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Guidelines for landslide susceptibility, hazard and risk assessment and zoning

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SUMMARY

The aim of this document is the recommendation of methodologies that can be used 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 included methodologies mainly focus on the evaluation of the probability of occurrence of different landslide types with certain characteristic, the assessment of the elements at risk (persons, buildings, infrastructures...), the potential degree of damage and the quantification of the vulnerability of the latter and the quantitative risk assessment (QRA). The present document is addressed to scientists and practicioner engineers, geologists and other landslide experts.

Note about contributors

The following organisations contributed to the work described in this deliverable:

Lead partner responsible for the deliverable:

Technical University of Catalonia (UPC)

Deliverable prepared by:
Jordi Corominas
Olga-Christina Mavrouli

Partner responsible for quality control:

Bureau des Recherches Géologiques et Minières (BRGM)
Hormoz Modaressi

Contributors:

International Center for Geohazards (ICG)
Farrokh Nadim
Bjørn Vidar Vangelsten

Università degli studi di Salerno (Unisa)
Leonardo Cascini
Settimio Ferlisi

Aristotle University of Thessaloniki (AUTH)
Stravoula Fotopoulou
Kyriazis Pitilakis

Eidgenössische Technische Hochsschule Zürich (ETHZ)
Harikrishna Narasimhan
Michael H. Faber

Università degli studi di Firenze (Unifi)
Filippo Catani
Veronica Tofani

Joint Research Centre (JRC)
Miet Van Den Eeckhaut
Javier Hervás

Fundación Agustín de Betancourt (FUNAB)
Manuel Pastor

Universitá degli Studi di Milano- Bicocca (UNIMIB)
Paolo Frattini
Federico Agliardi

Faculty of Geo-information Sciences and Earth Observation (ITC), University of Twente
Cees van Westen

Centre National de la Recherche Scientifique (CNRS)
Jean-Philippe Malet

Transport Research Laboratory (UK)
Jessica T. Smith
Mike G. Winter

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1 FOREWORD

(UPC and ITC)

The goal of this document is to recommend methodologies for the quantitative assessment and zoning of landslide susceptibility, hazard and risk at different scales (site specific, local, regional and national). It also includes a chapter in which some methodologies for verification of the models and validation of the results are presented.

The activities for Quantitative Risks Assessment (QRA) (IUGS Working Group on Landslides, 1997) include:

- determining the probability distribution and characteristics of potential landslides
- determining the probability distribution for the number and nature and characteristics of the elements at risk (persons, property) which could be affected by the hazard
- assessing the degree of damage, or probability of loss of life, due to that element’s interaction with the landslide for the exposed elements at risk
- determining the probability distribution of the consequences arising from the landslide hazard

Quantitative Risks Assessment (QRA) provides a rational basis to conceptualize landslide risk, to develop risk acceptability criteria, to perform cost-benefit analyses, and to evaluate different landslide risk management and mitigation alternatives in order to reduce existing risk to acceptable levels (Fell et al. 2008).

Quantitative Risk Assessment (QRA) of landslides is important for the stakeholders involved for different reasons: To scientists and engineers because risk is quantified in an objective and reproducible way and the results can be compared from one region to other. Furthermore it helps to the identification of the challenges in the required input data and the weaknesses of the analyses used. To the landslide risk managers because it allows the performance of a cost-benefit analysis, it provides the basis for prioritizing mitigation actions and the allocation of resources. To the citizens in general because QRA is a tool that helps for increasing the awararenes on the existing risk levels and for evaluating the efficiency of the actions undertaken,

For QRA, a higher degree of geological and geomechanical input data and high DEM quality are usually necessary to evaluate a range of possible scenarios, design events and return periods. As stated by Lee and Jones (2004), the probability of landsliding and the value of adverse consequences are only estimates. Due to the limitation of available information, the use of numbers may conceal that the potential for error is great. In that respect, QRA is not necessarily more “precise” than the alternative (Hungr et al. 2008). It facilitates however, clear and unambiguous communication of judgement between geoscience professionals and land owners and decision makers.

The classical expression for calculating landslide risk (R) is that proposed by Varnes (1984):

$$R= Hx(ExV)$$

Where:
H is Landslide Hazard, E the Exposed elements, and V their Vulnerability

In reality, the components of Risk such as H and E have to be disaggregated and each considered separately, which is the reason why risk assessment is so complex.

Generally, for large areas where the quality and quantity of available data are too scarce for quantitative analysis, a qualitative risk assessment may be more applicable; while for site-specific slopes that are amenable to conventional limit equilibrium analysis, a detailed quantitative risk assessment should be carried out (Dai et al. 2002).

As illustrated in there are three important components in risk analysis: hazards, vulnerability and elements-at-risk (Van Westen et al., 2008). They are characterized by both spatial and non-spatial attributes. Hazards are characterized by their temporal probability and intensity derived from frequency magnitude analysis. Intensity expresses the severity of the hazard, and expresses the localized impact of a landslide event, measured in different ways, such as height of debris (e.g. for debris flows), velocity (e.g. of debris flows, or large landslides), or impact pressure (e.g. for debris flows, rockfalls). Whereas the magnitude of a landslide, which can be represented best by the volume of the displaced mass, is a characteristic of the entire landslide mass, the intensity is locally variable, depending on the type of landslide, the location with respect to the initiation point of the landslide, whether an element at risk is on the moving landslide, in front of it, or directly above it.

The hazard component in the equation actually refers to the probability of occurrence of a hazardous phenomenon with a given intensity within a specified period of time (e.g. annual probability). Hazards also have an important spatial component, both related to the initiation of the hazard and the spreading of the hazardous phenomena (e.g. the areas affected by volcanic products such as lava flows) (Van Westen, 2009).

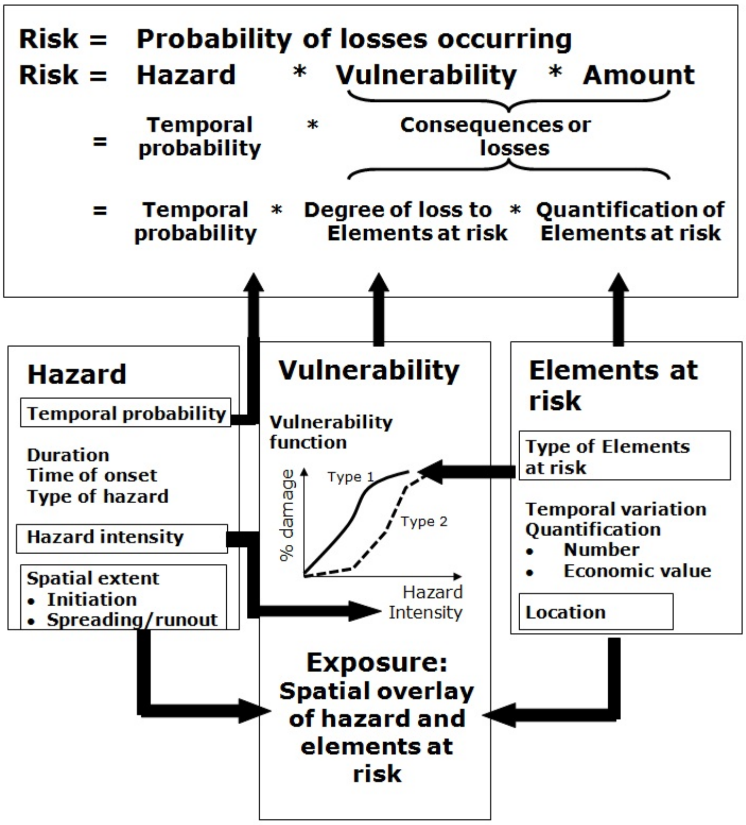

Figure 1.1 Components of the risk analysis

Elements-at-risk are the population, properties, economic activities, including public services, or any other defined values exposed to hazards in a given area (UN-ISDR, 2004). They are also referred to as “assets”. Elements-at-risk also have spatial and non-spatial characteristics. There are many different types of elements-at-risk and they can be classified in various ways. The way in which the amunt of elements-at-risk is characterized (e.g. as number of buildings, number of people, economic value or the area of qualitative classes of importance) also defines the way in which the risk is presented. The interaction of elements-at-risk and hazard defines the exposure and the vulnerability of the elements-at-risk. Exposure indicates the degree to which the elements-at-risk are actually located in the path of a particular hazardous event. The spatial interaction between the elements-at-risk and the hazard footprints are depicted in a GIS by map overlaying of the hazard map with the elements-at-risk map (Van Westen, 2009).

Vulnerability refers to the conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN-ISDR, 2004). The vulnerability of communities and households can be based on a number of criteria, such as age, gender, source of income etc. which are analyzed using a more qualitative approach involving the use of indicators rather than following the equation as indicated in Figure 1.1. Physical vulnerability is evaluated as the interaction between the intensity of the hazard, as previously described, and the type of element-at-risk, making use of so-called vulnerability curves (See chapter 8.1). For further explanations on hazard and risk assessment the reader is referred to textbooks such as Alexander (1993), Okuyama and Chang (2004), Glade, Anderson, and Crozier (2005), Smith and Petley (2008) and Alcantara-Ayala and Goudie (2010).

References

Alcantara-Ayala, I., Goudie, A.S. (2010) Geomorphological Hazards and Disaster Prevention. Cambridge University Press. Cambridge. 291 pp

Alexander, D. (1993). Natural disasters. UCL Press Ltd., University College, London.

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

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.Z., (2008). Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering Geology, 102, 85-98

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

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

IUGS Working Group on Landslides, Committee on Risk Assessment, 1997. Quantitative risk assessment for slopes and landslides – the state of the art. In D.

Cruden & R. Fell (editors). Landslide risk assessment. A.A. Balkema, Rotterdam. pp. 3-12

Lee, E.M., Jones, K.C. 2004. Landslide Risk Assessment. London:Thomas Telford Books

Okuyama, Y., Chang, S.E. (eds) (2004). Modeling spatial and economic impacts of disasters. Springer, Advances in spatial science. 329 pp

Smith, K., Petley, D.N. (2008). Environmental hazards. Assessing risk and reducing disaster. Taylor & Francis, London.

UN-ISDR, 2004. Terminology of disaster risk reduction. United Nationas, International Strategy for Disaster Reduction, Geneva, Switzerland http://www.unisdr.org/eng/library/lib-terminology-eng%20home.htm

Van Westen, C.J., Castellanos Abella, E.A., Sekhar, L.K. (2008) Spatial data for landslide susceptibility, hazards and vulnerability assessment : an overview. In: Engineering geology, 102 (3-4), 112-131

Van Westen, C.J. (ed) (2009). Distance Education course on the use of spatial information in Multi-hazard risk assessment. http://www.itc.nl/Pub/study/Courses/C11-AES-DE-01

Varnes, D.J. 1984. Landslide hazard zonation: a review of principles and practice. Natural Hazard Series. Vol. 3. UNESCO, Paris

2 DEFINITIONS AND TERMINOLOGY

(UPC, ITC and UNISA)

The terminology used in this deliverable follows that proposed by D.8.1 with three additions (exposure, magnitude and residual risk), based on the following references:

Fell,R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.Z., and on behalf of the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes (2008): *Guidelines for landslide susceptibility, hazard and risk zoning for land use planning*. Engineering Geology, Vol. 102, Issues 3-4, 1 Dec., pp 85-98. DOI:10.1016/j.enggeo.2008.03.022

Technical Committee 32 (Engineering Practice of Risk Assessment and Management)
of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE): Risk assessment – Glossary of terms. http://www.engmath.dal.ca/tc32/2004Glossary_Draft1.pdf

UN-ISDR, 2004. Terminology of disaster risk reduction. United Nationas, International Strategy for Disaster Reduction, Geneva, Switzerland http://www.unisdr.org/eng/library/lib-terminology-eng%20home.htm

Definitions of the main terms are:

Annual Exceedance Probability (AEP) **–** The estimated probability that an event of specified magnitude will be exceeded in any year.

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 works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by landslides.

Environmental risk – (a) The potential for an adverse effect on the natural system (environment). (b) the probability of suffering damage because of exposure to some environmental circumstance. The latter acception will not be used in this document.

Exposure – Exposure is the spatial overlay of a hazard footprint and (set of) elements at risk.People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses(UNISDR,2009).

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 description 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 size and volume, within a given period of time. Landslide hazard maps should indicate both the zones where landslides may occur as well as the runout zones. A complete quantitative landslide hazard assessment includes:

- 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
- runout probability: probability that the slide will reach a certain distance downslope

Individual risk to life – The risk of fatality or injury to any identifiable (named) individual who lives 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 – The collection of landslide features in a certain area for a certain period, preferably in digital form with spatial information related to the location (as points or polygons) 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 map - The subdivision of the terrain in zones that are characterized by the temporal probability of occurrence of landslides of a particular size and volume, within a given period of time. Landslide hazard maps should indicate both the zones where landslides may occur as well as the runout zones. A complete quantitative landslide hazard assessment includes:

- 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
- Volume/intensity probability: probability that the slide has a given volume/intensity
- Runout probability: probability that the slide will reach a certain distance downslope

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, 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 probablity – 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
- runout probability: probability that the slide will reach a certain distance downslope

Landslide risk map - The subdivision of the terrain in zones that are characterized by different probabilities of losses (physical, human, economic, environmental) that might occur due to landslides of a given type within a given period of time. The risk may be indicated either qualitatively (as high, moderate, low and no risk) or quantitatively (in numbers or economic values). Risk is quantitatively estimated by the product of probability x consequences. It is usually calculated as:

- On annual basis: i.e. the expected losses in a particular area being struck by a landslide of a given magnitude (intensity) in a given year.
- As 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 – 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. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.

Landslide susceptibility map – A map showing the subdivision of the terrain in zones that have a different likelihood that landslide of a type may occur. The likelihood may be indicated either qualitatively (as high, moderate low, and not susceptible) or quantitatively (e.g. as the density in number per square kilometres, or area affected per square kilometre). Landslide susceptibility maps 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.

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.

There are two main interpretations:

- Statistical-frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It includes also the idea of population variability. Such a number is called an “objective” or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
- Subjective probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the likelihood of a outcome, obtained by considering all available information honestly, fairly, and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes.

Qualitative risk analysis – An analysis which uses word form, descriptive or numeric rating 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.

Residual risk – the degree of existing risk given the presence of both stabilization and protection measures.

Risk – A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability × consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

Risk analysis – The use of available information to estimate 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 risk analysis and risk evaluation. In some communities (for instance those dealing with flood) risk assessment differs from risk evaluation by the fact that it includes subjective aspects such as risk perception.

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

Risk estimation – The process used to produce a measure of the level of health, property, or environmental risks being analysed. Risk estimation contains the following steps: frequency analysis, consequence analysis, and their integration.

Risk evaluation – The stage at which values and judgements 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 (or risk treatment).

Risk perception – The way how people/communities/authorities judge the severity of the risk, based on their personal situation, social, political, cultural and religious background, economic level, their level of awareness, the information they have received regarding the risk, and the way they rate the risk in relation with other problems.

Societal risk – The risk of multiple fatalities or injuries 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.

Susceptibility – see Landslide susceptibility.

Temporal–spatial probability of the element at risk – The probability that the element at risk is in the area affected by the landsliding, at the time of the landslide. It is the quantitative expression of the exposure.

Tolerable risk – A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

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). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide. Vulnerability could also refer to the propensity to loss (or the probability of loss), and not the degree of 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 describe the landslides. It is recommended that the classification and terminology described in Deliverable D8-1 be used. This is based on Cruden and Varnes (1996), Dikau et al. (1996), Hutchinson (1988),Varnes (1978) and IAEG (1990).

In these guidelines, for practical purposes, we have grouped landslide types in three categories:

- Rock falls and rock avalanches
- Shallow landslides and debris flows. This group includes small (up to few tens of thousands of cubic meters) first-time slope failures: planar debris and rock slides, debris flows, small rotational slides
- Large slow moving landslides and earthflows

References

Cruden, D.M., Varnes, D.J. 1996. Landslide Types and Processes, in Landslides. Investigation and Mitigation, Editors AK Turner. and RL Schuster. Special Report 247, Transport Research Board, National Research Council, Washington D.C.

Dikau, R, Brunsden, D, Schrott, L., Ibsen, M.L. 1996. Landslide Recognition. Wiley,Chichester.

Hutchinson, J.N. 1988. Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. In Ch. Bonnard (Ed.): Landslides. Proceedings 5th International Conference on Landslides. Lausanne. Vol. 1: 3-35

IAEG 1990. Suggested nomenclature for landslides. International Association of Engineering Geology Commission on Landslides,, Bulletin IAEG, No. 41,.13-16.

ISDR 2009. Terminology on Disaster Risk Reduction. http://www.unisdr.org/eng/library/lib-terminology-eng.htm

Varnes, D.J. 1978. Slope Movement Types and Processes. In Special Report 176: Landslides: Analysis and Control , editors R.L. Schuster and R.J. Krizek, TRB, National Research Council, Washington, D.C.,.11-33.

3 QRA FRAMEWORK

(ITC)

The general framework of this deliverable is based on the Guidelines for Landslide Susceptibility, Hazard and Risk Zoning prepared by the JTC-1 on Landslides and Engineered Slopes (Fell et al. 2008) and on the Disaster Risk Management (DRM) approach promoted by the United Nations through the International Strategy for Disaster Reduction – ISDR (Figure 3.1) . The overall framework of risk management 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 analyses generally contain the following steps: hazard identification, hazard assessment, inventory of elements at risk and exposure, vulnerability assessment and risk estimation. Since all these steps have an important spatial component, risk assessment 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 judgements 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

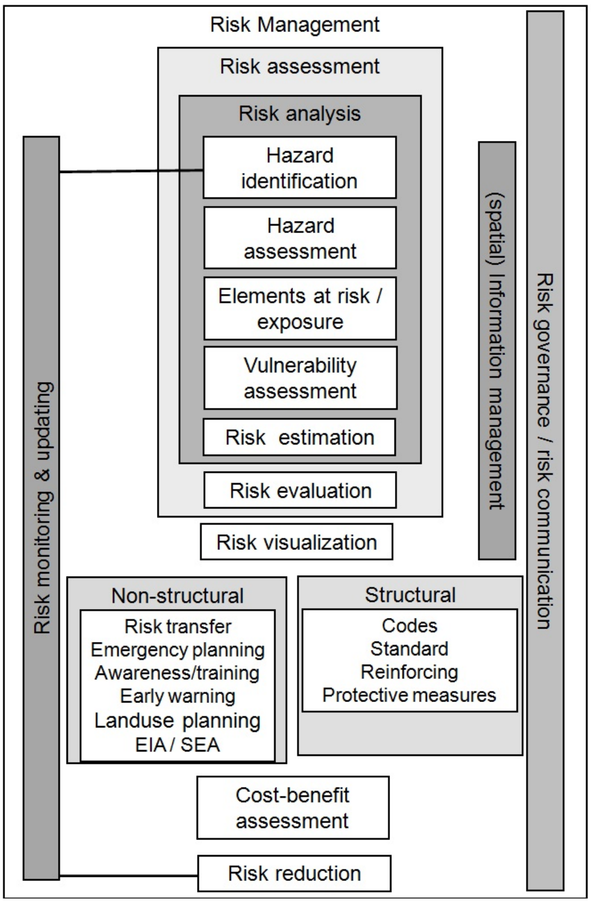

Figure 3.1 Landslide hazard and risk assessment and management framework

3.1 FRAMEWORK FOR MULTI-HAZARD LANDSLIDE RISK ASSESSMENT

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). Figure 3.1 based on Van Westen et al (2005) gives the framework of multi-hazard landslide risk assessment with an indication of the various components (A to H). The first component (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 input maps will be discussed in the next section.

The second session (B) focuses on susceptibility assessment, and is divided into two components. The first susceptibility component is the most frequently used, and 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 then form the input as source areas in the modelling of potential run-out areas (runout susceptibility).

The third section (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. Only 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 adition 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 section (D) 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 in defining vulnerability classes, and the application of available vulnerability curves or vulnerability matrices. Most of the focus is on determining physical vulnerability of elements at risk. Other types of vulnerability (e.g. social, environmental, and economic) are mostly analyzed using a Spatial Multi-Criteria Evaluation, as part of a qualitative risk assessment (G).

Section E gives the concept of risk assessment which integrates the hazard, vulnerability and both nature and amount of elements at risk (either as the number of people, number of buildings, or economic value). The 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 Section F present the quantitative risk 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.

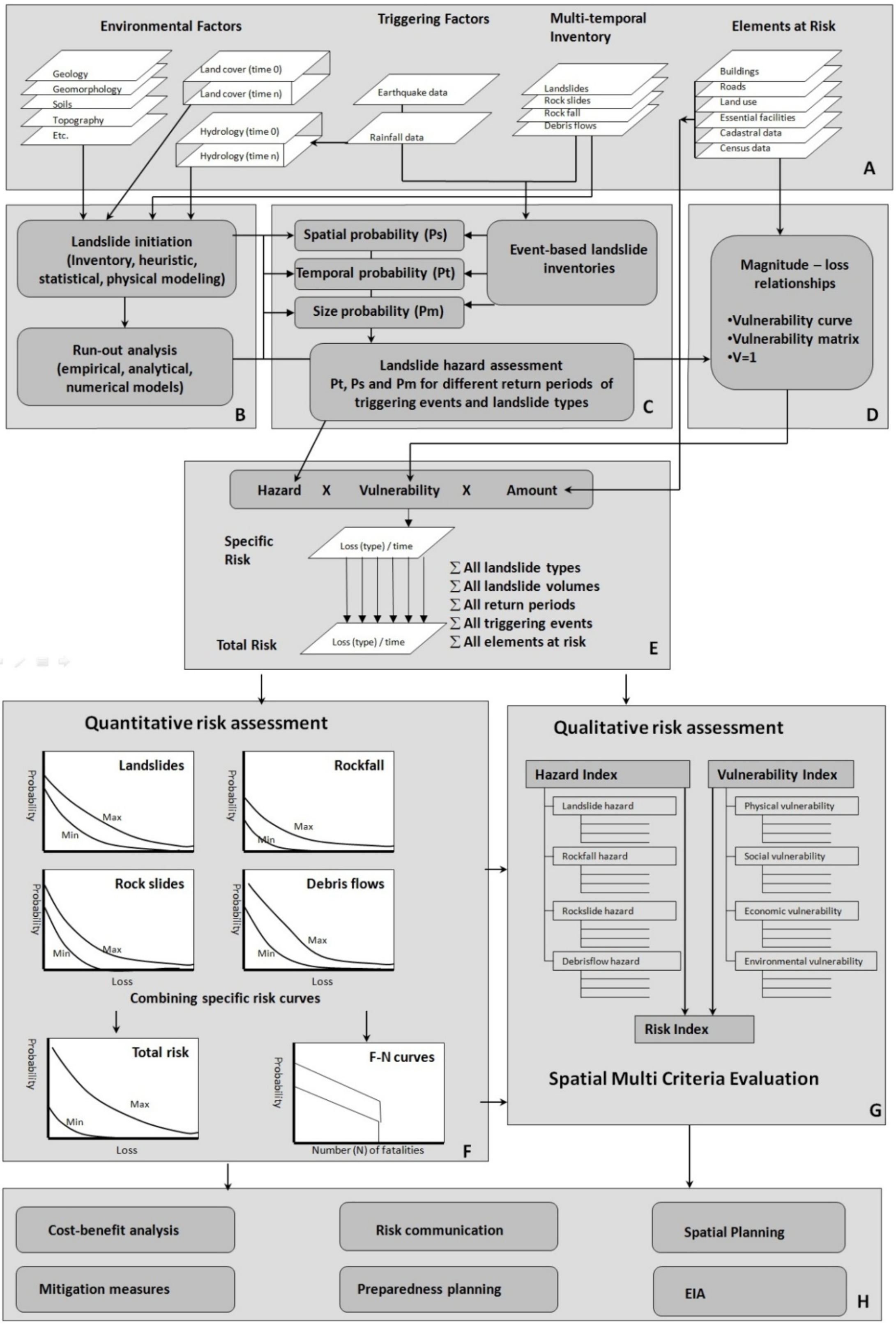

Figure 3.2 Framework of multi-hazard landslide risk assessment (based on Van Westen et al. 2005)

This could be done by generating two loss curves expressing the minimum and maximum losses for each return period of triggering events, or associated annual probability. The individual risks curves can be integrated into total risk curves for a particular area and the population loss can be expressed as F-N curves. The risk curves can be made for different basic units, e.g. administrative units such as individual slopes, road sections, census tracts, settlements, municipalities, regions or provinces.

Section G 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 session (H) deals with the use of risk information in various stages of Disaster Risk Management.

Landslide are caused by a range of causal and triggering factors (e.g. volcanic eruptions, earthquakes, meteorological extremes, and anthropogenic activites) and are also causing secondary hazards (e.g. tsunamis, seizes or dam break floods). This is illustrated in Figure 3.3. Therefore landslide risk assessment should take into account the different landslide types, their interrelations, and the secondary hazards caused by them.

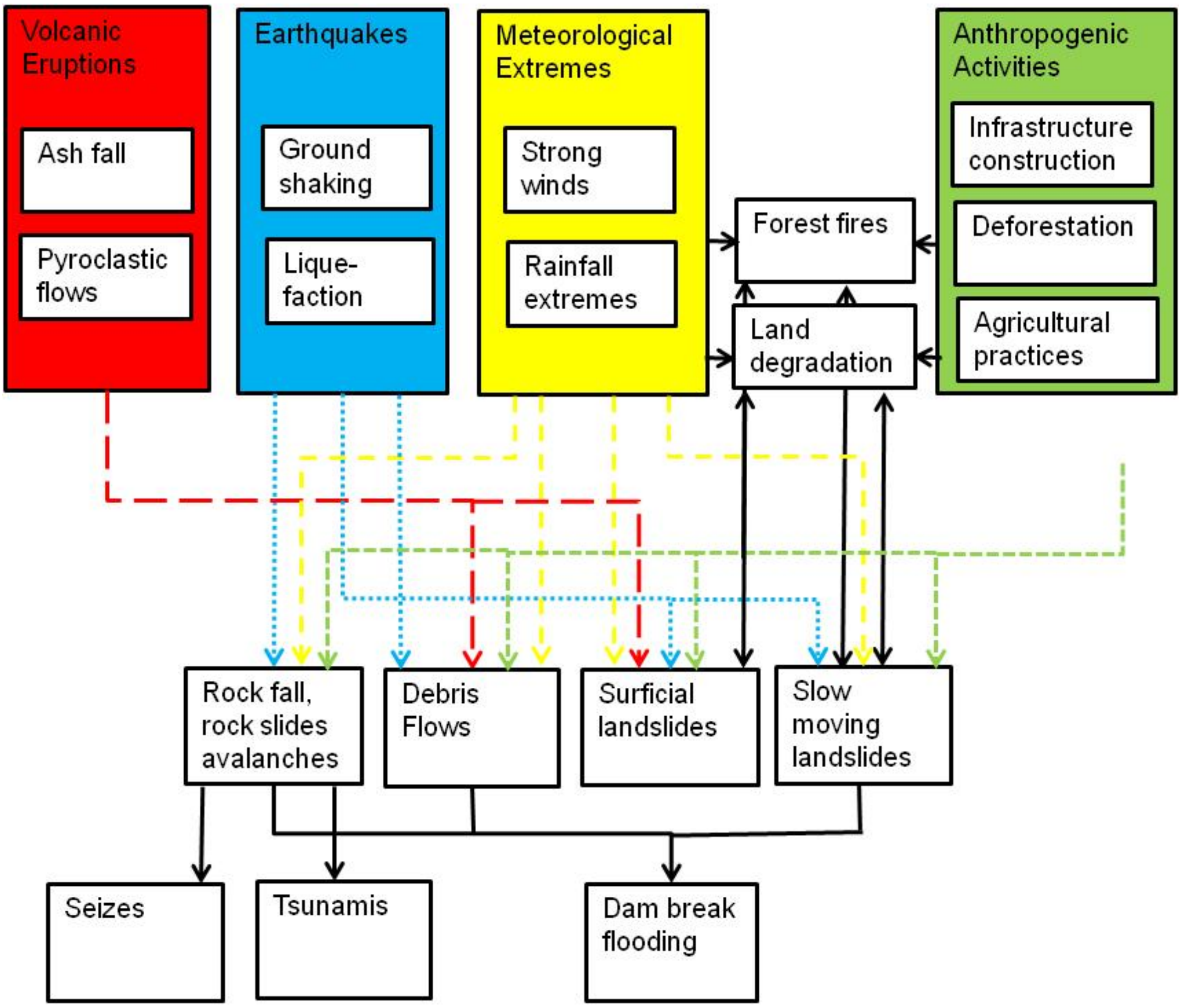

Figure 3.3 Causal factors, interrelationships and secondary hazards related to landslides

REFERENCES

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

Van Westen, C.J., Van Asch, T.W.J., Soeters, R., 2005. Landslide hazard and risk zonation; why is it still so difficult? Bulletin of Engineering geology and the Environment 65 (2), 167-184

4 LANDSLIDE ZONING AT DIFFERENT SCALES

(UNISA with contributions from UPC and ITC)

4.1.INTRODUCTION

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 (Ch. 2).

The first formal applications of landslide zoning, based on qualitative approaches, date back to the 1970’s (e.g. Brabb et al., 1972; Humbert, 1972; Humbert, 1977; Antoine, 1978; Kienholz, 1978; Nilsen et al.,1979) while quantitative methods have been developed in the 1980’s (Brand, 1988) and particularly in the 1990’s for the risk management of an individual slope (Wong et al., 1997; Hardingham et al., 1998) or a large number of slopes (Wong and Ho, 1998). These developments are well described by Ho et al. (2000) and Wong (2005).

Further significant developments of landslide zoning has been recorded during the last decade, as it is highlighted by the Guidelines developed by the Australian Geomechanics Society (AGS, 2000; AGS, 2007), the analysis of questions related to the scales of work (Cascini et al., 2005), 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 “Guidelines for landslide susceptibility, hazard and risk zoning for land use planning” (Fell et al., 2008a).

Starting from these developments, this Chapter intends mainly to provide a guidance on the applicability of the maps for landslide hazard and risk management at different scales considering that the purpose of zoning should be decided by those who are in charge of land use management who need: *i)* to decide the type and the level of zoning, *ii)* to understand the existing availability of potential input data, *iii)* to assess the implications for acquisition of new data taking into account that timeframes, budgets and resources limitations are strictly related to the purpose of zoning.

4.2. PURPOSE OF LANDSLIDE ZONING MAPS

Landslide zoning may be developed by preparing different maps that, according to the type of zoning, can be distinguished among (see also the definitions given Chapter 2):

- Landslide inventory map;
- Landslide susceptibility zoning map;
- Landslide hazard zoning map;
- Elements at risk map;
- Consequence scenario map;
- Landslide risk zoning map.

Within the framework of landslide hazard and risk assessment and management (Figure 3.1), the landslide zoning maps may have different role and objectives; moreover, they may pursue different purposes among those conventionally defined as *information*, *advisory*, *statutory* and *design* in Fell et al. (2008a). On the basis of these definitions and referring to the most recent documents (Fell et al., 2005; Cascini et al., 2005; AGS, 2007; Fell et al., 2008b), the purpose of zoning maps may be specified as follows:

- *Landslide inventory map* may be used for susceptibility zoning and/or as *information* for policy makers and the general public;
- *Landslide susceptibility zoning map* may be used to prepare the hazard map and/or, in combination with elements at landslide risk within the susceptible area, as *information* for policy makers and the general public. It may be also used as *advisory* where the available records of incident data allows the assessment of the societal risk (e.g., in terms of F-N curves) within the susceptible areas threatened by rapid to extremely rapid landslides (Cruden and Varnes, 1996);
- *Landslide hazard zoning map* can be used as *information, advisory* or *statutory* to control the development of threatened areas, representing the most efficient and economic way to reduce future damage and loss of life. Such maps also provide the appropriate element of decision for considering the feasibility of the development with or without any stabilisation or protective countermeasures (Cascini et al., 2005);
- *Elements at risk map* is used to prepare the *consequence scenarios map* and, in combination with the *landslide susceptibility zoning map,* may be used as *information* and *advisory* for policy makers and general public;
- *Consequence scenario map* may be used as *information* and *advisory* showing the areas that require QRA. Using quantitative procedures, this map provides for each element the consequence scenario related to its vulnerability and a given landslide hazard; in such a case, it may be used as *information, advisory* and *statutory*.
- *Landslide risk zoning map* may be used as *statutory* and allow the implementation of alert system aimed at protecting the human life. In addition, QRA provides a global view of the expected annual damage for the elements at risk due to the landslide hazard. It can be used as *statutory* and *design* and, on the basis of cost-benefit analysis, either control or stabilization works can be identified and designed for landslide risk mitigation.

Considering that the purpose of zoning may be pursued at different levels and scales, using different input data and procedures, suggestions and recommendations are necessary in order to make useful landslide zoning maps that must be prepared at an appropriate scale to get the information needed at that scale.

4.3. LANDSLIDE ZONING LEVELS

The scientific literature suggests a large number of methods for landslide inventory, susceptibility and hazard zoning (Atkinson and Massari, 1998; Evans and King, 1998; Baeza and Corominas 2001; Dai and Lee, 2002; Donati and Turrini 2002; Cascini et al., 2005; Cascini, 2008), while only few approaches are devoted to elements at landslide risk and landslide consequence scenario zoning (van Westen, 2004; van Westen et al., 2008; Bonnard et al., 2004; Remondo et al. 2005, Kaynia et al., 2008). Referring to the landslide analysis, all the available methods can be essentially placed in well defined categories that perform qualitative or quantitative landslide modelling and can be defined as *knowledge-driven/heuristic*, *data-driven/statistical* or *deterministic/probabilistic* (Soeters and van Westen, 1996 and Fell et al., 2008b).

Considering the quality of the input data and the complexity of the analyses performed as well as the mapping resolution, landslide zoning can be performed at a given level (*preliminary*, *intermediate*, *advanced*).

The *preliminary* level of zoning is associated to methods for which susceptibility, hazard and risk are assessed based on heuristic procedures (or expert judgement). Mapping of the landslides and their geomorphologic setting are the main input data.

The *intermediate* level of zoning is usually based on the results of data treatment techniques and empirical relations which outputs are confronted to the occurrence of landslide events. Usually, the laws governing the instability phenomenon are not directly considered. It requires significant amount of input data, most of them collected from images and DEM.

The *advanced* level of zoning is usually carried out with the help of physically based models to calculate quantitatively parameters such as probability of failure, run-out distance or landslide velocity and allow the analysis of risk scenarios. It requires high quality input data and the results can be presented in large scale maps.

4.4. LANDSLIDE ZONING MAP SCALES

The current practice in Europe (Corominas and Mavrouli, 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, the information provided, and the methodology that is used. In general, some common input data are used for all cases, i.e. geologic, geomorphologic and soil cover maps. The techniques to obtain input data for the landslide inventory and susceptibility maps vary in a wide range, resulting in various levels of quality and quantity of data. On the other hand, hazard and risk assessment is quantitative or qualitative, according to the use of: *i)* analytical procedures supported by computer simulation; *ii)* weighted indicators, expert judgment and field survey; *iii)* combination of the above two procedures.

On the basis of the current practice and considering that landslide zoning may be also requested by land developers or those developing major infrastructures (such as highways and railways), **Error! Reference source not found.** summarizes the most common mapping scales and types of landslide zoning that can be developed at different levels based on their application.

In particular, at *national* zoning scale (< 1:100,000) knowledge-driven/heuristic methods are suggested for a preliminary level landslide and susceptibility zoning even though risk zoning is also feasible at this scale (Castellanos et al. 2007; Malet et al. 2009).

At *regional* zoning scale (1:100,000 to 1:25,000) more advanced zoning level may be pursued; statistical analysis are recommended only when an appropriate dataset is available (Fell et al., 2008b). If requested, a qualitative risk assessment is recommended.

At *local* zoning map scale (1:25,000 to 1:5,000) all the zoning levels may be developed for qualitative/quantitative risk assessment. Particularly, the use of statistical analysis and deterministic approaches is encouraged for quantitative risk assessment once a high quality of all the necessary input data is guaranteed.

At *site-specific* zoning map scale (> 1:5,000), only an advanced zoning level for QRA is suggested. This needs the most complete dataset in order to properly enhance the worthiness of the deterministic approaches.

Independently from the selected approach and the level of zoning, the landslide inventory and the elements at risk are the basis for all the mapping, and it is important that these activities be done thoroughly. With this aim, the landslide inventory and the elements at risk should be mapped at a larger scale than the other zoning maps.

Table 4.1 Landslide mapping scales, types of landslide zoning and examples of zoning application

Scale description	Indicative range of scale	Typical area of zoning	Types of landslide zoning	Examples of zoning application
National	< 1:100,000	> 10,000 km^2	Inventory mapping, susceptibility zoning of geological contexts	Landslide inventory and susceptibility to inform policy makers and the general public.
Regional	1:100,000 to 1:25,000	1000 ÷ 10,000 km^2	Inventory mapping, susceptibility and hazard zoning referring to local areas	Landslide inventory and susceptibility zoning for regional development; or very large scale engineering projects. Preliminary level hazard mapping for local areas
Local	1:25,000 to 1:5,000	10 ÷ 1000 km^2	Hazard and risk zoning referring to single landslides (from qualitative to quantitative)	Landslide inventory, susceptibility and hazard zoning for local areas. Intermediate to advanced level hazard zoning for regional development. Preliminary to advanced level risk zoning for local areas and the advanced stages of planning for large engineering structures, roads and railways.
Site-specific	> 1:5,000	Several hectares to tens of square kilometres	QRA for individual slopes or singular locations	Intermediate and advanced level hazard and risk zoning for local and site specific areas and for the design phase of large engineering structures, roads and railways

Information provided by **Error! Reference source not found.**and the zoning purposes described in Section 4.1 can be finally combined in the **Error! Reference source not found.**.

Table 4.1 Recommended types of zoning and zoning map scales related to landslide zoning purpose (modified/adapted from Fell et al., 2008a)

Purpose	Type of zoning						Zoning level			Applicable zoning map scale
	Inventory	Susceptibility	Hazard	Elements at risk	Consequences	Risk	Preliminary	Intermediate	Advanced	
National and Regional zoning										
Information	X	X		X			X			1:250,000 to 1:25,000
Advisory	X	X	(X)	(X)	(X)	(X)	X	(X)		
Statutory	Not recommended									
Local zoning										
Information	X	X	X	X	(X)	(X)	X	(X)		1:25,000 to 1:5,000
Advisory	(X)	X	X	X	X	X	X	X	X	
Statutory		(X)	X	(X)	(X)	(X)		X	X	
Site-specific zoning										
Information	Not recommended									1:5,000 to 1:1,000
Advisory	Not commonly used									
Statutory		(X)	X	X	X	X		X	X	
Design		(X)	(X)	X	X	X		(X)	X	

Notes: X= applicable; (X) = may be applicable.

It is worth noting that, as it concerns land use planning and development (i.e., statutory purposes), the hazard and risk maps, need the appropriate level of zoning; otherwise, delivering building permits, expropriation and compensating measures may be affected by errors and an eventual controversy cannot be adequately supported. This can be avoided accurately defining the zoning boundaries at *local* and *site-specific* zoning scale.

Similar details are necessary to *design* the risk mitigation measures; particularly warning systems and urban emergency planes need to be defined at *local* scale, while the *site-specific* scale is the only one for the design of control and stabilization works.

At *national* and *regional* scales less detailed zoning maps are necessary for information and advisory purposes as well as for mapping the area that need a more advanced zoning level. These scales may be also profitable used to individuate and plan warning systems in charge of central Authorities.

4.5. LANDSLIDE ZONING DESCRIPTORS

Independently from the zoning level and the adopted scale, the use of common descriptors to differentiate magnitude and intensity of the landslides (relationships between magnitude and intensity are summarised in Section 7.2) as well as to describe, in the zoning maps, the degree of landslide susceptibility, hazard, consequence scenarios and risk is strongly encouraged in order to have a common language, allowing the comparison among different geo-environmental context (Fell et al., 2008a).

Different descriptors are required according to:

- 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 (scientific or technical);
- 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 biggest phenomena);
- the characteristics of the exposed elements (e.g., linear infrastructures or urbanised areas);
- the adopted risk acceptability/tolerability criteria which may vary from Country to Country [relevant published individual life loss risk tolerance criteria are summarised by Leroi et al. in 2005 with reference to hazardous chemical industries, dams and landsliding. In particular, the Authors show that the only two examples formally adopted for landslides are those provided by the Hong Kong Special Administrative Region Government and the Australian Geomechanics Society who suggest, **for the person most at risk (AGS, 2007)**, tolerable limits equal to 10^{-4}/annum – in the case of existing slopes – and to 10^{-5}/annum – in the case of new engineered slopes].

Referring to Fell et al. (2008a) for further details and bearing in mind the difficulties related to the assessment of quantitative values, **Error! Reference source not found.**-4.6 provide examples of landslide zoning descriptors for first-failure instability phenomena and for existing landslides.

Table 4.2 Example of landslide susceptibility zoning descriptors (modified from AGS, 2007)

	Rock falls	Small landslides on natural slopes	Large landslides on natural slopes
Susceptibility descriptors	Probability that rock falls will reach the area given rock falls occur from a cliff	Proportion of area in which small landslides may occur	Proportion of area in which large landslides may occur
High	> 0.5	> 0.5	> 0.5
Moderate	> 0.25 to 0.5	> 0.25 to 0.5	> 0.25 to 0.5
Low	> 0.01 to 0.25	> 0.01 to 0.25	> 0.01 to 0.25
Very low	0 to 0.01	0 to 0.01	0 to 0.01

Table 4.3 Example of descriptors for hazard zoning (Fell et al., 2008a). Values are proposed for a given landslide magnitude or magnitude range

	Rock Falls from Natural Cliffs or Rock Cut Slope	Slides of Cuts and Fills on Roads or Railways	Small Landslides on Natural Slopes	Individual Landslides on Natural Slopes
Hazard descriptors	Number/annum/ km of cliff or rock cut slope	Number/annum /km of cut or fill	Number/square km/annum	Annual probability of active sliding
Very High	>10	>10	>10	10^{-1}
High	1 to 10	1 to 10	1 to 10	10^{-2}
Moderate	0.1 to 1	0.1 to 1	0.1 to 1	10^{-3} to 10^{-4}
Low	0.01 to 0.1	0.01 to 0.1	0.01 to 0.1	10^{-5}
Very Low	< 0.01	<0.01	< 0.01	< 10^{-6}

Table 4.4 Example of descriptors for risk zoning using life loss criteria (Fell et al., 2008a)

Risk zoning descriptors	Annual probability of death of the person most at risk in the zone
Very High	>10^{-3}/annum
High	10^{-4} to 10^{-3}/annum
Moderate	10^{-5} to 10^{-4}/annum
Low	10^{-6} to 10^{-5}/annum
Very Low	< 10^{-6}/annum

Table 4.5 Example of descriptors for risk zoning using property loss criteria (AGS, 2007)

Likelihood		*Consequences to property* (with indicative approximate cost of damage) (				
	Indicative Value of Approximate Annual Probability	1: CATASTROPHIC 200%	2: MAJOR 60%	3: MEDIUM 20%	4: MINOR 5%	5: INSIGNIFICA 0.5%
A – Almost certain	10^{-1}	VH	VH	VH	H	M or L (2)
B – Likely	10^{-2}	VH	VH	H	M	L
C – Possible	10^{-3}	VH	H	M	M	VL
D – Unlikely	10^{-4}	H	M	L	L	VL
E – Rare	10^{-5}	M	L	L	VL	VL
F – Barely credible	10^{-6}	L	VL	VL	VL	VL

Notes: (1) As a percentage of the value of the property

(2) For cell A5, may be subdivided such that a consequence of less than 0.1% is Low Risk.

(3) L low, M medium, H high, VL very low, VH very high

4.1 RELIABILITY OF LANDSLIDE ZONING

It must be recognised that landslide zoning **is affected by uncertainties** and the results are only a prediction of performance of the slopes based on the available data. The potential sources of errors in the zoning process are:

Topographic map that at a preliminary zoning level must allow zoning boundaries to be defined with an appropriate accuracy. At an intermediate and advanced level of zoning these maps must allow capturing all the necessary elements to develop profitable statistical analysis, using GIS procedure, and deterministic procedures at slope scale.

Landslide inventories that generally represent the most source of error in landslide susceptibility and hazard zoning. These errors are due to the subjective nature of aerial photo interpretation, the vegetation covering of the area to be mapped, the rapid disappearance of shallow landslide. Inventory should be adequately supported by surface mapping in selected areas that takes into account geomorphologic and geotechnical aspect together with the damage survey of building interacting with landslides. Inventory of engineered slopes needs to be complete as much as possible in order to properly develop hazard zoning.

Vulnerability assessment often performed at the preliminary zoning level using empirical values that are not properly calibrated in the area on the basis of the effects caused by past events. At a more advanced level of zoning, vulnerability assessment often disregards the soil-structure interaction, a problem for which valuable theoretical solution are not always furnished in the scientific literature.

Model uncertainties, i.e. the intrinsic limitation of some statistical and deterministic methods used to assess susceptibility, hazard and consequence scenarios. Particularly, statistical methods for landslide zoning of first failure phenomena need appropriate input data, an advanced data set and a thorough calibration and validation before their use in the study area; with reference to active or occasionally reactivated landslides these data are not generally available and this explains the absence in the scientific literature of success in facing this problem. Deterministic approach often is used not having appropriate data on soil properties and groundwater regime or, in the case of landslides triggered by earthquake, they do not take into account the complex geomechanics behaviour of the slope during and after the main shock.

Limitations in the skill of the persons carrying out the zoning that is a multidisciplinary discipline and, too often, is developed not having the appropriate background and/or disregarding the triggering effects that can change during the time due to climate change or other relevant factors.

In order to assess the value of zoning, a report should be prepared on: the study area; the purpose of the zoning; the adopted landslide classification system; type, methods, scale and level of zoning; the completeness of the available data set; the uncertainties related to each step of the zoning as well as to the output zoning data.

Moreover, an appropriate procedure should be defined to select a consultant for zoning, generally an engineering geologist and/or a geotechnical professional, and a peer reviewer who should have a high level of the skills and experience in zoning process.

REFERENCES

AGS, 2000. Landslide risk management concepts and guidelines. Australian Geomechanics Society. Australian Geomechanics 35(1): 49-92.

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

Amatruda G., Bonnard, Ch., Castelli M., Forlati, F., Giacomelli L., Morelli M., Paro L., Piana F., Pirulli M., Polino R., Prat P., Ramasco M., Scavia C., Bellardone G.,Campus S., Durville J.-L., Poisel R., Preh H., Roth W., Tentschert E.H., 2004. A key approach: the IMIRILAND project method. In: Identification and mitigation of large landslides risks in Europe. IMIRILAND PROJECT – European Commission – Fifth Framework Program. Ch. Bonnard, F. Forlati, C. Scavia (Eds.), A.A. Balkema Publishers, pp. 13-43.

Atkinson, P.M., Massari, R., 1998. Generalised linear modelling of susceptibility to landsliding in Central Apennines, Italy. Computers and Geosciences 24, 373-385.

Baeza, C., Corominas, J., 2001. Assessment of shallow landslide susceptibility by means of multivariate statistical techniques. Earth Surface Processes and Landforms 26, 1251– 1263.

Bonnard et al., 2004 In: Identification and mitigation of large landslides risks in Europe. IMIRILAND PROJECT – European Commission – Fifth Framework Program. Ch. Bonnard, F. Forlati, C. Scavia (Eds.), A.A. Balkema Publishers, pp. 13-43.

Brabb, E.E., Pampeyan, E.H., Bonilla, M.G., 1972. Landslide susceptibility in San Mateo County, California. U.S. Geol. Surv., Misc. Field Studies, Map MF-360. Scale 1:62,500.

Brand, E.W. 1988. Special Lecture: Landslide risk assessment in Honk Kong. Proceeding of the V International Symposium on Landslides, Lausanne, Vol. 2, pp. 1059-1074.

Cascini, L. 2008. Applicability of landslide susceptibility and hazard zoning at different scales. Engineering Geology, 102, pp. 164-177.

Cascini, L., Bonnard, Ch., Corominas, J., Jibson, R., Montero-Olarte, J. 2005. Landslide hazard and risk zoning for urban planning and development. – State of the Art report. Proceeding of the International Conference on Landslide Risk Management. Hungr, Fell, Couture & Eberhardt (Eds.), A.A. Balkema Publishers, pp. 199-235.

Castellanos Abella, E.A., van Westen, C.J. 2007. Generation of a landslide risk index map for Cuba using spatial multi-criteria evaluation. In: Landslides : journal of the International Consortium on Landslides, 4 (2007)4, pp. 311-325.

Corominas, J., Mavrouli, O. (coordinators) 2010. Overview of landslide hazard and risk assessment practices. Deliverable 2.1 of the Work Package 2.1 - Harmonization and development of procedures for quantifying landslide hazard. SafeLand Project - 7th Framework Programme Cooperation Theme 6 Environment (including climate change) Sub-Activity 6.1.3 Natural Hazards.

Cruden, D.M., Varnes, D.J.,1996. Landslide types and processes. In: Turner, A.T., Schuster, R.L. (Eds.), “Landslides — Investigation and Mitigation”, Transportation Research Board Special Report No. 247. National Academy Press, Washington DC, pp. 36–75.

Dai, C.F., Lee, C.F., 2002. Terrain based mapping of landslide susceptibility using a geographic information system: a case study. Canadian Geotechnical Journal 38: 911-923.

Donati, L., Turrini, M.C. 2002. An objective method to rank the importance of the factors predisposing landslides with the GIS methodology — application to an area of the Apennines (Valneria; Perugia, Italy), Engineering Geology **63**: 277–290.

Evans, N.C., King, J.P., 1998. The natural terrain landslide study. Debris avalanche susceptibility. Technical Note TN 1/98, Geotechnical Engineering Office, Hong Kong.

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

Fell, R., Ho, K.K.S., Lacasse, S., Leroi, E. 2005. A framework for landslide risk assessment and management. In Landslide Risk Management, Editors O Hungr, R Fell, R Couture and E Eberhardt, Taylor and Francis, London,3-26

Hardingham, A.D., Ho, K.K.S., Smallwood, A.R.H., Ditchfield, C.S. 1998. Quantitative risk assessment of landslides – a case history from Hong Kong. Proceedings of the Seminar on Geotechnical Risk Management, Geotechnical Division, Hong Kong Institution of Engineers, pp. 145-152.

Ho, K.K.S., Leroi, E., Roberds, B. 2000. Quantitative risk assessment - application, myths and future direction. Proceedings of the International Conference on Geotechnical and Geological Engineering GeoEng2000, Melbourne, Vol. 1, pp. 269-312.

Hong, Y., Adler, R., Huffman, G. 2007. Use of satellite remote sensing data in the mapping of global landslide susceptibility. Natural Hazards, 43, 245-256

Humbert, M. 1972. Les Mouvements de terrains. Principes de réalisation d’une carte prévisionnelle dans les Alpes. Bulletin du BRGM. Section III, n°1 : 13-28.

Humbert, M. 1977. La Cartographie ZERMOS. Modalités d’établissement des Cartes des zones exposées à des risques liés aux mouvements du sol et du sous-sol. Bulletin du BRGM, Section III, n. 1/2: 5-8.

Kaynia, A.M., Papathoma-Köhle, M., Neuhäuser, B., Ratzinger, K., Wenzel, H., Medina-Cetina, Z. 2008. Probabilistic assessment of vulnerability to landslide: Application to the village of Lichtenstein, Baden-Württemberg, Germany. Engineering Geology 101: 33–48.

Kienholz, H., 1978. Map of geomorphology and natural hazards of Grindelwald, Switzerland, scale 1:10,000. Artic and Alpine Research 10, 169–184.

Leroi E., Bonnard Ch., Fell R., McInnes R., 2005. Risk assessment and management – State of the Art report. Proceeding of the International Conference on Landslide Risk Management. Hungr, Fell, Couture & Eberhardt (Eds.), A.A. Balkema Publishers, pp. 159-198

Malet, J.-P., Thiery, Y., Puissant, A., Hervás, J., Günther, A., Grandjean, G., 2009. Landslide susceptibility mapping at 1:1M scale over France: exploratory results with a heuristic model. In: Malet, J.-P., Remaître, A., Boogard, T. (Eds), Proc. International Conference on Landslide Processes: from Geomorphologic Mapping to Dynamic Modelling, 6 -7 February 2009, Strasbourg, France. CERG Editions, Strasbourg, pp. 315-320.

Nadim, F., Kjekstad, O., Peduzzi, P., Herold, C. and Jaedicke, C. 2006. Global landslide and avalanche hotspots. Landslides, Vol. 3, No. 2, 159-174.

Nadim, F., Kjekstad, O., 2009. Assessment of Global High-Risk Landslide Disaster Hotspots. In: Sassa, K., Canuti, P. (Eds.), Landslides - Diaster Risk Reduction. Springer, 213-221

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

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

Schwab, J.C., Gori, P.L., Sanjay, J. 2005. Landslide Hazard and Planning. Planning Advisory Service Report number 533/534. American Planning Association, Washington DC (USA).

Soeters, R., van Westen, C.J., 1996. Slope instability recognition, analysis and zonation. In: Turner, A.K., Schuster, R.L. (Eds.), Landslides Investigation and Mitigation. TRB Special Report 247. National Academy Press, Washington D.C., pp. 129–177.

van Westen, C.J., 2004. Geo-information tools for landslide risk assessment: an overview of recent developments. In: Lacerda, W.A., Ehrlich, M., Fontoura, S.A.B., Sayão, A.S.F. (Eds.), Proceedings 9th International Symposium on Landslides, Rio de Janeiro, Brasil, Vol. 1. Balkema, pp. 39–56.

van Westen, C.J., Castellanos, E., Kuriakose, S.L. 2008. Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. Engineering Geology, 102, pp. 112-131.

Wong, H.N. 2005. Landslide risk assessment for individual facilities– State of the Art report. Proceeding of the International Conference on Landslide Risk Management. Hungr, Fell, Couture & Eberhardt (Eds.), pp. 237-296, A.A. Balkema Publishers.

Wong, H.N., Ho, K.K.S. 1998. Overview of risk of old man-made slopes and retaining walls in Hong Kong. Proceedings of the Seminar on Slope Engineering in Hong Kong, Hong Kong, A.A. Balkema Publisher, pp. 193-200.

Wong, H.N., Ho, K.K.S., Chan, Y.C. 1997. Assessment of consequence of landslides. Proceedings of the International Workshop on Landslide Risk Assessment, Honolulu, Hawaii, USA, pp. 111-149.

5 INPUT DATA FOR LANDSLIDE RISK ASSESSMENT

(ITC)

Table 5.1 gives a schematic overview of the main data layers required for landslide susceptibility, hazard and risk assessment (indicated in the upper row of Table 5.1, Van Westen el al. 2008). These can be subdivided into four groups: landslide inventory data, environmental factors, triggering factors, and elements at risk. 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. 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 becomes more landslide monitoring. The environmental factors are a collection of data layers that are expected to have an effect on the occurrence of landslides, and can be utilized as causal factors in the prediction of future landslides.

The list of environmental factors indicated in Table 5.1 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, they do give an idea of the types of data included, related to morphometry, geology, soil types, hydrology, geomorphology and land use. It is not possible to give a prescribed uniform list of causal 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. Table 5.1 intends to provide a summary of this discussion. The basic data can be subdivided into those that are more or less static, and those that are dynamic and need to be updated regularly. Examples of static data sets are related to geology, soil types, geomorphology and morphography. The time frame for the updating of dynamic data may range from hours to days, for example for meteorological data and its effect on slope hydrology, to months and years (see Table 5.1). Landslide information needs to be updated continuously, and land use and elements at risk data need to have an update frequency which may range from 1 to 10 years, depending on the dynamics of land use change in an area. Especially the land use information should be evaluated with care, as this is both an environmental factor, which determines the occurrence of new landslides, as well as an element at risk, which may be affected by landslides.

Table 5.1 also gives an indication of the extent to which remote sensing data can be utilized to generate the various data layers (based on Soeters and Van Westen, 1996, Metternicht et al., 2005, and SafeLand, 2010). For a number of data layers the main emphasis in data acquisition is on field mapping, field measurements or laboratory analysis, and remote sensing imagery is only of secondary importance. This is particularly the case for the geological, geomorphological, and soil data layers. The soil depth and slope hydrology information, which are very important in physical modeling of slope stability are also the most difficult to obtain, and remote sensing has not proven to be a very important tool for these. On the other hand, however, there are also data layers for which remote sensing data can be the main source of information. This is particularly so for landslide inventories, digital elevation models, and land use maps.

In the following sections an overview is given of the methods for spatial data collection. Most emphasis is given to landslide inventories, given their high importance, but also a number of aspects dealing with environmental factors, triggering factors and elements at risk will be discussed and illustrated

Table 5.1 Schematic representation of basic data sets for landslide susceptibility, hazard and risk assessment. Left: indication of the main types of data, Middle: indication of the ideal update frequency, RS: column indicating the usefulness of Remote Sensing for the acquisition of the data, Scale: indication of the importance of the data layer at national, regional, local and site investigation scales, related with the feasibility of obtaining the data at that particular scale, Hazard models: indication of the importance of the data set for heuristic models, statistical models, physically-based models, and probabilistic models, Risk models: indication of the importance of the data layer for qualitative and quantitative risk analysis. (C= Critical, H= highly important, M= moderately important, and L= Less important, - = Not relevant)

Data		Update frequency (years)	RS	Scale				Hazard models				Risk methods	
Main Type	Data layer	10..... 1. … 0.002 (day)	Remote Sensing useful?	National	Regional	Local	Site Specific	Heuristic	Statistical	Physically based models	Probabilistic	(Semi) Quantitative	Qualitative
Landslide Inventory	Landslide Inventory	↔ ↔ ↔	H	C	H	H	H	C	H	H	H	Requires results of probabilistic hazard analysis	Requires results of heuristic, statistical or deterministic hazard analysis
	Landslide Activity	↔ ↔ →	H	M	C	C	C	H	C	C	C		
	Landslide Monitoring	→ → →	M	M	M	M	C	-	-	H	H		
Environ-mental factors	DEM	→	H	H	C	C	C	H	C	C	C		
	Slope angle/aspects etc	→ → ↔ →	H	L	H	H	H	H	H	H	H		
	Internal relief	→ ↔	H	H	M	L	L	H	L	-	-		
	Flow accumulation	↔ ← ←	H	L	M	H	H	L	M	H	H		
	Lithology	↔	M	H	H	H	H	H	H	H	H		
	Structure	↔ ↔	M	H	H	H	H	H	H	H	H		
	Faults	↔ ↔	M	H	H	H	H	H	H	-	-		
	Soil types	↔	M	M	H	C	C	H	H	C	H		
	Soil depth	↔	-	-	L	C	C	-	-	C	H		
	Slope hydrology	↔ ↔ ↔	-	-	-	C	C	-	-	C	H		
	Main geomorphology units		H	C	H	M	L	C	M	L	L		
	Detailed geomorph. units		H	H	H	H	L	H	H	M	L		
	Land use types		H	H	H	H	H	H	H	H	H		
	Land use changes		H	M	H	H	C	H	H	H	C		
Triggerin	Rainfall		L	M	M	C	C	H	H	C	C		

g factors	**Temp / Evapotranspiration**		**M**	**-**	**-**	**M**	**H**	**-**	**-**	**H**	**L**		
	Earthquake catalogs		**-**	**M**	**M**	**H**	**C**	**-**	**-**	**-**	**C**		
	Ground acceleration		**L**	**L**	**M**	**H**	**H**	**H**	**H**	**H**	**L**		
Elements at risk	**Buildings**		**H**	**L**	**M**	**C**	**C**	**-**	**-**	**-**	**-**	**C**	**C**
	Transportation networks		**H**	**M**	**M**	**M**	**H**	**M**	**M**	**M**	**M**	**H**	**H**
	Lifelines		**-**	**-**	**L**	**L**	**M**	**-**	**-**	**-**	**-**	**L**	**L**
	Essential facilities		**L**	**L**	**M**	**H**	**H**	**-**	**-**	**-**	**-**	**H**	**H**
	Population data		**L**	**H**	**H**	**C**	**C**	**-**	**-**	**-**	**-**	**C**	**C**
	Agriculture data		**H**	**L**	**M**	**H**	**M**	**-**	**-**	**-**	**-**	**L**	**M**
	Economic data		**-**	**L**	**M**	**H**	**H**	**-**	**-**	**-**	**-**	**L**	**M**
	Ecological data		**H**	**L**	**L**	**L**	**L**	**-**	**-**	**-**	**-**	**L**	**M**

5.1 LANDSLIDE INVENTORY MAPPING

In order to make a reliable map that predicts the landslide hazard and risk in a certain area, it is crucial to have insight in 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. Attempts have been made to standardize classification in nomenclature, activity, causes, rates of movement and remedial measures for landslides by the IAEG Commission on Landslides, UNESCO-WP/WLI, and the IUGS-Working group on Landslides (IAEG, 1990; IUGS, 1995, 2001; UNESCO, 1993a, 1993b. 1994)

Landslide inventories can be carried out using a variety of techniques, which are summarized in Table 5.2. For visual interpretation of landslides, stereoscopic imagery with a high to very high resolution is required (SafeLand, 2010). Optical images with resolutions larger than 3 meters (e.g. SPOT, LANDSAT, ASTER, IRS-1D), as well as SAR images (RADARSAT, ERS, JERS, ENVISAT) have proven to be useful for visual interpretation of large landslides in individual cases (Singhroy, 2005), but not for landslide mapping on the basis of landform analysis over large areas (Soeters and Van Westen, 1996; Metternicht et al., 2005; SafeLand, 2010). Traditionally, aerial photo interpretation has been the most used technique for landslide mapping (Cardinali et al. 2002). However, with the rapid development of new technologies this is starting to change. Very high resolution imagery (QuickBird, IKONOS, CARTOSAT-1, CARTOSAT-2, ALOS-PRISM, GEOYE) has become the best option now for landslide mapping from satellite images, and the number of operational sensors with similar characteristics is growing year by year, as more countries are launching earth observation satellites with stereo capabilities and resolution of 3 meters or better. The high costs may still be a limitation for obtaining these very high resolution images for particular study areas, especially for multiple dates after the occurrence of main triggering events such as tropical storms or cyclones. 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.

Another interesting development is the visual interpretation of landslide phenomena from shaded relief images produced from LiDAR DEMs, from which the objects on the earth surface have been removed; so called bare earth DEMs (Haugerud et al., 2003; Schulz, 2004). Also the combination of an Airborne Laser Scanner (ALS) and Terrestrial Laser Scanner (TLS) for the quantification of landslide volumes has been proven successfully. Terrestrial LiDAR measurements have also been successfully applied for the monitoring of individual landslides (Rosser et al., 2005). The use of shaded relief images of LiDAR DEMs also allows a much more detailed interpretation of the landslide mechanism as the deformation features within the large landslide are visible, and landslide can be mapped in heavily forested areas (Ardizzone et al., 2007; Van den Eeckhaut, 2007).

Many developments have taken place in the last decade related to methods for the automatic detection of landslides based on their spectral or altitude characteristics. Multi-spectral images such as SPOT, LANDSAT, ASTER and IRS-1D LISS3 have proven to be more applicable for landslide mapping based on image classification in conditions where landslides are fresh and unvegetated (Cheng, 2004, Nichol and Wong 2005). Image classification of multi-spectral images for landslide studies can be successful for identifying a large number of unvegetated scarps that have been produced during a single triggering event. However, practice has shown that the use of optical satellite imagery for multi-temporal landslide detection after major triggering events, especially in tropical areas, is often hampered by the persistent cloud cover in the affected area, which makes it difficult to obtain cloud-free images for a long period of time.

Image classification methods used for landslide mapping can be differentiated in pixel based and non-pixel based ones. Recent advances in computer vision and machine intelligence have led to the development of new techniques, such as object-oriented analysis (OOA) for automatic content extraction of both man-made and natural geospatial objects from remote sensing images (Akcay and Aksoy, 2008). OOA has the potential to accurately and meaningfully detect landslides by integrating the contextual information to image analysis, and thereby, reducing the time required for creation of landslide inventory for large areas (Martha et al., 2010). Also automatic detection of landslides using LiDAR derived DEMs have shown to be successful (Booth et al., 2009).

Many methods for landslide mapping make use of digital elevation models of the same area from two different periods. The subtraction of the DEMs allows visualizing where displacement due to landslides has taken place, and the quantification of displacement volumes. DEMs derived from spaceborne missions such as SRTM, ASTER and SPOT do not provide sufficient accuracy to differentiate actual landslide movement from noise, when overlaying two DEMs from different dates. High resolution data from Quickbird, IKONOS, PRISM (ALOS) and CARTOSAT-1 are able to produce highly accurate digital elevation models that might be useful in automatic detection of large and moderately large landslides.

Interferometric Synthetic Aperture Radar (InSAR) has been used extensively for measuring surface displacements. Multi-temporal InSAR analyses using techniques such as the Permanent Scatterers (PSInSAR; Ferretti et al. 2001), PSP (Persistent Scatterers Pairs) and SBAS (Small Base-line Subset) 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. 2008).

It is very important to obtain imagery as soon as possible after the occurrence of a major triggering event, so that accurate event-based landslide maps can be made, which in turn will make it possible to derive landslide hazard maps, that relate the frequency of a triggering event to the landslide density caused by the event. Such event-based landslide inventory maps should be stored in a landslide database implemented in GIS.

Much progress has been made in the development of landslide databases at regional or national level. One of the first comprehensive projects for landslide and flood inventory mapping has been the AVI project in Italy (Guzzetti et al., 1994). There are good examples in the literature of the use of landslide inventories for hazard assessment (Guzzetti, 2000; Chau et al., 2004). However, the existing landslide databases often present several drawbacks (Ardizzone et al., 2002) related to the completeness in space and even more so in time, and the fact that they are biased to landslides that have affected infrastructures such as roads.

Table 5.2 Overview of techniques for the collection of landslide information. Indicated is the applicability of each technique for different mapping scales (N=National, R=Regional, L=Local and S=Site specific. (H= highly applicable, M= moderately applicable, and L= Less applicable)

Group	Technique	Description	Scale			
			N	R	L	S
Image interpretation	Stereo aerial photographs	Analog format or digital image interpretation with single or multi-temporal data set	**M**	**H**	**H**	**H**
	High Resolution satellite images	With monoscopic or stereoscopic images, and single or multi-temporal data set	**M**	**H**	**H**	**H**
	LiDAR shaded relief maps	Single or multi-temporal data set from bare earth model.	**L**	**M**	**H**	**H**
	Radar images	Single data set	**L**	**M**	**M**	**M**
(Semi) automated classification based on spectral characteristics	Aerial photographs	Image ratioing, thresholding	**M**	**H**	**H**	**H**
	Medium resolution multi spectral images	Single data images, with pixel based image classification or image segmentation	**H**	**H**	**H**	**M**
		Multiple date images, with pixel based image classification or image segmentation	**H**	**H**	**H**	**M**
	Using combinations of optical and radar data	Either use image fusion techniques or mult-sensor image classification, either pixel based or object based	**M**	**M**	**M**	**M**
(Semi) automated classification based on altitude characteristics	InSAR	Radar Interferometry for information over larger areas	**M**	**M**	**M**	**M**
		Permanent scatterers for pointwise displacement data	**H**	**H**	**H**	**H**
	LiDAR	Overlaying of LiDAR DEMs from different periods	**L**	**L**	**M**	**H**
	Photogrammetry	Overlaying of DEMs from airphotos or high resolution satellite images for different periods	**L**	**M**	**H**	**H**
Field investigation methods	Field mapping	Conventional method	**M**	**H**	**H**	**H**
		Using Mobile GIS and GPS for attribute data collection	**L**	**H**	**H**	**H**
	Interviews	Using questionnaires, workshops etc.	**L**	**M**	**H**	**H**
Archive studies	Newspaper archives	Historic study of newspaper, books and other archives	**H**	**H**	**H**	**H**
	Road maintenance organizations	Relate maintenance information along linear features with possible cause by landslides	**L**	**M**	**H**	**H**

	Fire brigade/police	Extracting landslide occurrence from logbooks on accidents	**L**	**M**	**H**	**H**
Dating methods for landslides	Direct dating method	Dendrochronology, radiocarbon dating etc.	**L**	**L**	**L**	**M**
	Indirect dating methods	Pollen analysis, lichenometry and other indirect methods,	**L**	**L**	**L**	**L**
Monitoring networks	Extensometer etc.	Continuous information on movement velocity using extensometers, surface tiltmeters, inclinometers, piezometers	**-**	**-**	**L**	**H**
	EDM	Network of Electronic Distance Measurements, repeated regularly	**-**	**-**	**L**	**H**
	GPS	Network of Differential GPS measurements, repeated regularly	**-**	**-**	**L**	**H**
	Total stations	Network of Theodolite measurements, repeated regularly	**-**	**-**	**L**	**H**
	Ground-based InSAR	Using ground-based radar with slide rail, repeated regularly	**-**	**-**	**L**	**H**
	Terrestrial LiDAR	Using terrestrial laser scanning, repeated regularly	**-**	**-**	**L**	**H**

5.2 ENVIRONMENTAL FACTORS

Table 5.3 provides more details on the relevance of the most important environmental factors for landslide susceptibility assessment. The selection of the environmental factors that are used in the susceptibility assessment is depending on the type of landslide, the failure mechanism, the type of terrain and the availability of existing data and resources. Often different combinations of environmental factors should be used, resulting in separate landslide susceptibility maps for each failure mechanism, and landslide type.

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 leveling, EDM (Electronic Distance Measurement), differential GPS measurements, (digital) photogrammetry, InSAR, and LiDAR. Many derivate maps can be produced from DEMs using fairly simple GIS operations. Derivatives from DEMs can be used in heuristic analysis at small scales (hillshading images for display as backdrop image, physiographic classification, internal relief, drainage density), in statistical analysis at regional scales (e.g. altitude zones, slope gradient, slope direction, contributing area, plan curvature, profile curvature, slope length), in physically-based modeling at local scales (local drain direction, flow path, slope gradient) and in landslide run out modeling (detailed slope morphology, flow path, rock fall movement). The use of slope gradient maps in landslide hazard assessment is greatly affected by the resolution of the DEM. As a general rule of thumb the use of slope gradient maps is not advisable for small scale studies, whereas in regional scale studies slope maps, and other DEM derivatives such as aspect, slope length, slope shape etc. can be used as input factors for heuristic or statistical analysis.

In local and site investigation scale hazard assessment, DEMs are used in slope hydrology modeling and slope maps are used for physically-based stability modeling.

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 medium and small scale analysis the subdivision of geological formations into meaningful mapping units of individual rock types often poses a problem, as the intercalations of these units cannot be properly mapped at these scales. In detailed hazard studies specific engineering geological maps are collected and rock types are characterized using field tests and laboratory measurements. Digital geological maps of chronostratigraphy, lithostratigraphy, faults, tectonic lineaments, tectonic units and other themes are available on-line with scales ranging from 1:250.000 (for certain countries) to 1:50 million. For individual countries geological information is often digitally available at much larger scales. 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 restricted mostly to a site investigation level (e.g. Xie et al., 2003). Apart from lithological information structural information is very important for hazard assessment (e.g. for earthquakes, landslides, volcanic eruptions).

Table 5.3 Overview of environmental factors, and their relevance for landslide susceptibility and hazard assessment. Scale of analysis: N=National, M=Regional, L=Local and S=Site Specific. (H= highly applicable, M= moderately applicable, and L= Less applicable)

Group	Data layer and types	Relevance for landslide susceptibility and hazard assessment	Scales of analysis			
			N	R	L	S
Digital Elevation Models	Slope gradient	Most important factor in gravitational movements	L	H	H	H
	Slope direction	Might reflect differences in soil moisture and vegetation	H	H	H	H
	Slope length, shape, curvature	Indicator for slope hydrology	M	H	H	H
	Flow direction	Used in slope hydrological modeling	L	M	H	H
	Flow accumulation	Used in slope hydrological modeling	L	M	H	H
	Internal relief	In small scale assessment as indicator for type of terrain.	H	M	L	L
	Drainage density	In small scale assessment as indicator for type of terrain.	H	M	L	L
Geology	Rock types	Based on engineering properties of rock types	H	H	H	H

	Weathering	Depth of profile is an important factor	L	M	H	H
	Discontinuities	Discontinuity sets and characteristics	L	M	H	H
	Structural aspects	Geological structure in relation with slope angle/direction	H	H	H	H
	Faults	Distance from active faults or width of fault zones	H	H	H	H
Soils	Soil types	Engineering soils with genetic or geotechnical properties	M	H	H	H
	Soil depth	Soil depth based on boreholes, geophysics and outcrops	L	M	H	H
	Geotechnical prop.	Grain size, cohesion, friction angle, bulk density	L	M	H	H
	Hydrological prop.	Pore volume, saturated conductivity, PF curve	L	M	H	H
Hydrology	Water table	Spatially and temporal depth to ground water table	L	L	M	H
	Soil moisture	Spatially and temporal soil moisture content	L	L	M	H
	Hydrologic components	Interception, evapotranspiration, throughfall, overland flow, infiltration, percolation etc.	M	H	H	H
	Stream network	Buffer zones around streams	H	H	H	L
Geomorphology	Physiographic units	First subdivision of the terrain in zones related to overall physiographic setting	H	M	L	L
	Terrain Mapping Units	Homogeneous units of lithology, morphography and processes	H	M	L	L
	Geomorphology	Genetic classification of main landform building processes	H	H	M	L
	Slope facets	Geomorphological subdivision of terrain in slope facets	H	H	H	L
Landuse	Land use map	Type of land use/ land cover	H	H	H	H
	Land use changes	Temporal varying land use/ land cover	M	H	H	H
	Vegetation	Type, canopy cover, rooting depth, root cohesion, weight	L	M	H	H
	Roads	Buffers around roads in sloping areas with road cuts	M	H	H	H
	Buildings	Slope cuts made for building construction	M	H	H	H

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 on the number of measurements and the complexity of the geological structure (Günther, 2003). Another option is to map the relation between slope gradient/slope direction and bedding dip/dip direction for individual slope facets. Fault information is also used frequently as one of the environmental factors in a statistical landslide hazard assessment. The use of wide buffer zones around faults, which is now the standard practice should be treated with caution, as this might be only true for active faults. In other cases a very narrow buffer zone should be taken, which is related to the zone where rocks are fractured.

In terms of soil information required for landslide hazard assessment, there are basically two different thematic data layers needed: soil types, with associated geotechnical and hydrological properties, and soil sequences, with depth information. Table 5.4 gives an overview of the most important geotechnical, hydrological and vegetation characteristics required for modelling slope stability for soilslides, rock slides and reactivated landslides. Pedologic soil maps, normally only classify the soils based on the upper soil horizons, with rather complicated legends and are therefore less relevant in case of landslide deeper than 1-2 meters. Engineering soil maps describe all loose materials on top of the bedrock, and classify them according to the geotechnical characteristics. They are based on outcrops, borehole information and geophysical studies. Especially the soil depth is very difficult to map over large areas, as it may vary locally quite significantly. Soil thickness can be modeled using a correlation with topographic factors such as slope, or predicted from a process based model (Kuriakose et al., 2009). Given the fact that soil thickness is one of the most crucial factors in deterministic slope stability modeling, it is surprising that very limited work has been done on the modeling of soil thicknesses over larger areas.

Table 5.4 Overview of geotechnical and hydrological paramters required for deterministic slope stability assessment

	Soil slope stability: new failures	Existing landslides	Rock slope stability
Geotechnical characteristics	Soil types	Material types	Rock types
	Thickness and layering, depth to bedrock, paleotopography	Thickness of shear surface, interndiate shear surfaces	Weathering profile
	Particle size distribution, Plasticity (Atterberg limits)	Movement history, displacement	rock structure including orientation, occurrence and spacing of bedding, joints, faults and other discontinuities
	Soil density	Density of landslide materials	Rock density
	Shear strength (total and effective angle of internal friction and cohesion)	Residual shear strength	Uniaxial compressive Strength, shear strength along discontinuities
Hydrological	Ground water level fluctuations	Ground water level fluctuations	Ground water level fluctuations
	Saturated conductivity, initial	Saturated conductivity, initial	Permeabilities

	moisture content, infiltration capacity, soil retention curves	moisture content, infiltration capcity, soil retention curves	
Vegetation Characteristics	Vegetation type, surcharge	Vegetation type, surcharge	
	Rooting depth, rooting density, root cohesion	Rooting depth, rooting density, root cohesion	
	Canopy storage, throughfall ratio, evapotranspiration	Canopy storage, throughfall ratio, evapotranspiration	

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 contents 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. In most of the statistical methods the analysis is carried out for a number of basic mapping units, that can be either grid cells, slope facets that are derived from DEMs or unique conditions units which are made by overlaying a number of landslide preparatory factors, such as lithology, land cover, slope gradient, slope curvature and upslope contributing area (Cardinali et al., 2002)

Landuse is too often considered as a static factor in landslide hazard studies, and few researches involve constantly changing land use as a factor in the analysis (Van Beek and Van Asch, 2004). Changes in land cover and land use resulting from human activities, such as deforestation, forest logging, road construction, fire and cultivation on steep slopes can have an important impact on landslide activity. For a deterministic dynamic assessment it is very important to have temporal landuse/landcover 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 such as LANDSAT, SPOT, ASTER, IRS1-D, etc. 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.

5.3 TRIGGERING FACTORS

Information related to triggering factors generally has more temporal than spatial importance, except when dealing with large areas on a small mapping scale. This type of data is related to rainfall, temperature and earthquake records over sufficiently large time periods, and the assessment of magnitude-frequency relations. Rainfall and temperature data are measured in individual meteorological stations, and earthquake data is normally available as earthquake catalogs. The spatial variation over the study area can be represented by interpolating the point data, provided that enough measurement data is available. For example a map of the maximum expected rainfall in 24 hours for different return periods can be generated as the input in dynamic slope stability modeling. In the case of earthquake triggered landslides a map of the peak ground acceleration (PGA) could be used as input in subsequent infinite slope modeling. The use of weather radar for rainfall prediction in landslide studies is a field which is very promising (e.g. Crosta and Frattini, 2003).

5.4 ELEMENTS AT RISK DATA

Elements-at-risk inventories 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 gridcells, administrative units (countries, provinces, municipalities, neighbourhoods, census tracts) 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 damsite). The risk assessment will be done for these spatial units of the elements-at-risk, rather than for the ones used in the hazard assessment. Population data 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 have been 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).

Building information can be obtained in several ways. Ideally data is available on the number and types of buildings per mapping unit, or even in the form of building footprint maps. If such data is not available, building footprints maps can be generated using screen digitizing from high resolution images. Automated building mapping has also been carried out using high resolution satellite images, InSAR, and specifically using LiDAR.

5.5 QUALITY OF THE INPUT DATA

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.

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 sources of errors, which may occur in the generaton of input data for landslide hazard and risk analysis, are schematically represented in Table 5.5.

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. Slope angles, for example, can be measured at several points in the terrain, and these point values can be compared with a slope map dervied from a DEM to assess the degree of error. This evaluation is different for maps which are not based on factual, measured data, but on interpretation, such as the genetic elements of a geomorphological map. Such a map can also be checked in the field, but it is still possible that different geomorphologists will not agree on the specific origin of a certain landform. For maps based on interpretation, only the uncertainty of the map can be assessed, by comparison of different maps by different observers. This method will only render reliable results if the field experience of the observers and the mapping method are identical. Therefore, the actual uncertainty of such maps is difficult to determine in an absolute manner.

A better way is to express directly the uncertainty of the features that are mapped. This can be done for example for landslides, by including a parameter in the description of the landslide referring to the certainty of the landslide features. Spatial uncertainty can also be expressed by not drawing straight boundary lines, e.g. between two lithological units, but by drawing an “uncertainty buffer”. It is possible to include these “fuzzy” boundaries in the map, and assigning fuzzy values between 0 and 1.

The amount of uncertainty is strongly related to the degree of subjectivity of a map. The terms *objective* and *subjective* are used to indicate whether the various steps taken in the determination of the degree of hazard are verifiable and reproducible by other researchers, or whether they depend upon the personal judgment of the researcher. Many of the input maps used in landslide hazard analysis are based on aerial photo-interpretation and will therefore contain a large degree of uncertainty. Table 5.6 lists the factors that are considered to be important in controlling slope instability and a qualitative description of the degree of uncertainty (partly after Carrara et al., 1992). The degree of uncertainty 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. From this list it can be seen that many factors contain an inter-mediate or high degree of uncertainty, either because they are based on a limited amount of factual data (such as soil characteristics) or they are made by subjective interpretation.

Some of the factors with the highest degree of uncertainty are:

Spatial variability, detailed geotechnical information, as well as information on soil thickness, groundwater, rock structure and seismic acceleration can only be obtained for relative small areas, and at large scale. This is because a large amount of data points are required in order to be able to model the spatial variation of these phenomena.

Those maps in which image interpretation plays an important role, and in which the quality of the product depends largely on the experience of the interpreter, will produce the greatest inconsistencies. These maps will be quite erroneous if not based on thorough field checks (Fookes et al., 1991).

The landslide inventory map is the most important data layer, since this contains information on the locations where landslides have actually taken place. For each landslide information should be stored related to the type of landslide, the state of activity, and (if possible) the date of occurrence and damage caused.

Table 5.5 Main sources of uncertainty of input data for landsluide hazard and risk assessment

Group	Type	Example
Source data	Use of data from different sources that have not been checked in the field	Use of fault and lineament maps derived from different organisations
	Use of input data with different map scales	Combination of 1:100.000 lithological map with a 1:10.000 topomap
	Inappropriate scale of the source data	DEMs with high resolution derived from topographic maps with 50 m contour interval
	Geometric (positional) errors in the source data	Use of data with inaccurate coordinate systems
	Semantic errors in the compilation of maps	Use of wrongly classified landslide inventory maps
	Temporal errors in the compilation of maps	Use of outdated landuse maps
	Availability of incomplete data sets	Use of incomplete historical landslide inventories, or rainfall records
Image analysis	Non availability of imagery from right period	Images from suitable period after the occurrence of a major triggering event
	Non availability of imagery of the right type	Cloud cover in optical imagery that prevents mapping of phenomena
	Inexperience of image interpretor	Not enough experience to map landslides, or other thematic information
	Too limited time for image interpretation	Thestudy area os too large, and time for interpretation limited
	Inaccuracies due to the vague ("fuzzy") character of natural boundaries.	Changes between landuse types that have a gradual change
	Too much dependency on automated techniques	Generalization of rule sets used in image classification
Field data collection and map generation	Too limited time for field checking	Not enough fieldwork for landslide mapping and characterisation
	Spatial variation of data which cannot be represented	Lithological differences relevant to landslide occurrence that cannot be mapped at scale
	Uncertainty on subsurface conditions	Soil depth variations over larger areas are very difficult to model
	Lack of sufficient samples to represent spatial characteristics	Characterization of spatial variation of geotechnical characteristics
	Lack of sufficiently long period of measurement	Groundwater fluctuations in relation to major events ar onot recorded in project period.
	Lack of spatial units to link samples to	Characterization of elements at risk data to homogeneous units
GIS Processing	Errors in data entry	Digitizing errors, or errors in matching sptail and attribute data

	Errors in data storage	Errors due to the limited precision
	Errors in data analysis and manipulation	Errors in the conversion of data, errors in generating derivative maps.
	Errors in data output and application	Wrong legends, colour usage, combination with topographic data

Table 5.6 Relative uncertainties for several factors determining landslide hazard

Factor	*Uncertainty*
Slope angle	Low
Slope direction	Low
Slope convexity	Low
General lithological zonation	Low
Detailed lithological composition	High
General tectonic framework	Low
Detailed rock structure	High
Earthquake acceleration	High
Rainfall distribution	Intermediate
Geomorphologic setting	Low
Detailed geomorphologic situation	Intermediate
Present mass movement distribution	Intermediate
Present mass movement typology	Intermediate
Present mass movement activity	Intermediate/high
Past mass movement distribution	High
Soil type distribution	Low/intermediate
Soil characteristics	Intermediate/high
Soil thickness	High
Groundwater conditions	High
Land use	Low
Past climatologic conditions	High

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REFERENCES

Akcay, H.G., Aksoy, S. (2008). Automatic detection of geospatial objects using multiple hierarchical segmentations. IEEE Transactions on Geoscience and Remote Sensing 46, 2097-2111.

Ardizzone, F., Cardinali, M., Carrara, A., Guzzetti, F., Reichenbach, P. (2002). Impact of mapping errors on the reliability of landslide hazard maps. Natural Hazards and Earth System Sciences 2, 3-14.

Ardizzone, F. Cardinali, M., Galli, M., Guzzetti, F., and P. Reichenbach (2007). Identification and mapping of recent rainfall-induced landslides using elevation data collected by airborne Lidar. Nat. Hazards Earth Syst. Sci., 7, pp. 637-650.

Asselen, S.V., Seijmonsbergen, A.C. (2006). Expert-driven semi-automated geomorphological mapping for a mountainous area using a laser DTM. Geomorphology 78 (3-4), 309-320.

Booth, A.M., Roering, J. and Perron, J.T. (2009). Automated landslide mapping using spectral analysis and high-resolution topographic data: Puget Sound lowlands, Washington, and Portland Hills, Oregon. Geomorphology 100, 132-147.

Cardinali, M., Reichenbach, P. Guzzetti, F., Ardizzone, F., Antonini, G., Galli., Cacciano, M., Castellani, M., Salvati, P. (2002). A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy. Natural Hazards and Earth System Sciences 2, 57-72.

Carrara, A., Cardinali, M. and Guzetti, F. (1992). Uncertainty in assessing landslide hazard and risk. ITC-Journal 1992-2: 172-183.

Chau, K.T., Sze, Y.L., Fung, M.K., Wong, W.Y., Fong, E.L., Chan, L.C.P., (2004). Landslide hazard analysis for Hong Kong using landslide inventory and GIS. Computers & Geosciences 30 (4), 429-443.

Cheng, K.S., Wei, C., Chang, S.C. (2004). Locating landslides using multi-temporal satellite images. Advances in Space Research 33 (3), 296-301.

Crosta G.B., Frattini P. (2003) Distributed modelling of shallow landslides triggered by intense rainfall. Natural Hazards And Earth System Sciences NHESS, European Geophysical Society, vol. 3, 1-2, pp. 81-93 ISSN 1561-8633.

Farina, P., Casagli, N., & Ferretti, A. (2008). Radar-interpretation of InSAR measurements for landslide investigations in civil protection practices. Proc. 1st North American Landslide Conference, Vail, Colorado. 272-283

Ferretti, A., Prati, C., Rocca, F. (2001). Permanent scatterers in SAR interferometry. IEEE Transactions on Geoscience and Remote Sensing 39 (1), 8-20.

Fookes, P. G., Dale, S. G., and Land, J. M. (1991). Some observations on a comparitive aerial photography interpretation of a landslipped area, Quarterly Journal of Engineering Geology 24, 249–265

Günther, A., (2003). SLOPEMAP: programs for automated mapping of geometrical and kinematical properties of hard rock hill slopes. Computers and Geoscience 865-875

Guzzetti, F., Cardinali, M., Reichenbach, P. (1994). The AVI project: a bibliographical and archive inventory of landslides and floods in Italy. Environmental Management 18 (4), 623-633.

Guzzetti, F. (2000). Landslide fatalities and the evaluation of landslide risk in Italy. Engineering Geology 58 (2), 89-107.

Haugerud, R.A., Harding, D.J., Johnson, S.Y., Harless, J.L., Weaver, C.S., Sherrod, B.L. (2003). High-resolution LiDAR topography of the Puget Lowland, Washington - A bonanza for earth science. GSA Today 13, 4-10.

IAEG-Commission on Landslides (1990). Suggested nomenclature for landslides. Bulletin of the International Association of Engineering Geology 41, 13-16.

IUGS-Working group on landslide (1995). A suggested method for describing the rate of movement of a landslide. Bulletin of the International Association of Engineering Geology 52, 75-78.

IUGS-Working group on landslide (2001). A suggested method for reporting landslide remedial measures. Bulletin of Engineering Geology and Environment 60, 69-74.

Kuriakose, S.L., Devkota, S., Rossiter,D.G. and Jetten, V.J. (2009). Prediction of soil depth using environmental variables in an anthropogenic landscape, a case study in the Western Ghats of Kerala, India. Catena, 79(1), 27-38.

Martha, T.R., Kerle, N., Jetten, V., van Westen, C.J. and Kumar, K.V. (2010) Characterising spectral, spatial and morphometric properties of landslides for semi - automatic detection using object - oriented methods. Geomorphology, 116 (1-2), 24-36

Metternicht, G., Hurni, L., Gogu, R. (2005). Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. Remote Sensing of Environment 98 (2¬3), 284-303.

Nichol, J., Wong, M.S., 2005. Satellite remote sensing for detailed landslide inventories using change detection and image fusion. International Journal of Remote Sensing 26 (9), 1913-1926.

Pike, R.J., 2000. Geomorphometry - diversity in quantitative surface analysis. Progress in Physical Geography 24 (1), 1-20

Rosser, N.J., Petley, D.N., Lim, M., Dunning, S. A., Allison, R.J., (2005). Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. Quarterly Journal of Engineering Geology and Hydrogeology, 38(4), 363-375.

SafeLand deliverable 4.1, (2010). Review of Techniques for Landslide Detection, Fast Characterization, Rapid Mapping and Long-Term Monitoring. Edited for the SafeLand European project by Michoud C., Abellán A., Derron M.-H. and Jaboyedoff M. Available at http://www.safeland-fp7.eu

Schulz, W.H. (2004). Landslides mapped using LiDAR imagery, Seattle, Washington. U.S. Geological Survey Open-File Report 2004-1396.

Singhroy, V., 2005. Remote sensing of landslides. In: Glade, T., Anderson, M., and Crozier, M.J., (Eds.), Landslide Hazard and Risk. John Wiley and Sons Ltd., West Sussex, England, pp. 469-492.

Soeters, R., Van Westen, C.J. (1996). Slope instability recognition, analysis and zonation. In: Turner, A.K., Schuster, R.L., (Eds.), Landslides, Investigation and Mitigation. Transportation Research Board, National Research Council, Special Report 247, National Academy Press, Washington D.C., U.S.A., pp. 129-177.

UNESCO-WP/WLI, (1993a). Multilingual Landslide Glossary. Bitech Publishers Ltd., Richmond, Canada, 34 pp.

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

UNESCO-WP/WLI, (1994). A suggested method for reporting landslide causes. Bulletin of the International Association of Engineering Geology 50, 71-74.

Van Beek, L.P.H., Van Asch, T.W.J. (2004). Regional assessment of the effects of land-use change and landslide hazard by means of physically based modeling. Natural Hazards 30 (3), 289-304

Van Den Eeckhaut, M., Poesen, J., Verstraeten, G., Vanacker, V., Nyssen, J., Moeyersons, J., Van Beek, L.P.H., Vandekerckhove, L., (2007). The use of LIDAR-derived images for mapping old landslides under forest. Earth surface processes and landforms 32, 754-769.

Xie, M., Tetsuro, E., Zhou, G., Mitani, Y., (2003). Geographic Information Systems based three-dimensional critical slope stability analysis and landslide hazard assessment. Journal of Geotechnical and Geoenvironmental Engineering 129 (12), 1109-1118

6 SUGGESTED METHODS FOR LANDSLIDE SUSCEPTIBILITY ASSESSMENT

As was mentioned in chapter 2 and 3 landslide susceptibility assessment aims at subdividing the terrain in zones that have a different likelihood that landslides of a particular type may occur in future. Landslide susceptibility zoning involves the classification, area or volume (magnitude) and spatial distribution of existing and potential landslides in the study area. It may also include a description of the travel distance, velocity and intensity of the existing or potential landsliding. Landslide susceptibility zoning usually involves developing an inventory of landslides which have occurred in the past together with an assessment of the area with a potential to experience landsliding in the future, but with no assessment of the frequency (annual probability) of the occurrence of landslides. In some situations susceptibility zoning will need to be extended outside the study area to be zoned for hazard and risk to cover areas from which landslides may travel on to or regress into the area being zoned. It will generally be necessary to assess independently the propensity of the slopes to fail and areas onto which landslides from the source landslides may travel (Fell et al., 2008). Therefore this chapter is divided into two components. The first susceptibility component is the most frequently used, and 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). The resulting maps will then form the input as source areas in the modelling of potential run-out areas (runout susceptibility

6.1 LANDSLIDE INITIATION SUSCEPTIBILITY

(ITC and CNRS)

6.1.1 Introduction

A landslide susceptibility map contains a subdivision of the terrain in zones (which may be individual pixels in a GIS-derived map, slope facets, homogeneous units, or administrative units) that have a different likelihood of occurrence of landslides of a particular type. The likelihood may be indicated either qualitatively (as high, moderate low, and not susceptible) or quantitatively (e.g. as the density in number per square kilometres, area affected per square kilometre, Safety Factor or Probability of Failure). 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 by itself, which can be used in land use zoning, and environmental impact assessment. This is especially the case in small scale analysis or in situations where there is not sufficient information available on past landslide occurrences in order to assess the spatial, temporal and size (magnitude) probability of landslides. Landslide susceptibility maps should contain information on the type of landslides that might occur, on the expected sizes/volumes and on their spatial frequency. A landslide initiation susceptibility assessment may involve the following factors:

- The location of past landslide events with a classification of their type and activity.
- Whether the geological, topographical, geotechnical and climatic conditions are judged to be contributing to the possible occurrence of landslides.

- The proportion of the area which may be affected by the landslides (for small scale landslides) or the number of landslides per square km in the inventory of historic landsliding (for rock falls and small landslides)

Landslide initiation susceptibility maps should include:

A topographic basis, with contourlines or hillshading as backdrop and with drainage network, roads, settlements etc.

Zones with different classes of susceptibility to landslide initiation for particular landslide types, indicated by different colours (e.g. using the traffic light colour scheme, ranging from green indicating very low susceptibility to red with very high susceptibility). If the susceptibility map is used as the basis for landuse planning, then the number of classes should be limited (e.g. to less than 5), otherwise the map becomes very difficult to interpret, and use. If the susceptibility map is to be used as the basis for runout susceptibility and for hazard and risk assessment, no direct classification is needed, and the original values can best be used.

A legend with explanation of the susceptibility classes, either qualitatively or including information on expected landslide densities. A separate description on the validation of susceptibility maps is essential.

Superimposed on the susceptibility map should be an inventory of historic landslides, which allows the user to compare the susceptibility classes with the actual historic landslides.

There is a major difference in approaches for landslide susceptibility assessment depending on a number of aspects that are also interrelated:

- The objectives of the study. These could range from a prioritization of landslide susceptibility areas over large territories, land use planning, restrictive zoning, design of risk reduction measures, Environmental Impact Assessment, Preparedness planning etc.
- The scale of the study area (national, regional, local and site investigation). The scale of susceptibility assessment is closely related to the objective of the study.
- The available data. This refers to the various types of input data indicated in the previous chapter. The most important limiting factor is the availability of landslide inventory maps, with associated information on time of occurrence, type, size, volume and activity.
- The resources for data collection and time of study. This is closely related to the objective of the study, the scale of analysis and the available data. If given the objective of the study detailed analysis should be carried out and available data is limited, large investments for data collection are required.
- The type of landslides and failure mechanisms. In general separate landslide susceptibility maps should be made for different landslide types, as the input into subsequent hazard and risk assessment. Even if the same type of landslides is caused by different failure mechanisms, these should be identified and analysed separately.

- The homogeneity of the study area. For instance if geological or soil types are homogeneous over larger areas, it is possible to use even simple physically-based models over large areas.
- Whether the aim is to predict reactivation of existing landslides or to predict areas with first time failures. The assessment of the susceptibility for reactivation of existing landslides has a much lower uncertainty as the location of the event is known, and the methods focus on the evaluation of the conditions under which given landslides could be reactivated. Most of the methods used for reactivation analysis are based on detailed landslide inventories and analysis of historical activity supported by physically-based models, and are applied at local or site investigation scales. The analysis of landslide susceptibility for new failures is prone to much higher uncertainty, and a wider variety of methods is normally applied.

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

- 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 prime importance in any landslide susceptibility assessment.
- Areas with similar environmental settings (as characterized by topography, geology, soil, geomorphology and landuse) as the areas which have experienced landslides in the past are also likely to experience landslides in the future.

6.1.2 Methods for susceptibility assessment related to landslide initiation

Overviews and classification of methods for landslide initiation 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), Cascini et al. (2005), Chacon et al. (2006), Fell et al. (2008), Cascini (2008) and Dai et al (2008). The methods for landslide initiation susceptibility assessment are shown in Figure 6.1. They are subdivided in qualitative ones (landslide inventory analysis, and knowledge driven methods) and quantitative ones (data driven and physically-based models). The inventory-based methods are also required as a first step for all other methods, as they form the most important input and are used for validating the resulting maps.

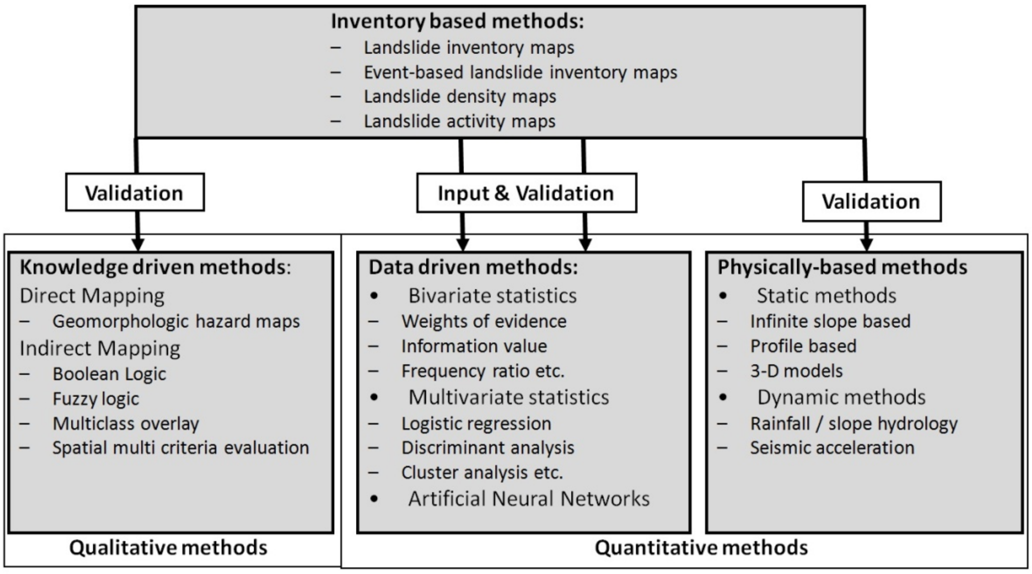

Figure 6.1 Methods for landslide initiation susceptibility assessment.

There is a difference between susceptibility methods for areas focusing on landslide reactivation and areas where landslides might occur in locations where there have been no landslides before.

6.1.3 Landslide inventory analysis

The most straightforward approach to landslide susceptibility assessment is a landslide inventory, giving the spatial distribution of landslides, represented either as points (on small scales) or as polygons (on large scales, with a legend explaining the type and activity. In areas that are characterized mainly by reactivated landslides this might be sufficient as a first level of information. Landslide inventory maps are the basis for most of the other landslide susceptibility assessment methods. They can, however, also be used as an elementary form of susceptibility map, because they display where in an area a particular type of slope movement has occurred. At national and regional scales the density of landslides (of different types) per administrative unit can be considered as an appropriate susceptibility map. Also density contour maps (isopleths maps) at such small scales can be a good solution. Temporal information should play an important role in landslide inventory maps. They should contain information on landslide occurrences over a longer period of time (e.g. over decades), and in case of slow moving or intermittent landslides, also on the landslide activity. Landslide activity should not be confused with the age of landslide occurrence. 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 event, earthquake). These are also referred to as multiple occurrences of landslide events (MORLE) by Crozier (2005). By correlating the density of landslides with the frequency of the trigger, it is possible to make a magnitude-frequency relation, required for hazard assessment. The landslide distribution can also be shown in the form of a density map within administrative units or to use counting circles for generating landslide density contours. This is applied only in national and regional scales. An overview of the methods and examples of references is given in Table 6.1.

Table 6.1 Recommended methods for landslide inventory analysis

Approach	References
Landslide distribution maps based on image interpretation. Generation of event-based inventories or MORLE.	Wieczorek, 1984; Crozier, M.J. 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

6.1.4 Knowledge driven methods

In knowledge driven or heuristic methods expert opinion plays a decisive role. A landslide susceptibility map can be directly mapped in the field by expert geomorphologists, or made in the office as a derivative map of a geomorphological map. This method is used extensively as the basis for local susceptibility mapping for landuse zoning in many countries. 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. This method is subjective and depends largely on the experience and time involvement of the expert. However, when carried out by expert geomorphologists, such susceptibility maps may provide highly accurate results, as the susceptibility can be assessed for every locality separately without the need to incorporate a certain degree of simplification of causal relationships which is required for most of the other methods. In the direct method GIS is used basically only as a tool for entering the final map, without extensive modeling. Direct mapping can also be supported with other methods (e.g. inventory, statistical or physically-based 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. This can also be done by combining all relevant factors using a GIS and assigning the susceptibility class to each individual combination. Or it can be done by giving weights to the classes of the individual factor maps and weights to the maps themselves. The terrain conditions are summated according to these weights, leading to susceptibility values, which can be grouped into hazard classes. This method of qualitative map combination has become widely used in slope instability zonation. Several techniques can be used such as Boolean overlay, Fuzzy logic, multi-class overlay and Spatial Multi-Criteria Evaluation. The drawback of this approach is that the exact weighting of the various parameter maps is difficult. These factors might be very site specific and cannot be simply used in other areas. They should be based on extensive field knowledge and be assigned by real experts with sufficient field knowledge of the important factors. The methods are subjective, but the weights assigned to the factors are transparent and can be discussed among experts, and defended against end users/decision makers. The resulting classes of the susceptibility map (high, moderate, low and not susceptible) can be characterized by the landslide density within these classes, obtained by overlaying the susceptibility map with the landslide inventory. This should be an iterative procedure, in which the experts adjust the weights until the susceptibility map gives a satisfactory classification of the landslides, in which the majority of landslides should occur in the high susceptible zones.

The heuristic methods are also applicable when no landslide inventories are available, although then the susceptibility classification cannot be verified and the resulting susceptibility classes cannot be characterized by a landslide density. These methods can be applied at all scales of analysis. It is the recommended method for a national scale. However, in regional and local scales they can also be applied and can be supported by other methods (e.g. statistical or physically-based modeling). Table 6.2 gives examples of the various knowledge driven methods.

Table 6.2 Recommended methods for knowledge driven landslide susceptibility assessement

Approach	References
Geomorphological mapping	Kienholz, 1978; Rupke et al., 1988; Seijmonsbergen, 1992; Cardinali et al, 2002
Direct mapping method	Barredo et al., 2000; van Westen et al., 2000
Multi-class weighting method	Malet et al., 2009; Mora and Vahrson, 1994
Spatial multi-criteria analysis	Ayalew et al., 2005; Castellanos and Van Westen, 2007;
Analytical hierarchy process (AHP)	Yoshimatsu and Abe, 2005; Yalcin, 2008;
Fuzzy logic approach	Ercanoglu and Gokceoglu, 2001; Chung and Fabbri, 2001

6.1.5 Data-driven landslide susceptibility assessment methods

In data-driven landslide susceptibility analysis, the combinations of factors that have led to landslides in the past are evaluated statistically and quantitative predictions are made for current landslide free areas with similar conditions. The methods assume that similar conditions that have lead to landslides in the past will do so in future. Susceptibility maps are mostly made for the present situation of the environmental factors, e.g. for the present state of landuse. If these aspects change, e.g. due to a land use change or construction of infrastructure, also the landslide susceptibility might change.

The methods are called data-driven as the data of the past occurrences of landslides is used to obtain information on the relative importance of each of the factor maps and classes. Three main data-driven approaches are used: bivariate statistical analysis, multi-variate methods, and Artificial Neural Network analysis.

In a bivariate statistical analysis, each factor map (slope, geology, land use etc.) is combined with the landslide distribution map, and weight values, based on landslide densities, are calculated for each parameter class (slope class, lithological unit, land use type, etc). Several statistical methods can be applied to calculate weight values, such as the information value method, weights of evidence modeling, 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 can be combined with heuristic methods and can also serve as the first step before multivariate statistical analysis is carried out. The method is mostly done on a grid level.

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 (morphometric) units. For each of the sampling units also the presence or absence of landslides is determined. The resulting matrix is then analyzed using multiple regression, logistic regression or discriminant analysis. With these techniques, good results can be expected. Since statistical methods required a substantially complete landslide inventory and a series of factor maps, they cannot be applied easily over very large areas. These techniques have become standard in regional scale landslide susceptibility assessment.

Artificial Neural Network (ANN) is defined as a non-linear function approximator extensively used for pattern recognition and classification. Neurons are the basic units of a neural network, which are organized to compute a non-linear function of their input(s). A neuron receives input(s) with an assigned weight (s), which influence the overall output of the neuron. It is possible to allocate more than one layer of neurons and pass the information and weights from one layer to the next one. The structure of layers, the weights and the connections, known as network topology, determine the behaviour of a network precision. The network is forced to find de relationship between the given classes, or continuous variables and the landslide occurrences.

Data-driven susceptibility methods can be affected by shortcomings like a) the general assumption that landslides occur due to the same combination of factors throughout a study area, b) the ignorance of the fact that 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. Table 6.3 provides examples of the various knowledge driven methods used.

Table 6.3 Recommended methods for data driven landslide susceptibility assessement

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

6.1.6 Physically-based landslide susceptibility assessment methods

These methods are based on modeling the processes of landslides using physically-based slope stability models. An overview of physically based models and their application for landslide susceptibility assessment is given in Brunsden (1999), Casadei et al. (2003), Van Asch et al. (2007) and Simoni et al., (2008). 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 to modeling shallow translational landslides. They can be subdivided in static models that do not include a time component, and dynamic models, which use the output of one time step as input for the next time step. Physically-based models for shallow landslides account for the transient groundwater response of the slopes to rainfall and or the effect of earthquake acceleration. The transient hydrology component is incorporated assuming a slope parallel flow either in its steady state as a function of slope and drainage area (called steady-state models) or by dynamically evaluating the entire process from rainfall to the transient response of the groundwater (called dynamic models). Dynamic models are capable to run forward in time, 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. They are therefore also applicable in the landslide hazard assessment (See next chapter). However, the resulting maps show the Safety Factor for each pixel for a given scenario. It is still complicated to determine the possible landlide size, although this is done by grouping pixels with the same low Safety Factos into potential landslide polygons. 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 frame work (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, it is often more time consuming and resource intensive to derive the necessary data required for physically-based models. 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). The main drawbacks of this method are the high degree of oversimplification and the need for large amounts of reliable input data. The methods are applicable only over larger areas only when the geomorphological and geological conditions are fairly homogeneous and the landslide types are simple. The methods generally require the use of groundwater simulation models. Stochastic methods are sometimes used for selection of input parameters.

GIS-based analysis of earthquake induced landslide susceptibility includes three components which are commonly used together: pseudo-static slope stability analysis, models for the attenuation of ground shaking, and (adapted versions of the) Newmark's displacement method (e.g. Jibson et al. 1998).

Apart from GIS-based models for slope stability assessment, there is also a range of detailed 2-D and 3-D models that normally are applied on cross sections or on single slopes (e.g. Slope/W, SLIDE, CLARA etc.). These require detailed information on geotechnical parameters, soil/rock layers, failure mechanisms, hydrological situation and seismic acceleration.

Numerical modelling applications can be subdivided in continuum modeling methods (e.g. finite element, finite difference, with software such as FLAC3D, VISAGE) and discontinuum modeling (e.g. distinct element, discrete element, with software such as UDEC). Limit Equilibrium Methods do not allow the evaluation of stress and strain conditions in the slope and are incapable to reproduce the crucial role played by deformability in slope movements (Bromhead, 1996; Van Asch et al., 2007). Finite Elements Methods and Finite Difference Methods are able to handle material heterogeneity, non-linearity and boundary conditions, but due to their internal discretization they cannot simulate infinitely large domains and the computation time can be problematic. Boundary Element Methods require discretization at the boundaries of the solution domains only, which simplifies the input requirements, but they are impractical when more than one material must be taken into account. It is the most efficient technique for fracture propagation analysis. Distinct Element Methods represent a discontinuous medium as assemblages of blocks formed by connected fractures in the problem domain, and solve the equations of motion of these blocks through continuous detection and treatment of contacts between the blocks. Handling large displacements including fracture opening and complete detachments is therefore straightforward in these methods although they are less suitable to model plastic deformation.

Hence, any numerical simulation will contain subjective judgements and be a compromise between conflicting detail of process descriptions and practical consideration. It is essential to define guidelines for the development of physically-based models that perform satisfactorily for a given problem (Van Asch et al., 2007).

Table 6.4 Recommended methods for physically-based landslide susceptibility assessment (location of the slope failure)

Type	Method	References
GIS-based limit equilbrium methods	Static infinite slope modeling (e.g. SINMAP, SHALSTAB)	Pack el al. 1998; Dietrich et al., 1995
	Dynamic infinite slope modeling with rainfall trigger (e.g. TRIGRS, STARWARS +PROBSTAB	Baum et al, 2002; Van Beek, 2002; Casadei et al. 2003; Simonie t al., 2008
	Earthquake induced infinite slope modeling (e.g. Newmark)	Jibson et al., 1998
Kinematic analysis for rockslopes	Stereonet plots, GIS based analysis of discontinuities (e.g. SLOPEMAP, DIPS)	Gunter, 2002;
2-D Limit equilibrium methods	2-D LEM with groundwater flow and stress analysis. E.g., SLOPE/W, SLIDE, GALENA, GSLOPE	GEO-Slope, 2011;
3-D Limit equilibrium	3-D slope stability analysis, e.g. CLARA-W, TSLOPE3,	Hungr, 1992; Gilson et al, 2008

methods	SVSLOPE	
Numerical Modeling	Continuum modeling (e.g. finite element, finite difference) , FLAC3D, VISAGE	Hoek et al, 1993; Stead et al, 2001
	Discontinuum modeling (e.g. distinct element, discrete element), e.g. UDEC	Hart, 1993; Stead et al., 2001

6.1.7 Selecting the best method of analysis

Not all methods for landslide hazard zonation are equally applicable at each scale of analysis. Some require very detailed input data, which can only be collected for small areas at the expense of a lot of efforts and costs. Aspects that are relevant for the selection of the method of analysis are presented in Table 6.5.

Table 6.5 Important aspects in the use of the main methods for landslide initiation susceptibility assessment.

	Important aspects	Scales of analysis			
		National	Regional	Local	Site
Inventory methods	Limited to knowing the spatial and temporal distribution. Can be carried out at all scales of analysis. Difficult to apply at small scales (it is quite time consuming to map landslide distribution over large areas, using image interpretation). Used in combination with a heuristic or statistical method at larger scales.	Yes, but difficult to obtain inventory for entire country	Yes, multi-temporal data should be obtained for a period as long as possible	No, but important data for validation of models	No, but important data for validation of models
Heuristic methods	A dominant role for the expert opinion of the analyst. Can be used at all scales of analysis. Increasing detail of the input data, going from small to large scales. Highly subjective, depending on the skill and experience of the analyst, but may result in the best output results, since they do not lead to generalization.	Best method at this scale. Causal factors and triggering factors can be weighted	Best method at this scale. Separate maps are made for different types	Yes, but in combination with other methods	Yes, but in combination with other methods

Statistical methods	The relative importance of the causal factors for landslides is analyzed using bivariate or multivariate statistics. These methods are objective, since the weights for the different factor maps contributing to slope instability are determined using a fixed method. They may lead to generalizations in those cases where the interplay of causal factors is very complex	No, because it is mostly not possible to get a good landslide inventory	Yes, if sufficient data on landslide locations and causal factors can be obtained	Best method for this scale. Correlating past landslides with combination of factors	No, not enough spatial variability of input factors.
Physically-based modelling	The hazard is determined using slope stability models, resulting in the calculation of factors of safety and failure probabilities. Provides the best quantitative information on landslide hazard. Can be used directly in the design of engineering works, or the quantification of risk. Requires a large amount of detailed input data, derived from laboratory tests and field measurements. Suitable only over small areas at large scales.	No, too difficult to parameterize the models	No, too difficult to parameterize the models, unless the area is very homogeneous.	Yes, but only if the area if fairly homogeneous	Best method for this scale. Different approaches can be selected. See table 6-4

Therefore a selection has to be made of the most useful types of analysis for each of the mapping scales, maintaining an adequate cost / benefit ratio. Table 6-5 gives an overview of the methods for landslide hazard analysis and recommendations for their use at the four scales indicated in Chapter 3.

There are several aspects that should be considered:

Selection of a method should suit the available data and the scale of the analysis. For instance, selecting a physical modeling 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.

In the case of lacking or incomplete landslide inventories, heuristic methods can still be applied.

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 into several subsets, each related to a particular failure mechanism, and linked to a specific combination of causal factors. Also only those parts of the landslides should be used that represent the situation of the slopes that failed.

Use of data with a scale or detail that is not appropriate for the hazard assessment method selected should be avoided. For instance, using an SRTM DEM to calculate slope angles used in statistical hazard assessment.

One should take care not to select factor maps because they can be easily obtained, such as DEM derivatives on a regional or local scale, or the use of satellite derived NDVI values as a causal factor instead of generating a land cover map.

One should avoid using factor maps that are not from the period of the landslide occurrence. For instance, in order to be able to correlate landslides with landuse/landcover changes, it is relevant to map the situation that existed when the landslide occurred, and not the situation that resulted after the landslide.

Much of the landslide susceptibility and hazard work is based on the assumption that “the past is the key to the future”, and that the 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”. Conditions under which landslide happened in the past change, and the susceptibility, hazard and risk 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) or changes in the elements at risk (e.g. city growth) the hazard and risk information needs to be adapted.

Landslide susceptibility maps should always be validated and presented with a legend showing the meaning of the classes in terms of measurable factors (e.g. landslide density, number of landslides, factor of safety etc.).

6.1.8 From susceptibility to hazard

Conversion of landslide susceptibility maps into landslide hazard maps requires estimates of spatial, temporal and magnitude probabilities of landslides (Guzzetti et al., 1999; Glade et al., 2005; Fell et al., 2008; Van Asch et al., 2007; Corominas and Moya, 2008; van Westen et al., 2008). The difference between susceptibility and hazard is the inclusion of probability (temporal, spatial and size probability). Figure 6.2 gives a schematic representation of how these 3 probabilities are derived and combined in a hazard assessment (Jaiswal et al., 2011). This will be further discussed in chapter 7.

The spatial probability required for hazard assessment is not the same as the landslide susceptibility. Although some methods (e.g. multivariate statistical methods) give the output in terms of probability, this is not the same as the spatial probability of occurrence of landslides given a certain triggering event. In most of the methods that convert susceptibility to hazards, triggering events and the landslide pattern caused, play a major role. Hence the importance of obtaining event-based landslide inventories or MORLES, for which one can determine the temporal probability of the trigger, the spatial probability of landslide occurring within the various susceptibility classes, and the size probability. In this approach, which is mostly carried out at regional and local scales, the susceptibility map is basically only used to subdivide the terrain in zones with equal level of susceptibility.

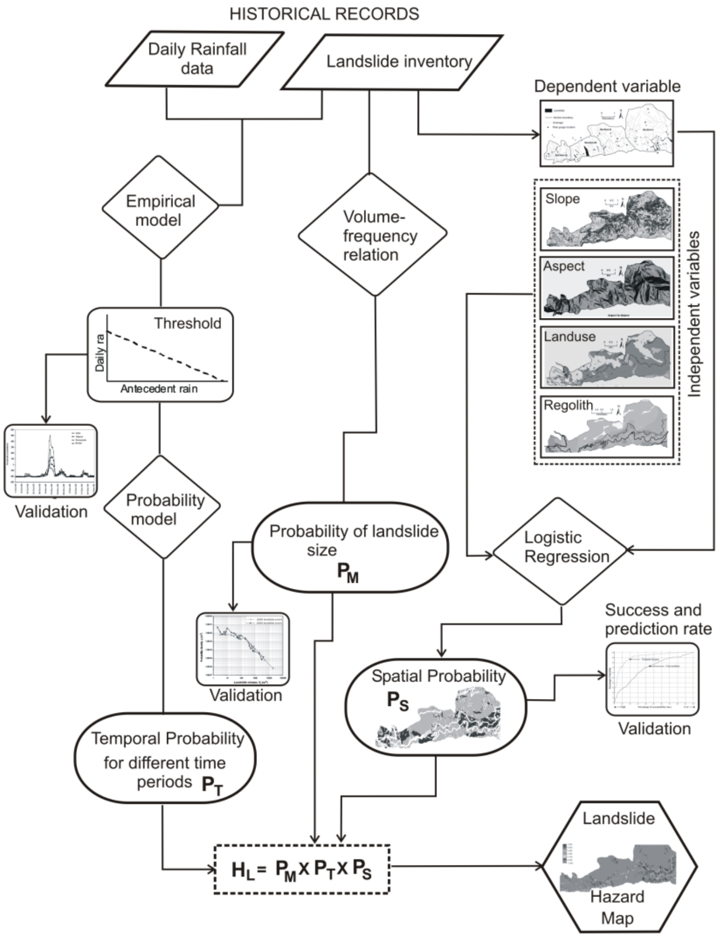

Figure 6.2 Parameters and process adopted for the quantitative assessment of landslide hazard (Jaiswal et al., 2011)

Size probability is the probability that the landslide will be of a particular minimum size. The quantitative estimation of the probability of occurrence of landslides of a given size is a key issue for any landslide hazard analysis (Malamud et al., 2004; Fell et al., 2008). Whereas the landslide susceptibility maps indicate classes with different levels of susceptibility to landslide occurrence, the translation in the expected number/area of landslides for given return periods, is what makes these useful for subsequent hazard and risk assessment. Magnitude probabilities of landslides can be estimated after performing the magnitude-frequency analysis of landslide inventory data. For estimating landslide magnitudes, the area of landslide (m^2) can be considered as a proxy (Guzzetti et al., 2005). The frequency-size analysis of landslide area can be carried out by calculating the probability density function of landslide area using the maximum likelihood estimation method assuming two standard distribution functions: (i) the Inverse-Gamma distribution function (Malamud et al., 2004), and (ii) the Double-Pareto distribution function (Stark and Hovius, 2001). See also chapter 7 for more information on this topic.

Temporal probability can be established using different methods. A relation between triggering events (rainfall or earthquakes) and landslide occurrences is needed in order to be able to assess the temporal probability. Temporal probability assessment of landslides is either done using rainfall threshold estimation, through the use of multi-temporal data sets in statistical modeling, or through dynamic modeling. Rainfall threshold estimation is mostly done using antecedent rainfall analysis, for which the availability of a sufficient number of landslide occurrence dates is essential. If distribution maps are available of landslides that have been generated during the same triggering event, a useful approach is to derive susceptibility maps using statistical or heuristic methods, and link the resulting classes to the temporal probability of the triggering events. The most optimal method for estimating both temporal and spatial probability is dynamic modeling, where changes in hydrological conditions are modeled using daily (or larger) time steps based on rainfall data. However, more emphasis should be given to the collection of reliable input maps, focusing on soil types and soil thickness. The methods for hazard analysis should be carried out for different landslide types and volumes, as these are required for the estimated damage potential. Landslide hazard is both related to landslide initiation, as well as to landslide deposition, and therefore also landslide run-out analysis should be included on a routine basis.

References

Aleotti, P. and Chowdury, R. 1999. Landslide hazard assessment: summary review and new perspectives. Bull. Eng. Geol. Env. (1999): 21-44, pp 21- 44

Ayalew L, Yamagishi H, Marui H, Kanno T (2005) Landslide in Sado Island of Japan: Part II. GIS-based susceptibility mapping with comparision of results from two methods and verifications. Eng Geol 81:432–445.

Baum, R.L., Savage, W.Z., and Godt, J.W. (2002). TRIGRS - A Fortran program for transient rainfall infiltration and grid based regional slope stability analysis, Open file report 02-424: Colorado, USA, U.S. Department of the Interior and U.S. Geological Survey

Bromhead, E.N. (1996). Slope stability modeling : an overview. In : Landslide recognition. Wiley & Sons, Chichester, 231-235.

Brunsden, D. (1999). Some geomorphological considerations for the future development of landslide models: Geomorphology. 30(1-2), p. 13-24.

Bulut F, Boynukalin S, Tarhan F, Ataoglu E (2000) Reliability of isopleth maps. Bull Eng Geol Environ 58:95–98

Carrara, A. (1983) Multivariate models for landslide hazard evaluation. Mathematical Geology, 15 (3):403- 426

Carrara A.; Guzzetti F.; Cardinali M.; Reichenbach P. (1999). Use of GIS technology in the prediction and monitoring of landslide hazard, Natural Hazards, Volume 20, Issue 2-3, 1999, Pages 117-135

Cardinali M, Reichenbach P, Guzzetti F, Ardizzone F, Antonini G, Galli M, Cacciano M, Castellani M, Salvati P (2002) A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy. Nat Hazards Earth Syst Sci 2:57–72

Casadei, M., Dietrich, W.E., and Miller, N.L. (2003). Testing a model for predicting the timing and location of shallow landslide initiation on soil mantled landscapes: Earth Surface Processes and Landforms. 28(9), p. 925-950.

Cascini, L., Bonnard, Ch., Corominas, J., Jibson, R., Montero-Olarte, J., 2005. Landslide hazard and risk zoning for urban planning and development. In: Hungr, O., Fell, R., Couture, R., Eberthardt, E. (Eds.), Landslide Risk Management. Taylor and Francis, London, pp. 199–235.

Cascini, L (2008) Applicability of landslide susceptibility and hazard zoning at different scales. Engineering Geology, Volume 102, Issue 3-4, Pages 164-177

Castellanos, EA, Van Westen CJ (2007) Qualitative landslide susceptibility assessment by multicriteria analysis: a case study from San Antonio del Sur, Guantanamo, Cuba. Geomorphology 94(3–4):453–466.

Chacon J, Irigaray C, Fernandez T, El Hamdouni R (2006) Engineering geology maps: landslides and geographical information systems. Bull Eng Geol Environ 65:341–411.

Chung CF, Fabbri AG (1993) Representation of geoscience data for information integration. J Non-Renewable Resour 2(2):122–139

Chung CF, Fabbri AG (2001) Prediction models for landslide hazard using fuzzi set approach. In: Marchetti M, Rivas V (eds) Geomorphology and environmental impact assessment. A.A. Balkema, Rotterdam, pp 31–47

Coe, J.A., Michael J.A., Crovelli, R.A., Savage, W.A. (2000) Preliminary map showing landslides densities, mean recurrence intervals, and exceedance probabilities as determined from historic records, Seattle, Washington. USGS Open-File report 00-303

Colesanti, C., Wasowski, J. (2006). Investigating landslides with space-borne Synthetic Aperture Radar (SAR) interferometry. Engineering Geology 88 (3-4), 173-199.

Corominas, J. and Moya, 2008. A review of assessing landslide frequency for hazard zoning purposes. Engineering geology 102, 193-213

Crozier, M.J. (2005). Multiple occurrence regional landslide events in New Zealand: hazard management issues. Landslides,2: 247-256

Dai, F.C., Lee, C.F. and Ngai, Y.Y. (2008). Landslide risk assessment and management: an overview . Engineering Geology, 64 (1), 65-87

Dietrich, W.E., Reiss, R., Hsu, M.-L., and Montgomery, D.R., (1995). A process-based model for colluvial soil depth and shallow landsliding using digital elevation data: Hydrological Processes. 9, p. 383-400

Dixon, N., and Brook, E. (2007). Impact of predicted climate change on landslide reactivation: case study of Mam Tor, UK. Landslides, 4, 137-147

Ercanoglu, M. and Gokceolglu, C. (2001). Assessment of landslide susceptibility for a landslide-prone area (north of Yenice, NW Turkey) by fuzzy approach. Environmental Geology 41 :720-730.

Ermini L, Catani F, Casagli N (2005) Artificial neural networks applied to landslide susceptibility assessment. Geomorphology 66:327–343

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.Z., (2008). Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering Geology 102, 85-98.

Geo-slope (2011). Slope/W.. Geo-Slope International ltd. Gagary, Canada. www.geo-slope.com

Gilson Gitirana Jr., Marcos A. Santos, Murray Fredlund, (2008). Three-Dimensional Analysis of the Lodalen Landslide, GeoCongress 2008, March 9 - 12, 2008, New Orleans, LA, USA

Glade T., Anderson M. & Crozier M.J. (Eds) (2005): Landslide hazard and risk.- Wiley. 803 p

Gorsevski, P.V., Gessler, P., and Foltz, R.B. (2000). Spatial prediction of landslide hazard using discriminant analysis and GIS. GIS in the Rockies 2000 Conference and Workshop: applications for the 21st Century, Denver, Colorado, September 25 - 27, 2000

Günther, A., (2003). SLOPEMAP: programs for automated mapping of geometrical and kinematical properties of hard rock hill slopes. Computers and Geoscience 865-875

Guzzetti, F., Carrara, A., Cardinali, M. and Reichenbach, P., (1999). Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology, 31(1-4): 181-216.

Guzzetti F., Cardinali M., Reichenbach P. and Carrara A., (2000). Comparing landslide maps: A case study in the upper Tiber River Basin, central Italy. Environmental Management, 25:3, 2000, 247-363.

Hart, R.D (1993). An introduction to distic element modeling for rock engineering. In: Hudson (ed.) comprehensive Rock engineering

Hoek, E., Grabinsky, M.W., and Diederichs (1993). Numerical modeling for underground excavations. Transactions of the Institution of Mining and Metallurgy – Section A 100: A22-A30.

Jaiswal P., van Westen C.J. (2009). Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds. Geomorphology 112, 96-105.

Jaiswal P., van Westen, C.J. and Jetten, V. (2011). Quantitative assessment of landslide hazard along transportation lines using historical records. Landslides (in press).

Jibson, R.W., Harp, E. L. and Michael, J.A..(1998). A Method for Producing Digital Probabilistic Seismic Landslide Hazard Maps: An Example from the Los Angeles, California, Area. US Geological Survey Open File Report 98-113

Kanungo, D.P., Arora, M.K., Sarkar, S. and Gupta, R.P., (2006). A comparative study of conventional, ANN black box, fuzzy and combined neural and fuzzy weighting procedures for landslide susceptibility zonation in Darjeeling Himalayas. Engineering Geology, 85(3-4): 347-366.

Keefer, D.K. (2002). Investigating landslides caused by earthquakes – a historical review. Surveys in Geophysics 23: 473–510

Kienholz H (1978) Maps of geomorphology and natural hazard of Grindewald, Switzerland, scale 1:10,000. Arctic Alpine Res 10(2):169–184

Lee, S., Ryu, J.-H., Won, J.-S. and Park, H.-J., (2004). Determination and application of the weights for landslide susceptibility mapping using an artificial neural network. Engineering Geology, 71(3-4): 289-302.

Lee S (2005) Application of logistic regression model and its validation for landslide susceptibility mapping using GIS and remote sensing data. Int J Remote Sens 26:1477–1491.

Luzi L (1995) Application of favourability modelling to zoning of landslide hazard in the Fabriano Area, Central Italy. In: Proceedings of the first joint European conference and exhibition on geographical information, The Hague, Netherlands, pp 398–402

Malamud, B.D., Turcotte, D.L., Guzzetti, F., Reichenbach, P., 2004. Landslide inventories and their statistical properties. Earth Surface Processes and Landforms 29, 687-711.

Malet, J.P., Thiery, Y, Hervás, J., Günther, A., Puissant, A, Grandjean, G. (2009). Landslide susceptibility mapping at 1:1M scale over France: exploratory results with a heuristic model. Proc. Int. Conference on Landslide Processes: from Geomorphologic Mapping to Dynamic Modelling. A tribute to Prof. Dr. Theo van Asch, 6 -7 February 2009. Strasbourg, France.

Mora S, Vahrson G (1994) Macrozonation methodology for landslide hazard determination. Bull Assoc Eng Geol XXXI(1):49–58

Ohlmacher CG, Davis CJ (2003) Using multiple logistic regression and GIS technology to predict landslide hazard in northeast Kansas, USA. Eng Geol 69 (3-4): 331–343

Pack, R.T., Tarboton, D.G., and Goodwin, C.N., (1998). The SINMAP Approach to Terrain Stability Mapping, 8th Congress of the International Association of Engineering Geology: Vancouver, British Columbia, Canada, International Association of Engineering.

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

Rupke, J., Cammeraat, E., Seijmonsbergen, A.C. and van Westen, C.J. (1988) Engineering geomorphology of the Widentobel catchment, Appenzell and Sankt Gallen, Switzerland : a geomorphological inventory system applied to geotechnical appraisal of slope stability. In: Engineering geology, 26 (1988)1, pp. 33-68.

Seijmonsbergen , A.C. , 1992. Geomorphological evolution of an alpine area and its application to geotechnical and natural hazard appraisal in the NW. Rätikon Mountains and S. Walgau (Vorarlberg, Austria), including map series at 1:10,000 scale. PhD-thesis, Faculty of Environmental Sciences, Department of Physical Geography, University of Amsterdam. 109 pp. ISBN: 90-6787-021-8.

Simoni, S., Zanotti, F., Bertoldi, G., and Rigon, R., (2008). Modelling the probability of occurrence of shallow landslides and channelized debris flows using GEOtop-FS: Hydrological Processes. 22(4), p. 532-545.

Soeters, R., Van Westen, C.J., 1996. Slope instability recognition, analysis and zonation. In: Turner, A.K., Schuster, R.L., (Eds.), Landslides, Investigation and Mitigation.

Suzen ML, Doyuran V (2004) Data driven bivariate landslide susceptibility assessment using geographical information systems: a method and application to Asarsuyu catchment, Turkey. Eng Geol 71:303–321.

Squarzoni, C., Delacourt, C., Allemand, P., 2003. Nine years of spatial and temporal evolution of the La Vallette landslide observed by SAR interferometry.. Engineering Geology 68 (1_2), 53_66.

Stark, C., P., Hovius, N., 2001. The characterisation of landslide size distributions. Geophysical Research Letters 28, 1091-1094.

Stead, D., Eberhardt, E., Coggan, J., and Benko, B. (2001). Advanced Numerical Techniques In Rock Slope Stability Analysis – Applications And Limitations. LANDSLIDES – Causes, Impacts and Countermeasures, 17-21 June 2001, Davos, Switzerland, 615-624

Valadao P, Gaspar JL, Queiroz G, Ferreira T (2002) Landslides density map of S. Miguel Island, Azores archipelago. Nat Hazard Earth Syst Sci 2:51–56

Van Asch, T.W.J., Malet, J.P., Van Beek, L.P.H. and Amitrato, D. (2007) Techniques, issues and advances in numerical modelling of landslide hazard. Bull. Soc. géol. Fr., 2007, 178 (2), 65-88

van Beek, L.P.H. (2002). Assessment of the influence of changes in Landuse and Climate on Landslide Activity in a Mediterranean Environment [PhD thesis]: Utrecht, The Netherlands, University of Utrecht.

Van Westen, C. J.: 1993, Application of Geographic Information Systems to Landslide Hazard Zonation, Ph-D Dissertation Technical University Delft. ITC-Publication Number 15, ITC, Enschede, The Netherlands, 245 pp.

Van Westen, C.J., Soeters, R. and Sijmons, K. (2000) Digital geomorphological landslide hazard mapping of the Alpago area, Italy. In: International journal of applied earth observation and geoinformation : JAG, 2 (2000)1, pp. 51-60.

Van Westen, C.J., Castellanos Abella, E.A. and Sekhar, L.K. (2008) Spatial data for landslide susceptibility, hazards and vulnerability assessment : an overview. In: Engineering geology, 102 (2008)3-4, pp. 112-131

Wieczorek, G.F. (1984). Preparing a detailed landslide-inventory map for hazard evaluation and reduction. Bulletin of the Association of Engineering Geologists 21 (3), 337– 342

Yalcın A (2008) GIS-based landslide susceptibility mapping using analytical hierarchy process and bivariate statistics in Ardesen (Turkey): comparisons of results and confirmations. Catena 1:1–12.

Yin, K. J. and Yan, T. Z.: 1988, Statistical prediction model for slope instability of metamorphosed rocks, Proceedings 5th International Symposium on Landslides, Lausanne, Switserland, Vol. 2, 1269-1272.

Yoshimatsu, H. and Abe, S. (2005). A review of landslide hazards in Japan and ssessment of their susceptibility using an analytical hierarchic process (AHP) method. Landslides DOI: 10.1007/s10346-005-0031-y

6.2 LANDSLIDE RUNOUT

(FUNAB and UPC)

This section will describe 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 such scale maps, except for very large events (Horton et al. 2008). Magnitude (mass, volume) of the landslide, propagation mechanism and characteristics of the path are the main factors determining the landslide runout.

Methods for assessing landslide runout may be classified as empirical and analytical/rational (Hungr et al. 2005). For hazard zoning purposes both methods are widely used given their capability of being integrated in GIS platforms.

6.2.1 Empirical

Empirical methods developed for assessing landslide runout are usually based on field observations and on the analysis, for different landslide mechanisms, of the relationship between morphometric parameters of the landslide (i.e. the volume of the landslide mass), characteristics of the path (i.e. local morphology, presence of obstructions), and the distance travelled by the landslide deposits. Empirical approaches are based on simplified assumptions and, consequently, they might not always have an evident interpretation. Methods for predicting landslide runout can be classified as geomorphologically-based, geometrical approaches and volume change methods Table 6.1.

6.2.1.1 Geologic evidences

Identification and 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 the basis for defining future travel distances. The geomophological analysis allows determining: (a) the farthest distance reached by previous landslide events; and (b) if enough number of landslide events is inventoried, statistics of distances reached and their probability.

Field work and photo interpretation are classical procedures used to define the spatial distribution and extent of past landslides. The outer margin of the landslide deposits give an appraisal of the maximum distances that landslides were able to reach during the present landscape, for a span of time that may last for several thousands of years (Hungr et al. 2005). The first constraint that this approach has to overcome is the proper identification of the landslide deposits. Old deposits may have been buried by new events, or removed by erosion total or partially, or masked by depositional features from other processes.

Geomorphological approach is appropriate from the analysis of high-magnitude low-frequency events that due to their abnormal size they may remain on the landscape for long span of time and can thus be identified. For instance, mapping the extent of large debris avalanches in the Puget Sound lowland close to Seattle (Scott & Vallance, 1993, Hoblitt et al. 1998), has allowed the delineation and subsequent dating of the largest lahars originating from Mount Rainier during the last 10,000 years. These deposits define the scenario of the maximum extent that similar events might reach in the future. It must be taken into account, however, that in ancient landslide events, the lack of continuous outcrops will make the delineation of the boundaries difficult, particularly in the farthest reaches. Uncertainties relating to the source, size, and mobility of future events preclude precise location of the hazard zone boundaries. The geomorphological approach does not give any clue of the emplacement mechanism. Furthermore, the slope geometry and the circumstances responsible for past landslides might have changed. Therefore, results obtained in a given place cannot be usually exported to other localities.

6.2.1.2 Geometrical approaches

Runout assessment can be carried out through the analysis of the geometrical relations between landslide parameters and distance travelled. The most commonly used indexes are the angle of reach (fahrböschung angle or travel distance angle) and the shadow angle. 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. Tangent of the angle of reach is the ratio between the vertical drop H and the horizontal component of the runout distance L. Empirical observations show a volume dependence of the angle of reach (α). A plot of the tangent of the reach angle (H/L) against the landslide volume shows that large landslides display lower angles of reach than smaller ones (Scheidegger 1973, Hsü 1975). The relation may be expressed by a regression equation that takes the following form:

$$\mathrm{Log}\ \tan\alpha = A + B\ \mathrm{Log}\ V$$

Where A and B are constants and V, the volume.

This relation has, in general, a lot of scattering and weak correlation coefficients. When splitting the landslides into different groups according to their predominant mechanism (i.e. rockfalls, debris flows, slides) and characteristics of the path (i.e. obstructed, channeled, etc), the scattering can be significantly reduced (Corominas, 1996).

When the landslide source and potential landslide volume are known, the runout distance (L) can be obtained from the following expression:

$$L = H / \tan\alpha$$

In practice, runout length can be obtained graphically by assuming 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 (Corominas et al. 2003).

The rockfall shadow is the area beyond the toe of a talus slope that falling boulders can reach by bouncing and rolling. Hungr & Evans (1988) and Evans & Hungr (1993) have used the concept of shadow angle (β) 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 in 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.

Both reach angle and shadow angle may be used to trace the maximum extent of the potential landslides (Corominas et al. 2003) and can be easily implemented on a GIS for local and site specific analyses (Jabodeyoff et al. 2005). 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 and Vilaplana, 2008). This allows their application to local-scale landslide susceptibility and hazard maps but as they do not provide kinematic parameters (velocity, kinetic energy) of the landslides these approaches can be hardly applied to site specific analyses.

6.2.1.3 Volume-change methods

The volume change method (Fannin & Wise 2001) estimates the potential travel distance of debris flows by imposing a balance between both 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 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 travel distances of two observed events.

Table 6.6 Empirical methods for assessing runout distance

		Activity	References
Empirical	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 or shadow angle to assess travel distance (maximum reach)	Corominas et al. 2003; Ayala et al. 2003; Jabodeyoff 2003; Jaboyedoff and Labiouse, 2003
		use empirical methods based on reach angle or shadow angle to assess travel distance accounting for the uncertainty in the empirical methods and data in puts (probability of reach)	Copons and Vilaplana, 2008
		Planimetric areas of lahar inundated valleys obtained from statistical analyses (volume-area relations) of previous paths	Li, 1983; Iverson et al. 1998
	Volume-change method	Runout calculated through a balance between volume entrained and deposited	Fannin and Wise, 2001

6.2.2 Rational methods

Rational methods are based on the use of mathematical models of different degrees of complexity. They can be classified as follows:

6.2.2.1 Discrete models

To be 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 it a suitable coefficient of restitution. On 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 rather small (friction, sometimes an 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 given granulometries can be generated. One main advantage of these methods is their ability to reproduce effects far beyond the reach of continuum modes, such as inverse segregation. (Calvetti et al 2000). Discrete element models are suitable for the simulation of rock avalanches, but it is not recommended their use in other situations (flowslides, lahars, mudflows…) because of the rheometry of the flowing materials.

6.2.2.2 Continuum based models

They are based on continuum mechanics, and can include coupling of the mechanical behaviour with hydraulics and thermo mechanics. Here we can consider the following groups.

(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. The model is based on the mixture theory. However, 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 discretize the equations using a suitable numerical model, such as finite elements or SPH. As an example, we can mention the work of Quecedo et al 2004 who analyzed the waves generated in reservoirs by landslides. 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.

(b) Velocity-pressure models (Biot-Zienkiewicz) In many occasions, 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. Again, the resulting model is 3D, and the computational effort to solve is large. Material point models, SPH, and ALE methods, such as used by Sosio et al 2008 can be used, but their field of application is restricted. One important point is that pore pressures can be fully described.

(c) Taking into account the geometry of most of fast propagating landslides, it is possible to use a depth integration approximation. The equations reduce from 3D to 2D, as all variables depend on (x,y), the z information being lost in the integration procedure. 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. Since then, they have been widely used by engineers and earth scientists. It is possible too to include information of the basal pore pressure, as done by Iverson et al 2001 and Pastor et al 2008. It is important to notice that even if the results obtained by these models can be plotted in 3D, giving the sensation 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 does consist on a succession of infinite landslides evolving over a variable topography. Here, pore pressure dissipation can be included, as done by Hutchinson (1986).

We summarize all these concepts in Table 6.7 below.

We will close this Section by recalling the main conclusions described here regarding the suitability and applicability of the models to different types of movements.

(i) Discrete element models are suitable for the simulation of rock avalanches, but it is not recommended their use in other situations (flowslides, lahars, mudflows…) because of the rheometry of the flowing materials.

(ii) 3D models based on mixture theory. 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. This kind of models can be applied to all types of movements with the exception of those which have important effects caused by their granularity.

(iii) Velocity-pressure models (Biot-Zienkiewicz). are a simplification stemming from above more general models. They can be used when the movement of water relative to soil skeleton is small. Therefore, they can be applied to avalanches and debris flows.

(iv) Depth integrated models can be applied to all types of movements as a suitable simplified approach. Their limitations are due to geometry of the flow rather than its type. 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. In the case of flowslides pore pressure has to be considered.

Table 6.7 Analytical methods for landslide runout assessment

			Type of landslide	References
Rational Methods	Discrete Models	Lumped	Rockfalls	Agliardi and Crosta, 2003; Dorren & Seijmonsbergen, 2003;
		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, S.B., Hutter, K. 1991 ; McDougall & Hungr 2004; Pastor et al 2008; Iverson and Denlinger 2001
		3D models	Avalanches, debris flows, mudflows, lahars, flowslides	Sosio et al. 2008; Agliardi, F. and Crosta, G.B. 2003; Quecedo et al 2004

References

Agliardi, F. and Crosta, G.B. 2003. High resolution three-dimensional numerical modelling of rockfalls. International Journal of Rock Mechanics and Mining Sciences, 40: 455-471

Alonso, E.E., Pinyol, N.M. 2010. Criteria for rapid sliding I: A review of the Vaiont case. Engineering Geology, Volume 114: 198-210

Bozzolo, D. and Pamini, R. 1986. Simulation of rock falls down a valley side. Acta Mechanica 63, 113-130

Calvetti, F., Crosta, G., Tatarella, M. 2000. Numerical Simulation of dry granular flows: from the reproduction of smale- scale experiments to the prediction of rock avalanches. Rivista Italiana di Geotecnica. Aprile- Giugno 2000, pag 21-38

Cannon, S. H. 1993. An empirical model for the volume-change behaviour of debris flows. Proceedings ASCE National Conference on hydraulic Engineering, San Francisco, CA. pp. 1768-1773

Copons, R., Vilaplana, J.M. 2008. Rockfall susceptibility zoning at a large scale: From geomorphological inventory to preliminary land use planning. Engineering Geology 102: 142–151

Corominas, J. 1996. The angle of reach as a mobility index for small and large landslides. Canadian Geotechnical Journal, 33: 260-271

Corominas, J., Copons, R., Vilaplana, J.M., Altimir, J., Amigó, J. 2003. Integrated landslide susceptibility analysis and hazard assessment in the Principality of Andorra. Natural Hazards 30: 421-435

Evans, S.G. & Hungr, O. 1993. The assessment of rockfall hazard at the base of talus slopes. Canadian Geotechnical Journal 30: 620-636

Dorren L.K.A., Seijmonsbergen, A.C. 2003. Comparison of three GIS-based models for predicting rockfall runout zones at a regional scale. Geomorphology, 56: 49-64

Fannin, R.J., Wise, M.P. 2001. An empirical-statistical model for debris flow travel distance. Canadian Geotechnical Journal, 38: 982-994

Hoblitt, R.P., Walder, J.S., Driedger, C.L., Scott, K.M., Pringle, P.T. & Vallance, J.W. 1998. Volcano Hazards from Mount Rainier, Washington, Revised 1998. USGS Open- File Report 98-428

Horton, P., Jaboyedoff, M., Bardou , E. 2008. Debris flow susceptibility mapping at a regional scale. In Locat, J., Perret, D., Turmel, D., Demers, D., and Leroueil, S. (Eds). Proceedings of the 4th Canadian Conference on Geohazards. From Causes to Management. Presse de l'Université Laval, Québec, pp. 399-406.

Hsü, K.J. 1975. Catastrophic debris stream (sturzstroms) generated by rockfalls. Geological Society of America Bulletin, 86: 129-140

Hungr, O. 1995. A model for the run out analysis of rapid flow slides, debris flows and avalanches. Canadian Geotechnical Journal,32: 610-623

Hungr, O. & Evans, S.G. 1988. Engineering evaluation of fragmental rockfall hazards. In Bonnard (ed.), 5th International Symposium on Landslides, Lausanne, Switzerland. A.A. Balkema, vol. 1: 685-690

Hungr. O., Corominas, J., Eberhardt, E. 2005. Estimating landslide motion mechanisms, travel distance and velocity. In Landslide Risk Management . O. Hungr, R. Fell, R. Couture and E. Eberhardt (Eds.). Taylor and Francis, London. pp.99-128

Hunter, G., Fell, R. 2003 Travel distance angle for rapid landslides in constructed and natural slopes. Canadian Geotechnical Journal, 40: 1123-1141

Hutchinson, J.N. 1986. A sliding-consolidation model for flow slides. Canadian Geotechnical Journal 23: 115-126

Iverson, R.M., Schilling, S.P., Wallance, J.W. 1998. Objective delineation of lahar-inundation hazard zones. GSA Bulletin, 110: 972–984

Iverson, R.I., Denlinger, R.P. 2001. Flow of variably fluidized granular masses across three dimensional terrain.1.Coulomb mixture theory", J.Geophys.Res. 106, N0.B1, pp. 537–552

Jaboyedoff, M. 2003. Conefall v 1.0. A program to estimate propagation zones of rockfall, based on cone methode (Quanterra). http://www.quanterra

Jaboyedoff, M., Labiouse, V. 2003. Preliminary assessment of rockfall hazard based on GIS data. ISRM 2003–Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy. pp.575.578

Kwan, J.S.H., Sun, H.W. 2005. An improved landslide mobility model. Canadian Geotechnical Journal, 43: 531–539

Li, T. 1983. A mathematical model for predicting the extent of a major rockfall. Zeitschrift für Geomorphologie 24: 473-482.

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

Pastor, M., Haddad B., Sorbino G. and Cuomo S. 2008. A depth integrated coupled SPH model for flow-like landslides and related phenomena. Int.J.Num.Anal.Meth.Geomech. 33:143–172

Pinyol, N.M., Alonso, E.E. 2010. Criteria for rapid sliding II.: Thermo-hydro-mechanical and scale effects in Vaiont case. Engineering Geology, Volume 114: 211-227

Pirulli,M., Preh, A., Roth, W., Scavia, C., Poissel, R. 2003. Rock avalanche run out prediction: combined application of two numerical methods. ISRM 2003–Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy. pp. 903-908

Quecedo, M. Pastor, M., Herreros, M.I. 2004. Numerical modelling of impulse wave generated

by fast landslides, Int.J.Numer.Meth.Engng., 59:1633-1656 (DOI: 10.1002/nme.934)

Savage, S.B., Hutter, K. 1991. The dynamics of avalanches of granular materials from initiation to runout. Part I: Analysis. Acta Mechanica 86: 201 – 223.

Scheidegger, A. 1973. On the prediction of the reach and velocity of catastrophic landslides. Rock Mechanics 5: 231-236

Scott, K.M. & Vallance, J.W. 1993. History of Landslides and Debris Flows at Mount Rainier: Water Fact Sheet. USGS Open-File Report 93-111

Sosio, R., Crosta, G.B., Hungr, O. 2008. Complete dynamic modeling calibration for the Thurwieser rock avalanche (Italian Central Alps). Engineering Geology 100: 11–26

Takahashi, T., Nakagawa, H., Harada, T., and Yamashiki, Y. 1992. Routing debris flows with particle segregation, J. Hydr. Res., 118(11): 1490–1507, 1992

7 SUGGESTED METHODS FOR LANDSLIDE HAZARD ASSESSMENT

The goal of the hazard assessment is to determine both the spatial and temporal occurrence of the landslides in the study area, including their attributes (i.e. size, motion characteristics). The analysis has to take into account all the possible mechanisms, including the reactivation and/or the acceleration of the existing landslides. The main challenge relates to the danger individuation which implies the consideration of the location and geometry of the potential failure, the capability of the unstable mass to travel, and its kinematics. The latter depend not only on the rheology of materials involved and motion mechanism but on the characteristics of the path such as the confinement or presence of obstacles.

Irrespective of the scale of work, hazard assessment should specify a time frame for the occurrence all the potential landslide types and magnitudes at any considered location. However, this is the most difficult part of the assessment, particularly for long runout landslides for which the probability of failure (at the source area) may be significantly different than that of the potentially affected area. Consequently, when calculating hazard at a particular location, it must be taken into account that: (a) different landslide types may occur with different time frames; (b) the target area may be potentially affected by landslides originating from different source areas; (c) the frequency that is observed at any target location or section will change with the distance to the landslide source.

The estimation of the frequency or the annual probability of occurrence of the landslides is therefore a critical component of the hazard assessment and because of this most of the efforts are oriented to the preparation of the magnitude-frequency relations.

7.1 LANDSLIDE FREQUENCY ASSESSMENT

(UPC)

Landslide frequency is a measure of likelihood expressed as the number of occurrences of an event in a given time. As the size (magnitude) of the landslide governs the runout distance, the area covered by the deposit, and the intensity of impact, frequency has to be assessed for each landslide magnitude class. It is well known that small landslides occur more frequently than large landslides.

(IUGS, 1997) suggest that the frequency of landsliding may be expressed in terms of:

- The number of landslides of certain characteristics that may occur in the study area in a given span of time (i.e. per year).
- The probability of a particular slope experiencing landsliding in a given period
- The driving forces exceeding the resistant forces in probability or reliability terms, with a frequency of occurrence being determined by considering the annual probability of the critical pore water pressures (or critical ground peak acceleration) being exceeded in the analysis

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). It may consist of either repetitive occurrence of first-time slope failures, reactivation events of dormant landslides, or acceleration episodes (surges) of active landslides. Rock falls 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 landslide is very appropriate when working with large areas and/or at small scale. Maps prepared at scales smaller than 1:25,000 can hardly 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.

For hazard zoning purposes it must be taken into account that the frequency is a spatially distributed parameter~~.~~ The observed frequency of the landslide events usually decreases with the distance from the landslide source. This is because the distance travelled by each landslide depends on its magnitude and on characteristics of the path such as rugosity, presence of obstacles or deflections in the trajectory (Nicoletti and Sorriso-Valvo, 1991; Corominas, 1996). Large landslides usually travel further away than smaller ones (Figure 7.1).

Two approaches are traditionally followed to assess the probability of occurrence of landslides (Aleotti and Chowdhury, 1999; Picarelli et al. 2005): (a) the analysis of the present conditions and evaluation of the potential for instability of both the slopes and the existing landslides, and (b) the observation of the occurrence of past landslide events, which are considered as repetitive events. The former usually does not take runout into consideration. In this case, the frequency of failure of each slope and propagation are assessed separately and then mathematically combined (Roberds, 2005). Instead, the observation of past events is performed at both at the source and at the arrival sites. In the latter case the frequency of each combination of slope instability and runout is assessed directly as, for instance, the frequency of a rockfall in a roadway based on statistics of past rockfall impacts in asphalt (i.e. Hungr et al. 1999).

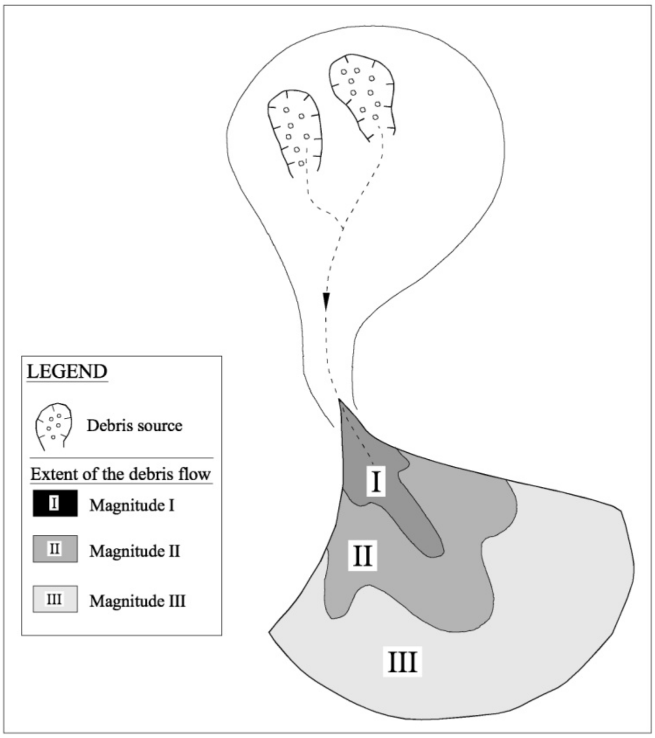

Figure 7.1 Extent of debris flow events with different magnitude M (MI < MII<MIII) and probability of occurrence (PI > PII>PIII). The combination of both parameters will define the levels of hazard in the debris fan and their boundaries (from Corominas and Moya, 2008)

7.1.1 Evaluation of the potential for the future slope failures

Chapter 6 has summarized the available methods (inventory based, knowledge driven, data driven, and physically-based) for landslide susceptibility analysis. Not all the methods described there can be used for a quantitative risk assessment. To this purpose, it is required that the outputs of the susceptibility analysis be expressed in quantitative (probabilistic) terms and could then be integrated in the hazard analysis.

The probability of failure of the slopes may be determined by means of stability analysis and numerical modelling, formal probability and reliability analyses, and event tree methods.

It is important to point out that the outputs of 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.

7.1.1.1 Geomechanical approach

The geomechanical approach considers slope failure as dependent on space, time and stresses within the soil. In this approach, hydrological models are coupled with slope stability models in which, parameters such as the slope angle, the thickness of the soil and soil strength properties have been taken into account. Coupled deterministic models used in regional analysis assume some simplifying hypothesis such as basic failure mechanism or homogeneous mechanical soil and rock properties. Distributed lithology and stratigraphy is usually derived from geological maps and geophysical surveys. When such information is not available, spatial interpolation or kriging techniques must be used to extend local soil properties to the whole area of interest. Examples of the use of stability models may be found in Olivares et al. (2003), Frattini et al (2004) and Savage et al. (2004). They show that it is possible, for instance, to determine the groundwater conditions that lead a given slope to fail for the first time and their probability of occurrence, which is obtained from the annual exceedance probability of the triggering factor. The outputs of the coupled models can be combined with digital topography and implemented on a GIS platform. These models may compute the factor of safety for each cell at any time during a rainstorm (Baum et al. 2005; Godt et al. 2008) and to incorporate the results in maps showing the safety factor values of the slopes. This type of approaches allows the analysis of possible scenarios (rainfall events) with different probability of occurrence. For earthquake triggered landslides, the peak ground acceleration may be determined for different return periods and the stability is calculated with a pseudostatic analysis (Jibson et al. 1998).

Recent developments of coupled deterministic models have incorporated transient vertical groundwater flow (Godt et al. 2008) while soil parameter uncertainty is accounted for by considering the cohesion and the friction angle as random variables within a given distribution (Simoni et al. 2008). However, as these methods compute the factor of safety for each cell, they do not foresee failures of different magnitudes which is fundamental for defining hazard level.

7.1.1.2 Formal probability and reliability analyses

The probability of failure of a slope is assumed as 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, the point estimate methods or Monte Carlo simulations (Wu et al. 1996). These methods take the uncertainty of the input parameters into account. Maps showing the spatially distributed probability of sliding maps have been prepared by combining FOSM equations of slope stability or other distribution functions with digital elevation models (Haneberg, 2004; Wu and Abdel-Latif, 2000). These approaches require a high computational effort to perform the calculations while upscaling to a regional level is made also by using simplified assumptions of the failure mechanisms (i.e. infinite slope) and of the hydrological conditions. These types of approaches usually reflect the uncertainty in the determination of the input parameters necessary to investigate the stability conditions of a slope but not includes the randomness, in time, of the frequency occurrence (Romeo et al. 2006).

7.1.1.3 Event tree methods (logic trees)

The event tree analysis is a graphical representation of all the events that can occur in a system. By using a logic model, it identifies and quantifies the probability of the possible outcomes following an initiating event. As the number of possible outcomes increases, the figure spreads out like the branches of a tree (Wong et al. 1997). 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 the slope failure, is simply the product of the respective branching node probabilities (Lee et al. 2000; Wong 2002). The event tree approach usually requires some expert judgement.

7.1.2 Frequency analysis of past landslide events

Probabilistic models may be developed based upon the observed frequency of past landslide events. This approach is performed in a way similar 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 completely hold for landslides, particularly the independency of the events. However, they may be accepted in a first approach and quite often, this type of analysis will be the only feasible method to estimate the probability of landsliding.

When working at regional level it must be taken into account that different landslide types occur with different temporal patterns. For instance, rockfalls may occur in annual bases in a rock cliff while reactivation of dormant mudslides may take place every tens of years. It is therefore recommended, that the assessment of landslide frequency is performed independently for each landslide mechanism present in the region. 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.

7.1.2.1 Probability analysis based on series of landslide events

The event tree analysis is a graphical representation of all the events that can occur in a system. By using a logic model, it identifies and quantifies the probability of the possible outcomes following an initiating event. As the number of possible outcomes increases, the figure spreads out like the branches of a tree (Wong et al. 1997). 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 the slope failure, is simply the product of the respective branching node probabilities (Lee et al. 2000; Wong 2002). The event tree approach usually requires some expert judgement.

Complete landslide records covering a long time span may be used to perform the probabilistic analyses (Corominas and Moya, 2008). This approach may be used for either the frequency assessment at any give slope or at any terrain unit located away from the landslide source (i.e. debris fan, threatened road etc). Two probability distributions have been used to assess the annual probability of occurrence of landslides: the binomial distribution and the Poisson distribution (Crovelli, 2000).

The binomial distribution can be applied for the cases considering discrete time intervals and only one observation for interval (usually a year), as is typically made 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:

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

Where T is the return period of the event, and λ is the expected frequency for future occurrences. It is also useful to assess the probability of landslide events for different periods of time, particularly the probability of one or more landslides to occur in a given number of years (t), $P(N\geq 1;t)$, which is:

$$P(N\geq 1;t)=1-P_0^t=1-\left(1-\frac{1}{T}\right)^t$$

where P_0 is the probability of no landslide occurring in a given year (= $1-\frac{1}{T}$), and P_0^t is the probability of no landslide occurring during the t years.

The Poisson distribution arises as a limit case of the binomial distribution when the increments of time are very small (tend to be 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:

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

where λ is the expected frequency of future landslide events. On the other hand, the probability of occurrence of one or more landslides in t years is:

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

which strongly depends on magnitude of the landslide events. Consequently, magnitude-frequency (MF) relations should be established in order to carry out the quantitative assessment of the landslide hazard.

7.1.2.2 Correlation with triggers

Definition of landslide triggering rainfall or earthquake thresholds has been a topic of interest for the last decades. Plotting storm intensity versus cumulative rainfall of observed landslide events allows the construction of regional specific curves identifying precipitation intensities which 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 the estimation on how often landslides occur in the study area but not which slopes will fail. In this case, the probability of occurrence of the landslide triggering rainfall allows calculating the relative frequency of landslides (i.e. # 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 (i.e. snow melting) and with landslide triggers occurring at local scale (i.e. river erosion). In this case, the return period obtained of the regional landslide trigger is only a minimum estimate of the landslide frequency.

7.1.3 Data treatment for frequency analysis

The probability analysis of past landslide events requires the availability of as complete as possible landslide records. The most reliable sources are the landslide inventories prepared by the technical units (i.e road maintenance teams). Unfortunately, complete inventories cover a short span of time, typically less than one hundred years (Hungr et al. 1999; Guzzetti et al. 2003) while large slope failures are seldom included. Vertical aerial photographs and, more recently, satellite images are routinely employed for landslide inventories and for mapping new slope failures. Frequency may be then calculated by counting the number of new landslides between photographs. The total is then divided by the time span separating the photo sets. 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.

Too short event sequences may give a misleading impression of the long-term instability of slopes, particularly when thresholds exist as it has been found in many geomorphic processes. It is always advisable to complete the existing records with landslides or their associated features dated with absolute dating techniques (Lang et al. 1999). Table 7.1 lists the activities required to assess the frequency landslides.

Table 7.1 Activities required for assessing the frequency of landslides

Activities	Comments	Scale
Analysis of rainfall including the effects of antecedent rainfall, rainfall intensity and duration on the incidence of individual landslides (the threshold) or large numbers of landslides	Relative frequency (landslides/km^2/yr). Neither the location nor the travel distance is taken into account. Appropriate for areas affected by homogeneous landslide sizes	Regional to local
Interpretation of numbers of landslides from aerial photographs and/or satellite images taken at known time intervals	Landslide frequency is averaged by considering the time span between sets of images.	Regional to local
Prepare incident databases including the volume (size) of the slide materials. Development of M-F relations	Absolute frequencies may be obtained in site specific studies (i.e. debris cone, rock wall). Relative frequencies are often prepared for linear facilities such as roads and railways (#landslides/km/year)	Local to site specific
Reconstruct landslide series using incremental dating techniques (i.e. dendrochronology)	In order to relate past landslide events to their magnitude it is often necessary the combination with other dating techniques and to carry out additional geomorphologic and sedimentologic analyses	Local to site specific
Reconstruct landslide series by dating the occurrence of past (pre-historic) landslide events	This approach is very appropriate for dating the occurrence of large and rare events (which remain in the landscape for a long time) and	Regional to site specific

	thus complete the landslide series	
Relating either stability index or factor of safety to rainfall or earthquake shaking, slope geometry, piezometric levels and geotechnical properties	Probality of failure is associated to the annual exceedance probability of the triggering factor	Regional to site specific

References

Aleotti, P. & Chowdhury, R. 1999. Landslide hazard assessment: summary review and new perspectives. Bull. Eng. Geol. Env., 58: 21-44

Baum, R.; Coe, J.A.; Godt, J.W.; Harp, E.L.; Reid, M.E.; Savage, W.Z.; Schulz, W.H.; Brien, D.L.; Chleborad, A.F.; McKenna, J. P. and Michael, J.A. 2005. Regional Landslide-Hazard Assessment for Seattle, Washington, USA. Landslides, 2: 266-279

Corominas, J. 1996. The angle of reach as a mobility index for small and large landslides. Canadian Geotechnical Journal 33: 260-271

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

Crovelli, R.A., 2000. Probabilistic models for estimation of number and cost of landslides. U.S. Geological Survey Open File Report 00-249, 23 pp.

http://pubs.usgs.gov/of/2000/ofr-00-0249/ProbModels.html

Frattini, P.; Crosta, G.B.; Fusi, N. & Dal Negro, P. 2004. Shallow landslides in pyroclastic soils: a distributted modelling approach for hazard assessment. Engineering Geology, 73: 277-295

Godt, J.W.; Baum, R.L.; Savage, W.Z.; Salciarini, D.; Schulz, W.H. & Harp, E.L. 2008. Transient deterministic shallow landside modelling: Requirements for suscepttibility and hazard assessment in a GIS framework. Engineering Geology, 102: 214-226

Guzzetti, F.; Reichenbach, P; and Wieczorek, G.F. 2003. Rockfall hazard and risk assessment in the Yosemite Valley, California, USA. Natural Hazards and Earth System Sciences, 3: 491-503

Guzzetti, F.; Peruccaci, S.; Rossi, M. And Stark, C. 2007. Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorology and Atmospheric Physics. DOI 10.1007/s00703-007-0262-7

Guzzetti, F.; Peruccaci, S.; Rossi, M. And Stark, C. 2008. The rainfall intensity-duration control of shallow landslides and debris flows: an update. Landslides, 5: 3-17

Haneberg, W.C. 2004. A rational probabilistic method for spatially distributed landslide hazard assessment. Environmental and Engineering Geoscience, X: 27-43

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

Hungr, O.; McDougall, S.; Wise, M. & Cullen, M. 2008. Magnitude-frequency relationships of debris flows and debris avalanches in relation to slope relief. Geomorphology, 96: 355-365

Jibson, R.W., Harp, E. L. and Michael, J.A..(1998). A Method for Producing Digital Probabilistic Seismic Landslide Hazard Maps: An Example from the Los Angeles, California, Area. US Geological Survey Open File Report 98-113

Lang, A.; Moya, J.; Corominas, J.; Schrott, L. & Dikau, R. 1999. Classic and new dating methods for assessing the temporal occurrence of mass movements. Geomorphology, 30 (1-2): 33-52

Lee, E.M.; Brunsden, D. & Sellwood, M. 2000. Quantitative risk assessment of coastal landslide problems, Lyme Regis, UK. In E. Bromhead, N. Dixon & M-L Ibsen (eds). Landslides, in research theory and practice. VIII International Symposium on Landslides. Thomas Telford. Vol. 2: 899-904

Nicoletti, P.G. & Sorriso Valvol, M. 1991.Geomorphic controls of the shape and mobillity of rock avalanches. Geological Society of America Bulletin, 103: 1365-1373

Olivares, L.; Andreozzi, L.; Damiano, E.; Avolio, B. & Picarelli, L. 2003. Hydrologic response of a steep slope in unsaturated piroclastic soils. In L. Picarelli (editor). Proceedings of the International Conference of Fast Slope Movements. Naples. Pitagora Editore. pp. 391-397

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

Reid, L.M. & Page, M.J. 2002. Magnitude and frequency of landsliding in a large New Zealand catchment. Geomorphology, 49: 71-88

Roberds, W. 2005. Estimating temporal and spatial variability and vulnerability. In O. Hungr, R. Fell, R. Couture and E. Eberthardt (editors) Landslide Risk Management. Taylor and Francis, London. pp. 129-157

Romeo , R.; Floris, M. And Veneri, F. 2006. Area-scale landslide hazard and risk assessment. Environmental Geology, 51: 1-13

Savage, W.Z.; Godt, J.W. & Baum, R.L. 2004. Modelling time-dependent areal slope instability. In W. Lacerda, M. Ehrlich, S.A.B. Fountoura & A.S.F. Sayao (editors). Landslide evaluation and stabilization. IX International Symposium on Landslides, Rio de Janeiro. A.A. Balkema. Vol.1: pp. 23-38

Simoni, S.; Zanotti, F.; Bertoldi, G. And Rigon, R. 2008. Modelling the probability of occurrence of shallow landslides and channelized debris flows using GEOtop-FS. Hydrological Processes, 22: 532-545

Wong, H.N.; Ho, K.K.S. and Chan, Y.C. 1997. Assessment of consequence of landslides. In D. Cruden and R. Fell (editors). Landslide risk assessment. A.A. Balkema. Rotterdam. pp. 111-149

Wu, T.H.; Tang, W.H. & Einstein, H.H. (1996). Landsllide hazard and risk assessment. In “Landslides – Investigation and Mitigation”, Trasportation Research Board Special Report No. 247 (A.T. Turner & R.L. Schuster ed.), National Academy Press, Washington DC: 106-118

Wu T.H. and Abdel-Latif, M.A. 2000. Prediction and mapping of landslide hazard. Canadian Geotechnical journal, 37: 781-795

7.2 PREPARING MAGNITUDE-FREQUENCY RELATIONS

(UPC and UNIMIB)

Determining the probability of occurrence of a range of landslide magnitudes is a fundamental step of the quantitative hazard assessment. Areas threatened by landslide events of potential catastrophic consequences might be ranked as a low hazard if their probability of occurrence is very low (Lateltin, 1997). Conversely, frequent landslides of low magnitude may determine that an area could be classified as of moderate or even high hazard.

Nevertheless, without a sound assessment of landslide occurrence probability (expressed in terms of the expected annual frequency of landslide events of 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 (i.e. spatial probability; Brabb, 1988).

When coping with natural hazards (e.g. earthquakes, floods, waves, landslides), the probability of damaging events must be defined with reference to a specific “magnitude”, i.e. to a specific event “size” of potentially occurring events. Magnitude can be portrayed by different descriptors depending on the considered phenomena. For example, earthquake energy release at source is used to describe earthquake magnitude, and water discharge provides a description of the magnitude of a river flood. For landslides, common measures of magnitude include landslide volume or area (when volume cannot be reliably known or estimated).

When dealing with long-runout landslides as rock/debris avalanches, debris flows, and rockfalls, landslide “intensity” (i.e. the geometrical and mechanical severity of the phenomenon) depends on both on its size at source (i.e. “magnitude”, a measure of the unstable mass) and its downslope dynamics (e.g. velocity, kinetic energy, flow depth) and related spatial variability. When dealing to the estimation of the probability of landslide events, landslide “magnitude” is usually considered.

7.2.1 Magnitude-Frequency (M-F) curves

Relationships between the frequency (a proxy of probability) of events falling in different magnitude classes (i.e. magnitude-frequency relationships) have been proposed and used 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:

$$\log N\left(m\right) = a - bM$$

where:

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

Early analyses for landslides (Hovius et al. 1997; and 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:

$$N_E = CA_L^{-\beta}$$

Where:
N_E is the cumulative number of landslide events with magnitude equal or greater than A
A_L is the landslide magnitude (usually expressed as its size: volume or area), and C and β are constants.

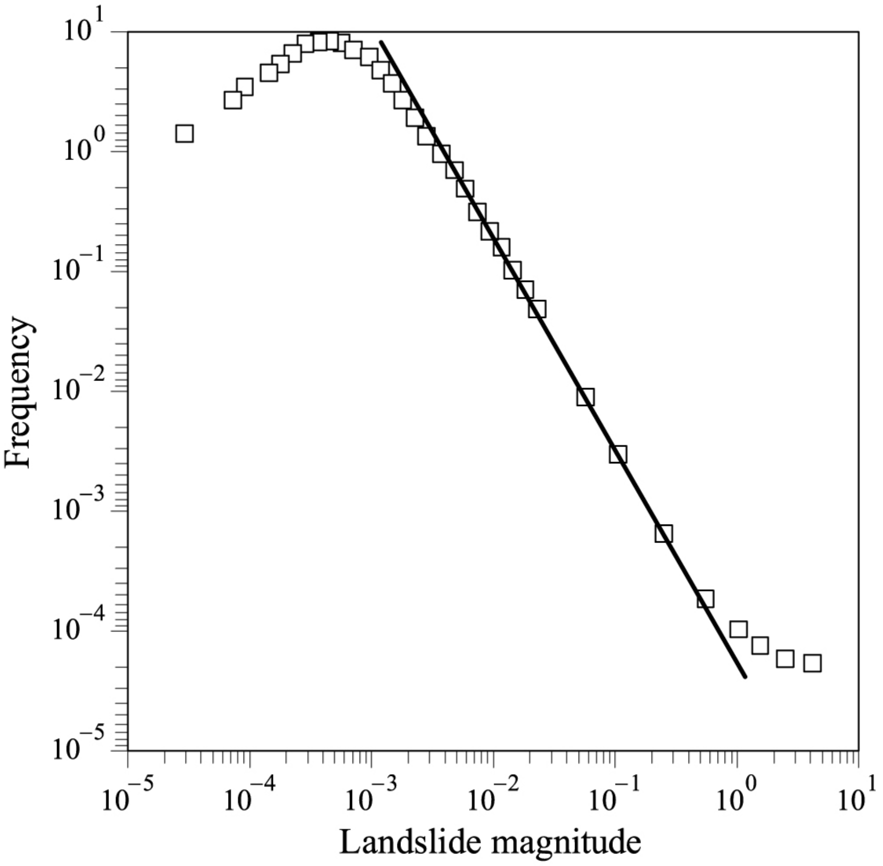

Figure 7.2 plot of the magnitude-frequency relation derived from landslide inventories. Magnitude expresses the landslide size (i.e. Km2). Frequency (here, non-cumulative)expresses, for instance, the number of events per year

The construction and interpretation of frequency-magnitude relations have been discussed by several researchers (i.e. Hungr et al. 1999; Guzzetti el al. 2002; Brardinoni and Church, 2004; Malamud et al. 2004; Van Den Eeckhaut et al. 2007; Guthrie et al. 2008; Brunetti et al. 2009).

The frequency distribution of events in a given magnitude classe is usually well decribed by the power law above a magnitude threshold. Below this threshold, a characteristic “roll-over” effects occurs, resulting in a deviation from the power law and in a unrealistic underestimation of smaller events. The rollover effect is usually not observed in magnitude-frequency curved derived by rockfall inventories, provided that they are statistically complete (Hungr et al., 1999; Malamud et al., 2004). Thus, flattening of rockfall magnitude frequency curves towards small magnitude values should be related to censoring effects (Hungr et al., 1999; Stark and Hovius, 2001).

7.2.2 Preparation 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 can be found in Table 7.2 Table 7.1andTable 7.3. On the other hand, landslide magnitude may be expressed as either in terms of multiple landslide occurrences or by the size of individual landslides.

Large individual landslides may simply require the assessment of frequency of reactivation events as their magnitude is always considered high. Likewise, it may be considered for small size short-runout landslides (Salciarini et al. 2008).

7.2.2.1 Regionally derived M-F relations

Extraordinary storm episodes and large earthquakes may originate multiple occurrences of landslide events (MORLE) at a regional level as defined by Crozier (2005). These processes usually trigger hundreds to tens of thousands of individual landslides in areas extending from some hundreds to tens of thousands of square kilometres.

In regional scale analysis 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). Such a relation has been obtained in some documented cases for storms (Reid and Page, 2003) and earthquakes (Keefer, 2002).

Regionally derived 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 noticing that in the aforementioned regional approaches, landslide runout is not considered in the analyses.

7.2.2.2 Spatial dependence of the M-F relations

Landslide frequency is a spatially distributed parameter (Corominas and Moya, 2008). Frequency-magnitude 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 depend 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 7.2).

7.2.3 Restrictions of M-F relations

The application of M-F curves must be performed with care. Limitations to their validity and practical applicability include statistical reliability and process representativity issues. As to the statistical reliability of M-F curves, it must be kept in mind that historical databases and inventories of landslide events (i.e. the preferred source of M-F information) are rarely available, and site-specific data collection may be unfeasible 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). Undersampling of low-magnitude events may be related to the existence of a detection cutoff threshold (e.g. for rockfalls along roads, very small blocks may not be considered as “landslide events”) or to “systemic censoring” due to factors affecting the physical processes involved in landsliding (e.g. effective countermeasures upslope the area of sampling).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 questions is whether the rate of occurrence of small landslides in a region be can be extrapolated to predict the rate of occurrence of large landslides. 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

Frequency and the return period are valid concepts only for repetitive events like floods and earthquakes. Landslide magnitude-frequency analyses assume the existence of steady conditions for both triggers and slopes. This assumption is, however, arguable because the conditions responsible for a given landslide frequency in the past might no longer exist (Lateltin 1997). In fact, climate and anthropogenic changes are the main uncertainty for extrapolating calculated frequencies to the future. In the Alps, since the Little Ice Age, vanishing permafrost has progressively left uncovered poorly consolidated debris masses on steep slopes. More than 60% of debris flows triggered by the 1987 heavy rains in the Swiss Alps had their origin on slopes of periglacial areas that were still glacier-covered about 150 years ago (Zimmermann and Haeberli, 1992). Continued warming could further enlarge these zones and amplify the activity of periglacial debris flows in the next decades or centuries.

M-F relations may be also affected the stationarity. Two very close consecutive rainfall events may not be able to de-stabilize the same slopes due to the lack of available movable material (colluvium, till) on the slopes. A major storm triggering multiple landsides, may have swept down the surficial formation on the slopes. Refilling of the slope hollows or the weathering of clayey formations may take long time and subsequent storm of similar or even higher intensity, may produce much less number of failures because the slopes have been emptied. The constraint to debris-flow activity, due to the availability of susceptible material was suggested in some European mountain ranges (Innes, 1985; Van Steijn et al. 1988) and in the Canadian Rockies (Cruden and Hu, 1993).

Table 7.2 Activities required for preparing regionally derived magnitude-frequency relations for landslides

	Methodology –data source	Reference
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. 1998; 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 7.3 Activities required for preparing spatially-dependant 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; 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 amd Friele, 2010; Stoffel et al. 2010; Corominas and Moya, 2010
	Landslide series completed by dating landslide deposits and field work.	VanDine 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

References

Agliardi, F., Crosta, G.B., Zanchi, A., Ravazzi, C. 2009a . Onset and timing of deep-seated gravitational slope deformations in the eastern Alps, Italy. Geomorphology 103: 113–129

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

Brardinoni, F., Church,M., 2004.Representing the landslidemagnitude–frequency relation, Capilano River Basin, British Columbia. Earth Surface Processes and Landforms, 29: 115–124

Brunetti, M.T., Guzzetti, F., Rossi, M. 2009. Probability distributions of landslide volumes. Nonlin. Processes Geophys., 16:

179–188

Bull, W.B., King, J., Kong, F., Moutoux, T., Philips, W.M., 1994. Lichen dating of coseismic landslide hazards in alpine mountains. Geomorphology, 10: 253-264

Bull, W.B., Brandon, M.T. 1998. Lichen dating of earthquake-generated regional rockfall events, Southern Alps, New Zealand. GSA Bulletin, 110. 60-84

Bunce, C.M., Cruden, D.M., Morgenstern, N.R., 1997. Assessment of the hazard from rockfall on a highway. Canadian Geotechnical Journal, 34: 344-356

Cardinalli, M.; Reichenbach, P.; Guzzetti, F.; Ardizzone, F.; Antonini, G.; Galli, M.; Cacciano, M.; Castellani, M. & Salvati, P. 2002. A geomorphological approach to the estimation of landslide hazards and risk in Umbria, Central Italy. Natural Hazards and Earth Systems Sciences, 2: 57-72

Chau, K.T., Wong, R.H.C., Liu, J., Lee, C.F., 2003. Rockfall hazard analysis for Hong Kong based on rockfall inventory. Rock Mechanics and Rock Engineering, 36: 383-408

Copons R, Vilaplana JM, Altimir J, Amigó J. 2000. Estimación de la eficacia de las protecciones contra la caída de bloques. Revista de Obras Públicas 3394:37–48

Corominas, J., Copons, R., Moya, J., Vilaplana, J. M., Altimir, J., and Amigó, J.: 2005. Quantitative assessment of the residual risk in a rock fall protected area, Landslides, 2, 343–357, 2005

Corominas, J. Moya, J. 2010. Contribution of dendrochronology to the determination of magnitude–frequency relationships for landslides. Geomorphology (in press). doi:10.1016/j.geomorph.2010.09.001

Crozier, M.J., 2005. Multiple occurrence regional landslide events in New Zealand: hazard management issues. Landslides,2: 247-256

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

Guthrie, R.H., Evans, S. G., 2004. Analysis of landslide frequencies and characteristics in a natural system, Coastal British Columbia. Earth Surface Processes and Landforms, 29: 1321-1339

Guthrie . R.H., Deadman , P.J., Raymond Cabrera, A, Evans, S. G. 2008. Exploring the magnitude–frequency distribution: a cellular automata model for landslides. Landslides 5: 151–159

Guzzetti, F., Malamud, B.D., Turcotte, D.L., Reichenbach, P., 2002. Power-law correlations of landslide areas in central Italy. Earth and Planetary Science Letters 195: 169-183

Guzzetti,F., Galli, M., Reichenbach, P., Ardizzone, F., Cardinali, M. 2005. Landslide hazard assessment in the Collazzone area, Umbria, Central Italy. Natural Hazards and Earth System Sciences, 6: 115–131

Hovius, N., Stark, C.P., Allen, P.A., 1997. Sediment flux from a mountain belt derived by landslide mapping. Geology, 25: 231-234

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

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

Innes, J.L., 1985. Magnitude-frequency relations of debris flows in northwest Europe. Geografiska Annaler, 67 A: 23-32

Jakob, M., Friele, P. 2010. Frequency and magnitude of debris flows on Cheekye River. British Columbia. Geomorphology, 114: 382-395

Jaiswal P., van Westen C.J., 2009. Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds. Geomorphology 112, 96-105.

Keefer, D.K. 2002. Investigating landslides caused by earthquakes – a historical review. Surveys in Geophysics 23: 473–510

Lateltin, O., 1997. Recommandations: prise en compte des dangers dus aux mouvements de terrain dans le cadres des activités de l'aménagement du territoire. OFAT, OFEE and OFEFP. Switzerland. 42 pp

Lee, E.M., Meadowcroft, I.C., Hall, J.W., Walkden, M. 2002. Coastal landslide activity: a probabilistic simulation model. Bull Eng Geol Env. 61:347–355

Malamud, B.D., Turcotte, D.L., Guzzetti, F., Reichenbach, P., 2004. Landslide inventories and their statistical properties. Earth Surface Processes and Landforms, 29: 687-711

Pelletier, J.D., Malamud, BD., Blodgett, T.,Turcotte, D.L., 1997. Scale-invariance of soil moisture variability and its implications for the frequency-size distribution of landslides. Engineering Geology, 48: 255-268

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

Salciarini, D., Godt, J.W., Savage, W.Z, Baum, R.L., Conversini, P. 2008. Modeling landslide recurrence in Seattle, Washington, USA. Engineering Geology, 102 (3-4): 227-237

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

Stoffel, M. 2010. Magnitude-frequency relationships of debris-flows – a case study based on field surveys and tree-ring records. Geomorphology, 116: 67-76

Van Den Eeckhaut, M., Poesen, J., Govers, G., Verstraeten, G., Demoulin, A. 2007. Characteristics of the size distribution of recent and historical landslides in a populated hilly region. Earth and Planetary Science Letters 256: 588-603

VanDine, D. F., Rodman, R. F., Jordan, P., Dupas, J. 2005. Kuskonook Creek, an example of a debris flow analysis. Landslides, 2 (4): 257-265, DOI: 10.1007/s10346-005-0017-

Van Steijn, H., De Riug, J., Hoozemans, F., 1988. Morphological and mechanical aspects of debris flows in parts of the French Alps. Zeits. Geomorphologie N.F. Suppl. Bd. 32/2: 143-161

Van Steijn, H., 1996. Debris-flow magnitude frequency relationships for mountainous regions of Central and Northern Europe. Geomorphology, 15: 259-273

Zimmermann, M., Haeberli, W., 1992. Climatic change and debris flow activity in high mountain areas-A case study in the Swiss Alps. Catena. Supplement Band, 22

7.3 LANDSLIDE HAZARD ASSESSMENT

(UPC with contributions from ITC and UNIMIB)

A fully quantitative assessment of landslide hazard should be made in terms of distributed probability of landslide events with a given magnitude. In practice, hazard assessment for landslide zoning purposes is graphically expressed in the form of discrete classes derived by heuristic (i.e. matrix) approaches. Different matrixes can be used for different types of landslides and depending on the adopted frequency and intensity descriptors. order to set up the Swiss Guidelines for hazard assessment, Raetzo et al. (2002) proposed a matrix which axes are landslide intensity (or magnitude) and frequency (Figure 7.3).

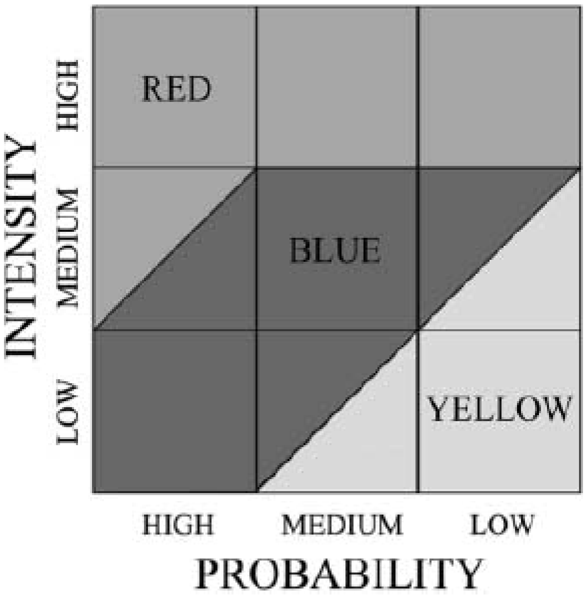

Figure 7.3 Chart of the degrees of danger for fall and earth flow processes (Raetzo et al. 2002)

Early landslide hazard matrices used landslide magnitude instead of intensity. As explained in the previous section, magnitude is a measure of the landslide size and it is usually expressed as either the area or volume. Even though it may be expected that the larger the landslide magnitude the higher the damaging potential is, this cannot be held in all the cases. For instance, a large creeping landslide mobilizing hundreds of millions of cubic metres with rate of displacements of few mm/yr, would cause only slight damages to buildings, infrastructures, and negligible thread to persons. Instead, a rockfall of few hundreds of cubic metres travelling at tens of m/s, it has the capability cause significant damage to structures and loss of lives. This is a major difference between either slow or short-runout landslides, and fast-moving, long-runout landslides, for which a significant component of the damaging potential derives from the propagation phase of landslide occurrence.

In this case, the parameter representing the potential damaging capability of a landslide is the landslide intensity. This may be expressed as (Hungr, 1997; AGS, 2007; Fell et al. 2008): velocity of the event coupled with its volume, kinetic energy, differential displacement, total displacement, peak discharge per unit of width, or impact pressure.

Assessment of the landslide intensity is not straightforward. The reason is that the intensity requires being either measured or computed. Unfortunately, even for the most well documented landslide inventories and data bases, the energy or velocity of the landslide event is seldom recorded. Monitoring systems implemented in a few selected creeping slopes and slow moving landslides, provide data on displacement and velocity on a regular basis. For regional analyses, these parameters are difficult to measure systematically, making the approach impracticable. Instead, magnitude-frequency relationships are more and more available. In practice, as it will be shown below when describing specific landslide types, the intensity is usually obtained by monitoring rate of displacement or calculated through runout models which take the landslide volume as input parameter (Jaboyedoff et al. 2005; Corominas et al. 2005).

Criteria for defining the intensity rating vary from one country to other, and even within the same country. The intensity parameter may be ranked based either on the potential damage or on the capability of both stabilization and protection systems to stop the movement. Example of ranking based on the potential damage is given in the Swiss Guidelines (Raetzo et al. 2002) in which intensity levels are defined based on the capability of the landslide to produce damage to buildings and infrastructures and loss of lives. Example based on the capability of the stabilization and protection systems is given in the Andorran experience (Corominas et al. 2003) in which intensity levels are defined based on the feasibility of landslide stabilization or implementing protection measures.

Even though magnitude is not the most appropriate parameter expressing the damaging capability of the landslide event, in the most simplified approaches it might be sometimes accepted as a proxy of the landslide intensity. There is a general consensus that large fast moving landslide phenomena generate always a high intensity level. The area potentially affected by the arrival of rock avalanche debris, large rockfalls, debris flow, or flow-slide events is consequently ranked as of high intensity irrespective of its velocity. Small slides instead will usually be associated to low levels of kinetic energy, velocity or impact pressure except for rockfalls and debris flows. On the other hand, landslide intensity may not be always essential for taking hazard management decisions, particularly in absence of exposed elements. Land-use planning options may be simply based on the analysis of the areal extent of small and large landslides irrespective of their size. This is particularly relevant in landslide hazard zoning at regional and national scales. At these scales of work, runout analysis cannot be performed while maps do not have enough resolution for plotting the spatial distribution of the intensity.

7.3.1 Objectives of the landslide hazard assessment and zoning. Where is hazard determined?

The purpose of the landslide hazard assessment determines the scale, the methodology and its results. The hazard assessment may have different objectives and spatial arrangement (Corominas and Moya, 2008):

- Areal analysis (Figure 7.4b). This type of analysis is usually performed in either regional or local planning zoning. The potential for slope failure must be evaluated at every single terrain unit. The landslide hazard is assessed at each land unit (pixel, cell, polygon, basin) and frequency may be expressed in relative terms as the number of landslides (of a given magnitude) per unit area (km^2, pixel, etc) per year.
- Linear analysis. (Figure 7.4c). Many infrastructures and facilities (motorways, railways, pipelines, etc.) have a linear layout. Hazard studies usually focus on the landslides (potentially) affecting the infrastructure. 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 (i.e. Jaiswal and Van westen, 2009; Jaiwal et al. 2010).
- Singular location analysis. Figure 7.4d). Detailed hazard analyses may be performed at specific sites such as debris fans, talus slopes, or for a specific element or set of exposed

elements. In these cases the 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. It may be a particular location, or of a specific element or set of exposed elements.

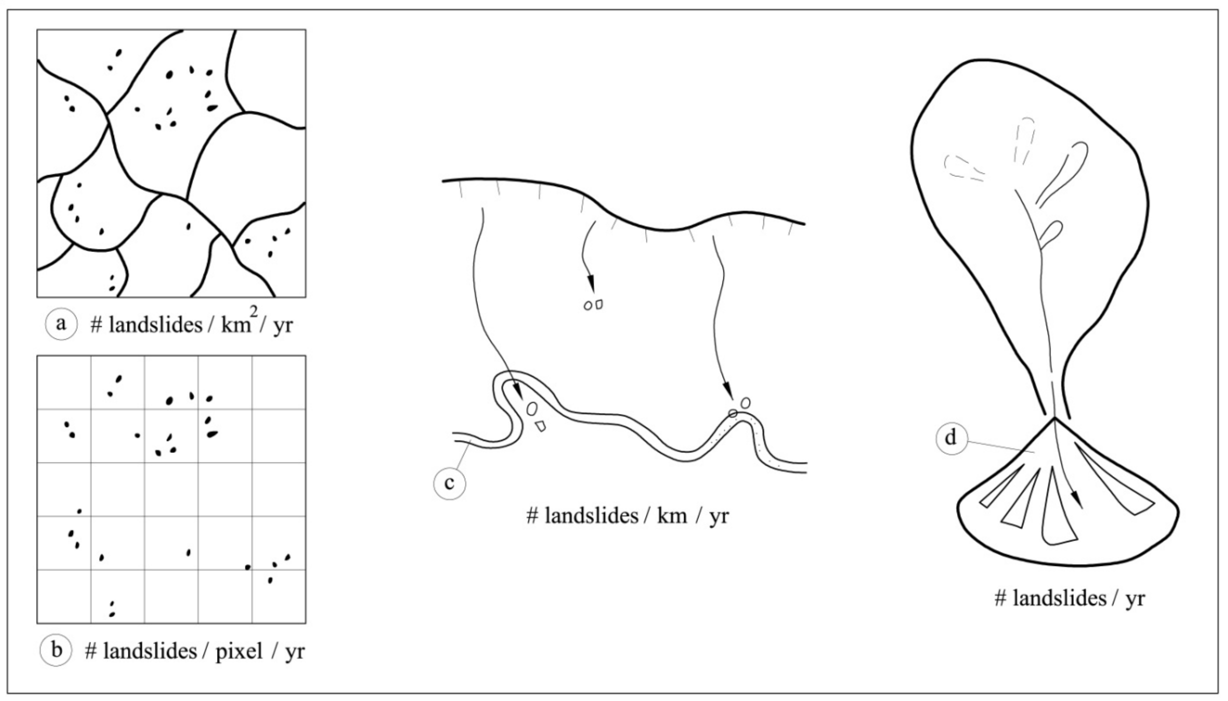

Figure 7.4 Examples of types of landslide hazard analyses: (a) and (b) areal; (c) linear; (d) singular location (based on Corominas and Moya, 2008)

7.3.2 Consideration of landslide runout

Landslide hazard zoning (areal analysis) is often performed for land-use planning. Two different situations may be considered depending on whether or not to the mobility of the landslides is included in the analysis. Short displacement landslides are well contained geographically and remain at or very close to the initiation zone. In this case, hazard assessment and zoning evaluates the potential for slope failure or landslide reactivation at each terrain unit. Long runout landslides can travel considerable distances from the source area. In this case, besides the potential for slope failure, landslide frequency (and consequent hazard level) must be calculated along the path (runout zone). 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. In this case, a magnitude-frequency relation is required at each slope or land unit and, afterwards, the estimation of the runout distance for each landslide magnitude

Hazard is directly calculated for each combination of slope instability mode and runout as, for instance, the magnitude-frequency of a rockfall in a roadway 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). This type of assessment may be also performed when working with land units that contain both landslide source and deposition area (Cardinalli et al. 2002). Landslide hazard assessment at the potentially affected area often based on the frequency-magnitude analysis of the events reaching the target location.

7.3.3 Restrictions associated to the scale of analysis

The scale of work, particularly for zoning purposes, conditions the type of approach to be followed. The largest restriction is however the availability of a landslide inventory of sufficient long time, containing landslides caused by different triggering events with different return periods. Funding available may also be a constraint and this may force the use of smaller scale zoning of the landslide hazard.

Resolution of small scale maps (regional or national scales) does not allow mapping individual small slope failures (up to few several thousands of cubic meters). These landslides have to be treated collectively. Because of this, neither runout nor intensity (magnitude)-frequency analyses can be performed at national or regional scales (small scale maps). Frequency (probability of occurrence) of landslides, for hazard zoning at small scale, is usually calculated in an integrated way. Two approaches may be followed to calculate frequency: (1) counting the number of new landslides on sequential aerial photographs and the total is divided by the number of years separating the photographs; (2) estimating the probability of occurrence from critical landslide trigger thresholds. Frequency absolute (the number of landslides per year) or relative figures (number of landslides per unit area and year).

Both approaches 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) in not required
- All landslides have similar size
- Runout distance is not calculated and neither the spatial distribution of the intensity

Medium scale maps have enough resolution to perform stability analyses or assessment of the probability of the slope failure and combine the outputs with runout or trajectographic analyses. The main restriction is that neither stability analyses nor the susceptibility assessment of the slopes are capable to develop magnitude-frequency relations. 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 the rugosity of the path or the material properties. One of the most important problems in runout modeling is the uncertainty of landslide volumes, which should result from prior susceptibility assessment, the uncertainty of rheological behaviour and associated parameters such as entrainment of materials.

Hazard assessment and zoning at large scale requires on one hand, high resolution DEM and on the other hand, high-quality input data. This scale allows the hazard analysis at cadastral level and the precise location of the exposed elements. Inaccuracies in either runout computation or spatial distribution of the landslide intensity may have important consequences on the landslide risk management decisions. A map showing the distribution of hazard intensity and the associated impact probability is the final product of a hazard assessment. Vulnerability of various elements at risk can be determined only once they are situated on this map (Hungr, 1997).

Table 7.4 Scale of work

Scale of work	Indicative range of scales	Runout	I(M)/F	Quantitative Hazard descriptor
National	< 1:100,000	Not included	Not considered	#landslides/administrative unit
Regional	1:100,000 to 1:25,000	Usually not included	Often fixed (constant) magnitude value	#events/km^2/yr #landslide/km^2/triggering event
Local	1:25,000 to 1:5,000	included	Spatially distributed magnitude (intensity)	Annual probability of occurrence of a given magnitude
Site specific	> 1:5,000	included	Spatially distributed intensity	Annual probability of a given intensity

7.3.4 Regional scale hazard analyses

Shallow landslides (i.e. slides, debris slides and debris flows) are often not recurrent at a given site. They are recurrent within a region and frequency analysis may be then conducted on a regional basis, its results being extrapolated to specific locations on the landslide density map (Hungr, 2006). Shallow landslides in a region may occur either as (1) scattered failures occurring throughout the study area over time or (2) multiple slope failures generated by particular landslide-triggering events (i.e. rain storm or earthquake) acting over a large area. Crozier (2005) defined the latter as multiple-occurrence of regional landslide events (MORLE). One single MORLE may usually involve hundreds to tens of thousands of individual landslides in areas extending from some hundreds to tens of thousands of square kilometres

Hazard assessment of failure occurring over defined time intervals can be performed based on landslide inventories prepared from successive aerial photographs or images. Sequential aerial photographs bracket the age of landslides. Frequency of the landslides may be calculated by counting the number of new landslides between photographs. The total is then divided by the time span separating the photo sets. Landslide hazard is performed on a regional basis and expressed by the number of landslides per unit area. 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). Magnitude-frequency (M/f) relations may be established, if resolution of the images is high enough to allow splitting the landslide inventory in several magnitude (area or volume) classes (Malamud et al. 2004). However, the spatial distribution of different magnitude classes is not presented in this type of approach, thus having little practical applicability in hazard management.

Hazard assessment of MORLE is performed by first establishing a relationship between occurrence of landslide events and the trigger. Many researchers have analyzed the relationship between the occurrence of MORLE and storm precipitation (i.e. Canon & Ellen, 1988; Schuster & Wieczorek, 2002; Guzzetti et al. 2008) or magnitude of seismic events (i.e. Keefer, 1984; Jibson et al. 1998). Given sufficient spatial resolution of storm rainfall records or of the earthquake magnitude, the spatial landslide occurrence (distribution) in these events should make it possible to identify the values of the triggers that produce the general instability of slopes and establish 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 (i.e. number of landslides/km^2) (Reid and Page, 2003; Keefer, 2002). However, in other study areas it has been found that the landslide density changes non-linearly with rainfall and that a reliable relationship can be hardly established (Govi & Sorzana, 1980). These type of relationships give an estimation on how often landslides may occur in the study area but not where the slopes will fail.

Hazard calculated from frequency of landslide triggers, does not require having a complete record of past landslides but it is necessary to dispose 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 (i.e. snow melting) and with local landslide activity (i.e. river erosion). Consequently, return periods obtained from regional landslide trigger is only a minimum estimate of the landslide frequency. The opposite effect may be observed if landslides remove the mantle of susceptible material leaving a much stronger residual surface that may be essentially stable under the prevailing triggering regime, thus producing the exhaustion of susceptible material—a process referred to as event resistance (Crozier and Preston 1999)

Neither the location nor the travel distance is taken into account in the above mentioned methodologies. When the landslides involved have low mobility (i.e. debris, slides, rotational landslides) or the scale of analysis is too small to show the landslide tracks, landslide hazard is quantified without taking into account the runout analysis. These approaches are only appropriate for areas having homogeneous geological and topographical conditions.

Table 7.5 Regional hazard assessment

	Methodology	Magnitude	Frequency	Hazard descriptor	Reference
Areal analysis	Recurrence of landslides is obtained from sets of aerial photographs and/or satellite images taken at known time intervals. Landslide frequency is then obtained	Landslide density Landslide size (area, volume)	Frequency of landslides is averaged by the time span between sets of images.	# landslides/km^2/yr # landslides/pixel/yr 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	Landslide density (i.e. landslides/km^2)	Return periods or the exceedance probability of the trigger magnitude	Probability of having # landslides/km^2 # landslides/pixel total slide area/km^2	Reid and Page (2003)
	Seismic shaking probability for given time intervals combined with probability of landsliding based on Newmark models	Number of landslides (normalized by distance)	Return periods or the exceedance probability of seismic shaking	Probability of landslide occurrence	Del Gaudio et al. (2003)

7.3.5 Local scale hazard assessment

7.3.5.1 Areal analysis

Areal landslide hazard assessment aims at determining the likelihood of landslides occurring on a terrain unit. To this purpose, it requires first of all the assessment of the stability of the slopes and existing landslides. This assessment is usually performed with either slope stability models or slope susceptibility analysis (spatial probability). The latter includes a wide variety of data treatment techniques such as the discriminant analysis, fuzzy logic, logistic regression, neural networks (Aleotti & Chowdhury, 1999) which results are usually presented in the form of landslide susceptibility maps. To perform quantitative hazard assessments, the key issue in this approach is to translate landslide susceptibility values in terms of spatial probability. Hazard may then be calculated as the conditional probability of slope failure once a landslide trigger (i.e. critical rainfall or earthquake) occurs or alternatively, it 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. The landslide recurrence was obtained by dividing the total number of landslide events inventoried in the unit by the time span of the investigated period and also the exceedance probability of having one or more landslides in each mapping unit, for different period.s. Finally, quantitative landslide hazard was estimated for each mapping unit as the joint probability of landslide magnitude (area), of landslide temporal occurrence and of landslide spatial occurrence (Figure 7.5).

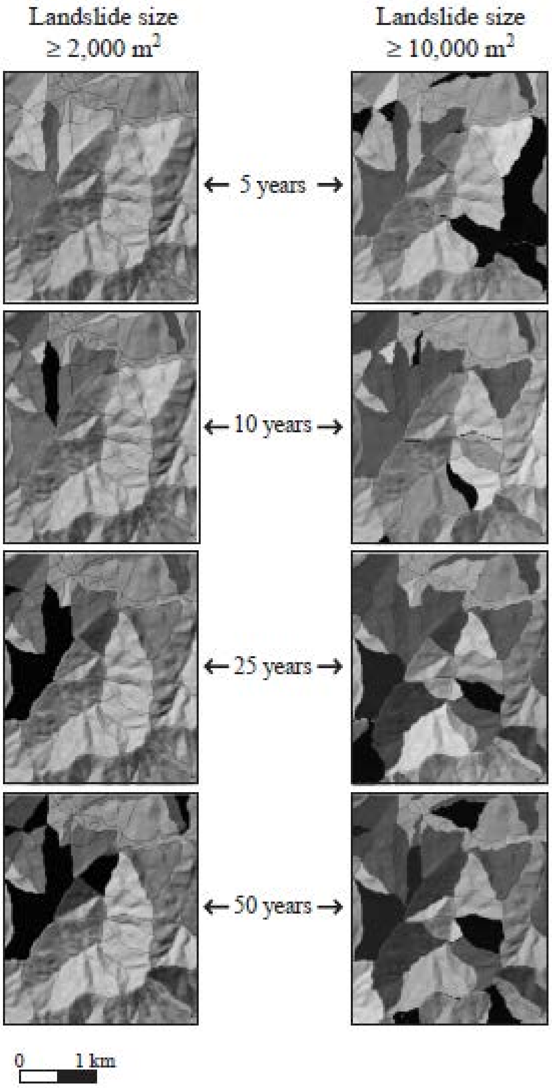

Figure 7.5 Landslide hazard maps for four periods, from 5to 50 years (from top to bottom), and for two landslide sizes (≥2000 m2 and ≥10,000 m2). Shades of gray show different joint probabilities of landslide size, of landslide temporal occurrence, and of landslide spatial occurrence (susceptibility).(Guzzetti et al 2005)

Quantitative hazard may also be performed by using deterministic approaches, which are based on slope stability analyses (Figure 7.6) combining spatially distributed hydrological models with slope stability models (Savage et al., 2004; Baum et al. 2005). The factor of safety of the slope may be computed at each terrain unit using simplifying hypothesis such as infinite slope stability model, while the probability of failure may be obtained from the annual exceedance probability of the critical trigger (groundwater level). 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 an earthquake with various return periods is examined using a pseudostatic analysis (Dai et al. 2002). These types of analyses do not provide the expected size of the mobilised landslide and maps obtained depict the potential for landslide occurrence from hillside source areas, but they do not depict landslide travel paths or areas of landslide deposition. In hazard analyses in which the landslide travel distance is not an issue or in studies performed at either small or medium scales, hazard may be expressed as the annual probability of either failure or reactivation at each terrain unit and zoning for specified hazard levels can prepared. Otherwise, landslide magnitude must first be determined and runout must be calculated for different landslide magnitudes to obtain the appropriate value of the quantitative landslide hazard.

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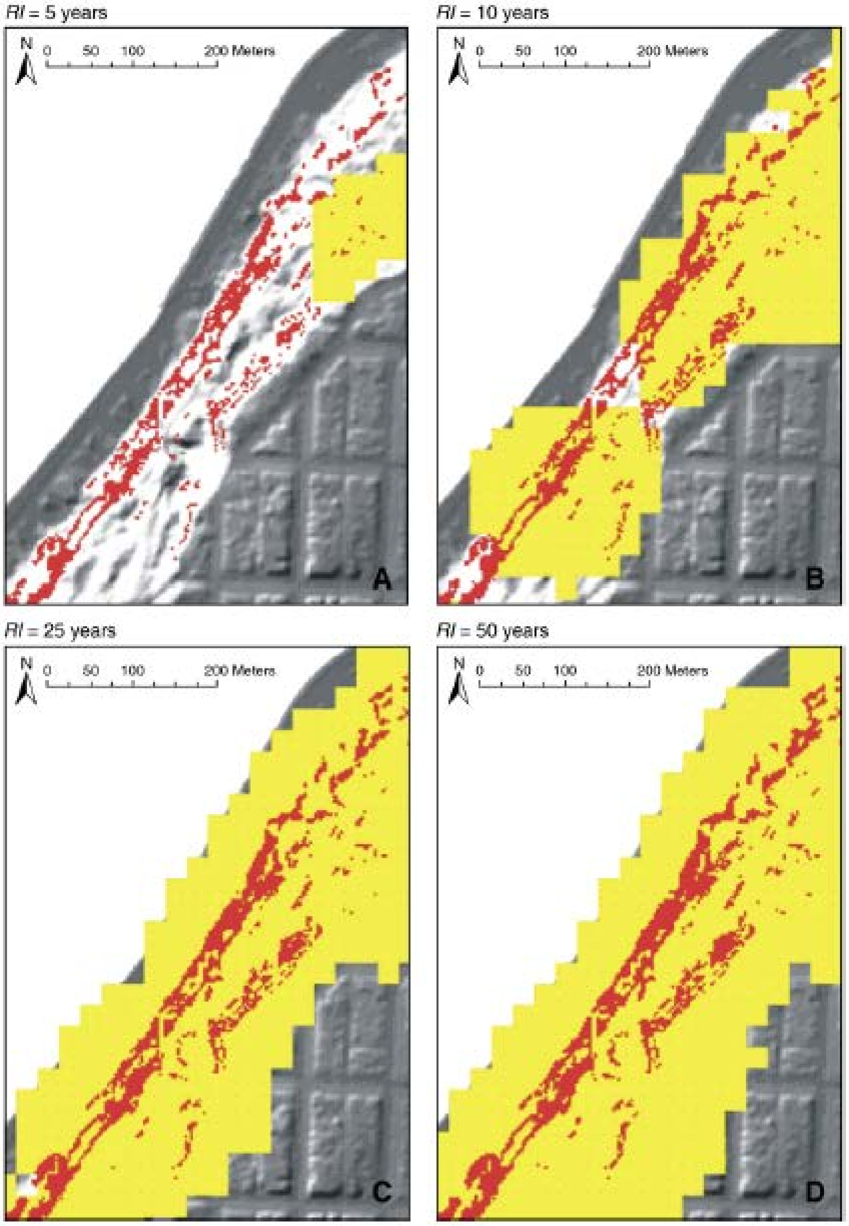


Figure 7.6 Slope stability analysis results with TRIGRS combined with critical rainfall precipitation for different recurrence intervals (Salciarini et al 2008)

Table 7.6 Local scale hazard assessment

		Methodology	Magnitude	Frequency	Hazard descriptor	Reference
Areal analysis	Runout not included	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
	Runout included	Combining probability of occurrence with empirical models (conefall) at identified sources	Block volume/ Kinetic energy	. From historical catalogues (M/f relations)	Kinetic energy limits for different rockfall magnitude and for established periods	Corominas et al. 2003; Jaboyedoff et al. 2005
		Combining probability of occurrence with trajectographic models implemented in a GIS	Block volume/ Kinetic energy	From historical catalogues (M/f relations)	Kinetic energy limits for different rockfall or debris flow magnitude and for established periods	Agliardi et al. 2009
Non-areal analysis	Runout not included	Hazard assessment performed at a reference section or location (i.e where the exposed element is located)	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)	Bunce et al. 1997; Hungr et al. 1999

7.3.5.2 Linear analysis

Linear landslide hazard analysis is typically performed for transportation corridors (Bunce et al. 1997; Hungr et al. 1999; Jaiswal and Van Westen, 2009; Jaiswal et al. 2010) and to singlular locations as well. This is a particular situation in which the exposed elements (cars and persons) are highly vulnerable to the occurrence of the landslide event either by direct impact or by collision against fallen debris. Given that low intensity events may cause significant damage, the hazard analysis is usually undertaken without any calculation of the velocity or kinetic energy. Magnitude of the event is used, for instance, to determine the number of affected lanes and the width of the landslide mass which is considered in the calculation of the encounter probability.
Hazard values may be expressed as either relative (i.e annual probability of occurrence of a given magnitude event per unit length) or absolute (number of events per year) terms.

7.3.6 Site specific hazard assessment

Detailed scale usually concerns areas of several hectares to tens of square kilometres and hazard assessment should allow the calculation of spatial distribution of the landslide intensity and its associated probability of occurrence. This will require high quality of input data and the use of sophisticated procedures (Fell et al. 2008). The results of hazard assessments, regardless of the approach adopted, are very sensitive to changes in the selected variables, such as materials rheology (properties), potential volume, path characteristics and precision of the DEM.
The goal of site specific analysis may be focussed on the analysis of the probability of failure of a slope (or the reactivation of a dormant landslide), the area potentially affected by the landslide path or both (Crosta et al. 2006).

7.3.6.1 First-time slope failures

For site-specific slopes, the probability of failure is usually considered as the probability of a factor of safety lesser than unity. The performance function of slopes, denoted by G(X) where X is the collection of random input parameters, is a function which defines the failure or safety state of a slope. The function is defined in such a way that failure is implied when $G(X) < 0$ and safety by $G(X) > 0$. The boundary defined by $G(X) = 0$ separating the safety and failure domains is called the limit state boundary.
The performance function for a slope is usually taken as (Dai et al. 2002):

$$G(X) = R(X) - S(X)$$

Where:
R(X) is the resistance and S(X) is the action

The performance function of a slope is usually formulated using simplified limit equilibrium methods. Once this function is defined, the probability of failure of a slope can be estimated by: (1) The first-order-second-moment (FOSM) method, that characterizes the frequency distribution of the factor of safety in terms of its mean value and standard deviation; (2) Monte Carlo simulation, that uses a computerized sampling procedure to approximate the probability distribution of the factor of safety by repeating the analysis many times.
Analysis of the reactivation potential individual dormant landslides is typically performed in rotational slides, earthflows and mudslides, with a potential for producing damage to buildings and

infrastructures. Reactivation events in such type of movements often result in small displacements, with associated cracking, bulging, and other deformational features. Lives are rarely threatened.

Displacements are usually too short to perform specific runout analyses. The relation between magnitude (local or global reactivation) and frequency of the events can be used to calculate hazard, although further judgement will be required to translate the landslide magnitude, in terms of damaging capability (intensity) of the landslide reactivation event. Not only the absolute displacements, but differential movements within the landslide mass, should be taken into account to express landslide intensity.

For landslides where piezometric levels are recorded over some time period, the probability of landslide reactivation and the onset of displacements may be calculated by combining hydrological and slope stability models (Cascini, 2008). An example is provided by Ko Ko et al (2003) who first of all, established the relationship between the slope instability and the associated critical piezometric levels. This relation was checked with a monitoring system (inclinometers and piezometres). Secondly, the probability of the piezometric level required for reactivation of the landslide was determined by analyzing its relation to rainfall record for a given period. The landslide triggering critical rainfall magnitude was identified and its probability of occurrence calculated. However, this type of approaches is not yet capable to establish a relationship between rainfall magnitude and intensity (rate of movement, differential displacements) of the landslides.

7.3.6.2 Active Landslides

In active slow moving landslides (creep type movement) it does not make sense to calculate the probability of occurrence as the landslide is already moving. Rates of displacements up to few millimetres per month can be accommodated by structures with minor ongoing repairs. However, active earthflows or the translational type of landslides showing creep movements may experience sudden acceleration (surges) of catastrophic consequences (Bonnard et al. 1995). Therefore, the aim of hazard assessment for active landslides is calculate the probability of keeping the same rate of movement and the potential for either their local or global reactivation.

The rates of movements can be related to a range of piezometric conditions and an estimate of their likelihood of occurrence made as a function of the probability of rainfall events (Baynes, 1997). The hazard analysis should then concentrate on the tendency to continue at the same rate of movement, to accelerate or to decelerate. This tendency can be associated with probabilities (DUTI, 1985; Einstein, 1997).

7.3.6.3 Rockfalls

The intensity of rockfalls depends on both the velocity and the volume of the mass in motion, and is usually described in terms of average or maximum kinetic energy, and sometimes of height of trajectories above local topography. A given rockfall volume will produce a changing velocity profile along its path and kinetic or impact energy will change as well (Crosta and Agliardi, 2003). Rockfall intensity is not biunivocally dependent of rockfall size (magnitude) as similar kinetic energy values may be obtained by different combinations of volumes and velocities. Therefore, rockfall hazard zoning must be performed with the support of trajectographic models that calculate the potential rockfall paths and the location of the stopping blocks, the velocity and kinetic energy of the blocks and the spatial distribution of the kinetic energy.

Two different approaches can be used for rockfall hazard assessment at site specific scale: (1) assess the probability of occurrence at the rockfall source and combine it with physically based (2-D or 3-D) rockfall simulation models. Outputs are usually block velocities, kinetic energies and height of bounces, with the associated exceedance probabilities; (2) assess the probability of occurrence rockfalls of different magnitudes at pre-defined locations (reference sections , roads, built areas etc.) using M/f relations derived from inventories of rockfall events (see section 7.2) (see Figure 7.7).

In the first approach mentioned, a critical issue is the definition of the characteristic rockfall volume that will be used as input parameter in the trajectographic analyses to calculate runout distances and energies for hazard assessment. The larger the initial volume, the longer the trajectory and the higher the kinetic energy along the path will be. It should be noted that in case of fragmental rockfalls, 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.

Fragmental rock fall is the more or less independent movement of individual rocks, as opposed to the sliding or mass flow of coherent or broken rock typical of a rock avalanche. Although there is no well defined volume limit, Evans and Hungr (1993) or Wieczorek at al (1998) have suggested that rock falls of less than 100,000 m^3 be characterized as fragmental rock falls that can be considered to move as single blocks. When compared to massive rockfalls or rock avalanches, movement of individual blocks will reduce significantly the intensity of the event.

The challenge in fragmental rockfalls is how to relate the initial rockfall mass volume at the source to the individual blocks reaching the bottom of the slope. Unfortunately, at present most of available codes do not consider the fragmentation process of rockfall. Using initial rockfall volumes may be excessively pessimistic and unrealistic. In case of small volume fragmented rockfalls it might be justified the use of individual blocks in the trajectograhic analyses. The size of the blocks should be representative of the most likely future rock fall events. It can be determined from the geometrical characteristics (length, spacing) of the main discontinuity sets observed on the rock face, and/or from the size distribution of the fragments on the slope (Corominas et al. 2005; Abruzzese et al. 2009)

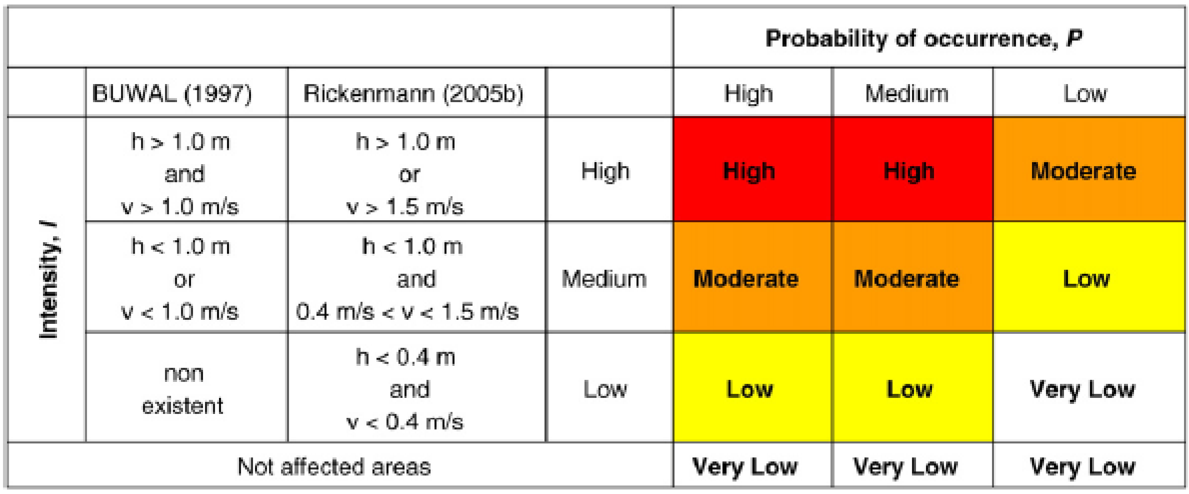
Table 7.7 Site specific rockfall and rock avalanche hazard assessment

	Methodology	Magnitude/Intensity	Frequency	Hazard descriptor	Reference
Runout considered	Combining probability of occurrence with empirical models (reach angle/shadow angle)	Volume	M/f		Copons et al. 2009
	Combining probability of occurrence with empirical models (conefall)	Block volume/ Kinetic energy	.	Spatially distributed kinetic energy for different rockfall magnitudes and for established periods	Jaboyedoff et al. 2005;
	Combining probability of occurrence with runout models	Block volume/ Kinetic energy	From hitorical an reconstructed catalogues (M/f relations	Annual probability of exceeding a kinetic energy for different rockfall magnitudes	Guzzetti et al. 2004; Corominas et al. 2005; Crosta et al. 2006; Agliardi et al. 2009
Runout not included	Landslide incident records (historical catalogues) reaching a reference section or location	Landslide size (volume)	Frequency of landslide magnitude classes is averaged by the recorded time span	Annual probability of occurrence of landslide magnitude classes (it may be normalized by length of the reference section or road)	Bunce et al. 1997; Hungr et al. 1999

7.3.6.4 Debris flows

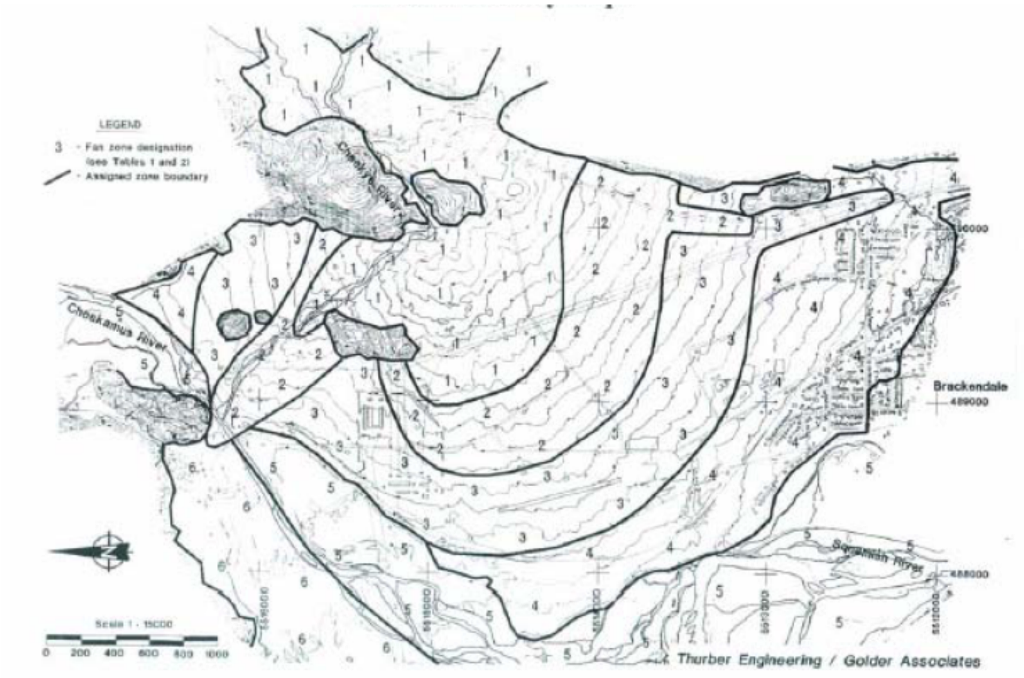
As in rockfalls the intensity of debris flows is not biunivocally dependent on the mobilized debris volume. Descriptors proposed for debris flow intensity include: velocity, flow depth, thickness of debris deposits, and impact pressures (see Table 7.8).

Table 7.8 Debris flow-hazard matrix proposed by different authors (taken from Hürlimann et al. 2008)



				Probability of occurrence, *P*		
	BUWAL (1997)	Rickenmann (2005b)		High	Medium	Low
Intensity, *I*	$h > 1.0$ m and $v > 1.0$ m/s	$h > 1.0$ m or $v > 1.5$ m/s	High	**High**	**High**	**Moderate**
	$h < 1.0$ m or $v < 1.0$ m/s	$h < 1.0$ m and 0.4 m/s $< v < 1.5$ m/s	Medium	**Moderate**	**Moderate**	**Low**
	non existent	$h < 0.4$ m and $v < 0.4$ m/s	Low	**Low**	**Low**	**Very Low**
Not affected areas				**Very Low**	**Very Low**	**Very Low**

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 hazard. An example of a debris flow hazard intensity map is shown in Figure 7.7. In this map, the concentric hazard intensity zones can be impacted by debris flows of three different magnitude classes, each with a different probability of occurrence and different runout characteristics. The intensity is expressed by different values of velocity and flow depth, obtained from a runout analysis. .



Hazard	Large debris flow (3-7 million m3)	Medium debris flow (1-3 million m3)	…
Average Frequency	1:3,200	1:500	…
Hazard Zone 1	V = 7 m/s * H = 5 m W = 1.5km P_i = 0.00031	V = 4 m/s H = 4 m W = 1.0 km P_i = 0.0013	…
Hazard Zone 2	V = 4 m/s H = 3.5 m W = 1.5 km P_i = 0.00019	…	…
…	…	…	…

* V = maximum flow velocity
H = deposit depth
W = width of damage corridor

Figure 7.7 Hazard intensity map of Cheekye Fan, B.C. (from Sobkowicz et al. 1995, in Hungr 1997)

Like in rockfalls, two different approaches can be used for debris flow hazard assessment at 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 (2-D or 3-D) debris-flow simulation models to define the affected area and the intensity parameters (Hürlimann, et al. 2006, 2008); (2) assess the probability of occurrence debris flows of different magnitudes at particular locations below the debris source (reference sections , debris fans etc.) using M/F relations (VanDine et al, 2005).

References

Abbruzzese, J.M., Sauthier, C., and Labiouse, V. 2009. Considerations on Swiss methodologies for rock fall hazard mapping based on trajectory modelling. Nat. Hazards Earth Syst. Sci., 9: 1095–1109

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

Aleotti, P. , Chowdhury, R,. 1999. Landslide hazard assessment: summary review and new perspectives. Bull. Eng. Geol. Env., 58: 21-44

Baum, R., Coe, J.A., Godt, J.W., Harp, E.L., Reid, M.E., Savage, W.Z., Schulz, W.H., Brien, D.L., Chleborad, A.F., McKenna, J. P., and Michael, J.A., 2005. Regional Landslide-Hazard Assessment for Seattle, Washington, USA. Landslides, 2: 266-279

Baynes F. J., 1997, Problems associated with geological characterisation for quantitative landslide risk assessment. In D.M. Cruden & R. Fell (editors). Landslide Risk Assessment. A.A. Balkema, Rotterdam, pp 153 – 164.

Bonnard, Ch., Noverraz, F., Lateltin, O. & Raetzo, H. 1995. Large landslides and possibilities of sudden reactivation. Felsbau, 13 (6): 401-407.

Cannon, S.H., Ellen, S.D., 1988. “Rainfall that resulted in abundant debris-flow activity during the storm”. In S.D. Ellen & G.F. Wieczorek (eds.). Landslides, floods and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay region, California. U.S. Geological Survey Professional Paper, 1434: 27-33

Cardinalli, M.; Reichenbach, P.; Guzzetti, F.; Ardizzone, F.; Antonini, G.; Galli, M.; Cacciano, M.; Castellani, M. & Salvati, P. 2002. A geomorphological approach to the estimation of landslide hazards and risk in Umbria, Central Italy. Natural Hazards and Earth Systems Sciences, 2: 57-72

Cascini, L. 2008. Applicability of landslide susceptibility and hazard zoning at different scales. Engineering Geology 102 (3-4): 164-177

Catani, F., Casagli, N., Ermini, L., Righini, R., Menduni, G. 2005. Landslide hazard and risk mapping at catchment scale in the Arno River basin. Landslides 2: 329–342

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

Corominas, J., Copons, R., Vilaplana, J.M., Altimir, J., Amigó, J. (2003). Integrated landslide susceptibility analysis and hazard assessment in the Principality of Andorra. Natural Hazards, 30, 421-435

Corominas, J., Copons, R., Moya, J., Vilaplana, J. M., Altimir, J., and Amigó, J.: 2005. Quantitative assessment of the residual risk in a rock fall protected area, Landslides, 2, 343–357, 2005

Crosta, G. B. and Agliardi, F. 2003 A methodology for physically-based rockfall hazard assessment, Natural Hazards and Earth System Sciences, 3, 407–422

Crosta a, G.B., Chen, H., Frattini, P. 2006. Forecasting hazard scenarios and implications for the evaluation of countermeasure efficiency for large debris avalanches. Engineering Geology 83: 236– 253

Crozier, M.J., 2005. Multiple occurrence regional landslide events in New Zealand: hazard management issues. Landslides,2: 247-256

Crozier M.J., Preston N.J. (1999) Modelling changes in terrain resistance as a component of landform evolution in unstable hillcountry. In: Hergarten S, Neugebauer HJ (eds) Process Modelling and Landform Evolution, Lecture Notes in Earth Sciences 78, Springer Verlag, pp 267–284

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

Del Gaudio, V., Pierri, P., Wasowski, J. 2003. An Approach to Time-Probabilistic Evaluation of Seismically Induced Landslide Hazard. Bulletin of the Seismological Society of America, 93 (2): 557–569

Evans, S.G., and Hungr, O., 1993, The assessment of rockfall hazard at the base of talus slopes, Canadian Geotechnical Journal, v. 30, pp. 620-636.

Govi, M., Sorzana, P.F., 1980. Landslide susceptibility as function of critical rainfall amount in Piedmont basins (North-Western Italy). Studia Geomorphologica Carpatho-Balcanica 14: 43-61

Guzzetti, F., Reichenbach, P., Ghigi, S. 2004. Rockfall Hazard and Risk Assessment Along a

Transportation Corridor in the Nera Valley, Central Italy. Environmental Management, 34 (2): 191–208

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P. 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides, 5: 3-17

Hungr. O. 1997. Some methods of landslide hazard intensity mapping. In D. Cruden & R. Fell (editors). Landslide risk assessment. A.A. Balkema, Rotterdam. pp. 215-226

Hungr, O. 2006 (personal comm.). Terminology of hazard and risk suggested definitions. International Workshop on Landslide Susceptbility, Hazard and Risk Zoning for Land Use Planning. Barcelona. Unpublished.

Hungr, O. and Evans, S. G. 1988. Engineering evaluation of fragmental rockfall hazards, in: Landslides, Proceedings of the 5th International Symposium on Landslides, Vol. 1., edited by: Balkema, Rotterdam, 685–690, 1988

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

Hürlimann, M., Copons, R., Altimir, J. 2006. Detailed debris flow hazard assessment in Andorra: A multidisciplinary approach. Geomorphology, 78 (3-4): 359-372

Hürlimann, M., Rickenmann, D., Medina, V., Bateman, A. 2008. Evaluation of approaches to calculate debris-flow parameters for hazard assessment. Engineering Geology, 102: 152-163

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

Jaiswal P., van Westen C.J., 2009. Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds. Geomorphology 112, 96-105.

Jaiswal P., van Westen C.J., Jetten V., 2010. Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India. Nat. Hazards Earth Syst. Sci. 10 (6), 1253-1267.

Jibson, R.W., Harp, E. L., Michael, J.A., 1998. A Method for Producing Digital Probabilistic Seismic Landslide Hazard Maps: An Example from the Los Angeles, California, Area. US Geological Survey Open File Report 98-113

Keefer, D.K., 1984. Landslides caused by earthquakes. Geological Society of America Bulletin, 95 (4): 406-421

Keefer, D.K. 2002. Investigating landslides caused by earthquakes – a historical review. Surveys in Geophysics 23: 473–510

Ko Ko, Ch., Flentje, P. Chowdhury, R. 2003. Quantitative Landslide Hazard and Risk Assessment: a case study. Quarterly Journal of Engineering Geology and Hydrogeology, 36, 261–272

Malamud, B.D., Turcotte, D.L., Guzzetti, F., Reichenbach, P., 2004. Landslide inventories and their statistical properties. Earth Surface Processes and Landforms 29, 687-711.Raetzo, H., Lateltin O., Bollinger D., Tripet, J.P. 2002. Hazard assessment in Switzerland –Codes of Practice for mass Movements. Bull Eng Geol Env. 61:263–268

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

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

Roberds, W. 2005. Estimating temporal and spatial variability and vulnerability. In Landslide Risk Management, Editors O Hungr, R Fell, R Couture and E Eberhardt, Taylor and Francis, London, pp. 129-158

Salciarini, D., Godt, J.W., Savage, W.Z, Baum, R.L., Conversini, P. 2008. Modeling landslide recurrence in Seattle, Washington, USA. Engineering Geology, 102 (3-4): 227-237

Savage, W.Z., Godt, J.W., Baum, R.L., 2004. Modelling time-dependent areal slope instability. In W. Lacerda, M. Ehrlich, S.A.B. Fountoura & A.S.F. Sayao (editors). Landslide evaluation and stabilization. IX International Symposium on Landslides, Rio de Janeiro. A.A. Balkema. Vol.1: pp. 23-38

Schuster, R.L., Wieczorek, G. F., 2002. Landslide triggers and types. In: J. Rybar, J. Stemberk & P. Wagner. Proceedings 1st European Symposium on Landslides, Prague. pp. 59-78

VanDine, D. F., Rodman, R. F., Jordan, P., Dupas, J. 2005. Kuskonook Creek, an example of a debris flow analysis. Landslides, 2 (4): 257-265, DOI: 10.1007/s10346-005-0017-

Wieczorek G.F., Morrissey, M.M., Iovine, Godt, J. 1998. Rock-fall Hazards in the Yosemite Valley. USGS. Open-File Report 98-467)

7.4 LANDSLIDE MULTI-HAZARD ASSESSMENT

(UNIFI and UNIMIB)

7.4.1 The concept and practice of multi-hazard

The assessment of multi-hazard, *strictu sensu*, 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, being the vulnerability dependent on landslide typology and intensity, to combine occurrence probabilities at the hazard stage into a single hazard value mùight hinder the correct determination of risk in the following stages.

In such cases, the usual procedure starts with the independent definition of the probabilities of occurrence (hazard) and, henceforth, the combination of effects is only performed at the final stage, with the overlay of expected losses in one or several quantitative risk scenarios.

We will therefore try to summarize the main aspects related to multi-hazard analysis in the context of a more general system in which every cause-effect couple depends on the whole set of risk parameters.

In the literature, whilst the specific case of multi-hazard assessment for the joint occurrence of different types of landslides is poorly documented, 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.

Some of these cases report actual applications in county to region level risk management planning and offer early examples of multi-hazard approach within natural risk assessment. The municipality of Cairns, Australia, leaded the AGSO Cities Project in the late ‘90s with a study encompassing a range of geohazards posing risks to urban communities (Granger et al., 1999). The hazards considered were earthquakes, landslides, floods and cyclones. Even though the approach was quite complete from the point of view of the number of geo-processes taken into account, the study did not attempt to understand the possible interconnections or cause-effect relationship among them. The same approach, in which several geohazards are accounted for one by one, is used by the FEMA in the United States. With the aid of the modelling software Hazus (http://www.fema.gov/plan/prevent/hazus/), the FEMA supports the development of states’ and local communities’ multi-hazard and multi-risk mitigation plans as a requirement for Federal funding after natural disasters (FEMA, 2006; McCarthy and Keegan, 2009).

Practical examples of multi-hazard approach methods are also offered by van Westen et al. (2002) which studied the case of the city of Turrialba (Costa Rica), as subjected to landslide, earthquake and flood risk. The authors propose three different schemes to assess hazard and vulnerability and integrate this knowledge into an overall figure only at the risk stage, given the very diverse nature of the natural disasters taken into account.

An interesting example of quantitative probabilistic assessment is proposed by Gerbaudo and Saffar (2007) concerning the multi-hazard estimation of expected losses in the city of Mayaguez (Puerto Rico) as a consequence of earthquakes and hurricanes. The novelty of the approach stands on the fact that specific recurrence time probability curves are prepared for each hazard type so that the subsequent stages of losses assessment are based on a common ground using comparable units. They also use deterministic hazard computation for specific scenarios in which it is possible to reach a better understanding of the expected outcomes of every different event.

Windstorms, flooding and earthquakes are instead the dangers that are included in a multi-hazard analysis for the city of Cologne (Germany) in a study similar to the previous one in which, again, the overall result is given only at the risk stage, after every single issue has been dealt with using specific one-hazard assessment methods (Grunthal et al., 2006). Here, the authors show another probabilistic approach to the computation of hazard in different cases and then combine the different outputs in a general risk map using expected losses (Figure 7.8).

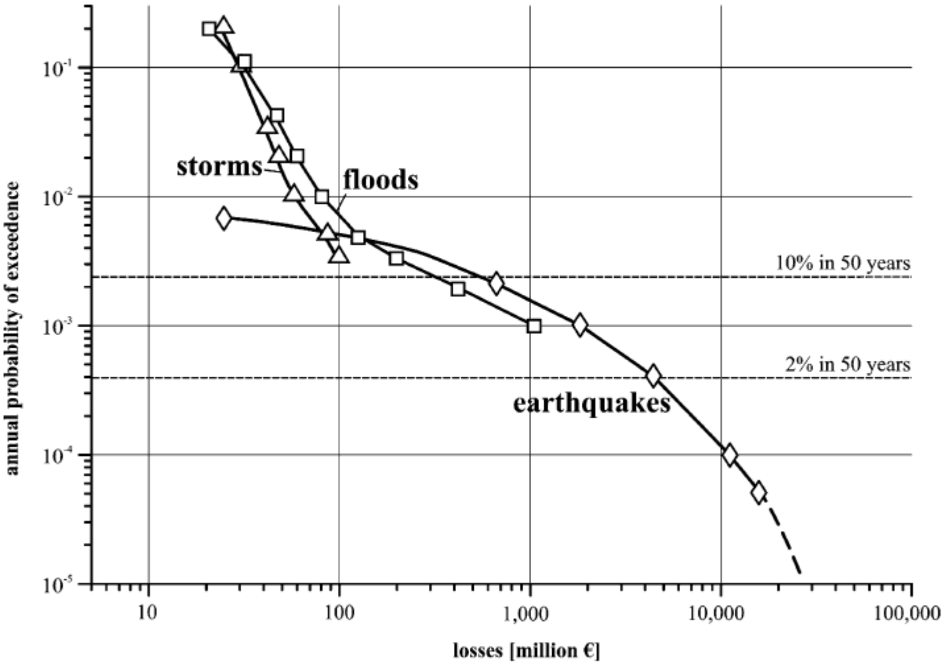


Figure 7.8 Risk curves of the hazards due to windstorms, floods and earthquakes for the city of Cologne. These curves comes directly from multiple one-by-one probabilistic hazard curves (from Grunthal et al., 2006)

Again, no attempt is made at overalying different events in time or in space for an in-depth inspection of possible domino effects.

Similarly, Ferrier and Haque (2003) propose a framework for the application of risk assessment procedures in cases of multi-hazard issues in Toronto (Canada). Blong (2003) is the only that attempts the definition of a multi-event index to rank and classify priorities in risk mitigation planning. Unfortunately, though, he does it only for damage assessment at the risk level, without explicitly incorporating a proposal for natural multi-hazard evaluation.

Concerning landslide related risks, or landslide as a secondary effect of a main damaging event, Lacasse et al. (2008) attempted an analysis of the possible risk patterns induced by a sudden collapse of the Aknes rock slide, illustrating, with the help of an event tree, the different ensuing scenarios which include the triggering of tsunamis (Figure 7.9).

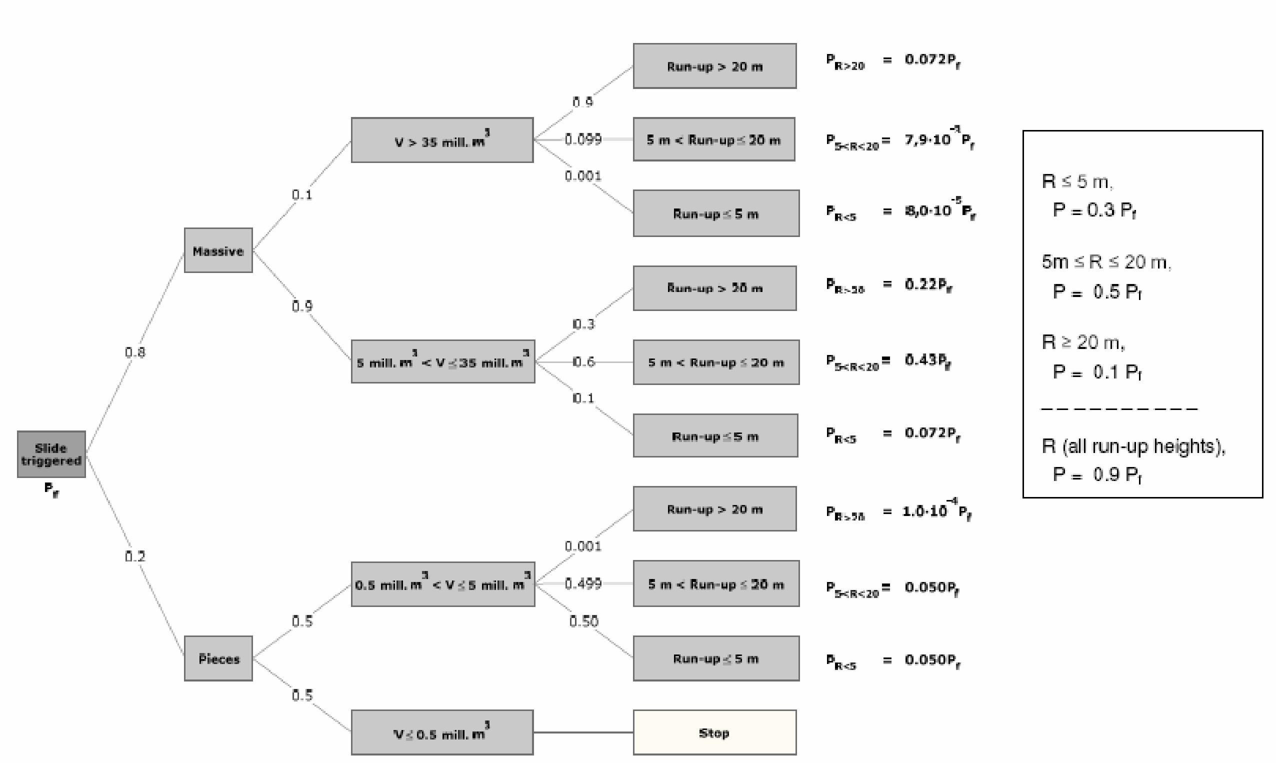


Figure 7.9 Bayesian Event tree for tsunami propagation, given that rock slide in Aknes has occurred (V= rockslide volume, R=run-up height). From Lacasse et al., 2008

In many examples of case studies in which a sort of multi-hazard is considered, the joint occurrence of two or more types of damaging events seems to include a cascading or positive feedback in which a domino effect has taken place.

In general, though, the basic multi-hazard has to do with the occurrence of different types of landslides in the same area, each with its own probability of occurrence. In case no domino effect occurs, we can consider the different events as independent. This means that the overall hazard will be given by the sum of the (independent) probabilities of the single mass movements. However, as a matter of fact, in the great majority of applications the joint probability of independent landslide event in an area is not of interest until we reach the risk assessment phase due to the fact that each different type of mass movement will have its specific intensity towards the existing elements at risk. This means that a separate assessment of intensity and vulnerability is necessary for each landslide acting on the area so, therefore, the joint probability must forcefully be computed at risk assessment stage, after the single parameters have been computed for every single mass movement. In this case, thus, it is quite inappropriate to speak of multi-hazard and we enter the field of multi-risk (see Chapter 8.2).

Multi-hazard, instead, is necessary when we expect some interdependence among several possible landslides (or different processes interacting with them). In such cases, when the potential events are not independent, 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 branchings) to quantitative ETs, where a numerical representation of the conditional probability or return time of every single chain node is calculated using suitable methods. The most used ET based on conditional probability is quite certainly the Bayesian Event Tree (BET), which will be described in detail in the following sections. There are, however, alternate approaches possible for reconstructing likely scenarios for multi-hazard concerning landslides.

It is necessary to distinguish among the various cases of landslide hazard analysis because the suitability of the different probabilistic methods depends on the scale of the study, the methodology used for assessing the hazard and the desired result.

Scale especially is a key factor, conditioning not only the way in which hazard can be assessed, but also our capability of understanding the interrelationships among multi-hazard factors. As an example, a BET can provide a nice method to understand and compare the different evolutionary paths after a dam break with all its possible outcomes and consequences at a local scale, along a single channel path. However, the same tool can prove itself incapable of coping with a similar problem distributed over a hydrographic basin with several possible failure points and many different paths.

This is mainly due to the fact that such probabilistic event-based methods lack a spatial capability whilst on the other hand spatial tools such as GISs lack a functional behaviour support, able to cope with data with dynamical position and attributes.

When spatial distribution of hazards is of concern, it is fundamental to implement ET-systems within GIS tools. In the cases in which the location under study has a very limited extent, it is possible to limit the multi-hazard analysis to only cause-effect networks.

Examples of coupling functional behaviour capability and spatial analysis are scanty and poorly documented in natural hazard analysis. There have been, however, attempts at proposing a scheme for connecting the two using spatially-aware systems engineering design modelling (see e.g. Eveleigh et al., 2006, 2007). Eveleigh and others (2007) provides preliminary but truly convincing results on cases of fire and flood hazard connected with secondary cascade-induced hazards on lifelines and emergency systems. Even though not directly related to landslide hazard, their examples show some prototype spatially-dependend versions of event trees.

7.4.2 Multi-hazard for landslides

It is well known that the term “landslides” encompasses a broad range of gravitational physical phenomena, comprising heterogeneous geological, geotechnical, geomorphologic and anthropic scenarios, and a very wide range of kinetic and geometric attributes. Moreover, landslides can be generated by both natural and anthropogenic sources. Triggering factors are characterized by very different return periods. The evaluation of landslide hazards for different landslide types and due to different causes in a given area is generally pursued through disjoint analyses. The implicit assumption of independence of the risk sources does not allow a unified assessment of the level of hazard. A multi-hazard index, which could subsequently be extended to a multi-risk perspective, could thus provide a more comprehensive estimate of landslide hazard for a given time interval. However, such direct approach requires a preliminary assessment of the problem and data at hand.

According to Table 7.2 and Table 7.3, landslide hazard analysis can be performed at local or regional scale. Furthermore, in both cases, the definition of probability of occurrence must consider also a prediction of intensity or magnitude. Depending on the scale and on the adopted methodology, the estimation of hazard can be based on different descriptors which, in turn, condition the subsequent use of joint probability using ET, BET or other techniques.

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

- 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 and system dynamics.

- Event Tree – Bayesian Event Tree: this category includes descriptive event trees, Bayesian event trees and in 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.
- Spatially averaged ET-BET: a specific, spatial-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:
- 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.
- 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.
- Spatial lumping of BETs, when necessary data are only known over discrete areas with constant values.
- Spatially averaged BET with Functional Bahaviour: 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 bahaviour rules (Eveleigh et al., 2006, 2007). This is a new and challenging approach with virtually no application in landslide studies. It obviously requires an unusual amount of available data that makes it more suitable for slope-local scale studies at the present stage.

The scheme in Table 7.9, 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 7.9 Multi-hazard methodological classes connected to different typologies of hazard and magnitude assessment at local and regional scale, according to the recommendation of this deliverable.

Regional scale	Magnitude	Frequency	Hazard descriptor	Multi-hazard methods and recommendations
Areal analysis	Landslide density Landslide size (area, volume)	Frequency of landslides is averaged by the time span between sets of images.	# landslides/km^2/yr # landslides/pixel/yr total slide area/km^2/yr	Spatially averaged joint probability and scenario-based BETs;
	Landslide density	Return periods or	Probability of having	Spatially

	(i.e. landslides/km^2)	the exceedance probability of the trigger magnitude	# landslides/km^2 # landslides/pixel total slide area/km^2	averaged joint probability and BETs; 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; Spatially-based BETs

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 bahaviour
		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 bahaviour
	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 bahaviour
		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 bahaviour

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 bahaviour

In the following section we illustrate a tentative conceptual and operational scheme for quantitative landslide multi-hazard assessment using conditional probability and Bayesian event trees.

7.4.3 Bayesian event trees – A landslide-oriented approach

In this section we present a basic framework for the use of ET analysis, and in particular of Bayesian event tree analysis, for the computation of multi-hazard in landslide risk assessment. This approach can be used as a blueprint to model a given limited scenario or as a paradigm to implement a multiple spatially-dependent BET analysis is a context such as a GIS system in case we perform a regional scale analysis.

Early examples of ET in landslide studies or natural disaster management are in most cases related to single slopes or connected to geotechnical reliability analysis. Whitman (2000) reports an example of event tree used as part of a risk evaluation for an earth dam (Figure 7.10). The succession of branching along the tree accounts for the possibilities that the downstream channel erodes back to the basin, that the foundation of the basin itself collapses leading to the breaching of the dam and so on. Every branch has an associated relative probability.

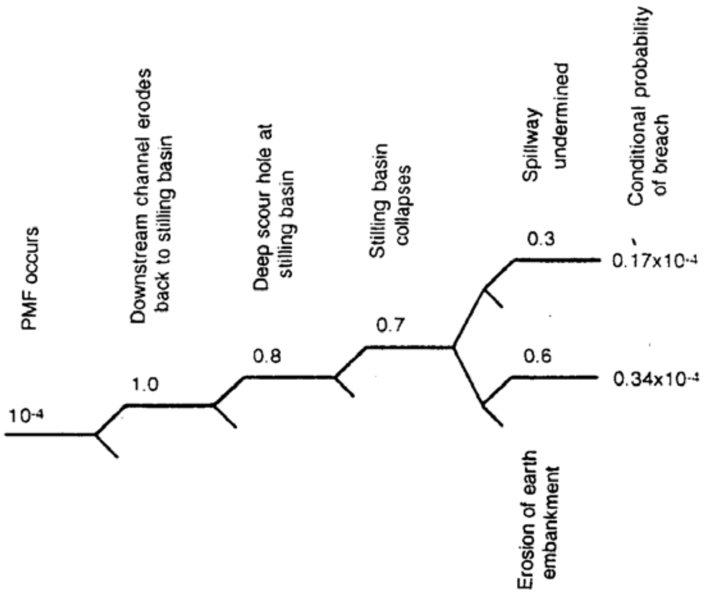


Figure 7.10 Example of BET for an event chain leading to earth dam breaching (from Whitman, 2000)

A similar approach, in which the ET is used to forecast and weight the possible evolution of a landslide displacement is offered by Carboni et al. (2002). The authors compute the probabilities of different event paths, encompassing various developments of the landslide displacement consequences, from the partial damming of the river Reno to the building of a landslide dam and the following breaching-flooding (Figure 7.11). Again, the most recent example of such application of a conditional probability event tree for the consequences of a landslide failure is offered by Lacasse et al., (2008) (see e.g. Figure 7.11).

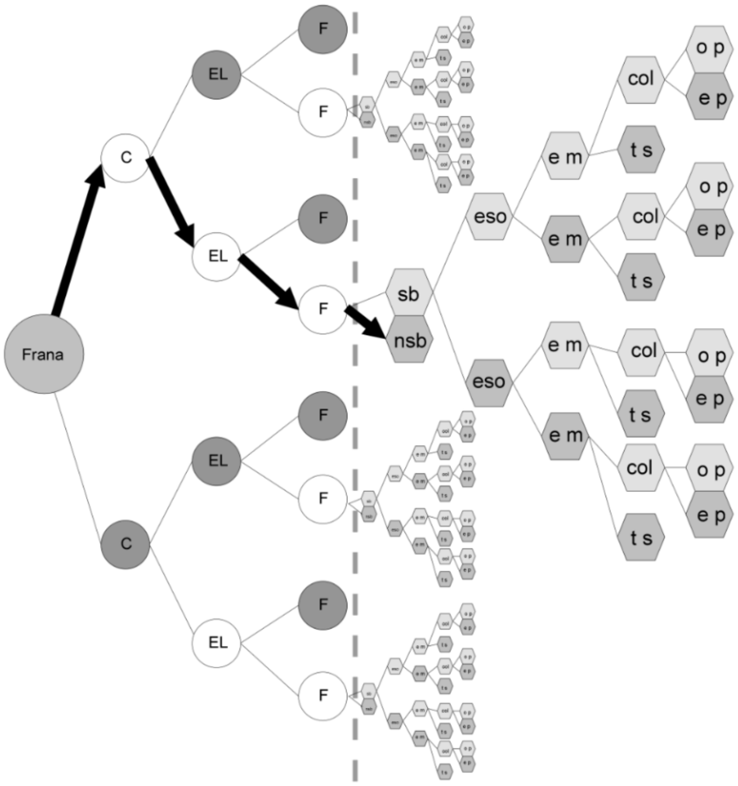


Figure 7.11 An event tree example related to the possible consequences of the Marano landslide (Italy). This ET accounts for the possible development toward the damming of a river and the further consequences of earth dam breaching (from Carboni et al., 2002)

An event tree is a graphical, hierarchical, tree-like representation of events in which branches are logical steps from a general prior event through increasingly specific subsequent events (intermediate outcomes) to final outcomes. Events at any given level of the tree need neither be mutually exclusive, nor aggregately exhaustive of all possible outcomes. Probabilities can be associated to each event throughout the tree. Such probabilities (with the exception of the first level of the tree) are conditional, in the sense that they are dependent on the occurrence of the event at the preceding level of the tree. Through the use of classical probability theorems, it is possible to calculate the probability of occurrence of any intermediate or terminal event along any one path of the tree (which corresponds to a landslide scenario). A Bayesian approach is particularly suitable in those cases in which subjective interpretation and modeling of uncertainty plays a relevant role.

In a Bayesian framework, systematic quantitative inferences of the posterior probability of a scenario $P(\theta|\beta)$ (e.g., the hazard associated with a landslide type for a given area) can be made using Bayes' theorem, on the basis of a prior probability distribution $P(\theta)$, representative of prior knowledge (or belief) regarding the scenario, and a measure of likelihood $P(\beta|\theta)$, given by new observations (or updated belief) β:

$$P(\theta \mid \beta) \propto P(\theta) \times P(\beta \mid \theta)$$

In a BET, conditional probabilities at each node are modeled as random variables through suitable probability density functions, rather than single probability values. In this way, both aleatory and epistemic uncertainties in initial, intermediate and terminal events can be addressed. The calculation of intermediate and terminal distributions can be pursued using Monte Carlo simulation.

The construction of an effective event tree requires a suitable replication of the sequential process which leads to the triggering and propagation of a landslide event. A tentative structure of a BET for multi-hazard for landslides - comprising 5 levels - is given in the following:

- Level 1: there is non-stationarity in geologic, geomorphologic, hydrogeologic and climatic conditions, or in anthropic activities
- Level 2: a triggering macro-factor occurs in a given time period
- Level 3: a triggering event having a specific source intensity will occur in a specific source location, given that a triggering event will occur
- Level 4: a landslide will occur at a specific genitive location, given that a triggering event of a given source intensity occurs in a specific source location.
- Level 5: a specific threshold value of a reference attribute (velocity, volume, depth, etc.) of the landslide event is attained at a specific target location as a consequence of the propagation effects of the landslide event initiated at the genitive location by the occurrence of a triggering event at the source location.

The conditional probabilities in each Level of the BET can be estimated using objective data, expert opinion and/or appropriate models (e.g. runout estimation models, frequency-magnitude relationships for a given area, etc.).

As can be seen in the Table 7.10, through BET it is possible to pursue multi-hazard estimation in a geographic perspective, i.e. by explicitly considering the effects of a triggering event in a source location on the initiation of a landslide event in a genitive location and, subsequently, on its propagation in other user-defined target areas.

By means of the BET structure, it is thus possible to take into account all those initial, intermediate and terminal events which are deemed to be relevant in a multi-hazard perspective with respect to local geological, geomorphologic, hydrogeologic and climatic conditions, and provide probability estimates for their occurrence in a reference time period. In order to rationalize the structure of the BET (namely, in Levels 3 and 4) and to optimize the computational expense of Monte Carlo simulation, it is important to include causal relationships which are compatible with the area under investigation. This could occur through the compilation of the following landslide triggering matrix. Compilation could occur on a binary basis (0: exclude or 1: include) or using ranking criteria (e.g., 1: not relevant – 3: very relevant).

Table 7.10 Example of a causal relationship building matrix for landslides

	rock						debris						earth						
	rock fall	rock topple	rotational rock slide	translational rock slide	rock spread	rock flow	debris fall	debris topple	rotational debris slide	translational debris	debris spread	debris flow	earth fall	earth topple	rotational earth slide	translational earth slide	earth spread	earth flow	complex
Water																			
rainfall																			
snowmelt																			
water-level change																			
river undercutting																			
Geodynamics																			
seismic shaking																			
liquefaction																			
volcanic activity																			
Human activity																			
vibrations																			
blasting																			
earthwork																			
vegetation removal																			
permeability modification																			

Once relevant causal relationships have been identified, it is possible to compile the BET. An example is shown in Figure 7.12 below.

The scheme in Figure 7.12 refers to a single (user-defined) threshold attribute of a landslide, a single (s-th) source location, a single (g-th) genitive location and a single (t-th) target location. The BET can be implemented for any combination of source, genitive and target locations to provide hazard estimates regarding the occurrence of landslide events of any given threshold attribute for a given time interval.

- Accounting for sequential dependence between landslide events

The dependence among events and possible cascade effects, by which the occurrence of one landslide event would increase the likelihood of occurrence of other landslides, can be modelled using the BET by increasing the number of levels, with the event tree replicating itself beginning from Level 3, which would become Level 6, and so on.

- Collective hazard

The BET as described above is able to yield hazard estimates for each path in the tree. It is of interest to obtain a synthetic estimate of collective hazard, i.e. the hazard referred to the simultaneous, non-sequential occurrence of more than 1 scenario. Given is a sequence of terminal, mutually independent events E1…En with known probabilities, the probability of occurrence of the union of n scenarios is:

$$P\left(\bigcup_{i=1}^{n} E_i\right) = P\left(E_1\right) + \ldots + P\left(E_n\right) - \sum P\left(\cap 2 \text{ events}\right) + \sum P\left(\cap 3 \text{ events}\right) + \ldots + \left(-1\right)^{n+1} P\left(\cap n \text{ events}\right)$$

in which the probabilities of occurrence of the single events P(Ei) are calculated using the BET described above. It remains to be seen whether the probabilities of intersection of events in a given temporal interval can be calculated based on the (subjectively or objectively estimated) return periods for each event.

This gives only the basic elements for establishing a multi-hazard computational framework. In the present form the method does not explicitly account for magnitude, thus requiring branching or duplication of probabilistic paths.

It does not yet encompasses spatial averaging or spatial distribution over a given area, either. We believe, however, that this could be a useful guideline to attempt multi-hazard analisys for landslides.

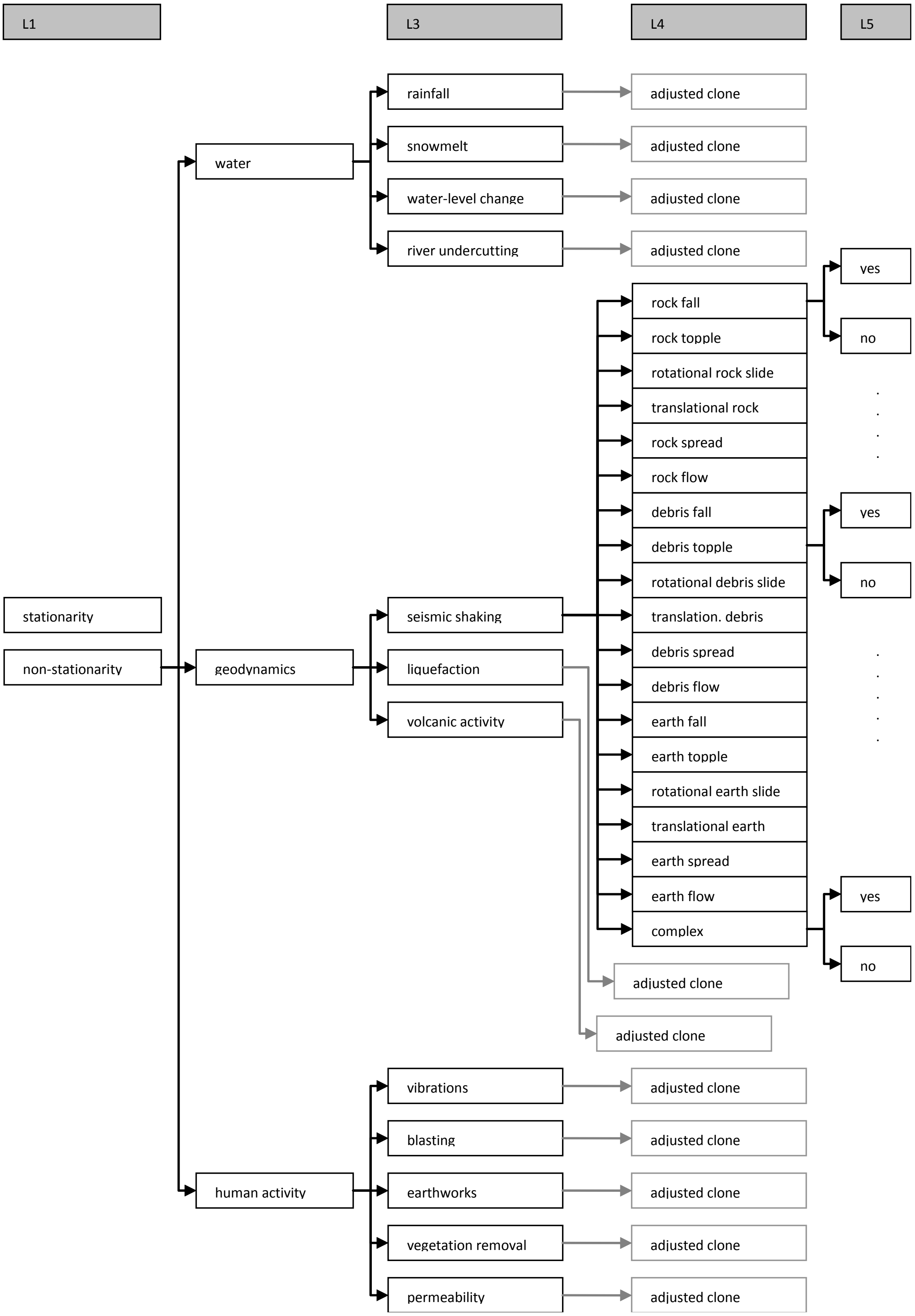


Figure 7.12 Tentative scheme of BET for landslide multi-hazard estimation

References

Blong, R., 2003. A new damage index. Natural Hazards, 30: 1-23.

Carboni, R., Catani, F., Iotti, A., Monti, L., 2002. The Marano landslide (Gaggio Montano, Appennino Bolognese) of February 1996. Quaderni Geol. Applic., 8(1):123-136 (in italian).

Eveleigh, T.J., Mazzucchi, T.A., Sarkani, S. 2006. Systems engineering design and spatial modelling for improved natural hazard risk assessment. Disaster Prev. Managem., 15(4): 636-648.

Eveleigh, T.J., Mazzucchi, T.A., Sarkani, S. 2007. Spatially-aware systems engineering design modelling applied to natural hazard vulnerability assessment. Systems Engineering, 10(3): 187-202.

FEMA, 2006. Multi-Hazard Mitigation Planning Official Documents and Website. http://www.fema.gov/plan/mitplanning/. Federal Emergency Management Agency U.S. Department of Homeland Security.

Ferrier, N., Haque, C.E., 2003. Hazards risk assessment methodology for emergency managers: a standardized framework for applications. Natural Hazards, 28(2/3): 271-290.

Gerbaudo, G.M., Saffar, A., 2007. Projecting catastrophic losses in a multi-hazard environment. Mecanica Computacional, 26: 2549-2564.

Grunthal, G., Thieken, A.H., Schwarz, J., Radtke, K.S., Smolka, A., Merz, B., 2006. Comparative risk assessment for the city of Cologne – Storms, floods, earthquakes. Natural Hazards, 38: 21-44.

Lacasse, S. Eidsvik, U., Nadim, F., Hoeg, K., Blikra, L.H. 2008. Event tree analysis of Aknes rock slide hazard. IV Geohazards Quebec, 4th Canadian Conf. on Geohazards, 551-557.

McCarthy, F.X., Keegan, N., 2009. FEMA's Pre-Disaster Mitigation Program: Overview and Issues. Congressional Research Service Report 7-5700, RL34537, 22 pp.

Westen, C. J., Montoya, L., Boerhoom L., Coto, E. B., 2002. Multi-hazard Risk Assessment using GIS in Urban areas: A case study for the city of Turrialba, Costa Rica. Proceedings of Regional Workshop on Best Practices in Disaster Mitigation, Lessons learned from the Asian Urban Disaster Mitigation Program and other initiatives, 24-26 September, Bali, Indonesia, 53-72.

Whitman, R.V., Organizing and evaluating uncertainty in geotechnical engineering 2000. Journal of Geotech. Geoenv. Eng., 583-593.

8 SUGGESTED METHODS FOR LANDSLIDE RISK ASSESSMENT

8.1 VULNERABILITY ASSESSMENT

(AUTH with contributions from UPC and TRL)

8.1.1 Introduction

The quantified vulnerability assessment is a sub-component of the quantified risk assessment. A hazard has a potential to become a risk only on the condition that exposed and vulnerable elements exist in the potentially affected area, including people, structures and infrastructures.

Landslide consequences present a large variation from slight to catastrophic. In recent decades numerous people have become the victims of landslides in many regions worldwide.

While there has been extensive research into quantifiying landslide hazard, research into consequence analysis and vulnerability assessment has been limited and remains in its infancy. An understanding and assessment of the vulnerability of elements exposed to landslide hazard is of key importance to landslide risk assessment

Two independent parameters are involved in the consequence analysis: exposure and vulnerability. Although exposure might abusively being considered as vulnerability for regional analysis at small scales, in reality these are two different parameters and confusion between them should be avoided: the exposure of an element depends on whether it will be affected by a rockfall, while the vulnerability expresses its degree of damage due to an event, irrespectively of whether the element will be affected.

Exposure may be estimated by overlaying and intersecting the maps of hazard, from one side, and of potentially exposed elements, from the other. In the case of landslides the distribution is aereal while in the peculiar case of rock falls the impact is punctual and the probability of impact with a static or mobile element must be calculated.

The methodologies that may be used for the vulnerability assessment present large differences between them, according to the landslide type, the type of exposed elements, and the scale of assessment. In the following, some methodologies are proposed considering these three factors.

8.1.2 Quantitative and qualitative vulnerability

Physical vulnerability of the exposed elements (buildings and infrastructure) and vulnerability of persons subjected to the different landslide hazards may be expressed in qualitative, semi-quantitative or quantitative terms. Quantitative estimates use numerical values or ranges of values, while qualitative estimates use descriptive ranks such as high, moderate and low. Both quantitative and qualitative estimates can be based on either objective (statistical or mathematical) estimates or subjective (professional judgmental or assumptive) estimates, or some combination of both. Whether qualitative or quantitative assessments are more suitable depends on both the desired accuracy of the outcome and the nature of the problem, and should be compatible with the quality and quantity of available data (Dai et al, 2002).

A qualitative approach, coupled with engineering judgement, uses descriptors to express a qualitative measure of the expected degree of loss (Cascini et al., 2005). Quantitative approaches, like that proposed by AGS (2007) for life-loss situations and Remondo et al. (2008), need data on both landslide phenomenon and vulnerable element characteristics (Fell et al, 2008).

When sufficient data is available, a quantitative risk analysis (QRA) is preferable compared to qualitative, as it allows for a more explicit characterization of the causes of damage (in terms of permanent deformation, tension cracks, number of fatalities monetary values etc.) and offers an improved basis for communication among the research community, local authorities and emergency planners (AGS, 2007; Uzielli et al., 2008).

Building on the challenge that there are multiple definitions, methods and scales of understanding social vulnerability, a related challenge is how to measure it once the system in question is defined (AEA, 2008). The main types of assessment approaches are largely based on qualitative or quantitative research traditions and approaches distiguishing important differences in their related paradigms. The most important aspect of indicator development is to ensure that the selected indicators serve the needs of the research question and test the concepts to be operationalised. The type of used approach may be determined by the required scale of the study or by whether the focus is upon analysing attributes or processes. For example, quantitative approaches based on statistical analysis may be more suitable for measuring attributes e.g. in larger scale studies, while more contextual and qualitative approaches will be appropriate for understanding processes and relationships e.g. in community level and bottom-up studies. However, both approaches may rely, to greater or lesser extents, on the use and development of indicators to measure social vulnerability (Tapsell et al. 2010).

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. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide. Vulnerability could 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 of them are reviewed in Fuchs et al. (2007) and Tapsell et al. (2010).

Different disciplines apply the term of vulnerability in different ways. The quantified vulnerability can be expressed in monetary terms (absolute or relative to the value of the exposed elements), or as a percentage of the per capita gross domestic product, or as 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.

8.1.3 Types of vulnerability

Depending on the type of loss, vulnerability can be classified into the following five main categories:

- Physical vulnerability, referring to the damage of buildings and infrastructures (transport, pipelines, telecommunications and energy supply lines…).

Of the five categories, physical vulnerability is arguably the most straightforward to quantify. The monetary impact of damage to a building or to infrastructure can be readily assessed and is easily understood even by those that are not directly impacted. Furthermore, the vulnerability of physical elements can be expressed in terms of the extent of damage as a result of a given event. While this ultimately feeds into vulnerability in monetary terms it provides another means by which vulnerability can be quantitatively assessed and expressed.

- Vulnerability of persons, referring to the life and health of persons.

In base terms the vulnerability of persons 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 or reduced quality of life which relate. Models used to assign such monetary values generally consider the cost of rescue, hospitalisation, and treatment, loss of earning potential (in both the short term in the case of injury and in the long term. Where a numeric scale such as monetary value is used vulnerability can be assessed by quantitative means. However, other impacts of the loss of life or injury due to a landslide, including trauma and loss of family, are wider-reaching and have social implications that do not readily lend themselves to quantification.

- Socio-economic vulnerability, referring to socio-politico-economical consequences including activities.

There are situations in which the socio-economic vulnerability of a group or community can be quantified, again using a monetary scale. For instance, where a landslide event results in the isolation of a community due to disrupted lifelines (e.g. road and rail), the vulnerability can be understood to hinge upon direct monetary losses or outlays as a result of this isolation. This may include loss of trade in tourist areas where the community is reliant on passing trade, or the need to use alternative, longer routes i.e. for travel to work and the additional expense of the commute. Socio-economic vulnerability cannot be fully understood in monetary terms due to wider implications as for the vulnerability of persons; however, for the economic understanding of a situation vulnerability can be quantified to a reasonable extent.

- Environmental vulnerability, referring to the impact on stream environments, forest cover, agricultures, wildlife, pollution due to leakages etc.

Focussing on the economic implications that a landslide may have, the vulnerability of elements of that particular environment can be quantified. As an example, the clean-up costs of pollution can be quantified or the loss of an economic resource i.e. forestry can be evaluated. Taking environmental vulnerability as a whole it would be difficult to assess the total monetary value, and therefore to quantify the vulnerability. Furthermore, it is important to remember that an environment is typically valued not in monetary terms but as a social, cultural and recreational resource which cannot be quantified.

- Cultural heritage vulnerability.

The monetary worth of a site of cultural heritage can, in some cases, be assessed which again provides a means of quantifying vulnerability. More often than not a site of cultural heritage has no real monetary expression as it is irreplaceable. The true value of cultural heritage is subjective. This would suggest that there is no true means of accurately quantifying the vulnerability of cultural heritage to landslide hazards.

Vulnerability to landslides is multi-faceted. Historical events indicate that the main potential landslide consequences are:

A. Direct consequences:

- physical damage of structures (fences, buildings and other types),
- blockage and destruction of roads and other traffic lines,
- injury or fatality of persons which are engulfed by the landslide mass, or are within buildings which collapse as a result of the landslide, or are within vehicles which have been pushed off the road or derailed by the landslide
- damage of telecommunications and energy supply lines,

B. Indirect consequences:

- disruption of activities and relevant socio-economical impact,
- traffic detours on transportation corridors,
- socio-economic impact,
- evacuation of the threatened areas and relevant socio-economical impact,
- decrease of tourism due to closure of visited sites or interruption of access,
- formation of dams in streams impacting on water quality and fish habitat,
- landslide generated tsunami (mainly due to large volume rockfalls and rockslides).

In this deliverable recommendations are given for the quantification of the physical vulnerabtility of buildings, vehicles and roads and persons. Here, only some basic mechanisms of landslides are considered: rockfalls, debris flow and slow-moving landslides. Additionally, for rock avalanches the vulnerability may always be considered 1. An extensive list of elements at risk is given by Alexander 2005 (Table 8.1).

Table 8.1 Elements at risk

Infrastructure	Buildings and rural production
Roads unasphalted rural roads asphalted rural roads main road divided highways limited access freeways (motorways) urban access roads private drives	Houses single family homes -semi-deteached and terraced housing Blocks of appartments Urbain insulae Farmhouses Villas and isolated buildings Prefabricated buildings
Railways main lines branch lines sidings buildings (stations etc.)	Public buildings town halls and public administration offices hospitals and clinics sports centres cemeteries churches and chapels -schools and other educational institutions Fire and ambulance stations Armed forces barracks and police stations
Bridges major road, rail, pipeline bridge and viaducts minor bridges culverts	Architectural heritage historic buildings fortifications monuments
Electricity transmission low-tension lines, on poles high-tension lines, on pylons transformers, switching stations and substations	Commercial buildings shops and stores office blocks warehouses and storage areas factories artisans premises and small businesses mechanics premises, motor showrooms and engineering workds heavy industrial plants and refineries
Telephone	Agriculture

low-tension lines on poles cellular telephone repeaters	tilled fileds marked gardens
Pipelines water supply: main pipelines and distributions networks sewer lines methane gas: main pipelines and distributions networks septic tanks and their feeder systems	
Other canals, navigable rivers and drainage channels water towers and tanks gas and storage facilities airfields, airports	

Furthermore, some indications on the quantification of social vulnerability using weighted indicators are provided.

8.1.4 Physical Vulnerability

A schematic overview of 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 in Figure 8.1 (Van Westen et al. 2006).

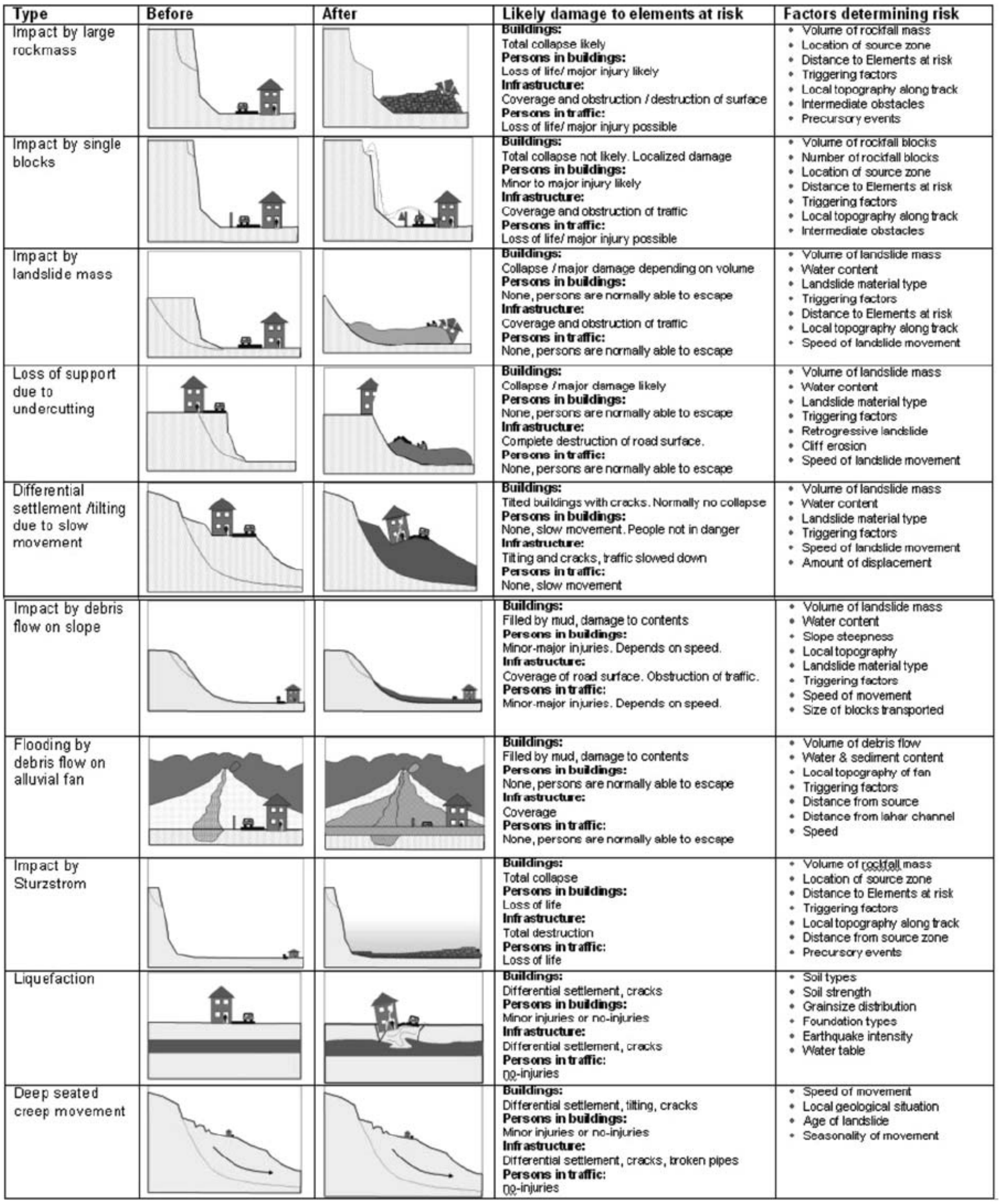
There is no unique vulnerability value for the exposed elements. Based on the potential consequences, vulnerability should be calculated according to the landslide type and the respective potential effects on the exposed elements and its intensity. An additional important factor is the geographic location of the exposed elements within the landslide body (crest, base etc.) given the variation of the soil movement and the consequect interaction with the structures and infrastructures, or in the case of rock falls, the location and the extent of the rock fall impact on the exposed elements.

For a landslide of given type, mechanism and intensity, the typology of the exposed elements is also a key factor in a vulnerability assessment methodology. Geometry, material properties, age, code design level, soil conditions, foundation and superstructure details, number of floors etc. are among typical typological parameters which determine the capacity of the building to withstand impact/erosion. In addition, due to their use, structure and size, the value or cost of these buildings will also be different. In the calculation, therefore each building will have a different value and for the same hazard (e.g. a 10 years return period landslide) the risk will be also different. This information is indispensable for a site specific analysis. In order to facilititate the data collection at local and regional scales, it can be observed that in most cases it is convenient to consider more aggregated levels in the form of homogeneous units (Van Westen, 2004). These should consist of groups of buildings, characterized by a relative homogeneity of building type, construction materials, number of floors and land use distribution.

8.1.5 Intensity parameters

The vulnerability of the exposed elements depends on the type and intensity of the landslide, which will determine the kind and gravity of the consequences. To quantify the landslide effect on the exposed element (mainly structures and infrastructures), proper intensity parameters should be used, as a link between the phenomenon and the response of the exposed element to it.

Intensity criteria have been proposed by Leone et al. (1996). In Figure 8.2, intensity parameters are given according to the landslide type.



Type	Before	After	Likely damage to elements at risk	Factors determining risk
Impact by large rockmass			**Buildings:** Total collapse likely **Persons in buildings:** Loss of life/ major injury likely **Infrastructure:** Coverage and obstruction / destruction of surface **Persons in traffic:** Loss of life/ major injury possible	- Volume of rockfall mass - Location of source zone - Distance to Elements at risk - Triggering factors - Local topography along track - Intermediate obstacles - Precursory events
Impact by single blocks			**Buildings:** Total collapse not likely. Localized damage **Persons in buildings:** Minor to major injury likely **Infrastructure:** Coverage and obstruction of traffic **Persons in traffic:** Loss of life/ major injury possible	- Volume of rockfall blocks - Number of rockfall blocks - Location of source zone - Distance to Elements at risk - Triggering factors - Local topography along track - Intermediate obstacles
Impact by landslide mass			**Buildings:** Collapse / major damage depending on volume **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Coverage and obstruction of traffic **Persons in traffic:** None, persons are normally able to escape	- Volume of landslide mass - Water content - Landslide material type - Triggering factors - Distance to Elements at risk - Local topography along track - Speed of landslide movement
Loss of support due to undercutting			**Buildings:** Collapse / major damage likely **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Complete destruction of road surface. **Persons in traffic:** None, persons are normally able to escape	- Volume of landslide mass - Water content - Landslide material type - Triggering factors - Retrogressive landslide - Cliff erosion - Speed of landslide movement
Differential settlement /tilting due to slow movement			**Buildings:** Tilted buildings with cracks. Normally no collapse **Persons in buildings:** None, slow movement. People not in danger **Infrastructure:** Tilting and cracks, traffic slowed down **Persons in traffic:** None, slow movement	- Volume of landslide mass - Water content - Landslide material type - Triggering factors - Speed of landslide movement - Amount of displacement
Impact by debris flow on slope			**Buildings:** Filled by mud, damage to contents **Persons in buildings:** Minor-major injuries. Depends on speed. **Infrastructure:** Coverage of road surface. Obstruction of traffic. **Persons in traffic:** Minor-major injuries. Depends on speed.	- Volume of landslide mass - Water content - Slope steepness - Local topography - Landslide material type - Triggering factors - Speed of movement - Size of blocks transported
Flooding by debris flow on alluvial fan			**Buildings:** Filled by mud, damage to contents **Persons in buildings:** None, persons are normally able to escape **Infrastructure:** Coverage **Persons in traffic:** None, persons are normally able to escape	- Volume of debris flow - Water & sediment content - Local topography of fan - Triggering factors - Distance from source - Distance from lahar channel - Speed
Impact by Sturzstrom			**Buildings:** Total collapse **Persons in buildings:** Loss of life **Infrastructure:** Total destruction **Persons in traffic:** Loss of life	- Volume of rockfall mass - Location of source zone - Distance to Elements at risk - Triggering factors - Local topography along track - Distance from source zone - Precursory events
Liquefaction			**Buildings:** Differential settlement, cracks **Persons in buildings:** Minor injuries or no-injuries **Infrastructure:** Differential settlement, cracks **Persons in traffic:** no-injuries	- Soil types - Soil strength - Grainsize distribution - Foundation types - Earthquake intensity - Water table
Deep seated creep movement			**Buildings:** Differential settlement, tilting, cracks **Persons in buildings:** Minor injuries or no-injuries **Infrastructure:** Differential settlement, cracks, broken pipes **Persons in traffic:** no-injuries	- Speed of movement - Local geological situation - Age of landslide - Seasonality of movement

Figure 8.1 Schematic overview of landslide damage types, related to different landslide types, elements at risk and the location of the exposed element in relation to the landslide (Van Westen et al. 2006)

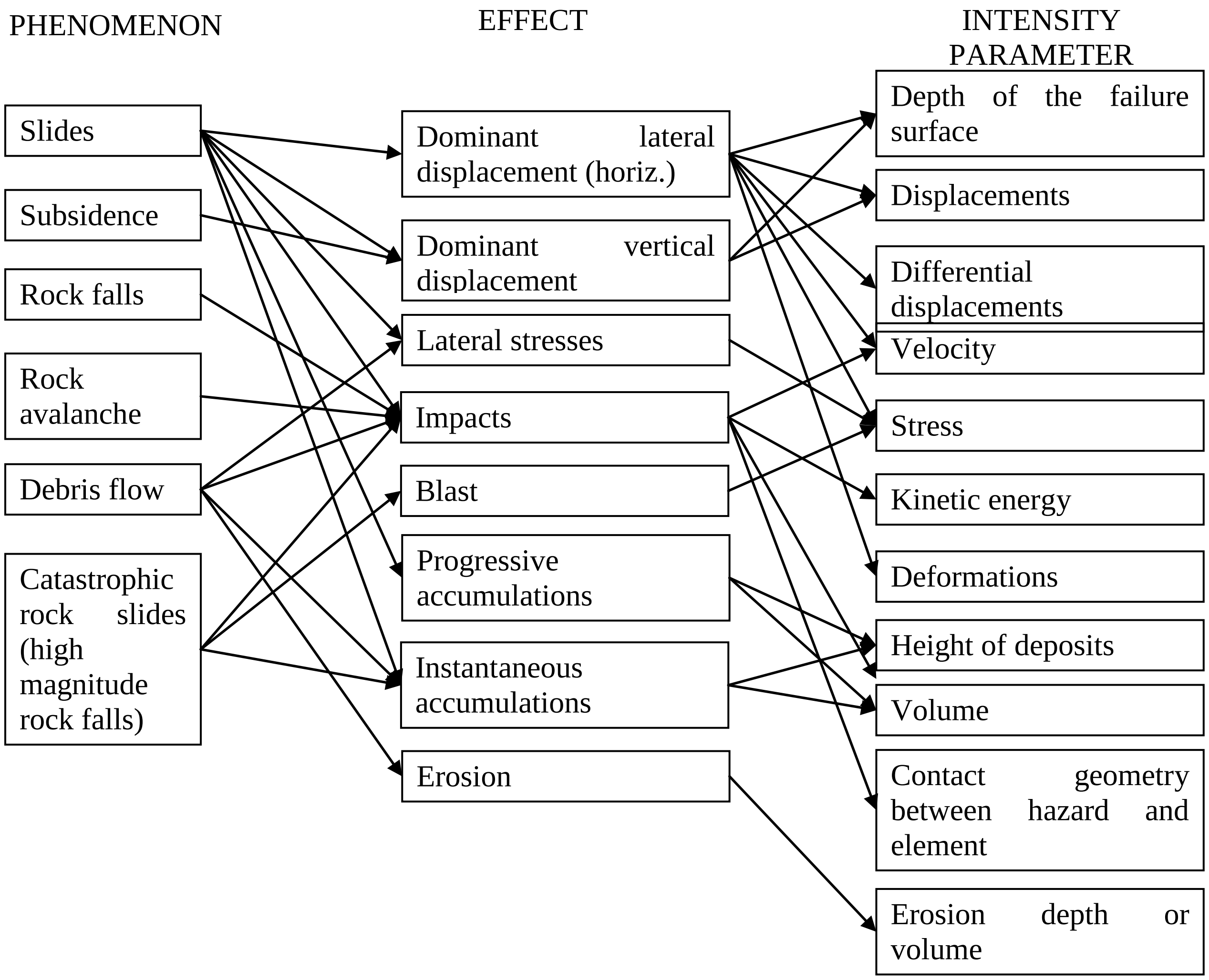


Figure 8.2 Proposed intensity criteria

8.1.5.1 Physical damage of structures

The effect of a landslide is dependent upon the typology of the structure and its particular characteristics. Heinimann (1999) classified structures according to their vulnerability to landslides as shown in the following Table. For the quantitative vulnerability assessment values may be attributed to them**.**

Table 8.2 Classification of structures according to their vulnerability to landslides (Heinimann, 1999)

Building category	Building structure	Resistance
0	Lightest structure	No
1	Light structure	Very weak
2	Mixed structure (concrete and timber)	Weak
3	Brick walls, concrete	Medium
4	Reinforced concrete	Strong
5	Reinforced	Very strong

Rockfalls

Historical rockfalls indicate that the extent of damage to buildings due to rockfalls presents large dispersion from slight non-structural damage to total collapse, according to the building's physical characteristics and the rockfall's size and velocity. Damage can be classified as: a) primary structural damage (of primary structural elements such as columns, beams, bearing walls etc. which determine the overall stability of the building), b) secondary structural damage (of secondary load-bearing elements such as slabs, etc.), c) primary non-structural damage that may cause injuries (i.e., infill walls, ceilings, etc), and d) secondary non-structural damage (i.e., furniture, fixtures, etc.), and e) damage to services (electrical and mechanical equipment etc.).

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Besides the rockfall magnitude and intensity, a key-issue for the type of damage according to this classification, is the impact location on the structure and the importance of the impacted members on the stability of the building. Three main impact locations are distinguished: a) a free-fall rock dropping on the roof, b) a rock moving on a trajectory path and hitting the exposed façade, and c) a rock passing through the façade and perforating a floor slab on a downwards movement.

For small scales, the simplification that rock fall events of similar magnitude produce the same level of damage can be made due to the resolution of the analysis. However, this assumption is not strictly true because the degree of damage caused by a rockfall of a given intensity also depends on the location of the impact, which should be taken into consideration for large (local and site-specific) scales. This applies especially to frame structures (reinforce-concrete, steel or timber), where the extensive damage of a column may lead to general instability and progressive collapse. For masonry structures the damage is usually local, because ought to the hyper-static load-bearing system alternative load paths may be easily found.

When primary structural members are impacted the damage is initially localized at the vicinity of the impact. If the latter is destroyed, the stability of the entire building maybe affected and a cascade of failures can be initiated, leading to extensive or total collapse disproportionate to the original cause. Taking this into account the potential for progressive collapse depending on the probability of intersection with a structural and non-structural element and the respective damage extent should be considered for the vulnerability assessment

Debris flows

Debris flows are usually characterized as fast moving phenomena whose maximum expected velocity, during their paroxysmal phase, corresponds to class 5 to 7 as established by Cruden and Varnes (1996) (Velocities may vary from $5\cdot10^{-1}$mm/sec to $5\cdot10^{3}$mm/sec).

In most of the encountered cases, these landslides, which are generally first-failure phenomena, are associated with the most severe damage to buildings and infrastructures, usually resulting to the complete destruction of any element within their path. Even when the initial landslide body is relatively small, its final volume may be very large because of their capability to cover large distances in a very short time involving part of the material encountered on the slope. The risk is then very high owing to the high magnitude of the landslide due to its mass and velocity and the exposition which may be very high too due to the long runout of the soil mass which can propagate even over relatively flat areas (Picarelli, 2010).

Slow moving landslides

While damage to the built environment resulting from the occurrence of rapid landslides such as debris flows and rock falls 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, 2010).

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.

For instance, a slow moving slide may produce tension cracks due to differential displacement to a building that may result to the partial or complete disruption of the structure's serviceability and stability. The type of response to permanent total and differential ground deformation depends primarily on the foundation type. A structure on a deep foundation compared to shallow foundations often has higher resistance ability and hence a lower vulnerability. For shallow foundations, the distinction is between rigid or flexible/unrestrained foundation systems. When the foundation system is rigid, the building is expected rather to rotate as a rigid body and a failure mainly attributed to the loss of functionality of the structure is anticipated. On the contrary, when the foundation system is flexible, the various modes of differential deformation produce structural damage (e.g. cracks) to the building members (Bird et al, 2006).

Generally, the vulnerability of buildings to slow moving slides may depend on (a) the hazard level (b) the rate of movement (relative slow to extremely slow moving slides) (c) the triggering mechanism (intense rainfall, earthquake, erosion, construction activities etc), (d) the specific strength and geometrical characteristics of the exposed buildings, (e) their position in relation to the potential sliding surface, and (f) the type of materials controlling the movement.

8.1.5.2 Vulnerability of roads and vehicles

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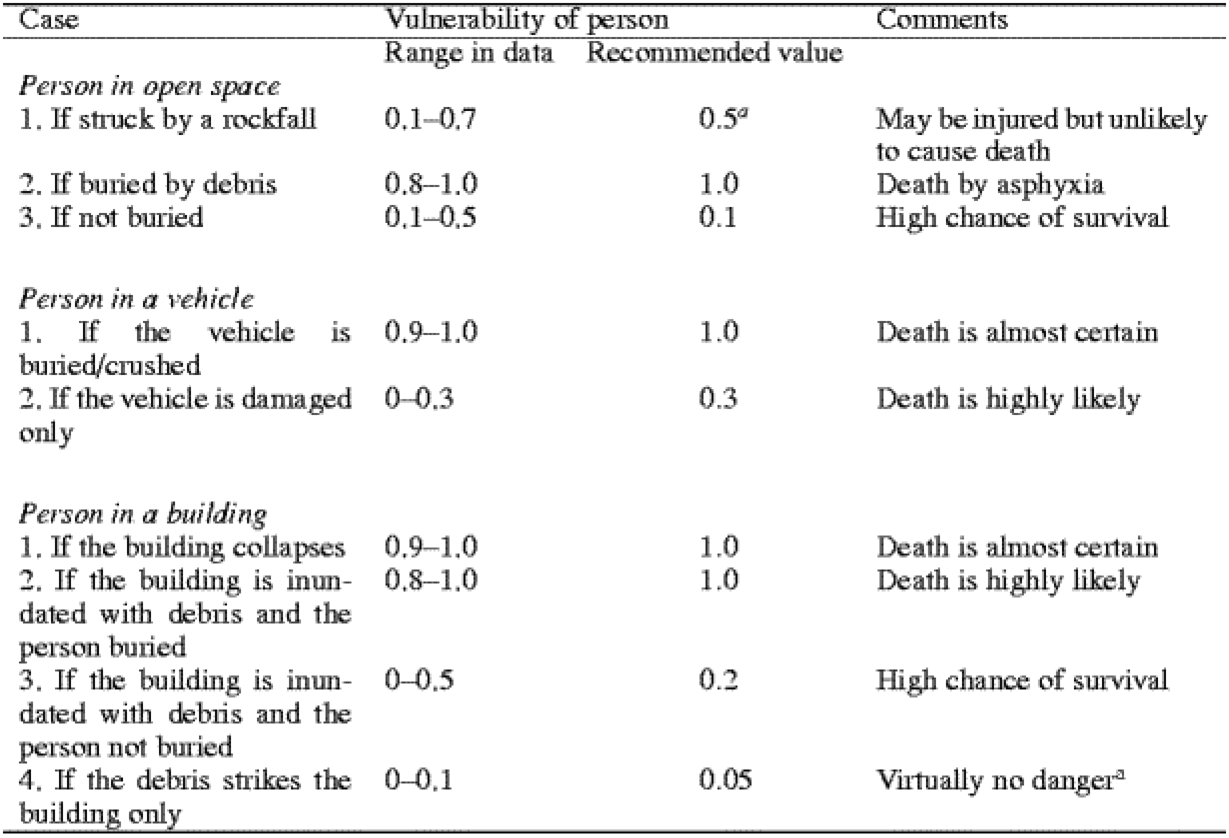
8.1.5.3 Vulnerability of persons

The (physical) vulnerability of persons refers to the potential of injury or loss of life due to a landslide event of a given intensity.

The vulnerability of a person is often relevant to the velocity of the phenomenon (slow moving landslides versus fast moving landslides), which is in relation with the warning time. Additionally, the vulnerability of a person varies according to whether the latter is directly affected by the landslide (e.g. for persons that are outdoors due to a rock impact or a soil mass movement) or indirectly (e.g. for persons in a moving vehicle or indoors due to building collapse).

Further parameters that are involved are the sensitivity of the population, depending on its age and capacity to anticipate a landslide, the capacity of understanding the phenomenon and to move away from the exposed zone etc. Finlay (1996) applies some values for people in open space, vehicles or buildings in landslide areas, which are applied for the risk assessment in Hong Kong (Table 8.3).

Table 8.3 Summary of Hong Kong vulnerability ranges and recommended values for death from landside debris in similar situations (from Finlay, 1996)



Case	Vulnerability of person		Comments
	Range in data	Recommended value	
Person in open space			
1. If struck by a rockfall	0.1–0.7	0.5[a]	May be injured but unlikely to cause death
2. If buried by debris	0.8–1.0	1.0	Death by asphyxia
3. If not buried	0.1–0.5	0.1	High chance of survival
Person in a vehicle			
1. If the vehicle is buried/crushed	0.9–1.0	1.0	Death is almost certain
2. If the vehicle is damaged only	0–0.3	0.3	Death is highly likely
Person in a building			
1. If the building collapses	0.9–1.0	1.0	Death is almost certain
2. If the building is inundated with debris and the person buried	0.8–1.0	1.0	Death is highly likely
3. If the building is inundated with debris and the person not buried	0–0.5	0.2	High chance of survival
4. If the debris strikes the building only	0–0.1	0.05	Virtually no danger[a]

For the quantification of the vulnerability of people two types of personal risk are considered: (a) the individual risk, expressed by the annual probability that a particular person may lose his/her life, and (b) the societal risk, expressed as the annual probability that one or more persons could be killed by landslides that depends on further social parameters in an impacted area like the population density, the developed activities in the area etc.

8.1.6 Quantification of vulnerability

The vulnerability of an element can be quantified using either a) vulnerability indices or b) fragility curves. A vulnerability index express the potential of loss at a scale from 0 (no loss) to 1 (total loss). Fragility curves express the probability of exceedance of a certain level of loss for a range of landslide intensity.

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:

- Judgemental / Heuristic: The vulnerability values are assessed by expert criterion. The results are approximate.
- Empirical: The vulnerability values are assessed based on the damage from historical event data, usually by statistical back-analysis. The obtained results are more realistic than in the previous case as they fit real-event data.
- Analytical: The vulnerability values are assessed by straightforward analytical simulation, using as an input the intensity of the phenomenon and the characteristics of the exposed

elements. The analysis methods vary according to the type of the exposed element. The results provide a higher level of detail than in the previous cases.

The choice of methodology depends directly on the scale and the coverage area of the vulnerability assessment. The existence and quality of the input data also plays a fundamental role.

For small regional scales, where only an approximate overview of the vulnerability is required and where there is little detailed input data, judgmental criteria are mostly used. For large regional and local scales, , either judgmental or empirical criteria might be used depending on the input data that is available. For site-specific scales the vulnerability assessment might be either empirical or analytical. The latter applies where the required level of detail is high and the acquisition of precise input data is feasible.

In the following, some recommendations are given based on a review of the actual practices which are applied by administrative authorities and research institutes. In many cases the proposed methodologies do not distinguish between the different processes and thus are included in the table of general landslides.

The methodologies are presented separately for buildings, roads and vehicles, and people. For the latter, information is given for the vulnerability of individual persons (referring to individual risk), as well as for the societal vulnerability which expressed the probability of one or mote fatalities in an area.

8.1.6.1 Rockfalls

Buildings

Leone et al (1996) proposed a judgmental/empirical damage scale for the vulnerability of buildings that correlates damage states and loss with vulnerability values. Heinimann (1999) attributed vulnerability values to buildings considering different structural typologies and three levels of rockfall intensities. AGSO (2001) proposed fixed vulnerability values for buildings, persons and roads independently of the rockfall intensity. Glade and Elverfeldt (2005) also proposed fixed vulnerability values for buildings for three levels of hazard (low, medium, high).

Uzielli and Lacasse (2007) and Uzielli (2008) developed a methodology for the physical vulnerability due to landslides, which is defined as a function of landslide intensity and susceptibility of vulnerable elements, based on expert judgment and empirical data. The methodology permits the incorporation of uncertainties, based on empirical data.

Agliardi et al (2009) proposed the back-analysis of real event damage data for the development of correlation functions between rockfall intensity and vulnerability of buildings due to rockfalls by regression.

Mavrouli and Corominas (2010a and 2010b), developed an analytical methodology for the calculation of the vulnerability of reinforced concrete structures, which are impacted at their base by single fragmented rockfalls. The methodology considers the potential for progressive collapse when key elements are destroyed by rockfall impact and proposed the quantification of vulnerability in function of the potential impact locations and the respective damage.

Table 8.4 Methods for assessing vulnerability of the exposed elements for rockfalls

ROCKFALLS	JUDGMENTAL / HEURISTIC	EMPIRICAL	ANALYTICAL	*scale*
BUILDINGS	Leone (1996), Heinimann (1999), AGSO (2001), Glade and Elverfeldt (2005),	Agliardi et al. (2009), Uzielli and Lacasse (2007), Uzielli (2008 AND 2010), Li et al. (2010)		regional
	Leone (1996), Heinimann (1999), AGSO (2001), Glade and Elverfeldt (2005)	Agliardi et al. (2009)		local
	Leone (1996), Heinimann (1999)		Mavrouli and Corominas (2010a and 2010b)	site-specific
ROADS AND VEHICLES				regional
			Bunce et al. (1997), Fell (2005)	local
			Bunce et al. (1997), Fell (2005)	site-specific
PERSONS (FOR INDIVIDUAL AND SOCIETAL RISK)	AGSO (2001), Glade and Elverfeldt (2005)	Wong et al. (1997), Finlay and Fell (1995), Uzielli and Lacasse (2007), Uzielli (2008 AND 2010), Li et al. (2010)		regional
	AGSO (2001), Glade and Elverfeldt (2005)	Wong et al. (1997), Finlay and Fell (1995),		local
	AGSO (2001), Glade and Elverfeldt (2005)	Wong et al. (1997), Finlay and Fell (1995),Uzielli and Lacasse (2007), Uzielli (2008 AND 2010), Li et al. (2010)		site-specific

Roadways and vehicles

Bunce et al. (1997) and Fell (2005) provided examples for the calculation of the probability of impact of rock falls on stationary and moving vehicles. Roberds (2005) provided a general framework for the vulnerability of roadways including impact of rock on vehicles as well as vehicles crushes on rock and follow-up accidents.

Persons

Glade and Elverfeldt (2005) proposed fixed vulnerability values for persons for three levels of hazard (low, medium, high). The vulnerability of persons at open space, in vehicle and in building can also be quantified using the the suggestion by AGSO (2001). Wong et al. (1997) and Finlay and Fell (1995) suggested vulnerability values for persons based on real event data for fatalities arising from landslide debris for rockfalls and debris flow, depending on where they are located geographically at the moment of the event (open space, vehicle, building). They also correlated the loss (injury or death) with these vulnerability values.

8.1.6.2 Debris flows

Buildings

Leone et al (1996) proposed a damage scale for the vulnerability of buildings that correlates damage states with vulnerability values, also for debris flow. Michael-Leiba et al. (2000) proposed fixed vulnerability values for buildings (as well as for persons and roads). Glade and Elverfeldt (2005) also proposed fixed vulnerability values for buildings for three levels of hazard (low, medium, and high), due to debris flow. Wong et al. (1997) proposed single vulnerability values for buildings impacted by debris flow depending on whether the debris depth is enough to cover a person or not, or to cause collapse. Borter (1999) suggested vulnerability values for the building structure in dependence on the debris flow intensity (low, medium, high). A range of magnitudes corresponding to these vulnerability values is also provided. Fuchs et al. (2007), based on real event damage data and through relation developed a vulnerability function is proposed, linking debris intensity (depth) to vulnerability values. The damage of the buildings for the real events was evaluated by expert criterion. The vulnerability due to debris flow can be expressed probabilistically following the methodology proposed by Uzielli (2008) and Li (2010). Fragility curves maybe produced for debris flow, for un-reinforced masonry structures and reinforced masonry structures using an analytical model proposed by Haugen and Kaynia that implements the HAZUS software. It can be implemented in a GIS platform and applied from site-specific to regional scale. The method uses the principles of dynamic response of simple structures to earthquake excitation

Roadways and vehicles

Leone (1996), Michael-Leiba et al. (2000), and Glade and Elverfeldt (2005) make respective suggestions for the vulnerability of roads as for persons (see previous paragraphs), which are exposed to debris flow. Winter et al. (2009), calculation the risk to life and limb of road users based on traffic flow and proposed diversion scores based on informed judgments of the potential consequences of a closure on the trunk road network within a given location.

A methodology for the vulnerability assessment of roadway systems due to debris flow hazard is developed in SAFELAND based on expert judgment and empirical criteria (WP2.2-D2.5). The method is based on the conduction of a questionnaire that is distributed to experts on debris flow and damage to roads. After a statistical analysis of the experts' responses, fragility curves are developed for different road typologies (local, high speed) and damage states (limited, serious, destroyed) as a function of the volume of material deposited on a road following a debris flow.

Table 8.5 Methods for assessing vulnerability of the exposed elements for debris flow

DEBRIS FLOW	JUDGMENTAL / HEURISTIC	EMPIRICAL	ANALYTICAL	*scale*
BUILDINGS	Leone (1996), Michael-Leiba et al. (2000), AGSO (2001), Glade and Elverfeldt (2005),	Wong et al. (1997), Uzielli and Lacasse (2007), Uzielli (2008), Kaynia et al. (2008), Li et al. (2010)	Haugen and Kaynia (2008)	regional
	Leone (1996), AGSO (2001), Glade and Elverfeldt (2005),	Wong et al. (1997)	Haugen and Kaynia (2008)	local
	Leone (1996)	Wong et al. (1997), Fuchs et al. (2007)	Haugen and Kaynia (2008)	site-specific
ROADS AND VEHICLES	Leone (1996), Michael-Leiba et al. (2000), Glade and Elverfeldt (2005),	Winter et al. (2009)		regional
	Leone (1996), Glade and Elverfeldt (2005),	Roberds (2005)	Roberds (2005)	local
	Leone (1996)	Roberds (2005)	Roberds (2005)	site-specific
PERSONS (FOR INDIVIDUAL AND SOCIETAL RISK)	Leone (1996), Michael-Leiba et al. (2000), AGSO (2001), Glade and Elverfeldt (2005),	Wong et al. (1997), Finlay and Fell (1995), Uzielli and Lacasse (2007), Uzielli (2008)		regional
	Leone (1996), AGSO (2001), Glade and Elverfeldt (2005),	Wong et al. (1997), Finlay and Fell (1995)		local
	Leone (1996)	Wong et al. (1997), Finlay and Fell (1995)		site-specific

Persons

Leone (1996) proposed a damage scale for the vulnerability of person that correlates the injury or loss with vulnerability values, also for debris flow. Michael-Leiba et al. (2000) proposed fixed vulnerability values for persons impacted by debris flow. AGSO (2001) also AGSO (2001) suggests fixed vulnerability values for debris independent from their intensity. Glade and Elverfeldt (2005) also proposed fixed judgmentally- based vulnerability values for persons for three levels of hazard (low, medium, high). Wong et al. (1997) proposed vulnerability values for persons based on death arising from landslide debris depending on whether they are located at the moment of the event (open space, vehicle, building). They also correlated the loss (injury or death) with these vulnerability values. Finlay and Fell (1995) also used these values.

8.1.6.3 Landslides (general)

Buildings

Leone et al. (1996) introduced the use of vulnerability matrices that correlate, in terms of vulnerability, the exposed elements to the characteristics of landslides. Its applicability also requires statistical analysis of detailed records on landslides and their consequences. AGSO (2001) proposed fixed vulnerability values for buildings, persons and roads for landslides. Remondo et al. (2008) performed a detailed inventory of exposed buildings to the study area to assess landslide vulnerability. Vulnerability values (0–1) were obtained by comparing damages experienced in the past by each type of building with its actual momentary value. The derived vulnerability values express the degree of potential monetary loss with respect to the total value of the element. Zêzere et al. (2008) estimated the vulnerability of buildings in regional/local scale under different landslide hazards based on the empirical or historic data, in conjunction with available data on buildings concerning age (state of maintenance), construction material and function. Uzielli et al. (2008) developed a method for scenario-based, quantitative estimation of physical vulnerability of the built environment to landslides based on expert judgment and empirical data. Vulnerability is defined quantitatively as a function of landslide intensity and the susceptibility of vulnerable elements. The method allows explicit consideration of the uncertainties in the parameters and models. Kaynia et al. (2008) explored the applicability of this methodology based on the First-Order Second-Moment (FOSM) approach to estimate landslide risks in regional scale. Li et al. (2010) based on the work of Uzielli et al. (2008) and Kaynia et al. (2008) proposed a quantitative model for vulnerability of buildings based on landslide intensity and resistance of exposed elements. A different approach was followed for slow moving and rapid slides.

Fotopoulou et al. (2011) developed an analytical methodology for the vulnerability assessment of RC buildings subject to earthquake triggering relative slow moving slides. The vulnerability is defined through specific probabilistic fragility functions for specified limit states. The fragility curves are numerically estimated in terms of peak ground acceleration at the “seismic bedrock”, versus the probability of exceedance of each limit state. A two steps uncoupled analysis is performed. In the first step, the differential permanent displacements at the building’s foundation level are estimated using a finite difference dynamic slope model. Gradually increasing acceleration time histories are applied at the base of the model to assess the building’s foundation response and the associated ground displacements are computed accordingly. Then, the calculated differential displacements are applied as input to building’s foundation model to assess the building’s response for different ground landslide displacements induced by the earthquake. Limit states are defined in terms of a threshold value of building’s material strain. The numerical (static time history) analyses of the buildings are performed through a fiber-based finite element code. The developed methodology is applied to different soil types, slopes geometries and building configurations allowing explicit consideration of various sources of uncertainties.

Roadways and vehicles

AGSO (2001), Remondo et al. (2008), Zêzere et al. (2008), Uzielli et al. (2008), Kaynia et al. (2008) and Li et al. (2010) developed relevant models for the vulnerability assessment of transport infrastructure as for buildings and Roberds (2005) provided a general framework for the vulnerability of roadways and vehicles.

Persons

Uzielli et al. (2008), Kaynia et al. (2008) and Li et al. (2010), as for other landslide types, developed analogous models for the vulnerability assessment of persons in open space, in vehicles and in buildings. Fell (2005), provides indications for the development of F-N curves as well as Wong et al. (1997), who additionally indicates how event trees can be used to this purpose

Table 8.6 Methods for assessing vulnerability of the exposed elements for landslides (general)

LANDSLIDES (general)	JUDGMENTAL / HEURISTIC	EMPIRICAL	ANALYTICAL	*scale*
BUILDINGS	AGSO (2001)	Uzielli and Lacasse (2007), Zêzere et al. (2008), Uzielli (2008), Kaynia et al. (2008), Remondo et al. (2008), Li et al. (2010)		regional
	AGSO (2001)	Remondo et al. (2008), Zêzere et al. (2008)		local
			Fotopoulou et al. (2010)	site-specific
ROADS AND VEHICLES	AGSO (2001)	Zêzere et al. (2008), Kaynia et al. (2008), Remondo et al. (2008), Li et al. (2010)		regional
	AGSO (2001), Roberds (2005)	Remondo et al. (2008), Zêzere et al. (2008), Roberds (2005)		local
				site-specific
PERSONS (FOR INDIVIDUAL AND SOCIETAL RISK)	AGSO (2001)	Kaynia et al. (2008), Li et al. (2010), Wong (2005), Fell et al. (2005), Leroi et al. (2005), Guzzetti et al. (2005), Wong et al. (1997), Finlay and Fell (1995)		regional
	AGSO (2001)	Kaynia et al. (2008), Li et al. (2010), Wong (2005), Fell et al. (2005), Leroi et al. (2005), Wong et al. (1997), Finlay and Fell (1995)		local
		Kaynia et al. (2008), Li et al. (2010), Wong (2005), Fell et al. (2005), Leroi et al. (2005), Wong et al. (1997), Finlay and Fell (1995)		site-specific

8.1.7 Social vulnerability

Liu (2006) proposed that social vulnerability is a sum function of both property and population vulnerability. Assessment indexes include the assets of buildings, traffic facilities, lifeline works, personal properties, and land resources for property vulnerability; age, education, and wealth of the inhabitants, natural population growth rate, and population density for population vulnerability...

Landslides rarely have socio-economic consequences at the global or national level, thus social vulnerability is usually assessed at a regional or local scale. Semi-quantitative methods are most commonly used. The latter are based on appropriate indicators (demographic, social, economic as well as those related to the level preparedness and capacity for recovery in a region) which can be weighted according to their influence on the total vulnerability of a society.

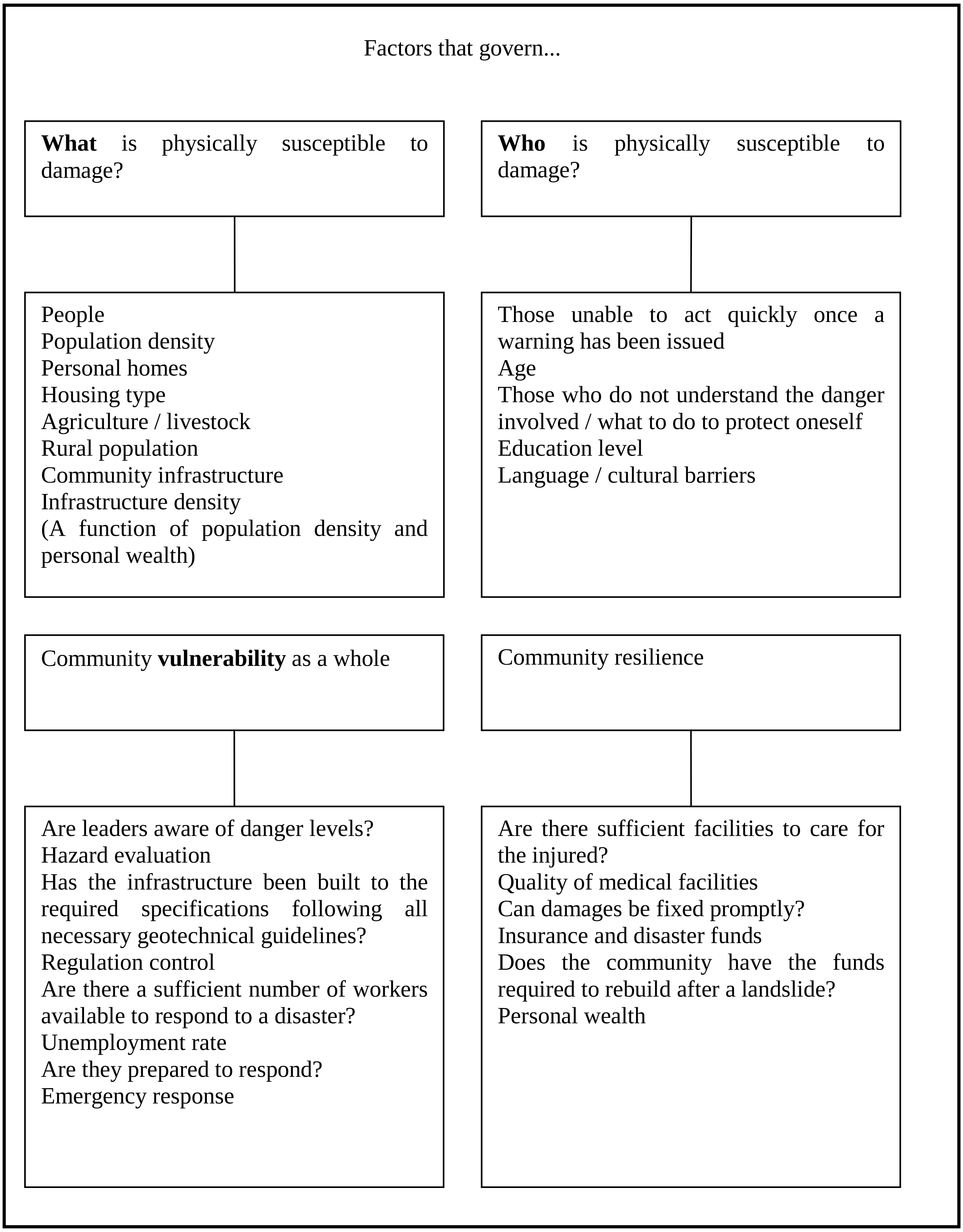
Within the Safeland project a vulnerability model has been developed (Deliverable 2.6: Methodology for evaluation of the socio-economic impact of landslides), based on a scoring system where the total score for each indicator is assessed according to the ranking rules described in the method. The final vulnerability value is a weighted average of the vulnerability indicator score values. The reasoning for using a semi-quantitative model based on a scoring system is:

Data availability: The ranking of indicators which can be made into 5 vulnerability classes requires less data than assessing a quantitative value to each indicator. Thus, such a model is more suitable for the level of detail (and budget...) in this study.

The possibility for combining qualitative and quantitative indicators: Through predefined ranking criteria for indicators, both quantitative and qualitative indicators may be ranked and combined into a semi-quantitative vulnerability parameter.

Validation of model: an explicit model expressing societal vulnerability quantitatively as the degree of loss (or probability of loss) does not exist.

For the selection of the indicators to be included in landslide vulnerability models the factors that should be considered are shown in Figure 8.3 (Safeland project, Deliverable 2.6: Methodology for evaluation of the socio-economic impact of landslides).



Factors that govern...

What is physically susceptible to damage?

People
Population density
Personal homes
Housing type
Agriculture / livestock
Rural population
Community infrastructure
Infrastructure density
(A function of population density and personal wealth)

Who is physically susceptible to damage?

Those unable to act quickly once a warning has been issued
Age
Those who do not understand the danger involved / what to do to protect oneself
Education level
Language / cultural barriers

Community **vulnerability** as a whole

Are leaders aware of danger levels?
Hazard evaluation
Has the infrastructure been built to the required specifications following all necessary geotechnical guidelines?
Regulation control
Are there a sufficient number of workers available to respond to a disaster?
Unemployment rate
Are they prepared to respond?
Emergency response

Community resilience

Are there sufficient facilities to care for the injured?
Quality of medical facilities
Can damages be fixed promptly?
Insurance and disaster funds
Does the community have the funds required to rebuild after a landslide?
Personal wealth

Figure 8.3 Factors that should be considered for the social vulnerability

The selection of vulnerability indicators can be based on the similar works made by: Castellanos Abella and Van Westen, 2007, Coburn et al. 1994; Leone et al. 1996; International Federation of Red Cross and Red Crescent Societies 1999; CEPAL and BID 2000; Commission on Sustainable Development 2002; Manoni et al. 2002; vanWesten 2002; Barbat 2003; Glade 2003; United Nations Development Program 2004; UNPD 2004.

The availability of data for the indicators should also be considered for their selection as well as particular local conditions (for example, the existence of protected zones, culturage heritage structures etc.).

References

AEA (2008) Preliminary assessment and roadmap for the elaboration of Climate Change Vulnerability Indicators at regional level. Reference: ENV.G.1/ETU/2008/0092r. Final Report to the European Commission. Restricted Commercial. ED45669. Issue Number 3. AEA, London.

AGS, 2007. Guideline for landslide susceptibility, hazard and risk zoning for land use management. Australian geomechanics society landslide taskforce landslide zoning working group. Australian Geomechanics 42 (1), 13–36.

AGSO, 2001. Natural hazards an the risk they pose to South-East Queenland. AGSO-Geoscience Australia. Digital report on CD-ROM. 389 Pages

Agliardi, F., Crosta, G.B. and Frattini, P.: Integrating rockfall risk assessment and countermeasure design by 3D modelling techniques, Nat. Hazards Earth Syst. Sci., 9: 1059-1073, 2006.

Barbat AH (2003) Vulnerability and disaster risk indices from engineering perspective and holistic approach to consider hard and soft variables at urban level. Information and indicators program for disaster risk management. Universidad Nacional de Colombia, Manizales, Colombia, p 19

Bird, J.F., Crowley, H., Pinho, R., Bommer, J.J. “Assessment of building response to liquefaction induced differential ground deformation”. Bulletin of the New Zealand Society for Earthquake Engineering 38 (4):215-234, 2006.

Borter, P.: Risikoanalyse bei gravitativen Naturgefahren, Bundesamt für Umwelt, Wald und Landschaft, Bern, 1999.

Bunce, C.M., Cruden, D.M. and Morgenstern, N.R. 1997. Assessment of the hazard from rockfall on a highway. Canadian Geotechnical Journal, 34: 344-356

Cascini, L., Bonnard, Ch., Corominas, J., Jibson, R., Montero-Olarte, J., 2005. Landslide hazard and risk zoning for urban planning and development. In: Hungr, O., Fell, R., Couture, R., Eberthardt, E. (Eds.), Landslide Risk Management. Taylor and Francis

Castellanos Abella, E.A. and van Westen, C.J. (2008) Qualitative landslide susceptibility assessment by multicriteria analysis : a case study from San Antonio del Sur, Guantánamo, Cuba. In: Geomorphology : an international journal of pure and applied geomorphology, 94 (2008)3-4, pp. 453-466.

CEPAL, BID (2000) A matter of development: how to reduce vulnerability in the face of natural disasters. CEPAL-DIB, Mexico

Coburn AW, Sspence RJS, Pomonis A (1994) Vulnerability and risk assessment. Disaster management training programme. Cambridge Architectural Research, Cambridge, UK, p 70

Commission on Sustainable Development (2002) Natural disaster and sustainable development: understanding the links between development. environment and natural disasters. Background paper No. 5, United Nations International Strategy for Disaster Reduction

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

Finlay, P.J., and Fell, R. A study of landslide risk assessment for Hong Kong. The University of New South Wales, Sydney, Australia (School of Engineering Report). 1995.

Fotopoulou, S., Pitilakis K., Anagnostopoulos, C. (2011). “Vulnerability Assessment of RC buildings due to earthquake induced slow moving slides”. 5th international Conference on Earthquake Geotechnical Engineering, Santiago, Chile.

Fuchs, S., Heiss, K., & Hóbl, J. 2007: Towards an empirical vulnerability function for use in debris flow risk assessment. Natural Hazards and Earth System Sciences 7: 495-506.

Glade T (2003) Vulnerability assessment in landslide risk analysis. Beitr Erdsystemforschung134(2):123–146

Glade, T. & Elverfeldt, K.v: MultiRISK: An innovative Concept to model Natural Risks.In Vancouver Geotechnical Society (ed.) Landslide risk management, Vancouver, 31.05. - 04.06.2005.

Guzzetti, F. (2005). Landslide Hazard and Risk Assessment. In: PHD thesis, Mathematics-Scientific faculty, University of Bonn, Bonn, Germany, 389.

Guzzetti F., Salvati P. & Stark C.P. (2005) Evaluation of risk to the population posed by natural hazards in Italy. In: Hungr et al. (eds.) Landslide Risk Management. 381-389.

Heinimann, H.R.: Risikoanalyse bei gravitativen Naturgefahren - Fallbeispiele und Daten, Umwelt-Materialen 107/I, Bern, 1999.

International Federation of Red Cross and Red Crescent Societies (1999) Vulnerabilityand capacity assessment. An international federation guide. International Federation of Red Cross and Red Crescent Societies, Geneva, p 29

Kaynia A., Papathoma-Köhle M., Neuhaeuser B., Ratzinger K., Wenzel H., Medina-Cetina Z.: Probabilistic Assessment of Vulnerability to Landslide: Application to the village of Lichtenstein, Baden-Württemberg, Germany. Engineering Geology. 101, 33-48. 2008.

King D and MacGregor C : Using social indicators to measure community vulnerability to natural hazards. Aust J Emerg Manage 15(3):52–57, 2000.

Leone, F., Aste, J.P., and Leroi, E.: L’évaluation de la vulnerabilité aux mouvements de terrain. Revue de géographie alpine. 84(1): 35–46, 1996.

Leroi, E., Bonnard, Ch., Fell, R., McInnes, R. (2005) Risk assessment and management In: Hungr, O., Fell, R., Couture, R., Eberhardt, E. (Eds.), Landslide Risk Management.Taylor and Francis, London, pp. 159–198.

Li, Z., F. Nadim, Huang H., Uzielli, M., Lacasse, S.: Quantitative vulnerability estimation for scenario-based landslide hazards." Landslides, pp. 1-10, 2010.

Liu (2006): Site-specific Vulnerability Assessment for Debris Flows: Two Case Studies, Journal of Mountain Science Vol 3 No 1 (2006): 20~27

Manoni S, Pergalani F, Boni MP, Petrini V (2002) Lifelines earthquake vulnerabilityassessment: a systemic approach. Soil Dyn Earthqu Eng 22:1199–1208

Mansour, M.F., Morgenstern N. I., Martin, C. D.: Expected damage from displacement of slow-moving slides, Landslides, 2010.

Mavrouli, O. and Corominas, J.: Vulnerability of simple reinforced concrete buildings in front of the rockfall impact, Landslides, 7 (2): 169-180, 2010a.

Mavrouli, O. and Corominas, J.: Rockfall vulnerability assessment for reinforced concrete buildings. Natural Hazards and Earth System Sciences, 10: 2055-2066, 2010b

Michael-Leiba, M., Baynes, F., and Scott, G.: Quantitative landslide risk assessment of Cairns, Australia, in E. Bromhead., N. Dixon and M-L. Ibsen (eds.), Landslides in Research, Theory and Practice, 3 volumes, Proceedings of VIII International Symposium on Landslides, Cardiff,Wales, 26–30 June 2000, Thomas Telford, London 2, pp. 1059–1064. 2000.

Remondo, J., Bonachea, J., Cendrero A : Quantitative landslide risk assessment and mapping on the basis of recent occurrences." Geomorphology 94: 496-507, 2008.

Roberds, W., 2005. Estimating temporal and spatial variability and vulnerability. In: Hungr, O., Fell, R., Couture, R., Eberhardt, E. (Eds.), Landslide Risk Management. Taylor and Francis, London, pp. 129–158.

Tapsell, S; McCarthy, S; Faulkner, H & Alexander, M (2010): Social Vulnerability and Natural Hazards. CapHaz-Net WP4 Report, Flood Hazard Research Centre – FHRC, Middlesex University, London (available at: http://caphaz-net.org/outcomes-results/CapHaz-Net_WP4_Social-Vulnerability.pdf).

United Nations Development Program (2004) Human development report 2004. United Nations, New York, p 299

UNPD (2004) Reducing disaster risk. A challenge for development. A global report.

Uzielli, M., Nadim, F., Lacasse, S., Kaynia, and A.M.: A conceptual framework for quantitative estimation of physical vulnerability to landslides, Eng. Geol. 102: 251–256, 2008.

Uzielli, M., Lacasse, S. Probabilistic estimation of vulnerability to landslides. Proceedings of the 13th Panamerican Conference on Soil Mechanics and Geotechnical Engineering. Margarita, July 16-20, 2007 (CD-ROM). 2007

Van Westen, C.J. (2004): Geo-Information tools for landslide risk assessment: an overview of recent developments. Proceedings of the IX International Symposium on Landslides, Lacerda, Ehrlich, Fontoura & Sayão (eds.), 1, A.A. Balkema Publishers, 39-56.

Van Westen CJ (2002) Hazard, vulnerability and risk analysis (http://www.itc.nl/ilwis/applications/application01.asp). ILWIS 2.1 Applications Guide. ITC

Winter, M.G., Macgregor, F., & Shackman, L. (2009) Hazard Rankings. In: Winter, M.G., Macgregor, F., & Shackman, L. (eds.), Scottish Road Network Landslides Study: Implementation. Transport Scotland, Edinburgh. Pp. 82-87

Wong, H.N., 2005. Landslide risk assessment for individual facilities. In: Hungr, O., Fell, R., Couture, R. Eberhardt, E. (Eds.), Landslide Risk Management. Taylor and Francis, London, pp. 237–298.

Wong, H.N., Chen, Y.M., Lam, K.C.:. Factual Report on the November 1993 Natural Terrain Landslides in Three Study Areas on Lantau Island. GEO Report No. 61, Geotechnical Engineering Office, Hong Kong, 42 pp.. 1997.

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

8.2 RISK ASSESSMENT METHODS

(ETHZ and ICG)

8.2.1 Risk management process

Risk assessment is part of an integrated risk management process where critical decisions must be made. Many risk management frameworks have been suggested in the literature, as well as in various guidelines and codes of practice. Figure 8.1 provides one such example of a framework for risk management. All these frameworks have the common objective of answering the following questions (modified from Lee and Jones 2004):

- What are the dangers and their magnitude? [Danger Identification]
- How often can the dangers of a given magnitude occur? [Hazard Analysis]
- What are the elements at risk? [Elements at Risk Identification]
- What is the potential damage to the elements at risk? [Vulnerability Assessment]
- What is the probability of damage? [Risk Estimation]
- What is the significance of the estimated risk? [Risk Evaluation]
- What should be done? [Risk Management]

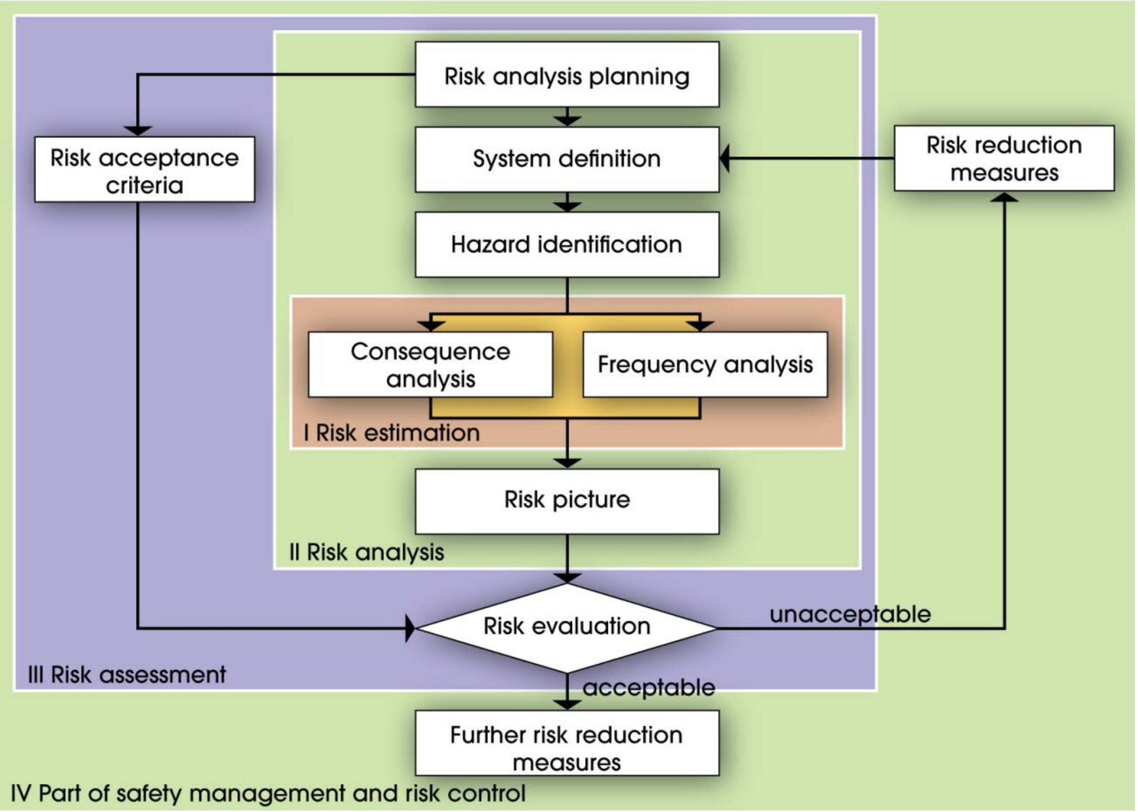


Figure 8.4 Risk estimation, analysis and evaluation as part of risk management and control (NORSOK Standard Z-013, 2001).

Fell *et al*. (2005) made a comprehensive overview of the state-of-the-art in landslide risk management. Figure 8.2 illustrates the integrated process for the assessment and management of the risk associated with landslide(s) suggested by Fell *et al.* (2005).

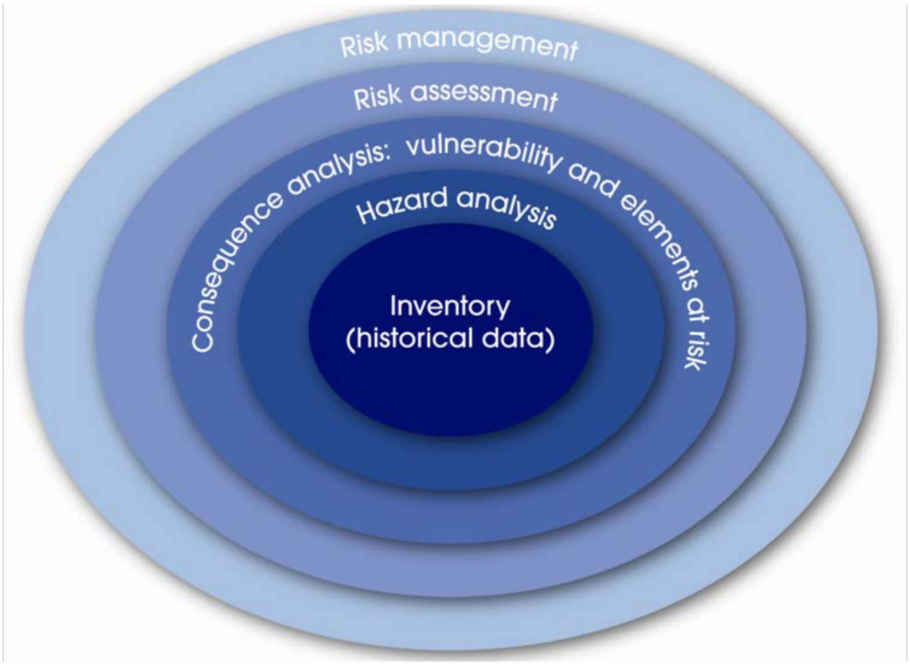


Figure 8.5 Integrated risk management process including risk assessment, starting with inventory of landslides at a location (modified from Fell *et al.* 2005)

Figure 8.3 summarises a general procedure for risk assessment for landslides. The key issue is the identification of potential triggers and their probability of occurrence, the associated failure modes and their consequences (Lacasse *et al.* 2010).

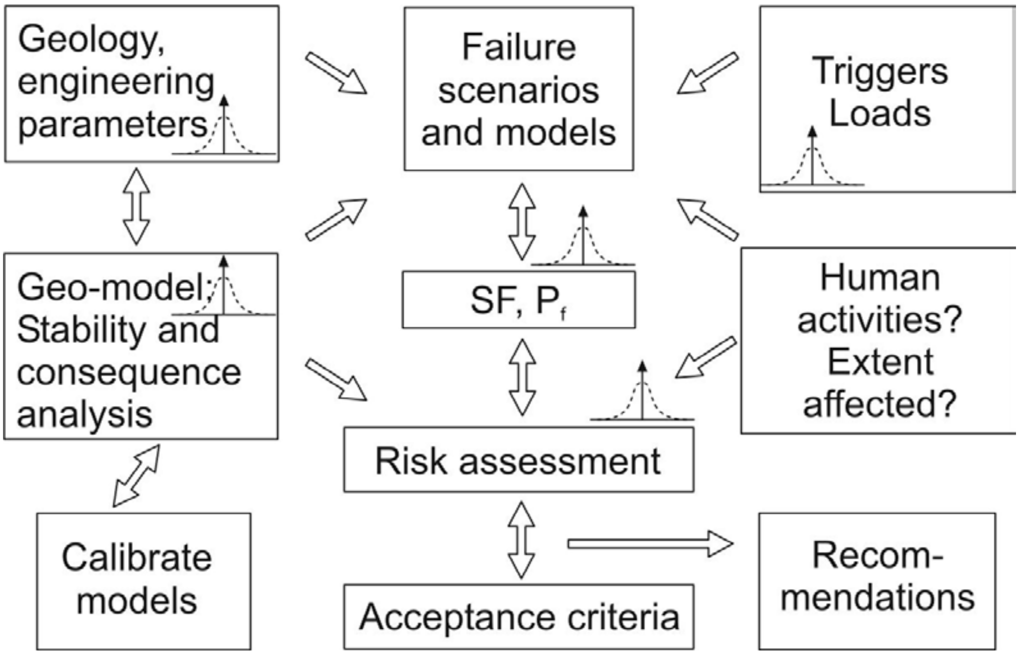


Figure 8.6 Procedure for risk assessment of slopes (Lacasse *et al.* 2010)

8.2.2 Elements at risk and their exposure to landslide(s)

A key step in quantitative landslide risk assessment is the identification of the “elements at risk” and the estimation of the outcome or “consequence” of the landslide event on these elements. In most landslide risk assessment studies reported in the literature (e.g. Agliardi *et al.* 2009, Bell and Glade 2004, Bründl et al. 2009, Cardinalli *et al.* 2002, Cassidy *et al.* 2008, Corominas *et al.* 2005, Dai *et al.* 2002, Evens *et al.* 2005, Guzzetti *et al*. 2003, Guzzetti *et al.* 2004, Hungr *et al.* 1999, Jaiswal *et al*. 2010, Lee *et al.* 2000, Lee and Jones 2004, Remondo *et al.* 2005, Wu *et al.* 1996) the elements at risk are persons, properties and infrastructure, although other consequential economic or environmental costs could also be considered.

In most landslide risk assessment studies, the focus is on the loss of human life. The expected number of fatalities depends on many factors, for example on which week-day and what time of the day the landslide occurs, whether a warning system is in place and working, etc. The potentially affected population could be divided into groups based on for example the temporal exposure to the landslide: people living in houses that are in the path of the potential landslide, locals in the area who happen to be passer-bys and tourists and/or workers who are coincidentally at the location during certain periods of the day of the year. The concept of spatial and temporal “exposure” is thus quite important in any landslide risk assessment. Lee and Jones (2004) define landslide exposure as “*the proportion of each category of element at risk expected to be effected by the landslide event*”. This is similar to the UNISDR definition of exposure quoted in Chapter 2. Temporal exposure is important for certain classes of landslides and mobile elements at risk, such as persons and cars. The quantitative assessment of temporal exposure is more difficult and challenging than the assessment of spatial exposure.

In a risk assessment framework, exposure is sometime considered as a component of vulnerability (e.g. Li *et al.* 2010, MOVE (Methods for the Improvement of Vulnerability Assessment in Europe EU FP7 project) and sometimes as a separate component in the risk equation (e.g. Fell *et al.* 2005). It may also be argued that temporal exposure should be included in the hazard assessment for the specific element(s) at risk. In practice, it does not matter whether exposure is evaluated explicitly or whether it is included as a component of vulnerability or hazard. The important issue is that it must be estimated and included in landslide risk assessment in a consistent manner.

8.2.3 Representation of reference area for risk assessment

In any consequence analysis, a reference area must be established. This is always a user-defined input to the analysis and therefore carries significant subjective judgment. The reference area encloses the totality of the elements at risk, and its size is often determined by the physical limits of the landslide. However, in many situations the consequences of a landslide are felt well beyond these physical limits. For example, a large landslide closing a major highway or railway link may have significant economic consequences for the communities that are connected by that artery. Therefore the definition and characterisation of a suitable “system” for analysis is a crucial step in landslide risk assessment.

Such a system representation can be performed in terms of logically interrelated constituents at various levels of detail or scale in time and space. Constituents may be physical components, procedural processes and human activities. The appropriate level of detail or scale depends on the physical or procedural characteristics or any other logical entity of the considered problem as well as the spatial and temporal characteristics of consequences. The important issue when a system model is developed is that it facilitates a risk assessment and risk ranking of decision alternatives which is consistent with available knowledge about the system and which facilitates that risks may be updated according to knowledge which may be available at future times.

The risk assessment for a given system is facilitated by considering the generic representation shown in Figure 8.7.

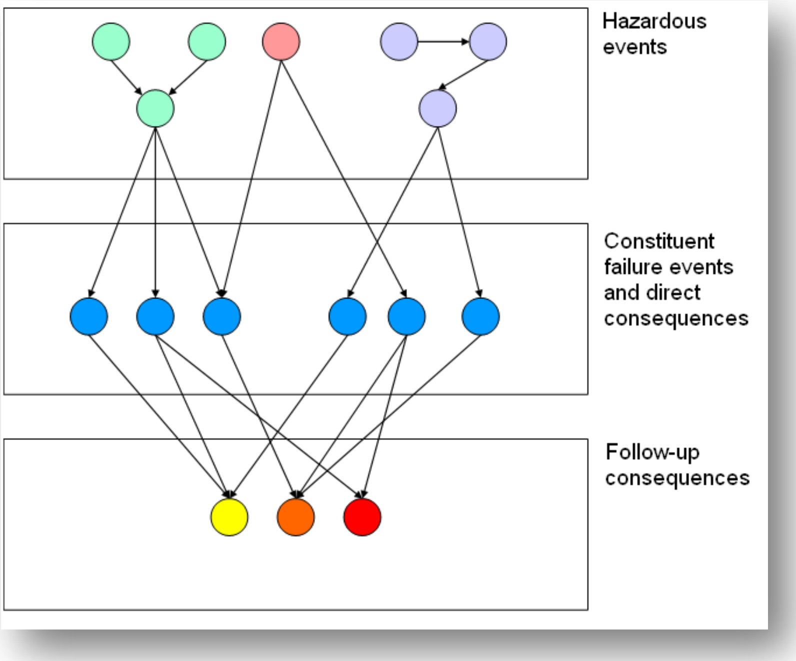


Figure 8.7 Generic representation used for the risk assessment of a system

Following Faber and Maes (2005), the damages of the constituents are considered to be associated with direct consequences. Direct consequences may include monetary losses, loss of lives, damages to the qualities of the environment or just changed characteristics of the constituents. Direct consequences, are thus defined as all marginal (not considering loss of system functionality) consequences associated with damages or failures of the constituents of the system. Based on the combination of events of constituent failures and the corresponding consequences, follow-up or indirect consequences may occur. Indirect consequences may be caused by e.g. the sum of monetary losses associated with the constituent failures and the physical changes of the facility as a whole caused by the combined effect of constituent failures. The indirect consequences in risk assessment play a major role and their modelling should be carefully considered (Faber and Maes 2004). Typically the indirect consequences evolve spatially beyond the boundaries of the facility and also have a certain sometimes even postponed development in time.

It should be understood that the system representation outlined above is only meaningful subject to a definition of what are considered to be hazard events; constituents of the system, their vulnerabilities and exposures; and direct and indirect consequences.

8.2.4 Modelling of uncertainties

Knowledge about the considered system context is a main success factor for risk assessment and optimal decision making. In the real world, uncertainty or lack of knowledge however characterizes the normal situation and it is thus necessary to be able to represent and deal with this uncertainty in a consistent manner. Bayesian statistics provides a basis for the consistent representation of uncertainty independent of their source and readily facilitates for the joint consideration of purely subjectively assessed uncertainties, analytically assessed uncertainties and evidence as obtained through observations.

There exist a large number of propositions for the characterization of different types of uncertainties. It has become standard to differentiate between uncertainties due to inherent natural variability, model uncertainties and statistical uncertainties. Whereas the first mentioned type of uncertainty is often denoted aleatory (or Type 1) uncertainty, the two latter are referred to as epistemic (or Type 2) uncertainties. Aleatory uncertainty is inherent to the heterogeneity which is present in virtually all parameters related to consequence evaluation. Epistemic uncertainty is composed essentially of measurement uncertainty, statistical estimation uncertainty and transformation uncertainty. Statistical estimation uncertainty results from possible bias in sample statistics due to limited sample numerosity. Measurement uncertainty derives from equipment, operator/procedural and random measurement effects. Transformation uncertainty is due to the approximations and simplifications inherent in empirical, semi-empirical, experimental or theoretical models used to relate measured quantities to non-measurable numerical parameters used in estimation. The absolute and relative magnitudes of aleatory and epistemic uncertainty are markedly case-specific.

This differentiation in uncertainties is introduced for the purpose of setting focus on how uncertainty may be reduced, rather than calling for a differentiated treatment in the risk assessment and decision analysis process. Epistemic uncertainty can be reduced by increasing the amount of data; however, aleatory uncertainty may remain unchanged, or even increase, with additional data and improved knowledge about the underlying variability of the paratmeters. In reality, the differentiation into aleatory uncertainties and epistemic uncertainties is subject to a defined model of the considered system. Any risk assessment process requires that all uncertainties are considered and treated in a consistent manner. The relative contribution of the two components of uncertainty depends on the spatial and temporal scale applied in the model. The risk assessment should hence include a description of all relevant assumptions made in connection with the system identification, as well as the modelling of consequences and frequencies. The level and type of knowledge available to support the assumptions, as well as the modelling of consequences and frequencies, should be explicitly stated and included in the risk analyses if relevant.

References

Agliardi, F, Crosta, G.B., Frattini, P. 2009. Integrating rockfall risk assessment and countermeasure design by 3D modelling techniques. Natural Hazards and Earth System Sciences, 9, 1059–1073

Bell, R., Glade, T. 2004. Quantitative risk analysis for landslides - Examples from Bvldudalur, NW-Iceland. Natural Hazards and Earth System Sciences, 4(1): 117-131

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

Cardinalli, M.; Reichenbach, P.; Guzzetti, F.; Ardizzone, F.; Antonini, G.; Galli, M.; Cacciano, M.; Castellani, M. & Salvati, P. 2002. A geomorphological approach to the estimation of landslide hazards and risk in Umbria, Central Italy. Natural Hazards and Earth Systems Sciences, 2: 57-72

Cassidy, M.J., Uzielli, M., Lacasse, S. 2008. Probability risk assessment of landslides: A case study at Finneidfjord. Canadian Geotechnical J. 45: 1250-1267

Corominas, J., Copons, R., Moya, J., Vilaplana, J.M., Altimir, J., Amigó, J. 2005. Quantitative assessment of the residual risk in a rockfall protected area. Landslides, 2 (4): 343-357

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

Evans, S.G., Cruden, D.M., Bobrowsky, P.T., Guthrie, R.H., Keegan, T.R., Liverman, D.G.E., and Perret, D. 2005. Landslide risk assessment in Canada: a review of recent developments. In Landslide Risk Management, Proceedings of the International Conference on Landslide Risk. Edited by O. Hungr, R. Fell, R. Couture and E. Eberhardt, Balkema, Leiden, p. 351-363.

Faber, M.H. & Maes, M.A. 2004. Modeling of Risk Perception in Engineering Decision Analysis. In: M.A. Maes & L. Huyse (eds.) Reliability and Optimization of Structural Systems; Proceedings of the 11th IFIP WG7.5 Working Conference, Banff, Canada, 2-5 November 2003. Rotterdam: Balkema.

Faber, M.H. & Maes, M.A. 2005. On Applied Engineering Decision Making for Society. In J.D. Sorensen & D. Frangopol (eds.) Reliability and Optimization of Structural Systems; Proceedings of the 12th IFIP WG7.5 Working Conference, Aalborg, Denmark, 22-25 May 2005. Rotterdam: Balkema.

Fell R, Ho, KKS, Lacasse S, and Leroi E. 2005. A framework for landslide risk assessment and management. In O. Hungr, R. Fell, R. Couture and E. Eberthardt (editors) Landslide Risk Management. Taylor and Francis, London. pp. 3-25

Guzzetti, F.; Reichenbach, P; and Wieczorek, G.F. 2003. Rockfall hazard and risk assessment in the Yosemite Valley, California, USA. Natural Hazards and Earth System Sciences, 3: 491-503.

Guzzetti, F., Reichenbach, P., Ghigi, S. 2004. Rockfall Hazard and Risk Assessment Along a Transportation Corridor in the Nera Valley, Central Italy. Environmental Management, 34 (2): 191–208.

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

Jaiswal P., van Westen C.J., Jetten V. 2010. Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India. Nat. Hazards Earth Syst. Sci. 10 (6), 1253-1267.

Lacasse, S., Nadim, F. and Kalsnes, B. 2010. Living with landslide risk. Geotechnical Engineering Journal of the SEAGS & AGSSEA, Vol. 41, No.4, December, ISSN 0046-5828

Lee, E.M., and Jones, D.K.C. 2004. Landslide risk assessment. Thomas Telford Publishing, London. 454pp.

Lee, E.M.; Brunsden, D. and Sellwood, M. 2000. Quantitative risk assessment of coastal landslide problems, Lyme Regis, UK. In E. Bromhead, N. Dixon & M-L Ibsen (eds). Landslides, in research theory and practice. VIII International Symposium on Landslides. Thomas Telford. Vol. 2: 899-904.

Li, Z., Huang, H., Nadim, F. and Xue, Y. 2010. Quantitative Risk Assessment of Cut-Slope Projects under Construction. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, December, pp. 1644-1654.

NORSOK standard Z-013 2001. "Risk and emergency prepar-edness analysis", Rev. 2, www.standard.no

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

Wu, T.H.; Tang, W.H. and Einstein, H.H. 1996. Landslide hazard and risk assessment. In “Landslides – Investigation and Mitigation”, Transportation Research Board Special Report No. 247 (A.T. Turner & R.L. Schuster ed.), National Academy Press, Washington DC: 106-118

8.3 RISK SCENARIOS

The most complete quantitative description of the possible losses (or risk) is in terms of a "probability distribution", which presents the relative likelihood of any particular loss value, or the probability of losses being less than any particular value. Alternatively, the "expected value" (i.e., the probability-weighted average value) of loss can be determined as a single measure of risk. A general scenario-based risk formulation is given by:

$$E\,[loss] = \sum_{all\,S}\ \sum_{all\,C} C \cdot P[C\,|\,S]\ P\,[S]$$

where C is a particular set of losses (of a collectively exhaustive and mutually exclusive set of possible losses), S is a particular scenario (of a comprehensive and mutually exclusive discrete set of possible scenarios), P[S] is the probability of occurrence of scenario S, P[C | S] is the conditional probability of loss set C given that scenario S has occurred, and E[loss] is the "expected value" of loss. "Loss" refers to any undesirable consequence,

Generally, one should consider several scenarios of plausible landslide triggers, estimate the extent, intensity and run-out distance of the triggered events, and estimate the upper and lower bounds on the annual probability of occurrence of the scenarios (Roberds, 2005). This scenario-based approach involves the following steps:

- Define scenarios for landslide triggering
- Compute the run-out distance, volume and extent of landslide for each scenario
- Identify the elements at risk and their vulnerabilities
- Estimate the loss for the different landslide scenarios
- Estimate the risk and compare it with tolerable or acceptable risk levels.

8.3.1 Characteristics of hazard events

Referring to Figure 8.4, the hazard events acting on the constituents of a system are defined as all possible endogenous and exogenous effects with the potential to cause consequences. A probabilistic characterization of all the events relevant for a system requires a joint probabilistic model for all relevant effects relative to time and space.

The characteristics of hazards are very different, depending on the individual hazard types. Events such as technical failures, accidents, explosions, rockfall, and landslides generally could be suddenly-occurring events. Floods and fire storms are generally more slowly evolving, while climatic changes are much slower. Other threats like human errors and malevolence, in turn, have their own patterns over time and space. In a risk management context, the characterization of hazards must take these differences into account in order to facilitate a realistic assessment of the possible consequences as well as to allow for the identification of possible relevant measures of risk prevention and loss reduction. It is also important to note that in many risk assessments, the joint representation of several hazards is required, for example when considering loads acting on a structure.

For suddenly-occurring events, usually the probability of the event itself is needed. However, more characteristics or indicators are needed to facilitate the modelling of the possible consequences of the event. Considering landslide events, typically applied indicators are the mean velocity of the movement and the volume of detachment. These characteristics or indicators are useful, because knowledge about them provides the basis for assessing the potential damages, such as the damages caused to buildings and infrastructure caused by the occurrence of a landslide.

8.3.2 Consequences

The consequences which potentially may be caused by different hazards are manifold and generally depend strongly on the specific characteristics of the hazard as well as the location where it occurs and the assets which are exposed. As a general rule, consequences should be assessed in regard to fatalities (loss of lives) and injuries, damages to the qualities of the environment and economic losses.

The risk assessment is greatly facilitated by considering the development of consequences as shown in the generic representation in Figure 8.8. However, in the assessment of consequences, it is useful to consider a further differentiation as illustrated in **Error! Reference source not found.** Figure 8.9. From Figure 8.9 is seen that two types of indirect consequences are differentiated, namely the indirect consequences due to physical system changes and the indirect consequences caused by the societal or public perception of these. The reason for this differentiation is to indicate how risk management may efficiently be supported by risk communication. The better and more targeted risk communication is undertaken before, during and after events of natural hazards, the smaller the consequences caused by perception will be. Often traditional risk assessments focus on the assessment of direct consequences and do not attempt to model the indirect consequences by rigorous modelling. Instead, indirect consequences are included by somehow amplifying the direct consequences by means of a risk aversion function, the characteristics of which generally are assessed subjectively. The often more important contribution to consequences are hence commonly modelled by means of the simplest possible approximation. The approach suggested here, where consequences are differentiated into different components is meant to circumvent such excessively simplistic modelling, bringing the indirect consequences into focus and indicating the different ways they might be controlled.

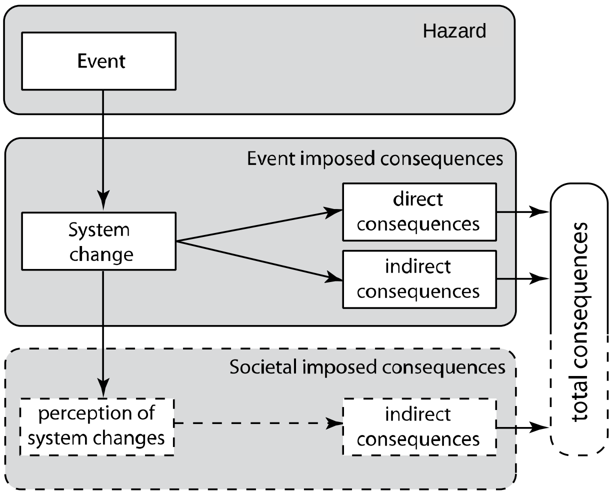


Figure 8.8 Representation of the mechanism generating consequences

As an example, the consequences to be considered for the assessment of the risks due to landslides on a roadway network are illustrated in Figure 8.9.

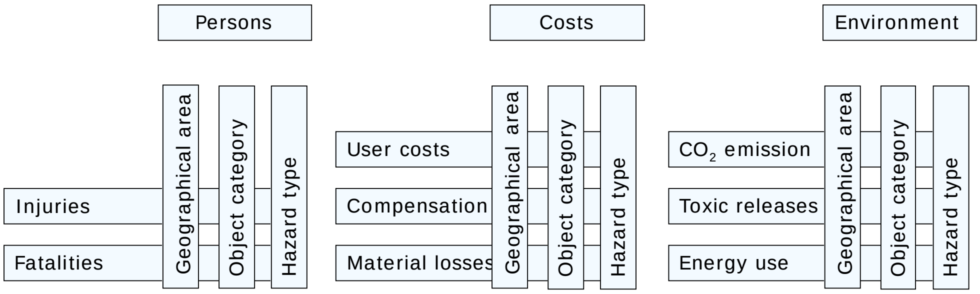


Figure 8.9 Example of different consequences to be considered in the assessment of risks due to landslides for a roadway network

Reference

Roberds, W.J. 2005. Estimating temporal and spatial variability and vulnerability - State of the Art Paper 5. Landslide Risk Management, Hungr, Fell, Couture & Eberhardt (eds), Taylor & Francis, London: 129-158.

8.4 QUANTIFICATION OF RISK

8.4.1 General approach for assessment of risk

The publication by JCSS (2008) describes a general approach for quantification of risk to engineering systems. A summary of this approach is provided below.
The risk R_E associated with one particular event E can be assessed through the product between the probability p_E that the event takes place and the consequences c_E associated with the event, i.e.:

$$R_E = p_E \cdot c_E$$

Risks must be related to an appropriate time frame T, such as e.g. one year. Therefore it is often relevant to consider the risks associated with the number of a specific type of event $n(T)$ within the considered time frame T. In such a case Equation 1 is appropriately written as:

$$R(T) = \sum_{i=0}^{\infty} P(n(T) = i) \cdot c_i$$

where $P(n(T) = i)$ is the probability of i events of the considered type within the time frame T and c_i is the consequence associated with the i events.

The above equation may also be written as:

$$R(T) = E\left[n(T)\right]c$$

where $E\left[n(T)\right]$ is the expected number of events of the considered type within the time frame T. The expected number of events may be established by integration over the rate of occurrences ν as:

$$E\left[n(T)\right] = \int_T E\left[\nu(t)\right] dt$$

As risks are normally associated with scenarios of events, it is important to be able to quantify either the probability or the rate of occurrence of the scenarios, and this in general necessitates a probabilistic modelling involving conditional probabilities or rates respectively. A clear specification of the time reference period to which the probabilities and consequently also the risks have to be related is also necessary.

Following the assessment and evaluation of the hazards and consequences associated with the system considered for risk assessment, the ensuing risks then need to be quantified and evaluated. For this purpose, the system considered for risk assessment is assumed to be exposed to hazard events (EX) with probabilistic characterisation $p(EX_k),\ k=1,\ n_{EXP}$, where n_{EXP} denotes the number of hazards. It is assumed that the considered system includes n_{CON} individual constituents, each with a discrete set of component damage states C_{ij} , $i=1,2..n_{CON}$, $j=1,2..n_{C_i}$, where n_{C_i} is the total number of different damage states of constituent i. The probability of direct consequences $c_D(\mathbf{C}_l)$ associated with the l^{th} of n_{CSTA} possible different state of damage of all constituents $\mathbf{C}_l$, conditional on the hazard event EX_k is described by $p(\mathbf{C}_l\,|EX_k)$ and the associated conditional risk is $p(\mathbf{C}_l\,|EX_k)c_D(\mathbf{C}_l)$. The risk R_D due to direct consequences, i.e. the expected value of the conditional risk due to direct consequences over all n_{EXP} possible hazard events and all constituent damage states n_{CSTA} is evaluated as:

$$R_D = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l\,|EX_k)c_D(\mathbf{C}_l)p(EX_k)$$

The functionality of the considered system depends on the state of the constituents. It is assumed that there are n_{SSTA} possible different states of the constituents S_m associated with indirect consequences $c_{ID}(S_m, c_D(\mathbf{C}_l))$. The probability of indirect consequences conditional on a given state of the constituents $\mathbf{C}_l$, the direct consequences $c_D(\mathbf{C}_l)$ and the hazard EX_k, is described by $p(S_m\,|\mathbf{C}_l, EX_k)$. The corresponding conditional risk is $p(S_m\,|\mathbf{C}_l, EX_k)c_{ID}(S_m, c_D(\mathbf{C}_l))$. The risk R_{ID} due to indirect consequences is assessed through the expected value of the indirect consequences in regard to all possible hazards and constituent states, as:

$$R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m, c_D(\mathbf{C}_l)) \times p(S_m\,|\mathbf{C}_l, EX_k)\,p(\mathbf{C}_l\,|EX_k)\,p(EX_k)$$

Finally, it should be mentioned that risks may be represented in different ways, including distribution functions of consequences, showing with what probability different ranges of consequences will occur. Other representations include density functions for risk estimates showing the uncertainty due to epistemic uncertainties. The best representation depends on the scope and purpose of the risk assessment.

To apply the JCSS (2008) methodology to landslides, the spatial boundaries and temporal scale of the analysis, i.e. the “system”, must be defined. Once the elements at risk within the system and their vulnerabilities have been established, the assessment of direct consequences is relatively straightforward. The assessment of indirect consequences and the consequences imposed by societal factors is, however, more challenging.

8.4.2 Indicators of risk

The risk assessment framework outlined in this section facilitates a Bayesian approach to risk assessment through the use of risk indicators. Risk indicators may be understood as any observable or measurable characteristic of the system or its constituents containing information about the risk. If the system representation has been performed appropriately, risk indicators will in general be available for what concerns the hazards for the system as well as the direct consequences and the follow-up/indirect consequences to the system. In a Bayesian framework for risk assessment, such indicators play an important role as they readily enable the updating of probabilities and information required in the risk assessment whenever new knowledge or information about the system becomes available. For the risk assessment in the context of landslide hazards, suitable risk indicators could be quantities related to the triggering event, the process of the landslide that has been triggered, damages to buildings and infrastructure, fatalities and injuries, damages to the qualities of the environment, economic losses, and socio-economic consequences.

Reference

JCSS 2008. Risk Assessment in Engineering. Internet Publication: http://www.jcss.ethz.ch/publications/JCSS_RiskAssessment.pdf

9 VALIDATION OF THE LANDSLIDE HAZARD AND RISK ASSESSMENT AND ZONING

(ITC and CNRS with contributions from UNIMIB and JRC)

An important issue in the development of landslide susceptibility, hazard and risk model is assessment of its “quality”. Some authors claim a model should be validated (Tsang, 1991; Power, 1993) before its application; others argue that models cannot be validated per se by any procedure but rather evaluated (Konikow and Bredehoeft, 1992; Oreskes et al., 1994; Oreskes, 1998). Aside from these conflicting conceptual and terminological views, evaluation of the robustness and reliability of a landslide model is always a difficult task. As landslide susceptibility, hazard and risk maps predict future events the best method would be to “wait and see”, and test the accuracy based on events that happened after the preparation of the maps. This is generally not considered a practical solution, and there are hardly any publications that deal with the validation of landslide susceptibility, hazard and risk maps that have been made some time ago.

In practice model evaluation is performed by developing the maps using a landslide inventory of a given time period and testing the result with another inventory from a later period. A common method for evaluating the accuracy of landslide susceptibility maps is to compare these with the existing landslide occurrence map and calculate the percentage of landslides within each hazard class (Carrara et al., 1990; 1991; Gee, 1992). However, the landslide occurrence maps themselves may contain a large degree of uncertainty or subjective elements (Fookes et al.,1991; Carrara, 1992; Carrara et al., 1992; Van Westen et al., 1993; Van Den Eeckhaut et al., 2007). Another way of assessing the reliability of hazard maps is the comparison of maps of the same area made independently by different teams. It has proven to be a rather difficult exercise, given the differences in background, knowledge of the area and time allocated to do the mapping (Van Westen et al., 1999; Van Den Eeckhaut et al., 2010).

This chapter gives an overview of the methods that can be used for the validation of landslide susceptibility and hazard maps, largely based on the publication by Frattini et al. (2010).

9.1 VALIDATION OF MAPPING

In the last decades, many efforts have been made to assess landslide susceptibility at a regional scale. In spite of a huge number of models produced using various methods, little attention has been devoted to the problem of result evaluation.

Model evaluation is a multi-criteria problem (Davis and Goodrich, 1990). The acceptance of a model needs to fulfil at least three criteria: its adequacy (conceptual and mathematical) in describing the system behaviour, its robustness to small changes of the input data (i.e. data sensitivity), and its accuracy in predicting the observed data.

With physically-based models, the first evaluation criterion is aimed at assessing whether the model provides a physically acceptable explanation of the cause–effect relationships. Alternatively, justification is given for using simplifications of physical processes. This is the case, for example, of susceptibility maps developed using simple infinite slope stability models coupled with simplified hydrological models (steady state: Montgomery and Dietrich, 1994, Burton and Bathurst, 1998, Borga et al., 1998; piston-flow: Green and Ampt, 1911, Crosta and Frattini, 2003; quasi-dynamic: Barling et al., 1994; diffusive: Iverson, 2000).

With statistical or empirical models, the first kind of evaluation focuses on how well the variables used by the models can describe the processes. Due to the complexity of natural systems, this kind of evaluation involves a large component of judgement by experts with a deep knowledge of landslide processes (Carrara et al., 2003).

The robustness of the model can be evaluated by systematically analyzing the variation of the model performance to small changes of input parameters or uncertainties. In the landslide susceptibility literature, only a few papers deal with robustness evaluation (Guzzetti et al., 2006) and (Melchiorre et al., 2006). The most relevant criterion for quality evaluation is the assessment of model accuracy, which is performed by analyzing the agreement between the model results and the observed data. In the case of landslide susceptibility models, the observed data comprise the presence/absence of landslides within a certain terrain unit used for the analysis.

In the pioneering susceptibility models produced beginning in the 1980s, accuracy was evaluated through visual comparison of actual landslides with susceptibility classification (Brabb, 1984 and Gökceoglu and Aksoy, 1996), or in terms of efficiency (or accuracy) (e.g., Carrara, 1983). In the last decade, different authors have proposed equivalent methods to evaluate the models in terms of landslide density within different susceptibility classes ("landslide density", Montgomery and Dietrich, 1994; Ercanoglu and Gokceoglu, 2002; and Crosta and Frattini, 2003; "degree of fit", Irigaray et al., 1999; Baeza and Corominas, 2001; and Fernández et al., 2003; "b/a ratio", Lee and Min, 2001; and Lee et al., 2003). Other authors chose to represent the success of the model by comparing the landslide density with the area of susceptible zone for different susceptibility levels (Zinck et al., 2001; "Success-Rate curves", Chung and Fabbri, 2003; Remondo et al., 2003; Zêzere et al., 2004; Lee, 2005; and Guzzetti et al., 2006). More recently, ROC curves have been adopted for model evaluation and comparison in the landslide literature (Yesilnacar and Topal, 2005; Begueria, 2006; Van Den Eeckhaut et al., 2006; Gorsevski et al., 2006; Frattini et al., 2008; and Nefeslioglu et al., 2008).

When a landslide susceptibility model is applied in practice, the classification of land according to susceptibility results in economical consequences. For instance, terrain that is classified as stable can be used without restrictions, increasing its economical value, whereas unstable terrain is restricted in use, and is consequently reduced in value. The misclassification of terrain in a model also produces economic costs. Hence, the performance of the models can be evaluated by assessing these costs, in order to select the best model, or the one that minimizes costs to society.

All the techniques used in the literature to assess the accuracy of landslide susceptibility models do not account for misclassification costs. This limitation is significant for landslide susceptibility analysis as the costs of misclassifications are very different depending on the error type. 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, $c(-|+)$, is equal to the loss of elements at risk that can be impacted by landslides in these units. This cost depends on the economic value and the vulnerability of elements at risk (e.g., lives, buildings and lifelines), and the temporal probability and intensity of landslides. 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, $c(+|-)$, 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 (slope gradient, altitude, aspect, distance from the main valley, etc.) and social economic (distance from an urban/industrial area, road, etc.) characteristics. With landslide susceptibility 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 event of a landslide.

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. A simple technique (Cost curves, Drummond and Holte, 2000) can be adopted to explicitly account for these costs (Frattini et al, 2010).

In the following, different techniques for the evaluation and comparison of landslide susceptibility model performance (accuracy statistics, ROC curves, Success-Rate curves, and Cost curves) are presented.

9.1.1 Accuracy statistics

As previously mentioned, accuracy is assessed by analyzing the agreement between the model results and the observed data. 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 cutoff value of susceptibility that divides stable terrains (susceptibility less than the cutoff) and unstable terrain (susceptibility greater than the cutoff).

The comparison of observed data and model results reclassified into two classes is represented through contingency tables or confusion matrices (Table 9.1). Accuracy statistics assess the model performance by combining correct and incorrect classified positives (i.e., unstable areas) and negatives (i.e., stable areas) (Table 9.2).

Table 9.1 Contingency table used for landslide model evaluation

		Predicted		
		True	False	
Observed	Positive	True positive	False positive	→ Positive predictive value
	Negative	False negative	True negative	→ Negative predictive value
		↓ Sensitivity	↓ Specificity	Accuracy

Table 9.2 Commonly used accuracy statistics. tp = true positives, tn = true negatives, fp = false positives (Error Type I), fn = false negatives (Error Type II), P = positive predictions (tp + fn), N = negative predictions (fp + tn), T = total number of observations. See also table Table 9.1.

Efficiency (Accuracy or Percent correct,	$\frac{tp+tn}{T}$
Odds ratio	$\frac{tp \cdot tn}{fn \cdot fp}$
True positive rate (TP)= sensitivity	$\frac{tp}{tp+fn}=\frac{tp}{P}=1\text{-}FN$
False positive rate (FP) = 1-specificity	$\frac{fp}{fp+tn}=\frac{fp}{N}=1\text{-}TN$
Threat score (critical success index)	$\frac{tp}{tp+fn+fp}$
Equitable threat score (Gilbert skill score)	$\frac{tp-tp_{random}}{tp+fn+fp-tp_{random}}$ where $tp_{random}=\frac{(tp+fn)(tp+fp)}{T}$
Pierce's skill score (True skill statistic)	$\frac{tp}{tp+fn}-\frac{fp}{fp+tn}=\text{TP-FP}$
Heidke skill score (Cohen's kappa)	$\frac{tp+tn-E}{T-E}$ where $E=\frac{1}{T}\left[(tp+fn)(tp+fp)+(tn+fn)(tn+fp)\right]$
Odd ratio skill score (Yule's Q)	$\frac{tp \cdot tn-fp \cdot fn}{tp \cdot tn+fp \cdot fn}$

The first statistic, presented in the field of weather forecasting (Finley, 1884), is the Efficiency (Accuracy or Percent correct, Table 10-2), which measures the percentage of observations that are correctly classified by the model. However, Gilbert (1884) showed that the Efficiency statistic is unreliable because it is heavily influenced by the most common class, usually “stable slopes” in the case of landslide susceptibility models, and it is not equitable. A statistic is equitable if it gives the same score for different types of unskilled classifications. In other words, classifications of random chance, “always positive” and “always negative”, should produce the same (bad) score (Murphy, 1996).

True Positive rate (TP) and the False Positive rate (FP) 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 (e.g., 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 (poorer scores for rarer events) since some true positives can occur purely due to random chance.

The Equitable threat score (Gilbert's skill score; Gilbert, 1884 and Schaefer, 1990) measures the fraction of observed and/or classified events that were correctly predicted, adjusted for true positives associated with random chance. As above, it does not distinguish the source of classification error.

The Pierce's skill score (True skill statistic; Peirce, 1884 and Hanssen and Kuipers, 1965) uses all elements of contingency table and does not depend on event frequency. This score may be more useful for more frequent events (Mason, 2003).

Heidke's skill score (Cohen's kappa; Heidke, 1926) measures the fraction of correct classifications after eliminating those classifications which would be correct due purely to random chance.

The odds ratio (Stephenson, 2000) measures the ratio of the odds of true prediction to the odds of false prediction. This statistic takes prior probabilities into account and gives better scores for rare events, but cannot be used if any of the cells in the contingency table is equal to 0.

Finally, the odd ratio skill score (Yule, 1900) is closely related to the odds ratio, but conveniently ranges between − 1 and 1.

As mentioned, accuracy statistics require the splitting of the classified objects into a few classes by defining specific values of the susceptibility index that are called cutoff values. For statistical models, such as discriminant analysis (e.g., Carrara, 1983) or logistic regression analysis (e.g., Chung et al., 1995; Atckinson & Massari, 1998; Dai & Lee, 2002; Ohlmacher & Davis, 2003; and Nefeslioglu et al., 2008), a statistically significant probability cutoff (pcutoff) 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. In different conditions (Van Den Eeckhaut et al., 2006), or for other types of landslide susceptibility models, such as physically-based (Van Westen and Terlien, 1996, Gökceoglu and Aksoy, 1996, Crosta and Frattini, 2003, Frattini et al., 2004 and Godt et al., 2008), heuristic (e.g., Barredo et al., 2000), artificial neural networks (Lee et al., 2003, Ermini et al., 2005 and Nefeslioglu et al., 2008), fuzzy logic (Binaghi et al., (1998) and Ercanoglu and Gokceoglu, 2004), the choice of cutoff values to define susceptibility classes is arbitrary, unless a cost criteria is adopted (Provost and Fawcett, 1997). A first solution to this limitation consists in evaluating the performance of the models over a large range of cutoff values by using cutoff-independent performance criteria. Another solution consists in finding the optimal cutoff by minimizing the costs of the models.

9.1.2 Cutoff independent performance criteria

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

The ROC analysis was developed during the Second World War to assess the performance of radar receivers in detecting targets. It has been adopted in different scientific fields, such as medical diagnostic testing (Goodenough et al., 1974; Hanley & McNeil, 1982; and Swets, 1988) and machine learning (Egan, 1975, Adams & Hand, 1999; and Provost & Fawcett, 2001). The Area Under the ROC 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 cutoffs. The points on the ROC curve represent (FP, TP) pairs derived from different contingency tables created by applying different cutoffs (Figure 9.1a). Points closer to the upper-right corner correspond to lower cutoff 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 (i.e., 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; i.e. 1-1 line) is defined operating range. In the case, model evalidation is performed with data not used for developing the model, a good model should have ROC curves for the evaluation and production data set that are closely located to each other in the ROC graph, and have AUC values above 0.7 (moderate acurate) or even above 0.9 (highly accurate; Swets, 1988).
Success-Rate curves (Zinck et al., 2001; and Chung & Fabbri, 2003;Figure 9.1b) represent the percentage of correctly classified objects (i.e., terrain units) on the y-axis, and the percentage of area classified as positive (i.e., unstable) on the x-axis. In the landslide literature, 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.

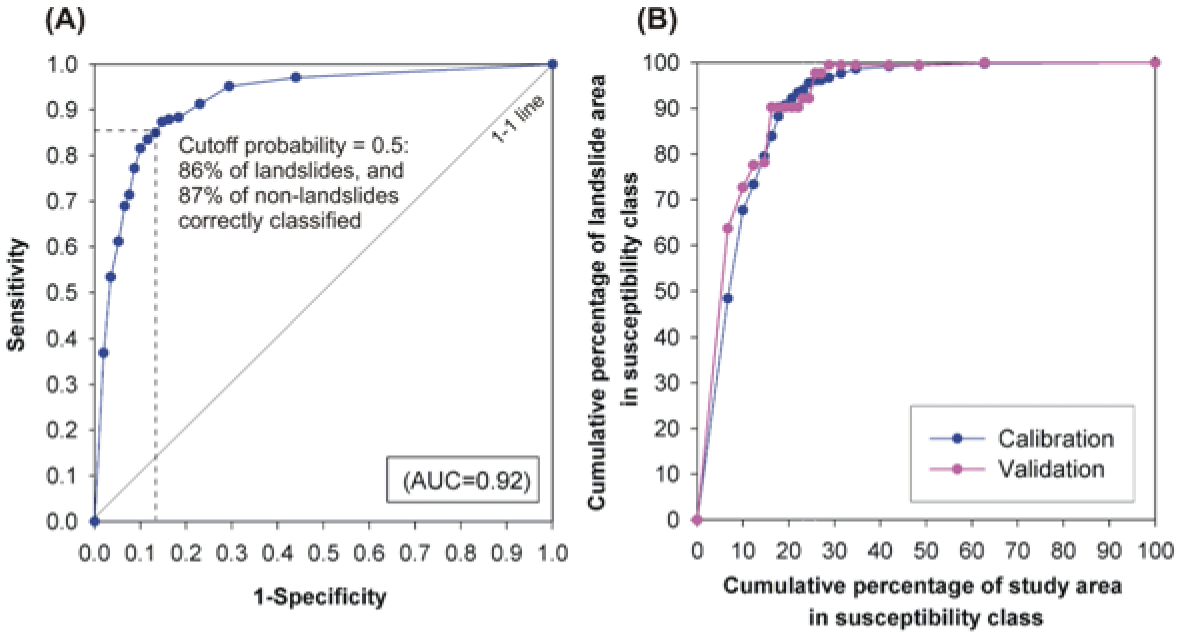


Figure 9.1 Example of (A) a ROC curve and (B) a success rate curve (after Van Den Eeckhaut et al., 2009)

9.1.3 Cost curves

The total cost of misclassification of a model depends on (Drummond and Holte, 2000 C. Drummond and R.C. Holte, Explicitly representing expected cost: an alternative to ROC representation, Proc. of the 6th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining (2000), pp. 198–207.Drummond and Holte, 2000):

- the percentage of terrain units that are incorrectly classified,
- the a-priori probability of having a landslide in the area (p(+)), and
- the costs of misclassification of the different error types.

In order to explicitly represent costs in the evaluation of model performance, Drummond and Holte (2006) proposed the Cost curve representation. The Cost curve represents the Normalized Expected cost as a function of a Probability-Cost function (Figure 9.2).
The Normalized Expected cost, NE(C) is calculated as:

$$NE(C) = \frac{(1-TP)\cdot p(+)\cdot c(-|+) + FP\cdot p(-)\cdot c(+|-)}{p(+)\cdot c(-|+) + p(-)\cdot c(+|-)}$$

where the expected cost is normalized by the maximum expected cost, that occurs when all cases are incorrectly classified, i.e. when FP and FN are both one. The maximum normalized cost is 1 and the minimum is 0.

The Probability-Cost function, PC(+) is:

$$PC(+) = \frac{p(+)\cdot c(-|+)}{p(+)\cdot c(-|+) + p(-)\cdot c(+|-)}$$

which represents the normalized version of p(+)c(−|+), so that PC(+) ranges from 0 to 1. When misclassification costs are equal, PC(+) = p(+). In general, PC(+) = 0 occurs when cost is only due to negative cases, i.e., positive cases never occur (p(+) = 0) or their misclassification cost, c(−|+), is null. PC(+) = 1 corresponds to the other extreme, i.e., p(−) = 0 or c(+|−) = 0.
A single classification model, which would be a single point (FP, TP) in ROC space, is a straight line in the Cost curve representation. A set of points in ROC space, the basis for an ROC curve, is a set of Cost lines, one for each ROC point. When evaluation a model, the lower the cost curve, the better the performance, and the difference between two models is simply the vertical distance of 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 susceptibility 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: a task beyond the capabilities of most investigators. 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., buildings, lifelines, roads; these contribute to false negative costs) and the area potentially suitable for building development (this contributes to false positive costs) (Frattini et al., 2010).

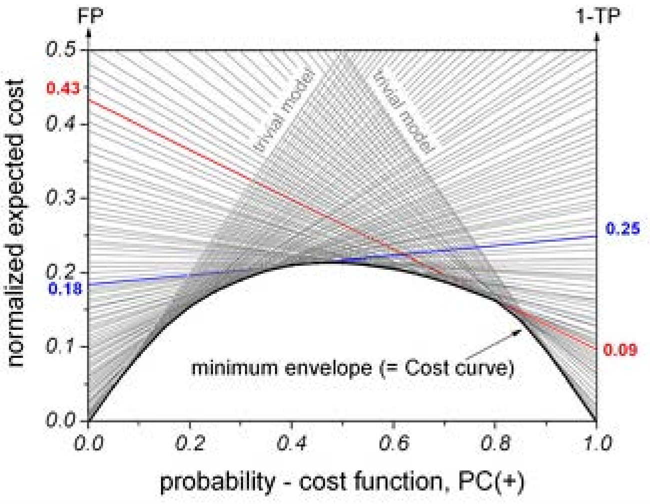


Figure 9.2 Example of a Cost curve. A straight line corresponds to a point in the ROC curve. The red line shows for example the line of a point with sensitivity (TP) 0.91 and 1-specificity (FP) 0.43 (after Frattini et al., 2010)

9.2 CONCLUSIONS

9.2.1 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 susceptibility models.

For statistical models, the application of cutoff-dependent accuracy statistics is straightforward and scientifically correct because the cutoff 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 susceptibility models.

For other kinds of models (e.g., physically-based, heuristic and fuzzy) there is no theoretical reason to select a certain cutoff, and the application of accuracy statistics is therefore unfeasible.

9.2.2 ROC and Cost curves

Evaluating landslide models with cutoff-independent criteria has the advantage that an a-priori cutoff value is not required, and the performance can be assessed over the entire range of cutoff values.

Using ROC and Success-Rate curves, different results are obtained . The difference is due to the following reasons. The first curve type 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. On the other hand, the Success-Rate curve is based on the analysis of spatial matching between actual landslides and susceptibility 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.

Success-Rate curve presents some theoretical problems when applied to grid-cell models. The number of true positives, in fact, contributes to both x- and y-axis. An increase in true positives causes an upward (toward better performance) and rightward (toward worse performance) shift 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 Success-Rate curve is sensitive to the initial proportion of positives and negatives. Hence, the application of Success-Rate curves to areas with a low degree of hazard (e.g., flat areas with small steep portions of the landscape, Fabbri et al., 2003 and Van Den Eeckhaut et al., 2006) will always give better results than application to areas with a high hazard (e.g., alpine valleys with steep slopes), even if the quality of the classification is exactly the same.

REFERENCES

Ardizzone, F., Cardinali, M., Carrara, A., Guzzetti, F., Reichenbach, P., 2002. Impact ofmapping errors on the reliability of landslide hazard models. Natural Hazard andEarth Systems Science 2, 3–14.

Atckinson, P.M., Massari, R., 1998. Generalised linear modelling of susceptibility lo landsliding in the Central Apennines, Italy. Computers & Geosciences 24 (4), 373–385.

Baeza, C., Corominas, J., 2001. Assessment of shallow landslide susceptibility by means of multivariate statistical techniques. Earth Surface Processes and Landforms 26 (12), 1251–1263.

Barredo, J., Benavides, A., Hervas, J. and van Westen, C.J. (2000) Comparing heuristic landslide hazard assessment techniques using GIS in the Tirajana basin, Gran Canaria Island, Spain. In: International journal of applied earth observation and geoinformation : JAG, 2 (2000)1, pp. 9-23

Begueria, S., 2006. Validation and evaluation of predictive models in hazard assessment and risk management. Natural Hazards 37 (3), 315–329.

Brabb, E.E., 1984. Innovative approaches to landslide hazard mapping. 4th International Symposium on Landslides, Toronto, Vol 1, pp. 307–324.

Binaghi, E., Luzi, L., Madella, P., Pergalani, F., Rampini, A., 1998. Slope instability zonation: a comparison between certainty factor and fuzzy Dempster–Shafer approaches. Natural Hazards 17, 77–97.

Bonham-Carter, G.F., 1994. Geographic Information System for Geoscientists: Modelling with GIS. Pergamon Press,Oxford. 398 pp.

Briggs, W.M., Ruppert, D., 2005. Assessing the skill of yes/no predictions. Biometrics 61, 799–807.

Carrara, A., 1983. Multivariate models for landslide hazard evolution. Mathematical Geology 15, 403–427.

Carrara, A., Crosta, G.B., Frattini, P., 2003. Geomorphological and historical data in assessing landslide hazard. Earth Surface Processes and Landforms 28 (10), 1125–1142.

Carrara, A., Crosta, G.B., Frattini, P., 2008. Comparing models of debris-flow susceptibility in the alpine environment. Geomorphology 94 (3–4), 353–378.

Carrara, A., Cardinali, M. and Guzzetti, F. (1992). Uncertainty in assessing landslide hazard and risk. ITC-Journal 1992-2, pp. 172-183.

Chung, C.F., Fabbri, A.G., 2003. Validation of spatial prediction models for landslide hazard mapping. Natural Hazards 30 (3), 451–472.

Chung, C.F., Fabbri, A.G., Van Westen, C.J., 1995. Multivariate regression analysis for landslide hazard zonation. In: Carrara, A., Guzzetti, F. (Eds.), Geographical Information Systems in

Assessing Natural Hazards. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 107–133.

Crosta, G.B., Frattini, P., 2003. Distributed modeling of shallow landslides triggered by intense rainfall. Natural Hazards and Earth System Sciences 3 (1–2), 81–93.

Dai, F.C., Lee, C.F., 2002. Landslide characteristics and slope instability modelling using GIS, Lantau Island, Hong Kong. Geomorphology 42, 213–228.

Davis, P.A., Goodrich, M.T., 1990. A proposed strategy for the validation of ground-water flow and solute transport models. Technical Report, Sandia National Labs., Albuquerque, NM (USA).

Davis, J.C., 2002. Statistics and Data Analysis in Geology, Third Edition. John Wiley & Sons, New York. 638 pp.

Drummond, C., Holte, R.C., 2000. Explicitly representing expected cost: an alternative to ROC representation. Proc. of the 6th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, pp. 198–207.

Drummond, C., Holte, R.C., 2006. Cost curves: an improved method for visualizing classifier performance. Machine Learning 65 (1), 95–130.

Egan, J.P., 1975. Signal Detection Theory and ROC Analysis. Series in Cognition and Perception. Academic Press, New York.

Ercanoglu, M., Gokceoglu, C., 2002. Assessment of landslide susceptibility for a landslide-prone area (north of Yenice, NW Turkey) by fuzzy approach. EnvironmentalGeology 41 (6), 720–730.

Ercanoglu, M., Gokceoglu, C., 2004. Use of fuzzy relations to produce landslide susceptibility map of a landslide prone area (West Black Sea Region, Turkey). Engineering Geology 75, 229–250.

Ermini, L., Catani, F., Casagli, N., 2005. Artificial neural networks applied to landslide susceptibility assessment. Geomorphology 66, 327–343.

Fabbri, A.G., Chung, C.F., Cendrero, A., Remondo, J., 2003. Is prediction of future landslides possible with a GIS? Natural Hazards 30 (33), 487–499.

Fawcett T (2006) An introduction to ROC analysis. Pattern Recognation Letters 27: 861-874.

Fernández, T., Irigaray, C., El Hamdouni, R., Chacón, J., 2003. Methodology for landslide susceptibility mapping by means of a GIS. Application to the Contraviesa Area (Granada, Spain). Natural Hazards 30, 297–308.

Finley, J.P., 1884. Tornado predictions. American Meteorological Journal 1, 85–88.

Fookes, P.G., Dale, S.G. and Land, J.M. (1991) Some observations on a comparitive aerial photography interpretation of a landslipped area. Quarterly Journal of Engineering Geology, 24, pp. 249-265

Frattini, P., Crosta, G.B., Fusi, N., Dal Negro, P., 2004. Shallow landslides in pyroclastic soil: a distributed modeling approach for hazard assessment. Engineering Geology 73, 277–295.

Frattini, P., Crosta, G.B., Carrara, A., Agliardi, F., 2008. Assessment of rockfall susceptibility by integrating statistical and physically-based approaches. Geomorphology 94 (3–4), 419–437.

Frattini, P., Crosta, G.B. and Carrara, A. (2010). Techniques for evaluating the performance of landslide susceptibility models. Engineering Geology, Volume 111, Issue 1-4, February 2010, Pages 62-72

Gee, M.D. (1992) Classification of landslide hazard zonation methods and a test of predictive capability.Proceedings 6th International Symposium on Landslides, Christchurch, New Zealand, Vol 2, pp 947-952.

Gilbert, G.F., 1884. Finley's tornado predictions. American Meteorological Journal 1, 166–172.

Godt, J.W., Baum, R.L., Savage, W.Z., Salciarini, D., Schulz, W.H., Harp, E.L., 2008. Requirements for integrating transient deterministic shallow landslide models with GIS for hazard and susceptibility assessments. Engineering Geology 103, 214–226.

Gökceoglu, C., Aksoy, H., 1996. Landslide susceptibility mapping of the slopes in the residual soils of the Mengen region (Turkey) by deterministic stability analyses and image processing techniques. Engineering Geology 44, 147–161.

Goodenough, D.J., Rossmann, K., Lusted, L.B., 1974. Radiographic applications of receiver operating characteristic (ROC) analysis. Radiology 110, 89–95.

Gorsevski, P.V., Gessler, P.E., Foltz, R.B., Elliot, W.J., 2006. Spatial prediction of landslide hazard using logistic regression and ROC analysis. Transactions in GIS 10 (3), 395–415.

Guzzetti, F., Reichenbach, P., Ardizzone, F., Cardinali, M., Galli, M., 2006. Estimating the quality of landslide susceptibility models. Geomorphology 81 (1–2), 166–184.

Hanley, J.A., McNeil, B.J., 1982. The meaning and use of the area under a receiver operating characteristic (ROC) curve. Radiology 143 (1), 29–36.

Hanssen, A.W., Kuipers, W.J.A., 1965. On the relationship between the frequency of rain and various meteorological parameters. Mededelingenen Verhandelingen 81, 2–15.

Heidke, P., 1926. Berechnung des Erfolges und der Güte der Windstärkevorhersagen im Sturmwarnungdienst (Calculation of the success and goodness of strong wind forecasts in the storm warning service). Geografika Annaler 8, 301–349.

Irigaray, C., Fernández, T., El Hamdouni, R., Chacón, J., 1999. Verification of landslide susceptibility mapping: a case study. Earth Surface Processes and Landforms 24, 537–544.

Lee, S., 2005. Application of logistic regression model and its validation for landslide susceptibility mapping using GIS and remote sensing data. International Journal of Remote Sensing 26 (7), 1477–1491.

Lee, S., Min, K., 2001. Statistical analysis of landslide susceptibility at Yongin, Korea. Environmental Geology 40, 1095–1113.

Lee, S., Ryu, J.H., Min, K., Won, J.S., 2003. Landslide susceptibility analysis using GIS and artificial neural network. Earth Surface Processes and Landforms 28, 1361–1376.

Mason, I.B., 2003. Binary events. In: Jolliffe, I.T., Stephenson, D.B. (Eds.), Forecast Verification. A Practitioner's Guide in Atmospheric Science. Wiley & Sons Ltd, Chichester, pp. 37–76.

MATE/MATL, 1999. Plan de Prévention des Risques (PPR): Risques de Mouvements de terrain, Ministère de l'Aménagement du Territoire et de l'Environnement (MATE), Ministère de l'Equipement des Transports et du Logement (METL). La Documentation Française, Paris. 74 pp.

Melchiorre, C., Matteucci, M., Remondo, J., 2006. Artificial neural networks and robustness analysis in landslide susceptibility zonation. Proc. International Joint Conference on Neural Networks, Vancouver, BC, Canada, July 16–21, 2006.

Melchiorre, C., Matteucci, M., Azzoni, A., Zanchi, A., 2008. Artificial neural networks and cluster analysis in landslide susceptibility zonation. Geomorphology 94 (3–4), 379–400.

Montgomery, D.R., Dietrich, W.E., 1994. A physically based model for the topographic control on shallow landsliding. Water Resources Research 30 (4), 1153–1171.

Murphy, A.H., 1996. The Finley affair: a signal event in the history of forecast verification. Weather Forecasting 11, 3–20.

Nefeslioglu, H.A., Gokceoglu, C., Sonmez, H., 2008. An assessment on the use of logistic regression and artificial neural networks with different sampling strategies for the preparation of landslide susceptibilitymaps. Engineering Geology 97 (3–4), 171–191.

Ohlmacher, G.C., Davis, J.C., 2003. Using multiple logistic regression and GIS technology to predict landslide hazard in northeast Kansas, USA. Engineering Geology 69 (33), 331–343.

Peirce, C.S., 1884. The numerical measure of the success of predictions. Science 4, 453–454.

Pepe, M.S., 2003. The Statistical Evaluation of Medical Tests for Classification and Prediction. Oxford University Press, New York.

Phoon, K.K., Kulhawy, F.H., 1999. Characterization of geotechnical variability. Canadian Geotechnical Journal 36 (4), 612–624.

Provost, F., Fawcett, T., 1997. Analysis and visualization of classifier performance: comparison under imprecise class and cost distributions. Proceedings of the Third International Conference on Knowledge Discovery and Data Mining. AAAI Press, Menlo Park, CA, pp. 43–48.

Provost, F., Fawcett, T., 2001. Robust classification for imprecise environments. Machine Learning 42 (3), 203–231.

Rawls, W.J., Brakensiek, D.L., Miller, N., 1983. Green-Ampt infiltration parameters from soils data. Journal of Hydraulic Engineering 109 (11), 62–70.

Remondo, J., González, A., Díaz de Terán, J.R., Cendrero, A., Fabbri, A., Chung, C.F., 2003. Validation of landslide susceptibility maps; examples and applications from a case study in northern Spain. Natural Hazards 30 (3), 437–449.

Schaefer, J.T., 1990. The critical success index as an indicator of warning skill. Weather Forecasting 5, 570–575.

Stephenson, D.B., 2000. Use of the “odds ratio” for diagnosing forecast skill. Weather Forecasting 15, 221–232.

Swets, J.A., 1988. Measuring the accuracy of diagnostic systems. Science 240 (4857), 1285–1293.

Thiery, Y. 2007. Susceptibilité du Bassin de Barcelonnette (Alpes du Sud, France) aux 'mouvements de versant' : cartographie morphodynamique, analyse spatiale et modélisation probabiliste. Thèse de Doctorat, Université de Caen-Basse-Normandie, Caen, France, 445p

Thiery, Y., Malet, J.-P., Sterlacchini, S., Puissant, A., Maquaire, O. 2007. Landslide susceptibility assessment by bivariate methods at large scales: Application to a complex mountainous environment, Geomorphology, 92(1-2): 38-59. doi: 10.1016/j.geomorph.2007.02.020

Van den Eeckhaut, M., Vanwalleghem, T., Poesen, J., Govers, G., Verstraeten, G., Vandekerckhove, L., 2006. Prediction of landslide susceptibility using rare events logistic regression: a case-study in the Flemish Ardennes (Belgium). Geomorphology 76 (3–4), 392–410.

Van Westen, C.J., Terlien, M.T.J., 1996. An approach towards deterministic landslide hazard analysis in GIS. A casa study from Manizales (Colombia). Earth Surface Processes and Landforms 21, 853–868.

van Westen, C.J., Seijmonsbergen, A.C. and Mantovani, F. (1999) Comparing landslide hazard maps. In: Natural hazards : journal of the international society for the prevention and mitigation of natural hazards, 20 (1999)2-3, pp. 137-158

Yesilnacar, E., Topal, T., 2005. Landslide susceptibility mapping: a comparison of logistic regression and neural networks methods in a medium scale study, Hendek region (Turkey). Engineering Geology 79 (3–4), 251–266.

Yule, G.U., 1900. On the association of attributes in statistics. Philosophical Transactions of the Royal Society of London 194A, 257–319.

Zêzere, J.L., Reis, E., Garcia, R., Oliveira, S., Rodrigues, M.L., Vieira, G., Ferreira, A.B., 2004. Integration of spatial and temporal data for the definition of different landslide hazard scenarios in the area north of Lisbon (Portugal). Natural Hazard and Earth Systems Science 4 (1), 133–146.

Zinck, J.A., López, J., Metternicht, G.I., Shrestha, D.P., Vázquez-Selem, L., 2001. Mapping and modelling mass movements and gullies in mountainous areas using remote sensing and GIS techniques. International Journal of Applied Earth Observation and Geoinformation 3 (1), 43–53.