (ALS) and Terrestrial Laser Scanner (TLS) has been proven very successful (Jaboyedoff et al. 2012). Apart from LiDAR the most useful tool for landslide inventory mapping and monitoring using remote sensing is in the InSAR domain. Interferometric Synthetic Aperture Radar (InSAR) has been used extensively for measuring surface displacements. Multi-temporal InSAR analyses using techniques such as the Persistent Scatterers (PS) (Ferretti et al. 2001), and Small Base-line (SB) (Berardino et al. 2002) can be used to measure displacement of permanent scatterers such as buildings with millimetre accuracy, and allow the reconstruction of the deformation history (Farina et al. 2006).

### 4.4 Predisposing factors

As topography is one of the major factors in landslide hazard analysis, the generation of a Digital Elevation Model (DEM), plays a major role. Digital Elevation Models (DEMs) can be derived through a large variety of techniques, such as digitizing contours from existing topographic maps, topographic levelling, EDM (Electronic Distance Measurement), differential GPS measurements, (digital) photogrammetry using imagery taken from the ground or a wide range of platforms, InSAR, and LiDAR. Global DEMs are now available from several sources, such as SRTM (Shuttle Radar Topography Mission: Farr et al. 2007) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer: METI/NASA 2009). In the near future a more accurate Global DEM is expected from TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurements) which will provide a DEM for the whole Earth with a relative height accuracy of <2 m, and a spatial resolution of 12m (Nelson et al., 2009; Smith and Pain, 2009). Many derivate maps can be produced from DEMs using fairly simple GIS operations.

Traditionally, geological maps form a standard component in heuristic and statistical landslide hazard assessment methods. Mostly the stratigraphical legends of existing geological maps are converted into an engineering geological classification, which gives more information on the rock composition and rock mass strength. In detailed hazard studies specific engineering geological maps are collected and rock types are characterized using field tests and laboratory measurements. For detailed analysis also 3-D geological maps have been used, although the amount of outcrop and borehole information collected will make it difficult to use this method on a scale smaller than 1:5000, and its use is generally restricted mostly to a site investigation level (e.g. Xie et al. 2003) at present although this may be expected to change in the future (e,g. Culshaw, 2005). Apart from lithological information structural information is very important for hazard assessment. At medium and large scale attempts have been made to generate maps indicating dip direction and dip angle, based on field measurements, but the success of this depends very strongly upon the number of structural measurements and the complexity of the geological structure (Ghosh et al. 2010).

Representation of soil properties is a key problem in the use of physically-based slope stability models for hazard assessment (Guimaraes *et al.* 2003). Regolith depth, often referred to by geomorphologists and engineers as soil depth, is defined as the depth from the surface to more-or-less consolidated material. Despite being a major factor in landslide modelling, most studies have ignored its spatial variability by using constant values over generalized land units in their analysis. Soil thickness can be modelled using a correlation with topographic factors such as slope, or predicted from a process based model (Kuriakose et al. 2009).

Geomorphological maps are made at various scales to show land units based on their shape, material, processes and genesis. There is no generally accepted legend for geomorphological maps, and there may be a large variation in content based on the experience of the geomorphologist. An important field within geomorphology is the quantitative analysis of terrain forms from DEMs, called geomorphometry or digital terrain analysis, which combines elements from earth sciences, engineering, mathematics, statistics and computer science (Pike 2000). Part of the work focuses on the automatic classification of geomorphological land units based on morphometric characteristics at small scales (Asselen and Seijmonsbergen 2006) or on the extraction of slope facets at medium scales which can be used as the basic mapping units in statistical analysis (Cardinali et al. 2002).

Land use is too often considered as a static factor in landslide hazard studies, and it is rare for research to consider constantly changing land use as a factor in the analysis (Van Beek and Van Asch 2004). For physically based modelling it is very important to have temporal land use/land cover maps and the respective changes manifested in the mechanical and hydrological effects of vegetation. Land use maps are made on a routine basis from medium resolution satellite imagery. Although change detection techniques such as post-classification comparison, temporal image differencing, temporal image ratioing, or Bayesian probabilistic methods have been widely applied in land use applications, fairly limited work has been done on the inclusion of multi-temporal land use change maps in landslide hazard studies (Kuriakose 2010).

## 4.5 Triggering factors

Input data related to triggering factors, of which precipitation, seismicity and anthropogenic activities can be considered the most important, has a very important temporal component, as often in hazard assessment the magnitude/frequency relation of the triggering event is used to determine the probability of landslide occurrence caused by that particular trigger. In order to establish such relations sufficiently complete records should be available from measurement stations over a sufficiently large period of time, covering the spatial variation in the triggering factor over the study area. Rainfall and temperature data are collected in individual meteorological stations, and the resulting values throughout the study area are derived through interpolation of the station data. Correlations are then made between precipitation indicators and dates of historical landslide occurrences in order to establish rainfall thresholds (Cepeda et al., 2012). A good example in Europe is the European Climate Assessment & Dataset project (http://eca.knmi.nl/). The use of weather radar for rainfall prediction in landslide studies is a field which is very promising (e.g. Crosta and Frattini 2003).

Physically-based models for landslide susceptibility can incorporate rainfall as a dynamic input of the model, in order to prepare susceptibility maps for future scenarios with climatic change (Collison et al 2000; Melchiorre and Frattini 2012; Comegna et al. 2012).The analysis of the susceptibility and hazard for earthquake triggered landslides is still not very well developed due to the difficulty in determining possible earthquake scenarios, and their associated co-seismic landslide distributions (Keefer 2002; Meunier et al. 2007; Gorum *et al.* 2011). In order to establish better relationships between seismic, geological and terrain factors for the prediction of co-seismic landslide distributions, more digital event-based co-seismic landslide inventories should be produced for different environments, earthquake magnitudes and faulting mechanisms. Another approach for earthquake induced landslide susceptibility mapping uses a heuristic rule-based approach in GIS with factor maps related to shaking intensity (using the USGS ShakeMap data), slope angle, material type, moisture, slope height and terrain roughness (Miles and Keefer 2009).

## 4.6 Elements at risk

Inventories of elements at risk can be carried out at various levels, depending on the requirement of the study. Elements-at-risk data should be collected for certain basic spatial units, which may be grid cells, administrative units or so-called homogeneous units with similar characteristics in terms of type and density of elements at risk. Risk can also be analyzed for linear features (e.g. transportation lines) and specific sites (e.g. a dam site).

Building information can be obtained in several ways. Ideally it is available as building footprint maps, with associated attribute information on building typology, structural system, building height, foundation system, etc. (Pitilakis et al. 2011). It can also be derived from existing cadastral databases, from (urban) planning maps or it may be available in an aggregated form as the number and types of buildings per administrative unit. If such data is not available, building footprint maps can be generated using screen digitisation from high resolution images, or through automated building mapping using high resolution multispectral satellite images and LiDAR (Brenner, 2005).

Population data sets have a static and dynamic component. The static component relates to the number of inhabitants per mapping unit, and their characteristics, whereas the dynamic component refers to their activity patterns, and their distribution in space and time. Population distribution can be expressed as either the absolute number of people per mapping unit, or as population density. Census data are the obvious source for demographic data. However, for many areas census data is not available, outdated, or unreliable. Therefore also other approaches may be used to model population distribution with remote sensing and GIS, to refine the spatial resolution of population data from available population information (so-called dasymetric mapping, Chen *et al*. 2004).

## 4.7 Data quality

The occurrence of landslides is governed by complex interrelationships between factors, some of which cannot be determined in detail and others only with a large degree of uncertainty. Some important aspects in this respect are: the error, accuracy, uncertainty and precision of the input data and the objectivity and reproducibility of the input maps (see Section 8). The accuracy of input data refers to the degree of closeness of the measured or mapped values or classes of a map to its actual (true) value or class in the field. An error is defined as the difference between the mapped values or classes and the true ones. The precision of a measurement is the degree to which repeated measurements under unchanged conditions show the same results. Uncertainty refers to the degree with which the actual characteristics of the terrain can be represented spatially in a map.

The error in a map can be assessed only if another map or field information is available which is error-free, and with which it can be verified (e.g. elevation). DEM error sources have been described by Heuvelink (1998) and Pike (2000), which can be related to the age of data, incomplete density of observations or spatial sampling, processing errors such as numerical errors in the computer, interpolation errors or classification and generalization problems and measurement errors such as positional inaccuracy (in the x and y directions), data entry faults, or observer bias. A review of the uncertainties associated with digital elevation models is given by Fisher and Tate (2006), Wechsler (2007) and Smith and Pain (2009). The quality of the input data used for landslide hazard and risk assessment is related to many factors, such as the scale of the analysis, the time and money allocated for data collection, the size of the study area, the experience of the researchers, and the availability and reliability of existing maps. Also existing landslide databases often present several drawbacks (Ardizzone *et al.* 2002; Van Den Eeckhaut and Hervás 2012) related to their completeness (or incompleteness) in space and even more so in time, and the fact that they are biased to landslides that have affected infrastructure such as roads.

# 5. Suggested methods for landslide susceptibility assessment

A landslide susceptibility map subdivides the terrain into zones of differing likelihood that landslides of a certain type may occur. Landslide susceptibility assessment can be considered as the initial step towards a landslide hazard and risk assessment, but it can also be an end product in itself which can be used in land-use planning and environmental impact assessment. This is especially the case in small-scale analyses or in situations where there is no sufficient information available on past landslide occurrence in order to assess the spatial and temporal probabilities of events.

Landslide susceptibility maps contain information on the type of landslides that might occur and on their spatial likelihood of occurrence in terms of identification of the most probable initiation areas (based on a combination of geological, topographical and land cover conditions) and of the possibility of extension (upslope through retrogression and/or downslope through runout). The likelihood may be indicated quantitatively through indicators (such as the density in number per square kilometres, or the area affected per square kilometre).

The methods for landslide susceptibility analysis are usually based on two assumptions:

The first is that the past is a guide to the future, so that areas which have experienced landslides in the past are likely to experience landslides in the future. Therefore the collection of detailed landslide inventories is of primary importance in any landslide susceptibility assessment;

The second is that areas with similar environmental settings (e.g. topography, geology, soil, geomorphology and land-use) as the areas which have experienced landslides in the past are also likely to experience landslides in the future.

In terms of visualisation, landslide susceptibility maps should include:

- Zones with different classes of susceptibility to landslide initiation and runout for particular landslide types; for the purpose of clarity, the number of classes should be limited to less than five.
- An inventory of historic landslides, which allows the user to compare the susceptibility classes with the actual historic landslides.
- A legend with an explanation of the susceptibility classes, including information on expected landslide densities.

## 5.1 Landslide susceptibility assessment

Overviews of the available methods (Fig. 2) for landslide susceptibility assessment can be found in Soeters and Van Westen (1996), Carrara et al. (1999), Guzzetti et al. (1999), Aleotti and Chowdury (1999), Dai et al. (2002), Chacón et al. (2006), and Fell et al. (2008a; 2008b). The methods are qualitative (inventory-based and knowledge-driven methods) and quantitative (data-driven methods and physically-based models) as shown in Fig. 2. The inventory-based methods are required as a first step for all other methods, as they form the most important input and are used for validating the resulting maps. An overview of the methods and examples of references is given in Table 4.

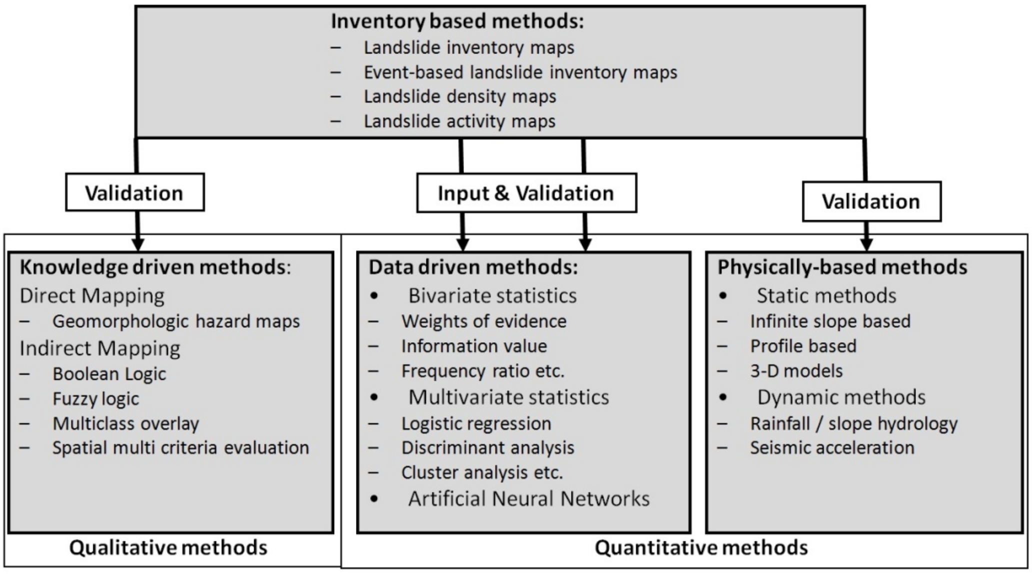


**Fig. 2** Methods for landslide susceptibility assessment

**Table 4** Recommended methods for landslide inventory analysis

| Approach | References |
|---|---|
| Landslide distribution maps based on image interpretation. Generation of event-based inventories or MORLE (Multiple Occurrence of Regional Landslide Events). | Wieczorek 1984; Crozier 2005 |
| Landslide activity maps based on multi-temporal image interpretation | Keefer 2002; Reid and Page 2003 |
| Generating inventories based on historical records | Guzzetti et al. 2000; Jaiswal and van Westen 2009 |
| Landslide inventory based on radar interferometry | Squarzoni et al. 2003; Colesanti and Wasowski 2006. |
| Representation of landslide inventory as density information, landslide isopleth maps | Coe et al. 2000; Bulut et al. 2000; Valadao et al. 2002 |

There is a difference between susceptibility assessment methods for areas focusing on landslide reactivation and areas where landslides might occur in locations where there have been no landslides before. It should be noted that there is a direct relation between the scale of the zoning maps and the complexity of the landslide susceptibility assessment methods, with more complex methods being applied at larger scales due to the larger data requirements. In knowledge driven or heuristic methods the landslide susceptibility map can be directly prepared in the field by expert geomorphologists, or made in the office as a derivative map of a geomorphological map. The method is direct, as the expert interprets the susceptibility of the terrain directly in the field, based on the observed phenomena and the geomorphological / geological setting. In the direct method GIS is used basically only as a tool for entering the final map, without extensive modelling. Knowledge-driven methods can also be applied indirectly using a GIS, by combining a number of factor maps that are considered to be important for landslide occurrence. On the basis of his/her expert knowledge related to past landslide occurrences and their causal factors within a given area, an expert assigns a particular weight to certain combinations of factors. In knowledge driven methods, susceptibility is expressed in a qualitative form. In the following, only the quantitative methods are discussed.

#### *5.1.1 Data-driven landslide susceptibility assessment methods*

In data-driven landslide susceptibility assessment methods, the combinations of factors that have led to landslides in the past are evaluated statistically and quantitative predictions are made for current non-landslide affected areas with similar geological, topographical and land cover conditions. The output may be expressed in terms of probability. These methods are called data-driven as the data from past landslide occurrences are used to obtain information on the relative importance of each of the factor maps and classes. Three main data-driven approaches are commonly used (bivariate, multivariate and active learning statistical analysis) (Table 5). In bivariate statistical methods, each factor map is combined with the landslide distribution map and weight values, based on landslide densities, are calculated for each parameter class. Several statistical methods can be applied to calculate weight values, such as the information value method, weights of evidence modelling, Bayesian combination rules, certainty factors, the Dempster-Shafer method, and fuzzy logic. Bivariate statistical methods are a good learning tool for the analyst to find out which factors or combination of factors plays a role in the initiation of landslides. It does not take into account the interdependency of variables and it has to serve as a guide in exploring the dataset before multivariate statistical methods are used. Multivariate statistical models evaluate the combined relationship between a dependent variable (landslide occurrence) and a series of independent variables (landslide controlling factors). In this type of analysis, all relevant factors are sampled either on a grid basis or in slope morphometric units. For each of the sampling units, the presence or absence of landslides is determined. The resulting matrix is then analysed using multiple regression, logistic regression, discriminant analysis, random forest or active learning. The results can be expressed in terms of probability. Data-driven susceptibility methods can be affected by shortcomings such as (a) the general assumption that landslides occur due to the same combination of factors throughout a study area, (b) ignorance of the fact that the occurrence of certain landslide types is controlled by certain causal factors that should be analysed/investigated individually, (c) the extent of control of some spatial factors can vary widely in areas with complex geological and structural settings, and (d) the lack of suitable expert opinion on different landslide types, processes and causal factors. These techniques have however become standard in regional-scale landslide susceptibility assessment.

**Table 5** Recommended methods for data driven landslide susceptibility assessment

| | Method | References |
|---|---|---|
| Bivariate statistical methods | Likelihood ratio model (LRM) | Lee 2005 |
| | Information value method | Yin and Yan 1988 |
| | Weights of evidence modelling | van Westen 1993; Bonham-Carter 1994; Suzen and Doyuran 2004 |
| | Favourability functions | Chung and Fabbri 1993; Luzi 1995 |
| Multivariate statistical method | Discriminant analysis | Carrara 1983; Gorsevski et al. 2000 |
| | Logistic regression | Ohlmacher and Davis 2003; Gorsevski et al. 2006a |
| ANN | Artificial Neural Networks | Lee et al. 2004; Ermini et al. 2005; Kanungo et al. 2006 |

### *5.1.2 Physically-based landslide susceptibility assessment methods*

Physically-based landslide susceptibility assessment methods are based on the modelling of slope failure processes. The methods are applicable only over large areas when the geological and geomorphological conditions are fairly homogeneous and the landslide types are simple (Table 6). Most of the physically-based models that are applied at a local scale make use of the infinite slope model and are therefore only applicable for the analysis of shallow landslides. Physically-based models for shallow landslides account for different triggers such as the transient groundwater response of the slopes to rainfall and/or the effect of earthquake excitation. Dynamic models are capable of making future temporal predictions, using rules of cause and effect to simulate temporal changes in the landscape. A dynamic landslide susceptibility model addresses the spatial and temporal variation of landslide initiation. Physically-based models are also applicable to areas with incomplete landslide inventories. The parameters used in such models are most often measurable and are considered as state variables having a unique value for a given moment in time and space. Most physically-based models are dynamic in nature, implying that they run forward (or backward) in time constantly calculating the values of the state variables based on the equations incorporated. If implemented in a spatial framework (a GIS model) such models are also able to calculate the changes in the values with time for every unit of analysis (pixel). The results of such models are more concrete and consistent than the heuristic and statistical models, given the white-box approach of describing the underlying physical processes leading to the phenomena being modelled. They have a higher predictive capability and are the most suitable for quantitatively assessing the influence of individual parameters contributing to shallow landslide initiation. However, the parameterization of these models can be complicated, in particular the spatial distribution of soil depth, which plays a decisive role. The advantage of these models is that they are based on slope stability models, allowing the calculation of quantitative values of stability (safety factors or probability of failure). The main drawbacks of this method are the degree of simplification and the need for large amounts of reliable input data.

**Table 6** Examples of methods for physically-based landslide susceptibility assessment (location of the slope failure)

| Type | Method | References |
|---|---|---|
| GIS-based limit equilibrium methods | Static infinite slope modelling | Pack el al. 1998; Dietrich et al. 1995 |
| | Dynamic infinite slope modelling with rainfall trigger | Baum et al 2002; Van Beek 2002; Casadei et al. 2003; Simoni et al. 2008 |
| | Earthquake induced infinite slope modelling (e.g. Newmark) | Jibson et al. 1998; Wang and Lin 2010 |
| Kinematic analysis for rockslopes | Stereonet plots, GIS based analysis of discontinuities | Günther 2003 |

| | | |
|---|---|---|
| 2-D Limit equilibrium methods | 2-D LEM with groundwater flow and stress analysis. | GEO-Slope 2011; |
| 3-D Limit equilibrium methods | 3-D slope stability analysis. | Hungr 1995; Gilson et al 2008 |
| Numerical Modelling | Continuum modelling | Hoek et al 1993; Stead et al 2001 |
| | Discontinuum modelling (e.g. distinct element, discrete element) | Hart 1993; Stead et al. 2001 |

### *5.1.3 Selection of the analysis method*

For landslide susceptibility analysis, there is a clear link between the scale of analysis and the type of method that can be used, basically related to the possibility of obtaining the required input data (Table 7).

**Table 7** Recommended quantitative methods for landslide susceptibility analysis at different scales

| | Quantitative methods | |
|---|---|---|
| | Data-driven statistical methods | Deterministic physically-based methods |
| National scale (<1:250.000) | No | No |
| Regional scale (1:25.000 – 1:250.000) | Yes | No |
| Local scale (1:5000 – 1:25.000) | Yes | Yes |
| Site specific (> 1:5000) | No | Yes |

There are several aspects that should be considered for the selection of the most appropriate method:

- The selection should suit the available data and the scale of the analysis; for instance, selecting a physically-based modelling approach at small scales with insufficient geotechnical and soil depth data is not recommended. This will either lead to large simplifications in the resulting hazard and risk map, or to endless data collection.
- The use of data of a scale, or with details, that are inappropriate for the hazard assessment method selected should be avoided.
- Different landslide types are controlled by different combinations of environmental and triggering factors, and this should be reflected in the analysis. The landslide inventory should be subdivided when possible into several subsets, each related to a particular failure mechanism, and linked to a specific combination of causal factors.

- The use of factor maps that are not from the period of the landslide occurrence should be avoided. For instance, in order to be able to correlate landslides with land use/land cover changes, it is relevant to map the situation that existed when the landslide occurred, and not the situation that resulted after the landslide.
- Finally, many landslide susceptibility assessments are based on the assumption that "the past is the key to the future", and that historical landslides and their causal relationships can be used to predict future ones. However, one could also follow the analogy of the investment market in stating that "results obtained in the past are not a guarantee for the future". The conditions under which landslides occurred in the past change and the susceptibility maps are made for the present situation. As soon as there are changes in the causal factors (e.g. a road with steep cuts is constructed in a slope which was considered as low hazard before), the susceptibility information needs to be adapted.

## 5.2 Landslide runout

This section describes the available methods for assessing landslide runout (travel distance) for different landslide types in quantitative terms and their applicability to different scales of work. Given the low resolution of the regional scale analyses, runout assessment is seldom performed for regional scale maps or smaller, except for very large events (Horton et al. 2008). Landslide magnitude (e.g. volume), propagation mechanism and characteristics of the path are the main factors affecting the landslide runout.

Methods for determining landslide runout may be classified as empirical and rational (Hungr et al. 2005). Both methods are widely used given their capability of being integrated in GIS platforms.

### *5.2.1 Empirical*

Empirical methods are based on field observations and on the analysis of the relationship between morphometric parameters of the landslide (e.g. the volume), characteristics of the path (i.e. local morphology, presence of obstacles), and the distance travelled by the landslide mass. Empirical approaches are based on simplified assumptions and their applicability for quantitative assessment may have restrictions. Methods for predicting landslide runout can be classified as geomorphologically-based, geometrical approaches and volume change methods (Table 8).

**Geomorphological evidences**

Mapping landslide deposits provides a direct measurement of the distance travelled by landslides in the past. The extent of both ancient and recent landslide deposits is used to define future travel distances. The geomorphological analysis allows the determination of: (a) the farthest distance reached by previous landslide events; and (b) if a sufficient number of landslide events is inventoried, statistics of distances reached and their probability.

The complete identification of historical landslide deposits is not always possible. Old deposits may have been buried by new events, or removed by erosion either totally or partially, or masked by depositional features from other processes. The geomorphological approach is appropriate for the analysis of high-magnitude low-frequency events that due to their abnormal size may remain on the landscape for a long span of time and may define the maximum extent of runout that similar events might achieve in the future. However, the uncertainties associated with the source, size, and mobility of future events precludes the definition of the precise location of the hazard zone boundaries. Furthermore, the slope geometry and the causative circumstances associated with past landslides might have changed. Therefore, results obtained in a given place cannot be extrapolated to other localities.

**Geometrical approaches**

Runout assessment can be carried out through the analysis of the geometrical relations between landslide parameters and distance travelled (Domaas, 1994). The most commonly used indexes are the angle of reach or travel distance angle (Hsü, 1975) and the shadow angle (Evans and Hungr, 1993). The angle of reach is the angle of the line connecting the highest point of the landslide crown scarp to the distal margin of the displaced mass. Empirical observations show a volume dependence of the angle of reach ($\alpha$). A plot of the tangent of the reach angle (the ratio between the vertical drop, $H$, and the horizontal component of the runout distance, $L$) against the landslide volume shows that large landslides display lower angles of reach than smaller ones (Scheidegger 1973). The relation may be expressed by a regression equation that takes the following form:

$$\log(tan\,\alpha) = A + B\ \log V \quad (2)$$

Where *A* and *B* are constants and *V* is the volume.

The runout length can also be obtained graphically by considering an angle of reach to the potential landslide volume, for which a line can be traced from the source; the intersection with the topographic surface will give both *H* and *L* (Finlay et al. 1999; Corominas et al. 2003; Copons et al. 2009).

The rockfall shadow is the area beyond the toe of a talus slope that falling boulders can reach by bouncing and rolling. Hungr and Evans (1988) and Evans and Hungr (1993) have used the concept of shadow angle ($\beta$) to determine the maximum travel distance of a rockfall. It is defined by the angle of the line linking the talus apex with the farthest block. The application of this method also requires the presence of a talus slope since the shadow angle is delineated from the talus apex, and the talus toe is used as the reference point beyond which the distance travelled by the fallen blocks is determined.

For debris flows, empirical methods have been developed that predict travel distances and inundation areas in fans. Volume, elevation and channel slope have been used to estimate the total travel distance (Rickenmann, 1999; 2005) or have been determined on the basis of the average channel slope (Prochaska et al. 2008). Volume balance criteria have been considered to delineate cross-sectional and inundated planimetric areas (Iverson et al. 1998; Crosta et al. 2003; Berti and Simoni, 2007).

These empirical methods can be implemented in a GIS for local and site specific analyses (Jaboyedoff et al. 2005; Berti and Simone, 2007; Scheidel and Rickenmann, 2010). Using envelopes to the most extreme observed events is conservative but not unrealistic because they are based on observed cases. This seems appropriate for preliminary studies of runout distance assessment. If enough data is available, it is possible to model the uncertainty in the runout distance by tracing the lines that correspond to the different percentiles (99%, 95%, 90%, etc.) of the spatial probability (Copons et al. 2009). Such approaches may be applied to local-scale landslide susceptibility and hazard maps but as they do not provide the kinematic parameters (velocity, kinetic energy) they are not really suitable for application to site specific analyses.

**Volume-change methods**

The volume change method (Fannin and Wise 2001) estimates the potential travel distance of debris flows by imposing a balance between the volumes of entrained and deposited mass. The path is subdivided into 'reaches', for which reach length, width and slope are measured. The model considers confined, transitional and unconfined reaches and imposes the conditions that there is no deposition for flow in confined reaches and no entrainment for flow in transitional reaches. Using the initial volume as input and the geometry of consecutive reaches, the model establishes an averaged volume-change formula by dividing the volume of mobilised material by the length of debris trails. The initial mobilized volume is then progressively reduced during downslope flow until the movement stops (i.e. the volume of actively flowing debris becomes negligible). The results give a probability of travel distance exceedance that is compared with the travel distances of two observed events.

**Table 8** Empirical methods for assessing runout distance

| | Activity | References |
|---|---|---|
| Geomorphologic | Map old and recent landslide deposits from aerial photos, satellite images and/or surface mapping. Assess limit (greatest likely travel distance for each landslide type). | Hoblitt et al 1998 |
| Geometrical | use empirical methods based on reach angle, shadow angle, or average channel slope to assess travel distance (maximum reach) | Corominas et al. 2003; Ayala et al. 2003; Jaboyedoff 2003; Jaboyedoff and Labiouse 2003; Prochaska et al. 2008 |
| | use empirical methods based on reach angle or shadow angle to assess travel distance accounting for the uncertainty (probability of reach) | Copons and Vilaplana 2008 |
| | Planimetric areas of lahar and debris flow inundated valleys obtained from statistical analyses (volume-area relations) of previous paths | Li 1983; Iverson et al. 1998; Rickenmann 1999; Berti and Simoni 2007 |
| Volume-change method | Runout calculated through a balance between volume entrained and deposited | Fannin and Wise 2001 |

### *5.2.2 Rational methods*

Rational methods are based on the use of analytical or numerical models of different degrees of complexity. They can be classified as discrete or continuum-based models.

**Discrete models**

These models are used in cases where the granularity of the landslide is important. The simplest case is that of a block, which falls on a slope. Its geometry can be modelled with precision or approximated by a simpler form. The model checks for impacts with the basal surface, applying a suitable coefficient of restitution. This approach is used for rockfall modelling, using either lumped (Piteau and Clayton, 1976; Stevens, 1998; Guzzetti et al., 2002), hybrid (Pfeiffer and Bowen, 1989; Jones et al., 2000; Crosta et al., 2004) or rigid-body approaches (Bozzolo and Pamini, 1986; Azzoni et al., 1995). At the other extreme, discrete elements have been used to model rock avalanches. The avalanche is approximated by a set of particles of simple geometrical forms (spheres, circles) with ad hoc laws describing the contact forces. The number of material parameters is generally small (friction, initial cohesion, and elastic properties of the contact). In many occasions, it is not feasible to reproduce all the blocks of the avalanche, which is approximated with a smaller number of blocks. The spheres (3D) or disks (2D) can be combined to form more complex shapes, and various granulometries can be generated. The main advantage of these methods is their ability to reproduce effects, such as inverse segregation, that are far beyond the capabilities of continuum modes (Calvetti et al. 2000). Discrete element models are suitable for the simulation of rock avalanches, but their use it is not recommended in other situations (flowslides, lahars, mudflows, etc.) because of the complex rheology of the flowing materials.

**Continuum based models**

Such models are based on continuum mechanics, and can include the coupling of the mechanical behaviour with hydraulics and thermo mechanics. Here we can consider the following four groups (Table 9).

(a) 3D models based on mixture theory. The most complex model category involves all phases present in the flowing material, as solid particles, fluid and gas. Here relative movements can be large, and this group of models can be applied to the most general case. Due to the great number of unknowns and equations, these models have not been used except when considering the mixture, which is correct for mudflows and rock avalanches. As the geometry is rather complex, no analytical solution exists and it is necessary to discretise the equations using a suitable numerical model. These models are very expensive in terms of computing time, but have to be used in situations where 3D effects are important, as in the case of waves generated by landslides or impact of the flowing material with structures and buildings (Quecedo et al. 2004). This kind of model can be applied to all types of movement with the exception of those which have important effects caused by their granularity

(b) Velocity-pressure models (Biot-Zienkiewicz). In many cases, the movement of pore fluids relative to the soil skeleton can be assumed to be small, and the model can be cast in terms of the velocity of the solid particles and the pore pressures of the interstitial fluids. This is the classical approach used in geotechnical engineering (Sosio et al. 2008) and can be applied to avalanches and debris flows. The resulting model is 3D, and the computational effort to solve it is large. One important point is that pore pressures can be fully described.

(c) Taking into account the geometry of most fast propagating landslides, it is possible to use a depth integration approximation. This method has been classically used in hydraulics and coastal engineering to describe flow in channels, long waves, tides, etc. In the context of landslide analysis, they were introduced by Savage and Hutter (1991). Since then, they have been widely used by engineers and earth scientists. It is also possible to include information on the basal pore pressure (e.g. Iverson and Denlinger 2001; Pastor et al 2008). It is important to note that even if the results obtained by these models can be plotted in 3D, giving the Impression that is a full 3D simulation, the model is 2D. Moreover, pressures and forces over structures are hydrostatic. Therefore, if this information is needed, it is necessary to couple the 2D depth integrated models with the full 3D model in the proximity of the obstacle. Depth integrated models provide an excellent compromise between computer time and accuracy. They have been used to describe rock avalanches, lahars, mudflows, debris flows and flowslides.

(d) Depth integrated models can be still further simplified, as in the case of the so called infinite landslide approaches. Indeed, the block analysis performed in many cases consists of a succession of infinite landslides evolving over a variable topography. Here, pore pressure dissipation can be included (e.g. Hutchinson 1986).

**Table 9** Rational methods for landslide runout assessment

| | | Type of landslide | References |
|---|---|---|---|
| Discrete Models | Lumped | Rockfalls | Agliardi and Crosta 2003; Dorren and Seijmonsbergen 2003; |

| | | | |
|---|---|---|---|
| | Hybrid/rigid body | Rockfalls | Crosta et al. 2004; Azzoni et al. 1995 |
| | Discrete element based models | Rock avalanches | Calvetti et al 2000 |
| Continuum based models | Infinite landslide models and Sliding-consolidation model | Avalanches, debris flows, mudflows, lahars, flowslides | Hutchinson 1986 |
| | Multi sliding block models (thermo mechanical) | Fast propagating landslides | Alonso and Pinyol 2010; Pinyol and Alonso 2010 |
| | Depth Integrated models | Avalanches, debris flows, mudflows, lahars, flowslides | Savage and Hutter K. 1991 ; McDougall and Hungr 2004; Pastor et al. 2008; Iverson and Denlinger 2001 |
| | 3D models | Avalanches, debris flows, mudflows, lahars, flowslides | Sosio et al. 2008; Quecedo et al. 2004 |

# 6. Landslide hazard assessment

Hazard assessment aims to determine the spatial and temporal probability of occurrence of landslides in the target area along with their mode of propagation, size and intensity. A complete analysis has to take into account all of the possible failure mechanisms, the reactivation of dormant landslides, and the acceleration of active ones. A well-known definition of landslide hazard refers to the probability of occurrence of a landslide of a given magnitude (Varnes 1984). The magnitude is the measure of the landslide size which is usually expressed as either the area or volume. However, the landslide magnitude is not the appropriate hazard descriptor. Even though it may be expected that the larger the landslide size the higher the damaging potential is, this cannot be held in all the cases. A large creeping landslide mobilizing hundreds of millions of cubic metres with rate of displacements of few mm/year would cause only slight damage to buildings or infrastructure, and negligible threat to people. In contrast, a rockfall of a few hundreds of cubic metres travelling at tens of m/s has the capability to cause significant damage to structures and loss of lives.

Landslide destructiveness is best represented by its intensity (Hungr  1997). Intensity is expressed differently depending on the propagation mechanism. For landslides causing localized impacts such as rockfalls, the velocity of the event coupled with its volume or the kinetic energy can be used. For slow moving landslides the differential displacement or the total displacement what may cause damage or disturbance to structural elements is used. The depth of debris, peak discharge per unit of width, or impact pressure can be used to characterize the intensity of flow-like movements. The assessment of landslide intensity is not straightforward because it is not an intrinsic characteristic of the landslide. It changes along the path and must be either measured or computed using dynamic models that take the landslide volume as an input parameter.  In areas affected by slow-moving landslides, magnitude has been used as a proxy of the landslide intensity (Guzzetti et al. 2005). Although it is not conceptually correct, it may be practical for deciding between different land-use planning options.

Irrespective of the scale of work, hazard assessment must specify a time frame for the occurrence of all potential landslide types and their intensity at any considered location. This is the most difficult part of the assessment because: (a) different landslide types may occur with different time frames; (b) the target area may be affected by landslides originating from different source areas; (c) the landslide frequency observed at any given location or section will change with the distance from the landslide source. Further discussion on these issues is found in Section 6.4.

## 6.1 Temporal occurrence of landslides

The temporal occurrence of landslides is normally expressed in terms of frequency, return period, or exceedance probability. The frequency represents the number of events in a certain time interval (e.g. annual frequency) and it can conveniently be assessed from empirical data. The return period is the inverse of the annual probability, and refers to the average time interval in which an event of a certain magnitude is expected to occur. The exceedance can be considered as the probability that one or more events can occur in a certain period, regardless of the magnitude of the events (Crovelli, 2000). Otherwise, if the magnitude of the events is accounted for, the exceedance probability can be considered as the probability that an event with magnitude equal to or larger than a certain value can occur in a certain period. Exceedance probability is preferable as a measure of temporal occurrence of landslides for a quantitative probabilistic hazard analysis, and can be derived from the frequency (or return period) by using an appropriate probabilistic model, such as binomial or Poisson models (Crovelli 2000).

Frequency may be absolute or relative (Corominas and Moya 2008). Absolute frequency expresses the number of observed events in a terrain unit (i.e. slope, debris fan, watershed, etc.). It may consist of either repetitive occurrence of first-time slope failures, reactivation events of dormant landslides, or acceleration episodes (surges) of active landslides. Rockfalls and debris flows are typical landslide types treated as repetitive events. Relative frequency is a normalized frequency. It is usually expressed as the ratio of the number of observed landslide events to the unit area or length (i.e. landslides/km$^2$/year). Relative frequency of landslides is appropriate when working with large areas and/or at small scale, and particularly, when dealing with multiple occurrence of regional landslide events or MORLE (Crozier 2005). Maps prepared at scales smaller than 1:25,000 cannot effectively address the frequency of individual small-size landsides (up to a few several thousands of cubic meters) because they are too small to be mapped and treated individually.

The approaches traditionally followed to assess the probability of occurrence of landslides are described next.

### *6.1.1 Heuristic methods (judgemental approach)*

Heuristic methods are based on the expert judgement of a group of specialists whose opinion may be quantified by assigning probabilities. One of the ways to systematise the heuristic evaluation is through event trees. The event tree analysis is a graphical representation of all the events that can occur in a system. By using a logic model, the probability of the possible outcomes following an initiating event may be identified and quantified. As the number of possible outcomes increases, the figure spreads out like the branches of a tree (Wong et al. 1997b). The branching node probabilities have to be determined to quantify the probability of the different alternatives. The probability of a path giving a particular outcome, such as a slope failure, is simply the product of the respective branching node probabilities (Lee et al. 2000; Budetta 2002; Wong 2005).

### 6.1.2 Rational methods (geomechanical approach)

The probability of slope failure may be determined by means of stability analysis and numerical modelling. It is important to point out that the outputs for these methods can be implemented on GIS platforms and used to prepare maps showing the potential for landslide occurrence from hillslope source areas. However, they are not intended to depict landslide paths or landslide deposition areas.

The geomechanical approach considers slope failure as dependent on space, time and stresses within the soil. This allows the calculation of the Factor of Safety, or the Probability of Failure. The latter is assumed to be the probability of the factor of safety being less than the unity. Several methods have been developed to estimate this probability, such as the First-Order-Second Moment (FOSM) method, point estimate methods and Monte Carlo simulations (Wu et al. 1996; Haneberg 2004; Wu and Abdel-Latif 2000). These methods take the uncertainty of the input parameters into account. In order to assign a probability of occurrence, it is necessary to explicitly couple the stability analysis with a triggering factor whose probability is known.

Slope stability may be coupled with hydrological models to simulate the effect of rainfall on slope stability. For single landslides at either local or regional scale, transient hydrogeological 2D or 3D finite element or difference models can be applied (Miller and Sias 1998; Tacher et al. 2005; Malet et al 2005; Shrestha et al. 2008). For shallow landslides, it is possible to implement regional scale analyses by using simplified hydrological methods which can be implemented in a GIS spatially-distributed analysis (Montgomery and Dietrich 1994; Pack et al. 1998; Iverson 2000; Crosta and Frattini 2003; Baum et al. 2005; Godt et al. 2008).

### 6.1.3 Empirical probability

Probabilistic models may be developed based upon the observed frequency of past landslide events. This approach is performed in a similar manner to the hydrology analyses, and the annual probability of occurrence is obtained. In this case, landslides are considered as recurrent events that occur randomly and independently. These assumptions do not hold completely true for landslides, particularly the independency of the events and that external (e.g. climatic) conditions are static. However, they may be accepted as a first order approach and, quite often, frequency analysis is the only feasible method to estimate the temporal probability of occurrence of landslides.

The binomial or the Poisson distributions are typically used to obtain probability of landsliding (Crovelli, 2000). The binomial distribution can be applied to the cases considering discrete time intervals and only one observation per interval (usually a year) is made, as is typically the case in flood frequency analysis. The annual probability of a landslide event of a given magnitude which occurs on average one time each *T* years is:

$$P(N = 1; t = 1) = \frac{1}{T} = \lambda \quad (3)$$

Where *T* is the return period of the event, and $\lambda$ is the expected frequency of future occurrences.

The Poisson distribution arises as a limit case of the binomial distribution when the increments of time are very small (tending to 0); which is why the Poisson distribution is said to be a continuous-time one. The annual probability of having *n* landslide events for a Poisson model is:

$$P(N = n; t = 1) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \quad (4)$$

Where, $\lambda$ is the expected frequency of future landslides. On the other hand, the probability of occurrence of one or more landslides in *t* years is:

$$P(N \geq 1; t) = 1 - e^{-\lambda t} \quad (5)$$

which strongly depends on magnitude of the landslide events. Consequently, magnitude-frequency (M-F) relations should be established in order to carry out the quantitative assessment of the landslide hazard. It must be taken into account that different landslide types occur with different temporal patterns. In the event that the same location is potentially affected by the arrival of different landslide types coming from different sources it will result in an increase of the probability of occurrence, and the combined frequency must be calculated.

### 6.1.4 Indirect approaches

Definition of landslide triggering rainfall or earthquake thresholds has been a topic of great interest in recent decades. Plotting rainfall intensity versus rainfall duration for observed landslide events allows the construction of regionally-specific curves identifying precipitation intensity-durations that cause shallow landslides and debris flows (Guzzetti et al. 2007, 2008).

Once the critical rainfall (or the earthquake) magnitude has been determined, the return period of the landslides is assumed to be that of the critical trigger. These types of relationships give an estimate of how often landslides occur in the study area but not which slopes will fail nor do they indicate the size of the failures. In this case, the probability of occurrence of the landslide triggering rainfall allows the calculation of the relative frequency of landslides (i.e. the number of landslides/km$^2$/year) which is useful for regional analyses of landslides of homogeneous size (Reid and Page 2002).

It must be taken into account that regional landslide triggering events might co-exist with other regional triggers (e.g. snow melting) and with other landslide triggers occurring at a local scale (e.g. river erosion). In this case, the return period obtained from the regional landslide trigger is only a minimum estimate of the landslide frequency.

## 6.2 Magnitude-Frequency relations

The landslide magnitude-frequency relation is the basis of quantitative hazard assessment. Without a sound assessment of landslide occurrence probability, expressed in terms of the expected annual frequency of landslide events of a given magnitude, or exceeding a magnitude threshold, a quantitative assessment of landslide hazard is not feasible. In this case, the problem can only be dealt with in terms of susceptibility (e.g. spatial probability; Brabb 1984).

Specific relationships between the frequency of events falling in different magnitude classes (i.e. magnitude-frequency relationships) have been observed for different natural hazards (e.g. earthquakes, floods). The first well-established magnitude-frequency relationship was proposed in seismology where a relation between earthquake magnitude and cumulative frequency was observed (Gutenberg-Richter equation), which is expressed as:

$$Log\ N(m) = a - bM \quad (6)$$

where:

*N(m)* is the cumulative number of earthquake events of magnitude equal or greater than *M*, and *a* and *b* are constants.

The probability density function according to the Gutenberg Richter relation can be calculated as the derivative of the corresponding cumulative density function. In practice, when simulating earthquakes, bounded versions of the Gutenberg-Richter relation are used, that account for a lower completeness cut-off earthquake magnitude and an expected upper one (Kramer 1996).

Early analyses for landslides (Hovius et al. 1997; Pelletier et al. 1997) found that magnitude versus cumulative frequency of the number of landslides are scale invariant and for a wide range of landslide magnitudes, the relation follows a power law which is formally equivalent to the Gutenberg-Richter equation:

$$N_{CL} = CA_L^{-\alpha} \quad (7)$$

Where:

$N_{CL}$ is the cumulative number of landslide events with magnitude equal or greater than *A*, and

$A_L$ is the landslide magnitude (usually expressed as its size: volume or area), and *C* and $\alpha$ are constants.

For the noncumulative distribution of landslides a similar distribution maybe used (Guzzeti et al., 2002b).

$$N_L = C'A_L^{-\beta} \quad (8)$$

where

$N_L$ is the noncumulative number of landslide events with magnitude equal or greater than *A*, and

$A_L$ is the landslide magnitude (usually expressed as its size: volume or area), and *C´* and $\beta$ are constants.

The construction and interpretation of frequency-magnitude relations have been discussed by several researchers (e.g. Guzzetti el al. 2002b; Brardinoni and Church 2004; Malamud et al. 2004; Guthrie et al. 2008; Brunetti et al. 2009). Power laws may usually be adjusted to the frequency distribution of events in a given magnitude class above a magnitude threshold. Below this threshold, a characteristic ‘roll-over’ effect may occur, resulting in a deviation from the power law and in an unrealistic underestimation of smaller events. While some researchers consider that the rollover effect is usually not observed in complete inventories and that flattening of the magnitude frequency curves towards small magnitude values should be related to censoring effects (Hungr et al. 1999; Stark and Hovius 2001; Malamud et al. 2004) others consider that rollover is the result of actual physiographic limitations (Pelletier et al. 1997; Guthrie et al. 2008) or the effect of cohesion (Van Den Eeckhaut et al. 2007).

### *6.2.1 Derivation of M-F relations*

Different approaches may be followed depending on whether M-F relations have been derived at a regional scale or at particular locations. Lists of possible references on how to prepare M-F relationships with different approaches or using different datasets are given in Table 10 and Table 11. Landslide magnitude may be expressed either in terms of MORLE or by the size of individual landslides.

In regional scale analyses a relation may be established between the intensity of the trigger (accumulated rainfall, rainfall intensity, earthquake magnitude) and the magnitude of the MORLE which is given by either the total number of landslides or preferably, by landslide areal density (i.e. number of landslides/km$^2$) (Frattini et al. 2010). Such a relation has been obtained in some documented cases for storms (Reid and Page 2003) and earthquakes (Keefer 2002). M-F relations can also be prepared from the analysis of aerial photographs or satellite images obtained at known time intervals. These M-F relations may have validity at a regional level but not for any particular slope or sub-region. It is important to note that in the aforementioned regional approaches, landslide runout is not considered in the analyses (Table 10).

In local scale analysis, the F-M relation calculated at the source area can be significantly different than that calculated further downhill, as the volume of the landslide influences travel distance and area covered by the deposit. Consequently, landslide frequency at any terrain unit is due to both the occurrence of a slope failure and the probability of being affected by landslides coming from neighbouring areas.

The probability that a given slope unit is affected by a landslide thus depends on the frequency of initiation, which must be scaled according to the frequency of reach, which in turn depends on landslide dynamics simulated by suitable models (Crosta and Agliardi 2003). For hazard zoning purposes, such scaling may be regarded as negligible for short-runout landslides, and hazard can be evaluated with respect to the landslide source. Conversely, when coping with long-runout landslides at the local or site-specific scale, M-F relations derived at the landslide source must be combined with runout models to obtain the areal frequency of different landslide magnitudes (Table 10 and Table 11).

**Table 10** Activities required for preparing non spatially-explicit magnitude-frequency relations for landslides

| | Methodology –data source | References |
|---|---|---|
| Occurrence of multiple-landslide triggering events | Landslide density (magnitude) is related to the intensity of the landslide-triggering storm | Reid and Page 2003 |
| | Landslide density (magnitude) is related to the intensity of the landslide-triggering earthquake | Keefer 2002 |
| | Relating factor of safety to rainfall or piezometric levels | Salciarini et al. 2008 |
| Cumulative occurrence of landslides over known time intervals | Analysis of landside records and historical archives | Jaiswal and Van Westen 2009 |
| | Identification and inventory of landslides from aerial photographs or satellite images | Hungr et al. 1999; Guthrie and Evans et al. 2004 |
| | Landslide series completed by dating landslide deposits and field work. | Schuster et al. 1992; Bull et al. 1994; Bull and Brandon 1998 |
| | Landslide series completed using proxy data such as silent witnesses (e.g. tree damages). | Van Steijn 1996 |

**Table 11** Activities required for preparing spatially-explicit magnitude-frequency relations for landslides

| | Methodology –data source | References |
|---|---|---|
| Source area | Landslide reactivation event series prepared from dating the associated landslide reactivation features | Agliardi et al. 2009a |
| | Size of landslide scars | Pelletier et al. 1997 |
| | Probabilistic analysis of cliff recession rates | Lee et al. 2002 |
| Reference section or location | Incident databases of roads and railway maintenance teams | Bunce et al. 1997;<br>Hungr et al. 1999; Chau et al. 2003 |
| | Spatial probability of occurrence combined with the excepted probability of occurrence at each slope | Guzzetti et al. 2005 |
| | Landslide series completed using proxy data such as silent witnesses (e.g. tree damages) | Jakob and Friele 2010; Stoffel 2010; Corominas and Moya 2010; Lopez Saez et al. 2012 |
| | Landslide series completed by dating landslide deposits and field work. | VanDine et al. 2005 |
| Integrated approach | Landslide frequency at the source area combined with runout models to obtain frequency of different landslide magnitude at given control section | Corominas et al. 2005; |
| | Landslide frequency at the source area combined with runout models to obtain spatial distribution of different landslide magnitude | Agliardi et al 2009b |

### *6.2.2 Restrictions of M-F relations*

The application of M-F curves must be performed with care. Limitations as to their validity and practical applicability include statistical reliability and the degree to which the processes used to determine them are fully representative of the physical process in play. The statistical reliability of M-F curves is affected by the facts that historical databases and inventories of landslide events (the preferred source of M-F information) are rarely available, and site-specific data collection may not be feasible for large areas or when budget constraints exits. Moreover, landslide size values reported in historical databases may be incomplete or estimated at the order-of-magnitude level of accuracy (Hungr et al. 1999). Data may be incomplete both in space (i.e. data sampling only in specific sub-areas) and in time (i.e. data recorded only for specific time windows). Under-sampling of low-magnitude events may be related to the existence of a detection cut-off threshold (e.g. for rockfalls along roads, very small blocks may not be considered as 'landslide events' or if they are they may not be reported) or to 'systemic censoring' due to factors affecting the physical processes involved in landsliding (e.g. effective countermeasures upslope the sampling area). M-F curves derived from inventories prepared from a single aerial photogram or image, or from a unique field campaign should be discouraged. These types of inventories do not reflect the actual frequency of different landslide magnitudes, as many small landslides might have disappeared due to erosion or they do not reflect the reactivation events that might have affected to large landslides (Corominas and Moya 2008).

A key question is whether the rate of occurrence of small landslides in a region can be extrapolated to predict the rate of occurrence of large landslides and *vice versa*. The answer to this question is not evident. As stated by Hungr et al. (2008), based on the analysis of debris flows and debris avalanches, an M-F derived from a region would underestimate the magnitudes if applied to a smaller sub-region of relatively tall slopes and overestimate in a nearby sub-region with lower relief. An even greater error could result if one was to attempt to estimate the probability of slides of a certain magnitude on a specific slope segment, the height of which is known

## 6.3 Landslide intensity-frequency relation

Combinations of magnitude-frequency pairs do not yield landslide hazard because landslide magnitude values are not suitable for being used in vulnerability curves for risk analysis. In order to assign a probability or frequency to events leading to a certain degree of damage (assessed through vulnerability curves) it is therefore necessary to assess intensity. The choice of the appropriate intensity parameter depends on the typology of landslides and the nature of element at risk. For instance, kinetic energy is the most frequently used parameter for rockfalls (Corominas et al 2005 Agliardi et al 2009b), whereas peak discharge (Jakob 2005), velocity (Hungr 1997; Bovolin and Taglialatela 2002, Calvo and Savi 2009), or depth ( Borter 1999; Fuchs et al. 2007) are used for debris flows. For large slides and earthflows, the displacement or displacement rate (Saygili and Rathje 2009; Mansour et al. 2011) can be suitable parameters.

Techniques to derive Intensity-Frequency relationships for each location along the slope can be different as a function of the typology of the landslide and the scale of the analysis. For local scale analysis of single landslides it is possible to simulate various scenarios with different volumes and associated probabilities (e.g. M-F relationships) through numerical models in order to determine the spatial distribution of intensity during landslide movement (Archetti and Lamberti 2003; Jaboyedoff et al. 2005; Friele et al. 2008). Hence, for each location on the slope it is possible to build the Intensity-Frequency curves by adopting the frequency values of M-F relationships and the intensities calculated by the models.

For slopes potentially affected by landslides which can fail from different source areas, the intensity at each location along the slope is not a single value for each frequency scenario, but a distribution of values. To characterize this distribution a simple statistic of the distribution is normally used, such as the arithmetic average (Agliardi et al. 2009b) or the maximum value (Gentile et al. 2008; Calvo and Savi. 2009) and the Intensity-Frequency curves are derived using this value of intensity and the frequency derived from M-F relationships.

However, this approach introduces a strong assumption about the distribution of intensity, because the arithmetic mean is appropriate only for normally distributed intensities, and the maximum value only consider outliers of the distribution, strongly overestimating the actual hazard.

An alternative approach for the calculation of Intensity-Frequency relationships for rockfall is to consider the probability distribution of kinetic energy for a given location and volume scenario (Jaboyedoff et al. 2005). By using 3D rockfall models it is also possible to analyse the convergence of different trajectories in the same location, thus characterizing the frequency distribution of kinetic energy (Frattini et al. 2012).

## 6.4 Landslide hazard evaluation

### 6.4.1 The object of the hazard analysis

The purpose of a landslide hazard analysis determines the scale, the methodology and its results. The hazard analysis may have different target areas and spatial arrangements (Corominas and Moya. 2008) including the following:

- Areal analysis is usually performed for either regional or local planning zoning. The potential for slope failure is evaluated at every single terrain unit (pixel, cell, polygon, basin) and the temporal occurrence may be expressed in relative terms as the number of landslides (of a given magnitude) per unit area ($km^2$, pixel, etc.) per year or as an exceedance probability. The intensity may be later integrated by combining the outputs with runout analysis.
- Linear analysis is performed for infrastructure and facilities (motorways, railways, pipelines, etc.) having a linear layout. The analysis may be performed at the source area (Michoud et al. 2012) but it usually focuses on the landslides (potentially) affecting the infrastructure. The hazard may be expressed as the number of landslides of a given magnitude reaching the infrastructure per unit length and per year or as the total number of landslides per year in the whole stretch. In both cases, frequency is expressed in relative terms and should be determined for segregated landslide volumes (e.g. Jaiswal and Van Westen. 2009; Jaiswal et al. 2010).
- Object oriented (point like) hazard analysis is performed at specific sites such as debris fans, talus slopes, or for an element or set of exposed elements. Hazard analysis is restricted to those landslides (potentially) affecting the site. Frequency may be expressed in absolute terms as the number of landslides of a given magnitude reaching the site per year.

According to whether or not the exact location of the slope failure, the landslide runout or both is shown, the analyses are considered spatially or non-spatially explicit.

### 6.4.2 Consideration of landslide runout

Areal hazard analysis can be addressed with or without the mobility of the landslides. Short displacement landslides are well contained geographically and remain at or very close to the initiation zone. In this case, hazard assessment and mapping considers the potential for slope failure or landslide reactivation at each terrain unit but intensity is not calculated (Cardinali et al. 2002). Long runout landslides can travel considerable distances from the source area. In this case, besides the potential for slope failure, landslide frequency (and consequent intensity level) must be determined along the path (spatially explicit analysis). Different landslide magnitudes will result in different travel distances and intensities.

To include landslide runout, two approaches may be considered (Roberds 2005): the probability of failure of each slope is first determined, propagation is calculated separately and then they are mathematically combined. For this, a magnitude-frequency relation is required for each slope or land unit and, afterwards, the estimation of the runout distance for each landslide magnitude. Alternatively, hazard is directly calculated for each combination of slope instability mode and runout as, for instance, the magnitude-frequency of a rockfall at a road based on statistics of past rockfall events (i.e. Bunce et al. 1997; Hungr et al. 1999) or on a debris fan (Van Dine et al. 2005).

### *6.4.3 Non-spatially explicit hazard analyses*

National and regional maps in which the scale usually does not allow accurate slope stability and runout analyses to be performed are non-spatially explicit. Hazard assessment is not fully achieved because intensity is not considered. This analysis is typically performed for shallow landslides, which are assumed as recurrent events within a region either as scattered failures occurring throughout the study area over time or generated by particular landslide-triggering events (i.e. rain storm or earthquake) acting over a large area (MORLE).

Hazard over defined time intervals can be assessed based on landslide inventories prepared from successive aerial photographs or images. Frequency of the landslides is calculated by counting the number of new landslides between photographs. Landslide hazard is expressed by the number of landslides per unit area in a given time span. This method provides valid estimates of the short term average frequency. It may be used for a mid and long-term average frequency only if the sampling period includes an average distribution of landslide-producing events (Corominas and Moya 2008).

For MORLE, first a relationship must be established between the occurrence of landslide events and the trigger, either storm precipitation (e.g. Guzzetti et al. 2008) or seismic events (e.g. Keefer 1984; Jibson et al. 1998). Given sufficient spatial resolution of storm rainfall records or of the earthquake magnitude, the distribution of landslides over the area should make it possible the establishment of rainfall intensity/landslide density or epicentral distance/landslide density functions. In a second step, the exceedance probability of either the rainfall intensity or earthquake magnitude can be related to the landslide density (e.g. number of landslides/km$^2$) (Reid and Page 2003; Keefer 2002). However, in some areas it has been found that the landslide density changes non-linearly with rainfall and that a reliable relationship cannot really be established (Govi & Sorzana 1980). These type of relationships give an estimation of how often landslides may occur in the study area but not where the slopes will fail. However, if combined with landslide susceptibility or probability maps it is possible to identify areas where landslides can be expected to occur, given threshold-exceeding rainfall (Baum and Godt 2010)

Hazard calculated from the frequency of landslide triggers, does not require a complete record of past landslides but it is necessary to determine a reliable relation between the trigger, its magnitude and the occurrence of the landslides. It must be taken into account that regional landslide triggering events might co-exist with other regional triggers (e.g. snow melting) and with local landslide activity (e.g. river erosion). Consequently, return periods obtained from regional landslide triggers are only a minimum estimate of the landslide frequency. The opposite may occur if landslides remove the mantle of susceptible material leaving an essentially stable residual surface – a process referred to as event resistance (Crozier and Preston 1999). Some authors propose a minimum 'safety' threshold for rainfall that has historically produced few landslides and an 'abundant' threshold for rainfall triggering many landslides (Wilson 2004)

Selected references on the afore-mentioned approaches for non-spatially explicit hazard analyses are given in Table 12.

**Table 12** Regional hazard assessment (non-spatially explicit)

| Methodology | Hazard descriptor | Reference |
|---|---|---|
| Recurrence of landslides is obtained from sets of aerial photographs and/or satellite images taken at known time intervals. Landslide frequency is then obtained | # landslides/km$^2$/yr<br># landslides/pixel/yr<br>total slide area/km$^2$/yr | Remondo et al. 2005; Guzzetti et al. 2005 |
| Different magnitude landslide triggering events are related to landslide density. Return periods or the exceedance probability of the trigger are then calculated | Probability of having<br># landslides/km$^2$<br># landslides/pixel<br>total slide area/km$^2$ | Reid and Page (2002) |
| Seismic shaking probability for given time intervals combined with probability of landsliding based on Newmark models | Probability of landslide occurrence | Del Gaudio et al. (2003) |

### 6.4.4 *Spatially-explicit hazard analysis*

In local and site specific scales, the resolution of the DEM usually allows the probability of landslide occurrence to be calculated at each analysed unit (e.g. pixel). The analyses may be performed by either including or excluding the runout analysis and the subsequent intensity calculation (Table 13):

**Hazard assessment without intensity calculation**

This type of analysis is usually carried out for landslides geographically contained (e.g. slow moving short-runout landslides) whose displacements cannot be represented outside the analysed spatial unit (e.g. cell or pixel). It is also performed for linear or point like features located far away from the landslide source in which landslide hazard is determined from the observation of past events. In both cases, intensity is not calculated and risk is assessed assuming simplifying assumptions for the vulnerability of the exposed elements.

a. Hazard analysis for geographically-contained landslides

Combined spatially distributed hydrological and stability models are used in either regional or local scale analyses to calculate the probability of landslides in land units (e.g. pixel, basin) containing both the landslide source and deposition area. Hazard is expressed as the annual probability of either failure or reactivation at each terrain unit. More specifically hazard is calculated as the conditional probability of slope failure once a landslide trigger (e.g. critical rainfall or earthquake) occurs. The factor of safety of the slope is computed at each terrain unit considering an infinite slope stability model in which the probability of failure is obtained as the annual exceedance probability of a critical rainfall event (Savage et al., 2004; Baum et al. 2005; Salciarini et al. 2008). For earthquake-induced failures, a conventional seismic hazard analysis is used to determine the peak ground accelerations (PGA) for different return periods and the stability of slopes, when subjected to earthquakes of varying return periods, is examined using a pseudo-static analysis (Dai et al. 2002).

Alternatively, the probability of landslide occurrence may be calculated based on the observed frequency of past landside events (Catani et al. 2005). An example of the latter is provided by Guzzetti et al. (2005) who defined geo-morpho-hydrological units, and obtained the probability of spatial occurrence of landslides for each unit by discriminant analysis.

b. Hazard analysis performed at a reference section or point-like object

Runout calculation is not required for the hazard analysis focussed on specific sections or locations. It is typically performed for transportation corridors in which landslide records are available and the exposed elements (cars and people) are highly vulnerable to low intensity landslides. Then, neither velocity nor kinetic energy is computed. Magnitude of the event is used to determine, for instance, the number of affected lanes or the width of the landslide mass and calculate the encounter probability (Bunce et al. 1997; Hungr et al. 1999; Jaiswal and Van Westen 2009; Jaiswal et al. 2010; Ferlisi et al. 2012). Hazard values may be expressed as either relative terms (i.e. annual probability of occurrence of a given magnitude event per unit length) or absolute terms (i.e. number of events per year).

**Combined landslide initiation and runout hazard analyses**

This type of analysis takes into account the spatial distribution of the landslide intensity. A given rockfall volume will produce a changing velocity profile along its path and the kinetic or impact energy will change as well (Crosta and Agliardi 2003). Rockfall intensity is not biunivocally dependent on rockfall size (magnitude) as similar kinetic energy values can result from different combinations of volumes and velocities. Therefore, rockfall hazard mapping must be performed with the support of runout models that calculate the potential rockfall paths, the location of obstructions that may stop blocks, the velocity and kinetic energy of the blocks, and the spatial distribution of the kinetic energy.

A critical issue is the definition of the characteristic rockfall volume. In the case of fragmented rockfalls (Evans and Hungr 1993), the hazard is caused by individual blocks that describe more or less independent trajectories. However, magnitude-frequency relationships which are the usual output of the rockfall inventories, links the frequency to the volume of the initial detached mass, but not to the size of the individual blocks that finally reach the reference section and this may result in an overestimation of the impact energy and an underestimation of the impact probability. Unfortunately, at present most of the available codes do not consider the rockfall fragmentation process. If a rockfall event is treated as an individual block in the runout analysis, it should be representative of the most likely future events. The representative block size can be determined from the geometric characteristics (i.e. length, spacing) of the main discontinuity sets observed on the rock face, and/or from the size distribution of the fragments on the slope (Agliardi et al. 2009b; Abbruzzese et al. 2009).

In debris flows, as in rockfalls, the intensity is not biunivocally dependent on the mobilized debris volume. Every debris flow event will produce a different distribution of intensity and probability of impact, based on its dynamics. According to Hungr (1997) the hazard intensity map must therefore present a scale of pairings of intensity and impact probability values for various types and magnitude classes of the flow. Two different approaches are typically used for debris flow hazard assessment at the site-specific scale: (1) assess the probability of occurrence of failure of a particular debris volume that will generate a debris flow and use a physically based (2D or 3D) runout models to define the affected area and the intensity parameters (Hürlimann et al. 2006, 2008); (2) assess the probability of occurrence of debris flows of different magnitudes at particular locations below the debris source (i.e. reference sections , debris fans) using M-F relations (Van Dine et al. 2005).

**Table 13** Spatially explicit landslide hazard analyses

| | | Methodology | Magnitude/Intensity | Frequency | Hazard descriptor | Reference |
|---|---|---|---|---|---|---|
| Landslide intensity not considered | Areal analysis | Combining spatial probability (susceptibility) with the probability of a landslide of a given magnitude and probability of occurrence | Landslide size (area, volume) | Frequency of landslides is averaged by the time span between sets of images. | exceedance probability of occurrence of a landslide of a given magnitude during an established period | Guzzetti et al. 2005; |
| | | Stability models combined with spatially distributed hydrological models and probability of the critical trigger | Landslide density | Return periods or the exceedance probability of the trigger magnitude | exceedance probability of the landslide trigger during an established period | Savage et al. 2004; Baum et al. 2005; Salciarini et al. 2008 |
| | object oriented analysis (linear or point like) | Hazard assessment performed at a reference section (e.g. road segment) | Landslide magnitude | Frequency of landslide magnitude classes is averaged by the recorded time span | Probability of x landslides of a given size per year (it may be normalized by length) | Bunce et al. 1997; Hungr et al. 1999; Jaiswal et al. 2010; Ferlisi et al. 2012 |
| | | Hazard assessment performed at a reference location (i.e. where the exposed element is located) | Landslide magnitude/ extent | From historical catalogues (M-F relations) | or debris flow magnitude and for established periods | VanDine et al. 2005 |
| Landslide intensity calculated | Areal analysis | Combining probability of occurrence at identified sources with empirical runout models | Volume/ kinetic energy/ extent | From historical catalogues (M-F relations) | Kinetic energy limits for different rockfall magnitude and for established periods | Guzzetti et al. 2003; Jaboyedoff et al. 2005; Blahut et al. 2010a; Jaboyedoff and Labiouse 2011 |
| | object oriented analysis (linear or point like) | Combining probability of occurrence with empirical-statistical runout models | Block volume | From slope angle frequency distributions | Number of events ≥ a given magnitude per year | Corominas et al. 2005; Agliardi et al. 2009b; Michoud et al. 2012 |
| | | Combining probability of occurrence with physically based runout models | Debris volume/ velocity | From historical catalogues (M-F relations) | | Hürlimann et al. 2006 2008 |

## 6.5 Landslide multi-hazard assessment

The term multi-hazard is frequently used in literature (Lewis, 1984; Granger et al. 1999) as an adjective to indicate ‘multiple sources of hazard’ that are analysed in parallel and finally integrated into a multi-risk assessment. The assessment of multi-hazard, sensu stricto, should be intended as the definition of the joint probability of independent events occurring in the same area in a given time span. In practice, however, multi-hazard is often considered solely in conjunction with risk analysis, for the assessment of expected losses. This is due to the fact that vulnerability is dependent on landslide typology and intensity and to combine occurrence probabilities at the hazard stage into a single hazard value might hinder the correct determination of risk in the following stages.

When multiple non-interacting sources of hazard are analysed, hazard assessment is performed independently for each source following specific guidance. In this sense, a real multi-hazard assessment is not performed, and the integration of different sources of hazards is done at the level of risk (e.g. combining F-N curves, sum of expected losses).

Multi-hazard assessment becomes relevant when hazard sources can interact, giving rise to a ‘domino’ effect that occurs when a hazard event triggers a secondary event; examples of such sequences include a landslide damming a valley bottom and the consequent and subsequent failure of the dam.

In the literature, there are several examples of applications that consider the combined effects of different natural (or man-made) hazards as concerning given sets of elements at risk (Van Westen et al. 2002; Lacasse et al., 2008; Kappes et al. 2010; Schmidt et al. 2011). Marzocchi et al. (2012) for two interacting hazards whose occurrence is $E_1$ and $E_2$ and where $H_1$ is the probability of occurrence of $E_1$, proposes the following equation:

$$\mathrm{H}_1 = \mathrm{p}(\mathrm{E}_1) = p((E_1|E_2)p(E_2) + p(E_1|\overline{E_2})p(\overline{E_2}) \quad (9)$$

Where $p$ represents a probability or a distribution of probability and $\bar{E}_2$ means that the event $E_2$ does not occur. The generalisation of Equation 9 to more than two events does not pose any particular conceptual problem even though it may require cumbersome calculations (Marzocchi et al. 2012).

Although the severe consequences of such domino sequences are well known, there is as yet no well-established and largely accepted methodology for the identification and the quantitative assessment of hazard of domino effects. Several qualitative criteria were proposed in the literature to identify the possibility of domino events, whereas only a few pioneering studies addressed the problem of the quantitative assessment of risk due to domino effects, most of them in relation to earthquakes (e.g. Keefer 1984; Romeo 2006).

Methodologies for the assessment of domino hazards involving natural events (e.g. landslides, floods, tsunamis, etc.) can be derived and adapted from the ones proposed for technological hazards. In particular, the methodology proposed by Cozzani and Zanelli (2001) is be useful for this purpose. The frequency of the secondary event *B* is calculated as:

$$f_B = f_A P_d \qquad (10)$$

where $f_B$ is the expected frequency of the secondary event *B*, $f_A$ is the expected frequency (events/year) of the first event *A*, and $P_d$ is the propagation probability, expressed as

$$P_d = P(B|A) \qquad (11)$$

where $P(B|A)$ is the conditional probability of *B* given *A*.

A fundamental tool for coping with interconnected probabilities, widely recognized as a standard in environmental impact assessment and industrial risk analysis, is the Event Tree or Cause-Effect Network. In a sentence, an Event Tree (ET) is a graphical or logical scheme able to represent direct and indirect chains of cause-effect as a consequence of a starting event, usually called First Impact. There are various typologies of ET, ranging from purely categorical (in which the descriptive sequence of events is reproduced with all the predictable branching) to quantitative ETs, where a numerical representation of the conditional probability or return time of every single chain node is calculated using suitable methods (Lee and Jones 2004). The most used ET based on conditional probability is the Bayesian Event Tree (BET).

The different approaches to relative/absolute probability assessment for multi-hazard can be broadly summarized in the following classes:

a. Joint probability: according to the fundamentals of probability theory, the concurrent occurrence of events can be calculated combining their respective probability using suitable rules and methods. This is a very basic, yet essential, tool that does not account for spatial dimensions, cascade effects or system dynamics.
b. Event Tree - Bayesian Event Tree: this category includes descriptive event trees, Bayesian event trees and general cause-effect propagation networks. Branching can be multiple or binary. Each branching can be assigned a conditional probability (Bayesian ET). This approach has explicit consideration of cascading higher order effects but does not fully account for spatial dimensionality of probability pathways. For this reason, in the context of hazard analysis, such methods should be more appropriately called Scenario-based BETs.
c. Spatially averaged ET-BET: a specific, spatially-aware version of BET can be envisaged when dealing with multiple multi-hazard paths over a given geographic space. Depending on the level of spatial and temporal knowledge of the single hazards this can be:
    1. Spatial distribution of single independent BETs, when hazard maps provide indication of a given probability of occurrence H(I) in a given time span over specific locations.
    2. Spatial averaging of BET probabilistic outcomes with statistical averaging, when hazard maps provide a spatially averaged (or statistically deduced) degree of hazard, in terms or either relative probability or probability in time.
    3. Spatial lumping of BETs, when necessary data are only known over discrete areas with constant values.
d. Spatially averaged BET with Functional Behaviour: the physical objects in geographic space interact dynamically and show behaviours that vary in time as a consequence of system evolution. This is not explicitly accounted for using the previous methods but can be included in multi-hazard analysis resorting to techniques able to dynamically modify the event trees according to functional

behaviour rules (Eveleigh et al. 2006, 2007). This is a new and challenging approach with virtually no application in landslide studies. It obviously requires that an unusually large amount of data to be available and that makes it more suitable for slope-local scale studies at the present stage.

In practical terms when dealing with the assessment of hazard, four different scenarios concerning multi-hazard for landslides can be possible:

1. Multiple types of landslides: Multiple types of landslides occurring at the same location, but not interacting with each other and causing a cascade or domino effect, and not necessarily occurring at the same time.
2. Composite landslides: According to Cruden and Varnes (1996) a composite landslide exhibits at least two types of movement simultaneously in different parts of the displacing mass.
3. Complex landslides: According to Cruden and Varnes (1996) a complex landslide exhibits at least two types of movement in temporal sequence providing a sort of cascade effect.
4. Multiple interacting landslides: multiple types of landslides (or several landslides of the same type) occurring at the same or in different locations but interacting so that there is a point in time and space (confluence point) when the effects are cumulated using suitable concepts.

For the first case the assessment of hazard is undertaken independently for each type of landslide and the results are merged only at the risk level. For composite landslides the joint probability approach can be considered for multi-hazard assessment while when complex landslides occur providing a cascade effect such as, for example, a slide evolving into a flow the ET or BET can be suggested. The fourth case requires the distributed use of ETs or BETs or a single ET/BET to account for the cumulated/cascading effects down-valley to the confluence point. The selection of the best approach of ET or BET among the ones listed above depends on the scale of analysis and on the hazard descriptors selected.

The scheme in Tables 14 and 15 based on the suggested methods for landslide hazard assessment for different scales and typologies, attempts a series of short recommendations on multi-hazard requirements for each case, according to the broad categories of methods just listed.

**Table 14** Suggested methods for multi-hazard assessment at regional scale

| Regional scale | Magnitude | Frequency | Hazard descriptor | Multi-hazard methods and recommendations |
|---|---|---|---|---|
| Areal analysis | Landslide density<br>Landslide size (area, volume) | Frequency of landslides is averaged by the time span between sets of images. | # landslides/km$^2$/yr<br># landslides/pixel/yr<br>total slide area/km$^2$/yr | Spatially averaged joint probability and scenario-based BETs; |
| | Landslide density (i.e. landslides/km$^2$) | Return periods or the exceedance probability of the trigger magnitude | Probability of having<br># landslides/km$^2$<br># landslides/pixel<br>total slide area/km$^2$ | Spatially averaged joint probability and BETs;<br>Spatially-based BETs |
| | Number of landslides (normalized by distance) | Return periods or the exceedance probability of seismic shaking | Probability of landslide occurrence | Spatially averaged joint probability and BETs;<br>Spatially-based BETs |

**Table 15** Suggested methods for multi-hazard assessment at local scale

| Local scale | | Magnitude | Frequency | Hazard descriptor | Multi-hazard methods and recommendations |
|---|---|---|---|---|---|
| Areal analysis | Runout not included | Landslide size (area, volume) | Frequency of landslides is averaged by the time span between sets of images. | exceedance probability of occurrence of a landslide of a given magnitude during an established period | Scenario-based BETs; Spatially averaged joint probability and BETs; Spatially-based BETs with functional behaviour |
| Areal analysis | Runout not included | Landslide density | Return periods or the exceedance probability of the trigger magnitude | exceedance probability of the landslide trigger during an established period | Spatially averaged joint probability and BETs; Spatially-based BETs with functional behaviour |
| Areal analysis | Runout included | Block volume/ Kinetic energy | .From historical catalogues (M/f relations) | Kinetic energy limits for different rockfall magnitude and for established periods | Scenario-based BETs; Spatially averaged joint probability and BETs; Spatially-based BETs with functional behaviour |
| Areal analysis | Runout included | Block volume/ Kinetic energy | From historical catalogues (M/f relations) | Kinetic energy limits for different rockfall or debris flow magnitude and for established periods | Scenario-based BETs; Spatially averaged joint probability and BETs; Spatially-based BETs with functional behaviour |
| Non-areal analysis | Runout not included | Landslide size (volume) or intensity | Frequency of landslide magnitude classes is averaged by the recorded time span | Probability of x landslides of a given size per year (it may be normalized by length) | Spatially lumped BETs with or without functional behaviour |

# 7. Suggested methods for quantitative landslide risk assessment

This section is dedicated to quantified risk assessment, taking landslide hazard as an input. It often necessary to calculate all of the parameters in Equation (1) for each magnitude class, as each class has a specific probability of occurrence, travel distance, intensity and impact probability. The global risk for an area can then be obtained by aggregation of the specific risks for different landslide magnitudes or intensities and for all of the exposed elements. However, for regional, or smaller, scale analyses this cannot apply because of the lack of detailed input data, and so the risk equation is simpler and more general.

Besides the direct risk (involving, for example, the physical loss of property or fatalities), the indirect risk must be added as well (e.g. disruption of economic activities, evacuation of the areas, etc.), but this is beyond the scope of this paper, which mostly focuses on the direct losses.

Risk descriptors vary according to the aim of the assessment, the nature and type of the exposed elements, as well as on the terms that are used for the description of the extent of the loss.

Landslide risk descriptors may be:

- Univariate, as for example €1,000,000/year.
- Multivariate, as for example (cumulative) probability of 0.0001 for a given level of loss. Loss might be a qualitative (e.g. low, moderate, severe) or quantitative (number of fatalities, money, etc.) variable.

For the second risk descriptor, representative risk scenarios should be established. Risk descriptors for an object or an area might be illustrated using (cumulative) frequency (or probability)-consequence curves (Fig. 3) or single values.

For the calculation of risk, two alternative types of analysis might be used which are deterministic or probabilistic. Deterministic risk assessment uses average or most unfavourable values (worst case scenario) of the risk components (variables of the risk equation) and it yields a univariate result expressing, respectively the average or maximum risk. In contrast, for the probabilistic analysis, all or some of the risk components are assumed not to be constant, but to follow a probability distribution, thus the results are presented in probabilistic terms, using pairs or plots of (cumulative) probability and consequences. Monte Carlo simulations may facilitate the probabilistic calculation of the risk, when the probability density functions fitting the distributions of the risk components are known.

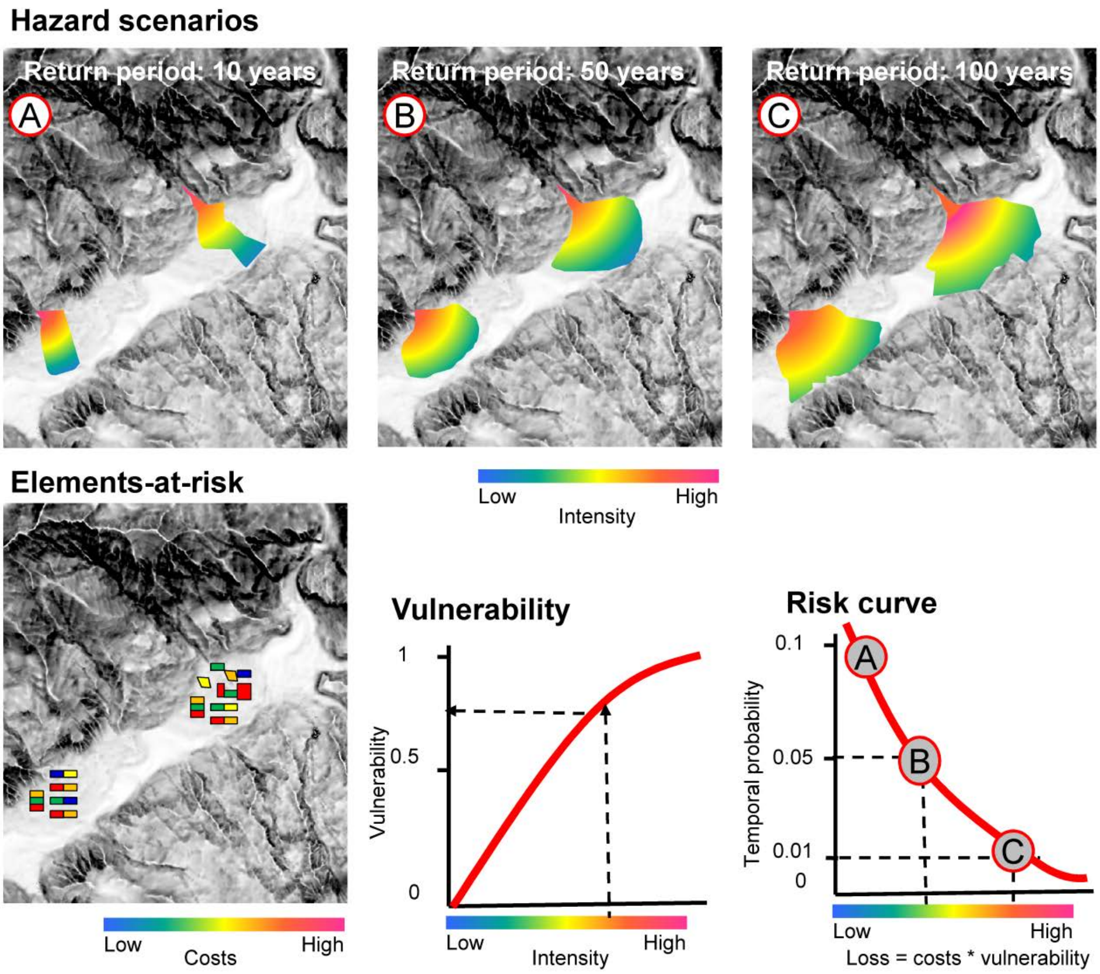


**Fig. 3** Example of a risk curve, plotting the temporal probability of different landslide scenarios with varying return period against the losses. Each of the scenarios results in intensity maps (e.g. impact pressure). Elements-at-risk (e.g. buildings) are characterized by their type, location and replacement costs. The vulnerability of each exposed element-at-risk is determined using a vulnerability curve for that particular structural type, and the intensity for the particular hazard scenario. The losses are determined by multiplying the vulnerabilities with the replacement costs for all exposed elements at risk. After defining a number of points a risk curve can be drawn. The area under the risk curve represents the annualized losses.

## 7.1 Vulnerability assessment

While there has been extensive research into quantifying landslide hazard, research into consequence analysis and vulnerability assessment has been limited. In the following, various types of landslide damage are described related to different landslide types and elements at risk. Directions on selecting appropriate vulnerability assessment methods are provided with respect to the exposed element, the landslide type and the analysis scale.

### *7.1.1 Types of vulnerability*

Different disciplines use multiple definitions and different conceptual frameworks for vulnerability. From a natural-sciences perspective, vulnerability may be defined as the degree of loss to a given element or set of elements within the area affected by the landslide hazard. For property, the loss will be the value of the damage relative to the value of the property. For people, it will be the probability of fatalities. Vulnerability can also refer to the propensity to loss (or the probability of loss), and not the degree of loss. In social sciences, there are multiple definitions and aspects of the term vulnerability depending on the scale and the purpose of the analysis.  Some are reviewed in Fuchs et al. (2007) and Tapsell et al. (2010).

The quantified vulnerability can be expressed in monetary terms (absolute or relative to the value of the exposed elements), as a percentage of the per capita gross domestic product, by the number of fatalities, or using other types of indicator scales (the latter especially for social vulnerability as described at King and MacGregor 2000). The degree of loss due to an event is the sum of direct and indirect losses.

Here vulnerability is considered to be either (a) physical or (b) for people.

~~a.~~ Physical vulnerability refers to the direct damage of buildings, utilities and infrastructure. The monetary impact of damage to a building or to infrastructure can be readily assessed and is easily understood. Furthermore, the vulnerability of physical elements can be expressed in terms of the extent of damage or the cost of recovery as a result of a given event.

b. Vulnerability of people (fatalities, injuries) relates to whether or not a landslide event will result in injury or fatalities. Again, monetary values can be assigned in cases of injury or loss of life (in terms of insurance value) or reduced quality of life. Models used to assign such monetary values generally consider the cost of rescue, hospitalization, and treatment, loss of earning potential (in both the

> short term, in the case of injury, and in the long term). Other impacts of the loss of life or injury due to a landslide have social implications that do not readily lend themselves to quantification.

An overview of potential landslide damage types, related to different landslide types, elements at risk and the location of the exposed element in relation to the landslide is presented by Van Westen et al. (2005).

**Vulnerability of buildings**

Experience indicates that the extent of damage to buildings due to landslides vary considerably according to the building characteristics, landslide mechanism, and the magnitude and intensity. The vulnerability may be expressed in terms of damage states varying from non-structural damage to extensive collapse. Damage may be structural or non-structural and damage to utility systems.

The typology of the exposed elements is a key factor in a vulnerability assessment methodology. The structural system, geometry, material properties, state of maintenance, level of design codes, foundation and superstructure details, number of floors, and other factors are among typical typological parameters which determine the capacity of buildings to withstand landslide actions. The cost of the damages varies with the type of the structure, its location and use. In order to facilitate data collection at local and regional scales, it is convenient in many cases to consider more aggregated levels in the form of homogeneous units. These should consist of groups of buildings, characterized by a relative homogeneity of structural type, construction materials, age, number of floors and land use distribution.

An additional important factor is the geographic location of the exposed elements within the landslide body (crest, transport zone, toe, runout zone, etc.) given the variation of the movement and the consequent interaction with the structures and infrastructure. Another parameter is the impact location on the structure and the importance of the impacted members to the stability of the building. The main impact locations are the roof of a building, its façade including structural and non-structural elements, and its foundation. For small scales, the simplification that events of similar magnitude produce the same level of damage can be made due to the resolution of the analysis. For detailed scales, especially in the case of rockfalls and debris flow, the impact point on the building and in particular on elements which are important for its stability should be taken into consideration. This applies especially to frame structures where for example, the damage of a column may initiate a cascade of failures. For masonry structures the damage is usually local as due to the inherent hyper-static load-bearing system, alternative load paths may be easily found.

The ‘resistance hierarchies’ between the main structural and the secondary non-structural elements are among the main parameters which may significantly influence building damage in the case of debris flow.

While damage to the built environment resulting from the occurrence of rapid landslides such as debris flow and rockfalls is generally the highest and most severe as it may lead to the complete destruction of any structure within the affected area, slow-moving slides also have adverse effects on affected facilities (Mansour et al. 2011).

The damage caused by a slow moving landslide on a building is mainly attributed to the cumulative permanent (absolute or differential) displacement and it is concentrated within the unstable area. The type of response to permanent total and differential ground deformation depends primarily on the foundation type. Deep foundations are less vulnerable than shallow foundations. Rigid foundations that permit the rotation of the building as a rigid body may be less vulnerable than flexible foundations (Bird et al. 2006).

**Vulnerability of roads, railways and vehicles**

Vulnerability of a road or railway system may be attributed both to the partial or complete blockage of the road or the track as well as to structural damage, including damage to the surfacing which is associated with the level of serviceability. Information regarding the type (e.g. highway, main road, or unpaved road), width, and traffic volume is necessary to assess the vulnerability of transportation infrastructure and vehicles (due to traffic interruption) to various landslide hazards. The AADT (Annual Average Daily Traffic) as being representative of the typical traffic flows, can be used to this end.

For moving elements like vehicles, the assessment of vulnerability needs to have a good historical record of landslide events and related damages (Dai et al. 2002). The vulnerability of a vehicle on the road depends on its relative position with respect to the landslide at a specific time and whether it is directly impacted from a landslide or crushes into it or derails due to damage to the infrastructure. Furthermore, important contributing factors are the type of vehicle (in relation to its average speed), the magnitude of the landslide and the density of vehicles (traffic volume) in a particular time and section of road. Hence, vehicle vulnerability to landslides is a space and time depending event that can be quantified using statistical data and/or stochastic approaches.

**Vulnerability of people**

Physical vulnerability of people refers to the probability that a particular life will be lost, given that the person(s) is affected by the landslide (AGS 2007). It depends on many factors such as the landslide type, size and intensity; the resistance and mobility of the individual people affected by the landslide hazard; and their relative position in the exposed area. The resistance of the person to landslides is believed to be also a function of the intellectual maturity (e.g. perception about risk) and physical ability (e.g. age) (Uzielli et al., 2008). This type of vulnerability might be quite important for a fast moving landslide (debris flow, rockfall) but is generally negligible for slow moving landslides. Due to the complex, dynamic nature of the population, vulnerability changes over time. Considering the large uncertainties and complexities associated with the physical vulnerability of persons to landslides, all existing methodologies are based on expert judgment and empirical data.

### *7.1.2 Quantification of vulnerability*

The vulnerability of an element at risk can be quantified using either vulnerability indices or fragility curves. The vulnerability index expresses the degree of damage on a relative scale from 0 (no damage) to 1 (total damage). Vulnerability curves express the conditional probability of reaching or exceeding a certain damage state (e.g. slight, moderate, extensive, complete), due to a landslide event of a given type and intensity. In this way, it is possible to explicitly include both epistemic and aleatory uncertainties in the vulnerability modelling approach (as for example for structural typology, resistance of materials, age, state of maintenance, etc.). Most procedures for developing vulnerability curves in the literature (e.g. ATC-13, 1985; Shinozuka et al. 2000; Cornell et al. 2002; Nielson and DesRoches 2007; Porter et al. 2007 etc.) have been initially proposed for earthquakes but they can also be modified for the case of landslides. A two-parameter lognormal distribution function is usually adopted due to its simple parametric form to represent a fragility curve for a predefined damage/limit state (Koutsourelakis 2010; Fotopoulou and Pitilakis 2012a).

The methodologies used for the quantification of vulnerability can be classified according to the type of input data and evaluation of the response parameters into judgmental / heuristic, data driven (using data from past events) and analytical (using physical models).The existence and quality of the input data also play a fundamental role.

**Judgmental/Heuristic methods**

Judgmental / heuristic methods usually provide discrete values for a range of landslide intensities. Based on the economic value of buildings for a given area, roads and infrastructure, Bell and Glade (2004) established fixed vulnerability values as a function of the return period of debris flow and rockfalls. In the same way, they attributed vulnerability values for people inside and outside buildings. Further values for people in open space, vehicles or buildings in landslide areas, applied for the risk assessment in Hong Kong were proposed by Finlay and Fell (1996), based on the observation of real events.

For the physical damage of roads due to debris flow, Winter et al. (2012) presented a methodology based on the statistical analysis of data obtained by questionnaires, completed by recognised experts in the field of debris flow hazard and risk assessment, to calculate vulnerability curves.

**Table 16** Judgmental / Heuristic methods for assessing vulnerability

| Exposed elements | Landslide mechanism | Application scale | Methodology | Reference |
|---|---|---|---|---|
| Buildings, roads and infrastructures, people inside and outside buildings | Debris flow, rockfalls | Local, regional | Direct attribution of fixed values for events of different return periods. | Bell and Glade 2004 |
| People in open spaces, vehicles or buildings | Debris flow, rockfalls | Local, regional | Fixed values from observation from historic records in Hong Kong. | Finlay and Fell 1996 |
| Roads | Debris flow | Regional | Statistical analysis of inventory data for the construction of vulnerability curves. | Winter et al. 2012 |

## Data driven methods

Data driven methods for vulnerability assessment are the most frequently used as they offer both simplicity and reliability, at the same time though a degree of subjectivity is also introduced. Their sophistication and the incorporation of uncertainties varies significantly and their applicability is limited by the need for inventory data to be available in the study area. Vulnerability is calculated as a function of the landslide intensity.

Agliardi et al. (2009b) proposed the back-analysis of real event damage data to obtain correlations between rockfall intensity and vulnerability of buildings by regression. The result was a site-specific empirical vulnerability function obtained by fitting damage and impact energy values through a sigmoid function. In the same way, Quan Luna et al. (2011) used inventoried building damage from debris flow to calculate a sigmoid function to obtain vulnerability as a function of the height of accumulation, the impact pressure and the kinematic viscosity.

Uzielli and Lacasse (2007) and Uzielli et al. (2008) incorporated the uncertainties in the quantification of the vulnerability. They suggested its probabilistic evaluation by means of an approach relying on first-order second-moment (FOSM) approximation of uncertainty, which was also applied by Kaynia et al (2008). A similar probabilistic model was proposed by Li et al. (2010) too.

For debris flows, Fuchs et al. (2007; 2008) Papathoma-Köhl et al. (2012) and Akbas et al. (2009) developed a vulnerability function, which links intensity (debris depth) to vulnerability values.

**Table 17** Data driven methods for assessing vulnerability

| Exposed elements | Landslide mechanism | Application scale | Methodologies | Reference |
|---|---|---|---|---|
| Buildings | Rockfalls | Site-specific, local | Back analysis of real event damage data. Vulnerability associated to impact energy and expressed by a sigmoid function. | Agliardi et al., 2009 |
| Buildings | Debris flow | Site specific, local | Back analysis using damage data coupled with the information from modelling outputs. Vulnerability associated to height of accumulation or impact pressure or kinematic viscosity and expressed by a sigmoid function. | Quan Luna et al. 2011 |

| | | | | |
|---|---|---|---|---|
| Buildings, people | Various types | Regional | Probabilistic analysis based on first-order second-moment approximation of uncertainties. A vulnerability value of is obtained. | Uzielli et al. 2008 Uzielli and Lacasse 2007; Kaynia 2008; Li et al. 2010 |
| Buildings | Debris flow | Local, regional | Calculation of a single function obtained by regression on real event data and correlation with debris height. | Fuchs et al. 2007 & 2008 Papathoma-Köhl et al. 2012 Akbas et al. 2009 |

**Analytical methods**

Analytical methods are used less frequently because of their complexity in comparison to the methods described above and the lack of detailed input data. For the implementation of such methods a distinction is usually made between the structural typologies of buildings.

Vulnerability to the impact of rockfalls at the base of reinforced concrete structures, may be analysed using the methodology developed by Mavrouli and Corominas (2010a; 2010b). The methodology considers the potential for progressive collapse when key elements are destroyed by rockfall impact (analysed using the finite element method). It yields discrete probabilistic vulnerability values for varying intensities and fragility curves incorporating the uncertainty of the impact location.

Fotopoulou and Pitilakis (2012a; 2012b) developed an analytical methodology for the vulnerability assessment of reinforced concrete buildings subjected to earthquake-triggered slow-moving slides. The fragility curves were estimated in terms of peak ground acceleration or permanent ground displacements at the ‘seismic bedrock’, versus the probability of exceeding each limit state based on a two-step uncoupled numerical modelling approach. The developed method is applied to different soil types, slopes geometries and building configurations allowing explicit consideration of various sources of uncertainty. Negulescu and Foerster (2010) also calculated vulnerability curves as a function of the differential settlements of a reinforced concrete frame building.

Vulnerability curves may be produced for debris flow, for un-reinforced masonry structures and reinforced masonry structures using the method proposed by Haugen and Kaynia (2008) that implements the HAZUS software (NIBS 2004). The method uses the principles of dynamic response of simple structures to earthquake excitation. Additionally, Zuccharo et al. (2010) presented another analytical method for the calculation of vulnerability curves, which is based on the resistance of a reinforced concrete RC frame and the infill wall, in probabilistic terms, using a Monte Carlo simulation. The resistance hierarchy between the distinct elements is taken into consideration.

**Table 18** Analytical / Physical model-based methods for assessing vulnerability

| Exposed elements | Landslide mechanism | Application scale | Methodologies | Reference |
|---|---|---|---|---|
| Buildings (RC frames) | Rockfalls | Site specific, local | Evaluation of column’s resistance. Application of the finite element method for the progressive collapse potential. Yields a vulnerability matrix and v curves associated to the impact energy and the uncertainty of the impact location. | Mavrouli and Corominas 2010a and 2010 b |
| Buildings (RC frames) | Slow moving | Site-specific | Calculation of damage from earthquake-induced landslides using a finite slope model and the finite difference method. Parametric analysis and statistical evaluation for the construction of fragility curves. | Fotopoulou and Pitilakis 2012a, 2012b |
| Buildings (RC frames) | Slow moving | Site-specific | Using of numerical simulations and concepts of earthquake analysis for the calculation of vulnerability curves associated to differential settlements. | Negulescu and Foerster 2010 |
| Buildings | Debris flow | Site specific, local, regional | Uses of the principles of dynamic response of simple structures to earthquake excitation. Vulnerability curves associated to the impact force. | Haugen and Kaynia 2008 |
| Buildings (RC frames & masonry) | Debris flow | Site specific, local, regional | Probabilistic evaluation of damage by calculation of elements’ resistance, using the Monte Carlo method for various structural typologies. Calculation of fragility curves | Zuccaro et al. 2012 |

## 7.2 Risk assessment

The risk analysis may refer to a single object, a linear feature or an area as for hazard. Areal analysis is usually required by local and regional governments for the purposes of land planning or the design of protection measures. It is very demanding with reference to the required data for the calculation of the hazard and the vulnerability parameters and it presents many restrictions for performing detailed runout analysis and incorporating landslide kinematics. The areal analysis is typically performed at a regional scale and implemented in GIS platforms using maps for the illustration of the risk (Agliardi et al. 2009b). The latter may be expressed as the annual monetary loss per pixel or area unit, or as the probability for a given risk scenario (Remondo et al. 2005). Risk assessment for linear features, for example referring to roads or railways is a very common procedure. The risk might be calculated either for the entire line or some selected parts, specifically those that are most at risk. This analysis does not necessarily require the assessment of the frequency at the source area but an inventory of the events reaching the infrastructure which should be as complete as possible. Instead, if the landslide occurrence is evaluated at the source, propagation analysis is needed (Roberds 2005). Even though the landslide intensity best expresses the damaging potential of the landslides, it is rarely considered in this type of analyses (Bunce et al. 1997; Hungr et al. 1999).

Object-orientated analysis is performed with respect to buildings, road cuts or specific facilities. Landslide analysis is usually undertaken using analytical and/or numerical models and includes the calculation of the spatial parameters referring to the probability of a given landslide magnitude or velocity reaching the exposed element(s). Restrictions in this case might stem from the scarcity of data to properly assess the probability or frequency of occurrence. Risk may be expressed as the annual monetary loss per object or the annual probability of property damage or loss of life for different risk scenarios.

### *7.2.1 Exposure*

Exposure is an attribute of people, property, systems, or other elements present in areas potentially affected by landslides. It is calculated as the temporal-spatial probability of the elements at risk being within the landslide path and also needs to be incorporated in the risk equation. The calculation of the exposure depends mainly on the scale of the analysis and the type of the potentially exposed elements. Whether an element is exposed or not is determined by its location with respect to the landslide path, which varies according to the landslide mechanism. For exposure, there is an important distinction between static elements (buildings, roads, other infrastructures, etc.) and moving elements (vehicles, persons, etc.).

**Static elements**

In the case of rockfalls, the affected elements are located within the rockfall path. Exposed elements for fragmented rockfalls have limited spatial intersection, while for rock avalanches and rockslides the intersection is bigger. For fragmented rockfalls and for small scales with low resolution, all existing elements next to rockfall prone cliffs are assumed to be exposed. For site-specific and local scales, and when the trajectory is included in the analysis, this is delimited to only those elements which are situated within the potential rockfall paths. In the latter case, the exposure component varies as a function of the block size.

The impact probability may be obtained by considering the percentage area that contains structures in one or more reference sections reached by the rockfall paths (Corominas et al. 2005; Corominas and Mavrouli 2011b). For large scale analyses, where detailed information on the spatial probability of a block reaching a building is required, the probability of individual block trajectories may be computed. Some rockfall sources produce paths that have a higher probability than others of affecting some buildings and this has to be taken into account.

In comparison with rockfalls, debris flows may affect more extensive areas, due to their increased mobility and possibility for inundation. In some cases, deposition areas affect entire urban areas. The spatial exposure for an area can be calculated as the ratio of the affected area to the total area. Whether the latter will be calculated as a function of the flow kinematics (e.g. discharge rate) or not, depends on the availability of propagation information, according to the analysis scale, as previously.

For slow moving landslides, the exposed elements may be located on it, as well as next to the landslide scarp and in the landslide runout zone. Because of this, the type of applied actions and damage may vary. Again, if the scale and the resolution of the analysis permit it, the exposure of each element may be calculated as a function of the landslide kinematics.

The calculation of the exposure of linear elements such as roads and railways requires kinematic analysis when the frequency or probability of landslide occurrence is calculated at the source. If it is calculated to intersect directly on the infrastructure then the exposure is equal to one.

**Moving elements**

The quantification of the temporal and spatial probability of moving elements must take into account the characteristics of their movement. Vehicles might be exposed to landslides in different ways: they may be affected either while stationary or while moving and by being hit by a rock or soil mass or by hitting (crashing into) a rock or soil mass obstructing or blocking the road. The case of vehicles been buried or becoming entrained in debris flow and landslides and thus becoming part of the mass movement is also a consideration.

The calculation of the impact probability can be made for direct impacts of rocks or soil on vehicles and it depends amongst others factors upon the frequency of the vehicles, the fragmented rock sizes or the geometrical characteristics of the debris flow or the landslide, and the length of the vehicles. Basic simplifying assumptions that are usually made for the exposure of vehicles is that their distribution is temporally and spatially uniform  and that all vehicles have the same length (Bunce et al. 1997).

The temporal and spatial probability of a moving rock or soil mass intersecting a particular stationary vehicle, is proportional the length of infrastructure occupied by the vehicle. For multiple events, the probability that no vehicle is hit is equal to:

$$P(S) = 1 - (1 - P(S\colon H))^{Nr} \qquad (12)$$

Where:

*P(S:H)* is the probability that a vehicle occupies the portion of the road affected by a landslide, and

$N_r$ is the Number of events

For a particular moving vehicle, the temporal probability of intersection is also calculated as a function of the occupying time, which depends on the frequency of the moving vehicle, and its average length and speed. The width of the rock or the soil mass is usually neglected.

Persons are also affected by landslides in open spaces and while occupying buildings and vehicles. Their temporal and spatial probability is calculated as a function of the exposure of the buildings or vehicles, and the percentage of time and/or space they occupy in them (Fell et al. 2005). Thus, for people inside buildings it depends on their use and their occupancy during specific time spans. In some cases, ski resorts for example, where the population varies between seasons, the seasonal exposure should also be taken into account. Risk assessment can be performed either for the most exposed people or for the average exposed of people.

### *7.2.2 Risk calculation*

Examples of applications of QRA are summarized in Table 19; although in some of them the calculation of the risk components is not strictly quantitative, the proposed methodologies yield quantitative results.

Practical examples at site-specific and local scale are provided in the literature for people inside vehicles in the case of rockfalls (Fell et al. 2005) and of debris flows (Archetti and Lamberti 2003; Budetta 2002). Wilson et al. (2005), beside the direct impact of debris on vehicles, also consider the risk of the vehicles running into the debris. The case-study of Jakob and Weatherly (2005) also describes the calculation of frequency-fatality curves for people, where the vulnerability is calculated empirically from past data, as a function of the debris discharge rate. At a regional scale the procedure presented by Bell and Glade (2004) can be used for both debris flow and rockfalls for the risk assessment for buildings; the procedure is mainly based on judgmental and empirical data.

At more detailed scales, for rockfalls, Agliardi et al. (2009) developed an analytical procedure for the QRA based on data from the back analysis of a real rockfall event which included data on the damage of buildings. Corominas et al. (2005) showed an example of risk quantification for blocks hitting people inside buildings. A methodology for the rockfall risk assessment for buildings was further proposed, for application at site-specific scale by Corominas and Mavrouli (2011a), including the analytical probabilistic vulnerability of buildings as a function of the rock block impact location. Ferlisi et al. (2012) provided a methodology for the calculation of risk for people inside vehicles moving along a road.

For slow-moving landslides (amongst other types) Catani et al. (2005) proposed a methodology that yields results in terms of expected economic losses for buildings, using remote sensing techniques.

Finally, Ho et al. (2000) and Lee and Jones (2004) presented practical cases of risk calculation for a range of landslide types and exposed elements with emphasis on the calculation of F-N curves.

**Table 19** QRA application examples

| Landslide mechanism | | Exposed elements | Specific characteristics | References |
|---|---|---|---|---|
| Debris flow and shallow slides | Intensity not accounted | People, linear infrastructures and buildings | Risk calculated at each pixel | Jaiswal et al. 2011; Zêzere et al. 2008 |
| | | People inside vehicles | Risk in road sections provided in probability terms. | Archetti and Lamberti 2003; Budetta 2002; Wilson et al. 2005; |
| | Intensity accounted | Buildings, people | Judgmental or empirical evaluation of risk parameters. | Bell and Glade 2004; Tsao et al. 2010 |
| | | People | Vulnerability in function of the debris discharge rate. | Jakob and Weatherly 2005 |
| Rockfalls | Intensity accounted | Buildings, people inside buildings | Intensity calculated in a reference section | Corominas et al. 2005 |
| | | Buildings | Intensity calculated at each exposed element | Agliardi et al. 2009; Corominas and Mavrouli 2011a |
| | Intensity not accounted | Moving elements (persons, vehicles) | Exposure is calculated in a generic way for all the elements at risk | Bunce et al. 1997; Hungr et al. 1999; Ferlisi et al. 2012 |
| Slow moving | Intensity accounted | Buildings | Vulnerability and risk expressed in economic terms. | Catani et al. 2005 |
| Various types | Intensity not accounted | People, linear infrastructures and buildings | Practical examples at site-specific scale, local and regional scales | Fell et al. 2005; Gosh et al. 2011; Ho and Ko 2009; Remondo et al. 2008; Quinn et al. 2011 |

## 7.3 Risk scenarios

In a study area of a given geo-environmental context, the different stages of movements of existing or potential landslide phenomena of a given type are controlled by mechanisms that are often interrelated (Leroueil et al. 1996). Their geometrical and kinematical characteristics, in turn, may differ depending on the factors driving and accompanying the slope instability processes (Leroueil 2001; Cascini et al. 2009) producing different risk scenarios as a result. Therefore, independently from the adopted scale of landslide risk analysis and zoning, it is necessary to understand the possible landslide mechanisms that may occur in the study area. Thus several landslide hazard scenarios can be considered (not necessarily the worst case), with their potential consequences, so as to quantitatively estimate the respective direct and indirect risk components.

The total risk must be summed from the risks from a number of landslide hazards (Amatruda et al. 2004; Fell et al. 2005). Summing different risk values of several scenarios implies the hypothesis that each considered scenario occurs independently. Based on this, it is often accepted that similar landslide mechanisms of very different magnitudes and probability of occurrence produce different scenarios.

A general scenario-based risk formulation is given by Roberds (2005), with a particular emphasis on the analysis of consequences; examples on the topic are provided by Hungr (1997) and Roberds and Ho (1997).

# 8. Evaluation of the performance of landslide zonation maps

The evaluation of the uncertainties, robustness and reliability of a landslide zonation map is always a difficult task. As landslide susceptibility, hazard and risk maps predict future events, the best evaluation method would be to 'wait and see', and test the performance of the zoning based on events that happened after the preparation of the maps. This is generally not considered as a practical solution, notwithstanding that subsequent events can provide a qualitative degree of confidence for users of the maps provided that the limitations of the inevitably very short time period considered are understood. Testing the performance of models is a multi-criteria problem encompassing (1) the adequacy (conceptual and mathematical) of the model in describing the system, (2) the robustness of the model to small changes of the input data (e.g. data sensitivity), and (3) the accuracy of the model in predicting the observed data (Davis and Goodrich 1990; Begueria 2006).

In practice, model performance is evaluated by using a landslide inventory of a given time period and testing the result with another inventory from a later period. However, the landslide inventory maps themselves may contain a large degree of uncertainty (Van

Den Eeckhaut et al. 2006; Guzzetti et al. 2012). Another way of assessing the model performance is the comparison of maps of the same area made independently by different teams, which has proven to be a rather difficult exercise (Van Westen et al. 1999; Van Den Eeckhaut et al. 2009b). To characterize the predictive power of a zonation map, the landslide inventory should be separated into two populations (one used for generating the zonation map, and a second for analysing the accuracy). This can be done by using a random selection of the landslides, or by using two temporally different inventory maps. The comparison of zonation maps created by different methods may also give a good idea of the accuracy of the prediction.

This section provides an overview of the methods that can be used for evaluating the performance of landslide susceptibility and hazard maps. The term performance is here used to indicate whether the zonation maps make a correct distinction between potentially landslide free and landslide prone areas.

## 8.1 Uncertainties and robustness of the zonation maps

The nature of uncertainties and the increasing trend towards more complex models (e.g. by moving from heuristic to statistical and process-based models) motivates the need for enhanced model identification and evaluation tools (Saltelli et al. 2004; van Asch et al. 2007) to prove that increased complexity indeed provides better model results.

For the assessment of landslide models, aleatory and epistemic uncertainties are commonly considered. An aleatoric uncertainty is presumed to be the intrinsic randomness of a phenomenon. An epistemic uncertainty is presumed as being caused by lack of knowledge or data. Differences in the interpretation of the data by experts participating in the zonation belong to the latter.

The term robustness characterises the change in the accuracy of the classification due to perturbation in the modelling process (Alippi et al., 2004). Often, robustness analyses focus only on disturbance in the model performance due to errors in input parameters (Melchiorre et al. 2011). In this context, the term sensitivity (Homma and Saltelli 1996) is used both to identify the key parameters whose uncertainty influences the output uncertainty the most (e.g. global sensitivity) and to emphasize the key parameters with respect to the output itself and not to its uncertainty (local sensitivity analysis).

For landslide zoning assessments, quantitative variance-based methods for global sensitivity analyses (e.g. to investigate influence of the scale and shape of the distribution of parameters) and graphical methods for local sensitivity analyses may be considered Melchiorre and Frattini (2012). For introducing perturbations in the different input parameters, probabilistic techniques based on the moment theory are used in order to express input parameters as mathematical functions instead of unique values (Baecher and Christian, 2003). Such approaches allow outcomes based on several theoretical input data sets determined and confidence intervals encompassing these return paths to be derived.

Sensitivity analysis of input parameters in landslide zoning assessments at site and local scales have been performed by Gray and Megahan (1981), Malet et al. (2004; 2005), or Hürlimann at al. (2008). At the regional scale, sensitivity analysis exists for both multivariate statistical models and process models. Hydrological coupled slope stability models applying bootstrapping indicate that physical modelling based on mean values may not always be practical (Blijenberg 2007). Other examples are given by van Beek (2002), Gorsevski et al. (2006b), and Melchiorre and Frattini (2012). For multivariate statistical models, only a few papers deal with robustness evaluation by performing ensembles of models calibrated for different samples of landslides from the same inventory (Guzzetti et al., 2006; Van Den Eeckhaut et al. 2009b; Rossi et al., 2010) or by calibrating models for different landslide inventories of the same region (Blahut et al. 2010b). Fewer studies investigated the impact of, for example, different classifications of the independent variables derived from lithological, soil or land cover maps (Thiery et al. 2007). Melchiorre et al. (2011) defined, for example, a robustness index showing the sensitivity to variations in the data set of independent (predictor) variables.

## 8.2 Accuracy of the zonation maps

None of the techniques presented in the literature to assess the accuracy of landslide zoning models account for the economic costs misclassification. This limitation is significant for landslide susceptibility analysis as the costs of misclassifications are very different depending on the error type:

- Error Type I (false positive) means that a unit without landslides is classified as unstable, and therefore limited in their use and economic development. Hence, the false positive misclassification cost amounts to the loss of economic value of these terrain units. This cost is different for each terrain unit as a function of its environmental and socio-economic characteristics.

- Error Type II (false negative) means that a terrain unit with landslides is classified as stable, and consequently used without restrictions. The false negative misclassification cost is equal to the loss of elements at risk that can be impacted by landslides in these units.

With landslide zoning models, costs related to Error Type II are normally much larger than those related to Error Type I. For example, citing a public facility such as a school building, in a terrain unit that is incorrectly identified as stable (Type II error) could lead to very large social and economic costs.

In the following, different techniques for the evaluation of landslide model performance are presented.

### *8.2.1 Cut-off-dependent accuracy statistics*

The accuracy is assessed by analysing the agreement between the model outputs and the observations. Since the observed data comprise the presence/absence of landslides within a certain terrain unit, a simpler method to assess the accuracy is to compare these data with a binary classification of susceptibility in stable and unstable units. This classification requires a cut-off value of susceptibility that divides stable terrains (susceptibility less than the cut-off) and unstable terrain (susceptibility greater than the cut off). The comparison of observed data and model results reclassified into two classes is represented through contingency tables or confusion matrices (Table 20). Accuracy statistics assess the model performance by combining correct and incorrect classified positives (e.g., unstable areas) and negatives (e.g., stable areas) (Table 21).

**Table 20** Contingency table used for evaluating the performance of landslide zoning models

| Model Prediction<br>Observations | True (unstable terrain unit) | False (stable terrain unit) | |
|---|---|---|---|
| Positive (landslide) | True positive | False positive | → Positive predictive value |
| Negative (stable terrain unit) | False negative↓ | True negative↓ | → Negative predictive value |
| | Sensitivity | Specificity | |

The efficiency, which measures the percentage of observations that are correctly classified by the model, is unreliable because it is heavily influenced by the most common class, usually ‘stable terrain unit’, and it is not equitable (e.g. giving the same score for different types of unskilled classifications) and this must be taken into account. True Positive (TP) rate and the False Positive (FP) rate are insufficient performance statistics, because they ignore false positives and false negatives, respectively. They are not equitable, and they are useful only when used in conjunction (such as in ROC curves). The Threat score (Gilbert 1884) measures the fraction of observed and/or classified events that were correctly predicted. Because it penalizes both false negatives and false positives, it does not distinguish the source of classification error. Moreover, it depends on the frequency of events (and thus poorer accuracy scores are derived for rarer, usually larger magnitude, events) since some true positives can occur purely due to random chance. Alternatively Peirce’s skills score (Peirce 1884) or the odds ratio (Stephenson 2000) may be used.

Accuracy statistics require the splitting of the classified objects into a few classes by defining specific values of the susceptibility index that are called cut-off values. For statistical models, a statistically significant probability cut-off (p[cut-off[) exists, equal to 0.5. When the groups of stable and unstable terrain units are equal in size and their distribution is close to normal, this value maximizes the number of correctly predicted stable and unstable units. However, the choice of cut-off values to define susceptibility classes is arbitrary and, unless a cost criterion is adopted (Provost and Fawcett 1997), depends on the objective of the map, the number of classes and the type of modelling approach.

A first solution to this limitation consists in evaluating the performance of the models over a large range of cut-off values by using cut-off independent performance criteria. Another option consists in finding the optimal cut-off by minimizing the costs of the models.

**Table 21** Commonly used accuracy statistics. $t_p$ = true positives, $t_n$ = true negatives, $f_p$ = false positives (Error Type I), $f_n$ = false negatives (Error Type II), $P$ = positive prediction ($\mathbf{t_p}$ + $f_n$), $N$ = negative prediction ($f_p$ + $t_n$), $T$ = total number of observations  (see also Table 20)

| Accuracy statistics | Formula |
|---|---|
| Efficiency (Accuracy or Percent correct) | $\frac{tp + tn}{T}$ |

| | |
|---|---|
| True positive rate (Sensitivity) | $\frac{tp}{tp+Fn} = \frac{tp}{P}$ = 1 -Fn |
| False positive rate (Specificity) | $\frac{fp}{fp+tn} = \frac{fp}{N}$= 1 - Tn |
| Threat score (Critical success rate) | $\frac{tp}{tp+fn+fp}$ |
| Peirce's skill score (True skill statistic) | $\frac{tp}{tp\,.fn}$ - $\frac{fp}{fp\,+.Tn}$ |
| Heidke skill score (Cohen's kappa) (Heidke, 1926) | $\frac{tp\,+\,tn-E}{T-E}$where E $= \frac{1}{T}\,[(tp+fn)(tp+fp)+\ (tn+fn)(tn+fp)]$ |
| Odds ratio | $\frac{tp\,.\,tn}{fn\,.\,fp}$ |
| Odd ratio skill score (Yule's Q) | $\frac{tp\,.\,tn-fp\,.\,fn}{tp\,.\,tn+fp\,.\,fn}$ |

### *8.2.2 Cut-off-independent accuracy statistics: ROC curves and SR curves*

The most commonly-used cut-off-independent performance techniques for landslide zoning models are the Receiver Operating Characteristic (ROC) curves and the Success-Rate curves (SR).

The ROC analysis was developed to assess the performance of radar receivers in detecting targets, and has been adopted in different scientific fields (Adams and Hand, 1999; Provost and Fawcett, 2001). The Area under the ROC Curve (Area Under Curve, AUC) can be used as a metric to assess the overall quality of a model (Hanley and McNeil 1982): the larger the area, the better the performance of the model over the whole range of possible cut-offs. The points on the ROC curve represent (FP, TP) pairs derived from different contingency tables created by applying different cut-offs (Fig. 4). Points closer to the upper-right corner correspond to lower cut-off values. A ROC curve is better than another if it is closer to the upper-left corner. The range of values for which the ROC curve is better than a trivial model (e.g. a model which classifies objects by chance, represented in the ROC space by a straight line joining the lower-left and the upper-right corner; e.g. 1-1 line) is defined as the operating range. In the case that the model accuracy is evaluated with data not used for developing the model, a good model should have ROC curves for the evaluation and production data set that are located close to each other in the ROC graph, and have AUC values above 0.7 (moderately accurate) or even above 0.9 (highly accurate; Swets 1988).

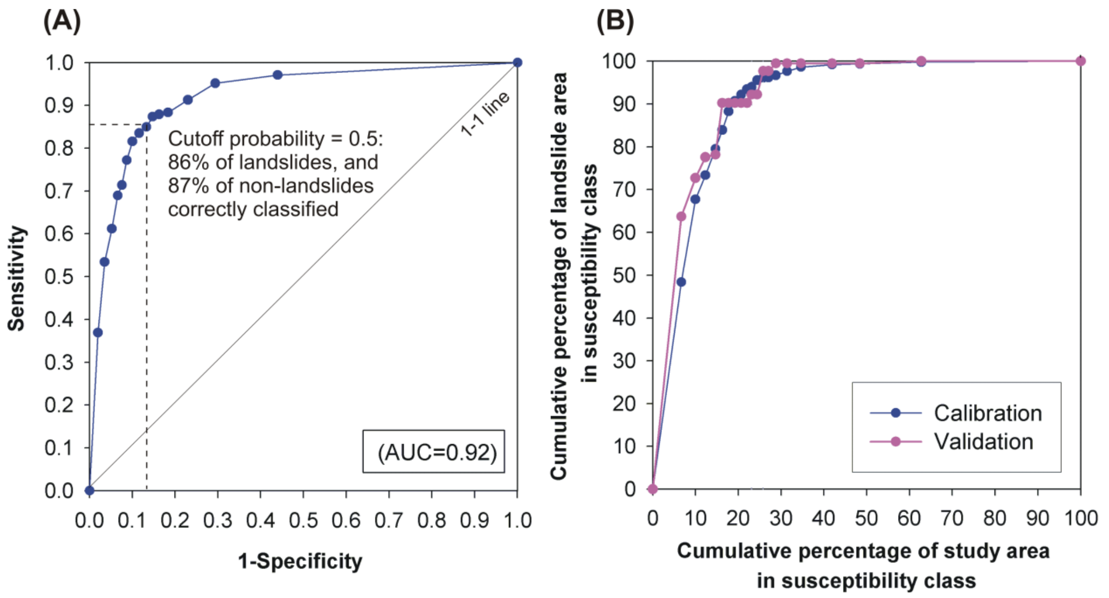


**Fig. 4** Example of a ROC curve (left) and a Success-Rate curve (right) (after Van Den Eeckhaut et al. 2009b)

Success-Rate curves (Zinck et al. 2001; Chung and Fabbri 2003; Fig. 4) represent the percentage of correctly classified objects (e.g. terrain units) on the y-axis, and the percentage of area classified as positive (e.g. unstable) on the x-axis. For landslide zoning assessments, the y-axis is normally considered as the number of landslides, or the percentage of landslide area, correctly classified. In the case of grid-cell units where landslides correspond to single grid cells and all the terrain units have the same area, the y-axis corresponds to TP, analogous with the ROC space, and the x-axis corresponds to the number of units classified as positive.

### *8.2.3 Cost curves*

Accounting for misclassification costs in the evaluation of model performance is possible with ROC curves by using an additional procedure (Provost and Fawcett 1997), but the results are difficult to visualize and assess. Cost curves (Drummond and Holte 2006) represent the Normalized Expected cost as a function of a Probability-Cost function (Fig. 8), where the expected cost is normalized by the maximum expected cost that occurs when all cases are incorrectly classified (e.g. when FP and FN are both one). The maximum normalized cost is 1 and the minimum is 0.

A single classification model, which would be a single point (FP, TP) in the ROC space, is thus a straight line in the cost curve representation (Fig. 5). The lower the cost curve, the better the accuracy of the model, and the difference between two models is simply the vertical distance between the curves.

In order to implement cost curves, it is necessary to define a value for the Probability-Cost function, which depends on both the a-priori probability and the misclassification costs. For landslide zoning models, given the uncertainty in the observed distribution of the landslide population, a condition of equal-probability is a reasonable choice (Frattini et al. 2010).

Misclassification costs are site-specific and vary significantly within the study area. A rigorous analysis would estimate them at each terrain unit independently, and evaluate the total costs arising from the adoption of each model by summing up these costs. This requires the contribution of the administrators and policy makers of local (municipality) and national authorities. In order to estimate the average cost of false negatives and false positives, a land-use map can be used to calculate both the area occupied by elements potentially at risk (e.g. contributing to false negative costs) and the area potentially suitable for building development (e.g. contributing to false positive costs) (Frattini et al., 2010).

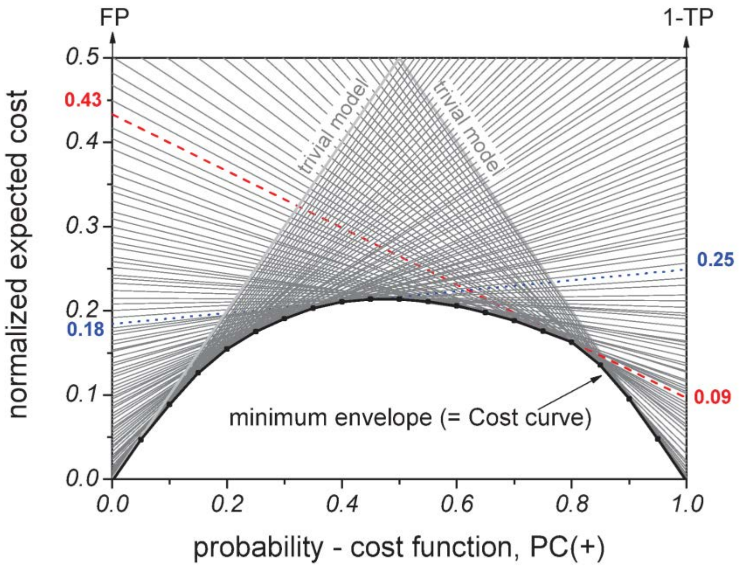


**Fig. 5** Example of a Cost curve. A straight line corresponds to a point in the ROC curve. The red line shows for example the line of a point with sensitivity (TP) 0.91 and 1-specificity (FP) 0.43 (Frattini et al. 2010)

For this reason, the predicted susceptibility maps must be carefully analysed and critically reviewed before disseminating the results. The tuning of statistical techniques and the independent validation of the results are already recognized as fundamental steps in any natural hazard study to assess model accuracy and predictive power. Validation also may permit the the degree of confidence in the model to be established and the comparison of results from different models. For this reason, the spatial agreement among susceptibility maps produced by different models should also be tested, especially if these models have similar predictive power.

### 8.3 Limits on the use of accuracy statistics

The application of each statistic is reliable only under specific conditions (e.g., rare events or frequent events) that should be evaluated case by case, in order to select the most appropriate method (Stephenson 2000). This is a limitation for a general application to landslide zoning assessments. For statistical models, the application of cut-off-dependent accuracy statistics is straightforward and scientifically correct because the cut-off value is statistically significant. This is true only when assuming equal a-priori probabilities and equal misclassification costs, conditions that are normally violated by landslide models. For other kinds of zoning models (heuristic, physically-based) there is no theoretical reason to select a certain cut-off, and the application of accuracy statistics is therefore not feasible.

Evaluating the performance of landslide zonation maps with cut-off-independent criteria has the advantage that an a-priori cut-off value is not required, and the performance can be assessed over the entire range of cut-off values. Using ROC and SR curves, different results are obtained because the ROC curve is based on the analysis of the classification of the statistical units, and describes the capability of the statistical model to discriminate among two classes of objects, while the SR curve is based on the analysis of spatial matching between actual landslides and zonation maps. Thus it considers the area of both the landslides and the terrain units, and not only the number of units correctly or incorrectly classified.

SR curves present some theoretical problems when applied to grid-cell models. The number of true positives, in fact, contributes to both the x- and y-axes. An increase in true positives causes an upward shift (toward better performance) and rightward shift (toward worse performance) of the curve. In some cases the rightward shift can be faster than the upward one, causing an apparent loss of performance with increasing true positives, and this is clearly a misleading evaluation of model performance. Moreover, the SR curve is sensitive to the initial proportion of positives and negatives. Hence, the application of SR curves to areas with a low degree of hazard (e.g. flat areas with small steep portions of the landscape) will always give better results than application in areas with a high hazard (e.g. mountain valleys with steep slopes), even if the quality of the classification is exactly the same.

Another important aspect is that the above mentioned statistics are not spatially explicit, meaning that similar shapes of ROC and SR curves may reflect different spatial patterns of stable and unstable predicted landscape units. Therefore, integrating consistency maps (agreement /disagreement) representing the predictions of different models (with very similar success/prediction rates) in the model evaluation is a step towards achieving more robust performance analyses. Such types of approach allow the identification of spatial sectors of the study area in which the predictions could be in agreement/disagreement (Sterlacchini et al. 2011). Such approaches necessitate performing an integration of information by soft fusion techniques. For this reason, landslide zonation maps should be distributed together with maps aimed at visualizing the level of accuracy of the predicted results to provide the end-users with informative selection criteria.

# 9. Summary

This paper presents a focussed review of the key components of a quantitative risk assessment (QRA) for landslide hazards. This is important as such processes allow scientists and engineers to quantify risk in an objective and reproducible manner and to compare the results from one location (site, region, etc.) to another. Notwithstanding this it is important to understand that estimates of risk, quantitative or not are only estimates. Limitations in the available information and the use of numbers may conceal potentially significant error bands. In that respect, QRA is not necessarily more objective than qualitative estimations as, for example, probability may be calculated based on personal judgment. It does, however, facilitate, clear and unambiguous communication between geoscience professionals and land owners and decision-makers.

Recommended methodologies for the quantitative assessment of the landslide hazard, vulnerability and risk at different scales (site specific, local, regional and national) have been presented. In addition, methodologies for the verification and validation of the results are also given.

The methodologies described focus on the evaluation of the probability of occurrence of different landslide types with certain characteristics. Methods to determine the spatial distribution of landslide intensity, the characterisation of the elements at risk, the assessment of the potential degree of damage and the quantification of the vulnerability of the elements at risk, and the QRA are also described.

The paper is intended to be used by scientists and practising engineers, geologists and other landslide experts.

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# Annex - Definitions and terminology

Most of the terms used in this document are consistent with landslide hazard and risk definitions proposed by international committees such as Fell et al. (2008a), TC32 (2004) and UN-ISDR (2004).

**Consequence –** The outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain; damage, injury or loss of life.

**Danger –** The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The danger can be an existing one (such as a creeping slope) or a potential one (such as a rock fall). The characterisation of a danger does not include any forecasting.

**Elements at risk –** The population, buildings and engineering structures, economic activities, public services, utilities, infrastructure, cultural and environmental features in the area potentially affected by landslides.

**Exposure –** The presence of people, structures, property, systems, or other elements in zones that may be impacted by landslides.

**Frequency –** A measure of likelihood expressed as the number of occurrences of an event in a given time. See also Likelihood and Probability.

**Hazard –** A condition with the potential for causing an undesirable consequence. The characterization of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

**Hazard zoning –** The subdivision of the terrain in zones that are characterized by the temporal probability of occurrence of landslides of a particular intensity, within a given period of time. Landslide hazard maps should indicate both the zones where landslides may occur as well as the runout zones.

**Individual risk to life –** The risk of fatality or injury to any identifiable individual who is within the zone impacted by the landslide; or who follows a particular pattern of life that might subject him or her to the consequences of the landslide.

**Landslide inventory –** A record of recognized landslides in a particular area combined with attribute information. These attributes should ideally contain information on the type of landslide, date of occurrence or relative age, size and/or volume, current activity, and causes. Landslide inventories are either continuous in time, or provide so-called event-based landslide inventories, which are inventories of landslides that happened as a result of a particular triggering event (rainfall, earthquake).

**Landslide activity –** The stage of development of a landslide; pre-failure when the slope is strained throughout but is essentially intact; failure characterized by the formation of a continuous surface of rupture; post-failure which includes movement from just after failure to when it essentially stops; and reactivation when the slope slides along one or several pre-existing surfaces of rupture. Reactivation may be occasional (e.g. seasonal) or continuous (in which case the slide is '"active').

**Landslide hazard assessment –** The estimation of the zones where landslides of a particular type, volume, runout and intensity may occur within a given period of time.

**Landslide hazard map –** A map showing the subdivision of the terrain in zones that are characterized by the probability of occurrence of landslides of a particular intensity. Landslide hazard maps should indicate both the zones where landslides may occur as well as the runout zones.

**Landslide intensity –** A set of spatially distributed parameters related to the destructive power of a landslide. The parameters may be described quantitatively or qualitatively and may include maximum movement velocity, total displacement, differential displacement, depth of the moving mass, peak discharge per unit width or kinetic energy per unit area.

**Landslide magnitude –** The measure of the landslide size. It may be quantitatively described by its volume or, indirectly by its area. The latter descriptors may refer to the landslide scar, the landslide deposit or both.

**Landslide probability –** In the framework of landslide hazard the following types of probability are of importance:

- Spatial probability: the probability that a given area is hit by a landslide.
- Temporal probability: the probability that a given triggering event will cause landslides.
- Size/volume probability: probability that the slide has a given size/volume.

- Reach probability: probability that the slide will travel a certain distance downslope.

**Landslide risk map –** A map showing the subdivision of the terrain in zones that are characterised by different probabilities of losses that might occur due to landslides of a given type within a given period of time. It is usually calculated as:

- the expected losses in a particular area being struck by a landslide of a given magnitude (intensity) in a given year,
- a recurrence interval, i.e. the expected losses in a particular area being struck by the 100-year landslide event, or
- the cumulative losses during a given time interval due to landslides with different return periods.

**Landslide susceptibility assessment –** A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area.

**Landslide susceptibility map –** A map showing the subdivision of the terrain in zones that have a different likelihood that a landslide of a given type may occur. It should indicate both the zones where landslides may occur as well as the runout zones.

**Likelihood –** Used as a qualitative description of probability or frequency.

**Population at risk –** All the people who would be directly exposed to the consequences of landslides.

**Probability –** A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event.

**Qualitative risk analysis –** An analysis which uses word form, descriptive or numerical scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur.

**Quantitative risk analysis –** An analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

**Recurrence interval –** The long-term average elapsed time between landslide events at a particular site or in a specified area. Also known as return period.

**Reach probability/runout probability –** Probability that a specified landslide will reach a certain distance

**Residual risk –** The degree of existing risk given the presence of risk mitigation measures.

**Risk –** A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often defined as the probability of the landslide event multiplied by the consequences.

**Risk analysis –** The use of available information to calculate the risk to individuals, population, property, or the environment, from hazards. Risk analyses generally contain the following steps: scope definition, hazard identification, vulnerability evaluation and risk estimation.

**Risk assessment –** The process of making a recommendation on whether existing risks are acceptable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation phases.

**Risk control /risk treatment –** The process of decision making for managing risk, and the implementation or enforcement of risk mitigation measures and the re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input.

**Risk evaluation –** The stage at which values and judgments enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

**Risk management –** The complete process of risk assessment and risk control

**Societal risk –** The risk of multiple fatalities, injuries, or disruption of activities in society as a whole: one where society would have to carry the burden of a landslide causing a number of deaths, injuries, financial, environmental, and other losses.

**Spatio-temporal probability of the element at risk –** The probability that the element at risk is in the landslide path, at the time of its occurrence. It is the quantitative expression of the exposure.

**Validation –** The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

**Verification -** The process of determining that the implementation of the model accurately represents the developer's conceptual description of the model and its solution.

**Vulnerability –** The degree of loss to a given element or set of elements exposed to the occurrence of a landslide of a given magnitude/intensity. It is expressed on a scale of 0 (no loss) to 1 (total loss).

**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 is important that those carrying out landslide mapping use consistent terminology to classify and characterize landslides. It is recommended that the classification and terminology are based on well-known schemes such as Cruden and Varnes (1996), Hungr et al. (2001, 2012), and IAEG (1990).