1

Landslide Hazard and Risk: Issues, Concepts and Approach

M.J. Crozier and T. Glade

1.1 Underpinning Issues

In the broad non-technical sense 'hazards' are defined as those processes and situations, actions or non-actions that have the potential to bring about damage, loss or other adverse effects to those attributes valued by mankind. The concept is thus applicable to all walks of life. In industry a hazard might be a power failure or a computer malfunction, in business it might be a breach of security or a poor investment decision, and in the environment it might be a spill of toxic substances or even a damaging landslide. Although the potential for something adverse to occur is appreciated, there is uncertainty as to when the hazard will realize its potential, and thus the threat is generally expressed as a likelihood or probability of occurrence of a given event magnitude in a specified period of time. Technically, we refer to this adverse condition as 'the hazard'. Thus, in common usage, the term 'hazard' has two different meanings: first, the physical process or activity that is potentially damaging; and second, the threatening state or condition, indicated by likelihood of occurrence. Generally the meanings are obvious from the context within which they are used.

The consequences of hazard occurrence can be great or small, as well as direct or indirect; the latter pair linked to the primary impact by a chain of dependent reactions that may be manifest at some distance in time and space from the initial occurrence. Clearly the consequences depend on the context in which they occur, the particular elements and attributes affected, and their value and level of importance.

In simple generic terms, the important concept of 'risk' can thus be seen as having two components: the likelihood of something adverse happening and the consequences if it

Landslide Hazard and Risk Edited by Thomas Glade, Malcolm Anderson and Michael J. Crozier
 ISBN: 0-471-48663-9

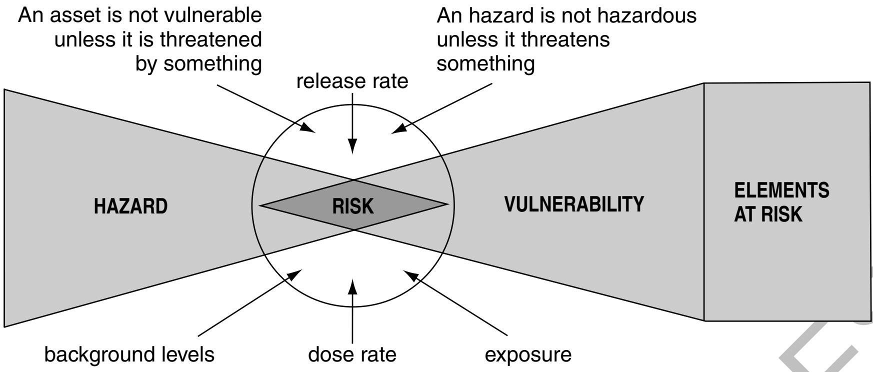

Figure 1.1 *Conceptual relationship between hazard, elements at risk, vulnerability and risk (Alexander, 2002)*

does. The level of risk, then, is the combination of the likelihood of something adverse occurring and the consequences if it does. The level of risk thus results from the intersection of hazard with the value of the elements at risk by way of their vulnerability (Figure 1.1).

Traditionally hazard and risk studies have been developed separately for industrial, financial, human, environmental and natural systems. For example, industrial systems may focus on operational malfunctions and consequent economic losses; financial systems on investment risks; human systems on crime, health or conflict; and environmental systems on pollution and resource quality. Within natural systems, where landslides are recognized as one of the 'natural hazards', the focus is on potentially dangerous events and situations arising from the behaviour of the atmosphere, biosphere, lithosphere and hydrosphere. The fact that natural forces are responsible for generating the threatening conditions distinguishes natural hazards from those of other systems, although there are many situations where the distinction between systems is not clear-cut.

The generic concepts pertaining to hazard and risk outlined above are equally applicable to landslides although they may be expressed in more process-specific terms. For landslides, the 'adverse something' might be a large rockslide and its 'likelihood' expressed as the probability of its occurrence. Similarly, the consequences will depend on what is affected by the landslide, the degree of damage it causes and the costs incurred.

In global terms, landslides generate a small but important component of the spectrum of hazard and increasing risk that faces mankind (Figure 1.2) (Alcántara-Ayala, 2002). If there were a choice, people would inhabit and rely for their well-being on the safe places of the earth – away from the threat of landslide. But even then that would presume there was sufficient knowledge of hazard and risk to allow an informed decision. However, mankind has been placed progressively at the mercy of nature through population pressure, increasing demands for resources, urbanization and environmental change. It is the intersection of humanity with landslide activity that has recast a natural land-forming process into a potential hazard (Figure 1.3a). Furthermore, economic globalization has enhanced reliance on communication and utility corridors. Fuel lines, water and sewage reticulation, telecommunication, energy and transport corridors, collectively referred to as 'lifelines' in hazard studies, are highly vulnerable to landslide disruption (Figure 1.3b).

Landslides present a threat to life and livelihood throughout the world, ranging from minor disruption to social and economic catastrophe. Spatial and temporal trends in

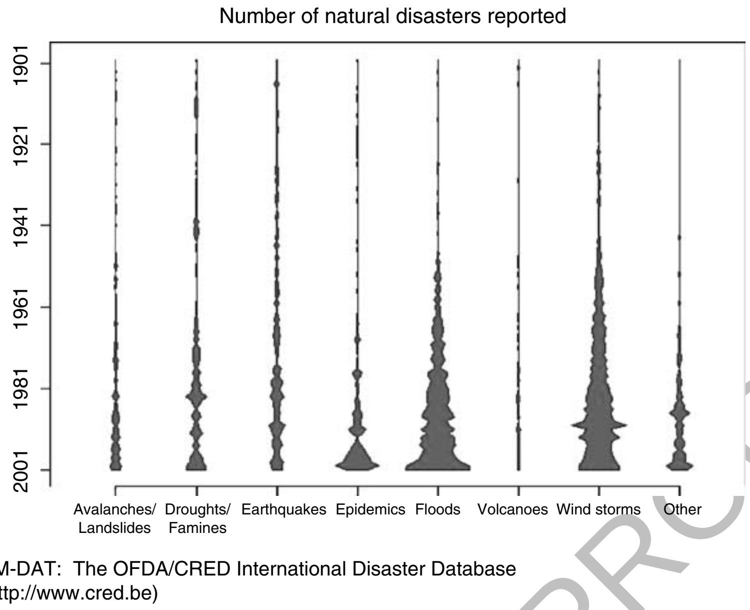

Figure 1.2 *Comparison of the number of natural disasters from different natural hazards reported within the International Disaster Database maintained by OFDA/CRED (refer to http://www.cred.be for most recent numbers)*

the level of this threat (Figure 1.4) have driven the current international and national concerns about the issue of hazard and risk reduction. However, these trends are difficult to determine accurately because of the variable quality and consistency of record keeping. These problems arise from a range of factors, including: variability and improvements in observational techniques; changes in population density, the mix of different agencies involved and the variability of recording protocols; as well as heightened economic and social awareness. One source for economic data of damage caused by natural hazards is the statistics regularly published by the re-insurance company Munich-RE (Münchner Rückversicherung, 2000). Although one has to be cautious with interpretations based on these figures, a trend is visible of increased economic costs for the insurance companies resulting from natural events. As well as economic loss, landslides have also caused numerous humanitarian disasters throughout history. A selection of major landslide disasters of more than 1000 deaths is given in Table 1.1.

Two hundred years or so of science and practice related to slope stability problems have transformed the landslide from an 'act of God' into a comprehensible geophysical process. Society demands that such knowledge carries a responsibility, a 'duty of care' and, in some instances, an obligation to act. The formalization and apportioning of this responsibility is in its infancy in many parts of the world. Nevertheless, whether driven by legal, moral or economic concerns, there is a continuing need to seek out and refine tools for risk reduction, be they scientific, engineering, legislative, economic or educational.

In the simplest terms, landslide hazard can be depicted as the physical potential of the process to produce damage because of its particular impact characteristics and the magnitude and frequency with which it occurs (or is encountered). Landslide risk, on the

Figure 1.3a *Examples of a society exposed to natural processes from Bíldudalur, Iceland. A petrol station on a bridge that crosses a drainage line susceptible to snow avalanches, debris flows and slush flows*

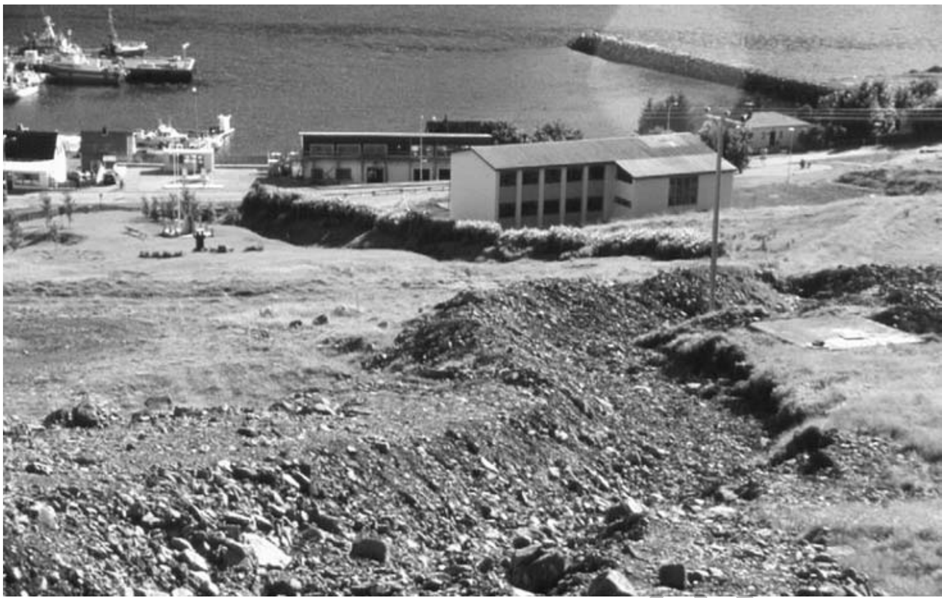

Figure 1.3b *A pole of the main power supply, a freshwater tank, and a school in the background close to the same drainage line (photos by T. Glade)*

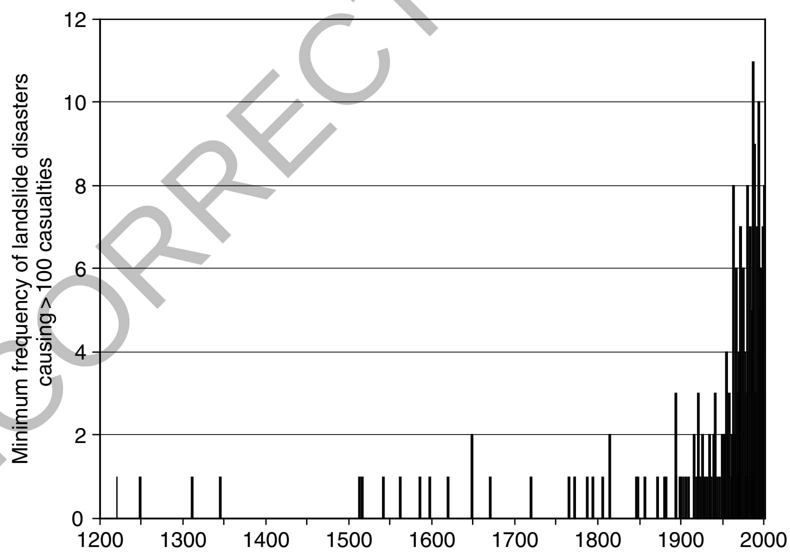

Figure 1.4 *Minimum frequency of recorded landslide disasters for the world, causing more than 100 deaths (Glade and Dikau, 2001). Refer to Table 1.1 for a selection of data*

Table 1.1 *Selection of major natural disasters due to landslides causing more than 1000 deaths. All data are based on respective sources. Type of process named where identifiable from the source (based on Glade and Dikau, 2001)*

Event	Trigger	Date	Location, region, country	Consequences	Source
Bergsturz	n.i.	1219	Plaine d'Oisans, Isère, France	>1000 casualties	Flageollet (1989)
Bergsturz	n.i.	24.11.1248	Mont Granier, Savoie, France	1500 to 5000 casualties	Flageollet (1989)
Landslide	n.i.	1310	Zhigui, Hubei, China	3466 casualties	Tianchi (1989)
Landslide	n.i.	1561	Xitan, Zhigui, Hubei, China	>1000 casualties	Tianchi (1989)
Bergstürze	Earthquake	24.11.1604	Arica, Chile	>1000 casualties	Nussbaumer (1998)
Bergsturz	n.i.	25.08.1618	Plurs, Bergell, Switzerland	>2000 casualties	Nussbaumer (1998)
Landslide	Earthquake	19.06.1718	Gansu Provonz, China	40 000 families buried	Tianchi (1989)
Lahar	Volcanic erup.	12.08.1772	Vulkan Papandayan, Java	2000–3000 casualties	Nussbaumer (1998)
Landslide	Earthquake	10.10.1786	Kangding-Louding, Sechuan, China	100 000 casualties	Tianchi (1989)
Lahar	Volcanic erup.	10.02.1792	Vulkan Unzendake, Japan	10 000 casualties	Nussbaumer (1998)
Lahar	Volcanic erup.	19.02.1845	Vulkan Nevada del Ruiz, Colombia	1000 casualties	Nussbaumer (1998)
Landslide	n.i.	09.1857	Montem./Basilic., Italy	5000 casualties	Nussbaumer (1998)
Lahar	Volcanic erup.	1919	Java, Indonesia	5110 casualties, 104 villages dest.	Brand (1989)
Landslide	Earthquake	16.12.1920	Kansu, China	>200 000 casualties	Bell (1999); Nussbaumer (1998)
Landslide	Earthquake	1920	Haiyuan, China	100 000 casualties	Tianchi (1989)
Landslide	Earthquake	25.08.1933	Sichuan, Diexi, China	6800 casualties	Tianchi (1989)
Debris-flow	n.i.	14.12.1941	Huaraz, Peru	4000–6000 casualties, 1/4 of Huaraz dest.	Erickson *et al.* (1989); Nussbaumer (1998)

Landslide	n.i.	1945	Japan	1200 casualties	Oyagi (1989)
Landslide	Earthquake	1949	Khait, Tajikistan	12 000 casualties	Alexander (1995)
Landslide	Earthquake	15.08.1950	Assam, India	Approx. 30 000 casualties	Nussbaumer (1998)
Landslide	Rainfall	1958	Shizuoka, Japan	1094 casualties, 19,754 buildings dest.	Oyagi (1989)
Landslide	n.i.	29.10.1959	Minatilan, Mexico	5000 casualties	Nussbaumer (1998)
Debris-flow	n.i.	10.01.1962	Nevados, Mt Huascaran, Peru	4000 casualties, village Ranrahirca dest.	Erickson *et al.* (1989); Nussbaumer (1998)
Landslide	n.i.	10.10.1963	Vaiont Dam in the Piave Valley, Italy	1189 casualties, some villages dest.	Müller (1964); Nussbaumer (1998); Petley (1996); Smith *et al.* (1996); Soldati (1999)
Landslide	Rainfall	1966	Rio de Janeiro, Brazil	1000 casualties	Smith *et al.* (1996)
Landslide	Rainfall	1967	Sierra des Araras, Brazil	1700 casualties	Erickson *et al.* (1989)
Lahar	Earthquake	31.05.1970	Ancash, Yungaytal, Peru	66 794 casualties	Alexander (1995); Nussbaumer (1998)
Landslide	n.i.	20.09.1973	Choloma, Honduras	2800 casualties	Nussbaumer (1998)
Lahar	Volcanic erup.	13.11.1985	Nevado del Ruiz, Colombia	>25 000 casualties	Nussbaumer (1998)
Landslide	n.i.	03.04.1987	Cochancay, Ecuador	1000 casualties	Nussbaumer (1998)
Landslide	Earthquake	23.01.1989	Tajikistan	Up to 10 000 casualties; 2 villages dest.	Nussbaumer (1998)
Landslide	n.i.	07.06.1993	Nepal	3000 casualties	Nussbaumer (1998)
Debris-flow	Rainfall	12.1999	Venezuela	30 000 casualties, 400 000 homeless	Larsen *et al.* (2001)

other hand, is the anticipated impact or damage, loss or costs associated with that hazard. Ideally hazard can be characterized by statements of 'what', 'where', 'when', 'how strong' and 'how often', demanding knowledge of variation in both spatial conditions and temporal behaviour. The ultimate test of landslide hazard prediction would be the forecast, that is, the ability to state for particular places 'where' and 'when' something will happen and what it will be like. Our ability to forecast landslide hazard with this precision is limited, and consequently landslide hazard and risk predictions are generally couched in terms of likelihoods and probabilities. However, in global terms, even this level of landslide hazard and risk assessment is rarely achieved. For example, assessments of regional landslide 'hazard', if they exist at all, are more likely to rank components of the terrain in terms of their potential for landslide occurrence (susceptibility) or simply indicate the presence or absence of existing landslides (Crozier, 1995).

Most work on landslide 'hazard' assessment has been site-based and driven by development projects and engineering concerns. Conventionally this has been approached by stability analysis of the site, generally determined from the balance of shear stress and strength and expressed as a factor of safety. Recognition of the natural variability of factors controlling stress also suggests that the factor of safety is more realistically evaluated in probabilistic terms. The major challenge for site-based stability analysis is the conversion of the factor of safety or equivalent stability assessment into a useful expression of hazard that can then be used as a component of risk assessment. This would involve employing the factor of safety along with temporal variability in triggering factors to determine the probability of failure per unit of time. Probability of occurrence, in turn, needs to be qualified by a statement of expected behaviour of the failure in terms of its impact characteristics. Predicting the nature of the landslide, particularly for first-time failures, is yet another challenge for landslide hazard science. For example, there are sufficient studies available to allow a reasonable prediction of runout length based on landslide volume (e.g. Crosta *et al.*, 2003; Crozier, 1996; Hsu, 1975; Hungr, 1995); it is the prediction of volume, as well as other impact characteristics, of first-time failures that remains the problem.

Whereas there is a generally accepted well-defined pathway for research required to refine our understanding of hazard, there is much less unanimity on what constitutes the causes of risk, particularly the underlying causes. The wide discrepancy in losses experienced between rich countries and poor countries has focused attention on the role and causes of vulnerability. The dominant view, referred to by social scientists as the 'behaviourist' paradigm (Alexander, 2000; Smith, 2001), attributes vulnerability to a lack of knowledge, insufficient preparedness and inappropriate adjustment to specific hazards. The 'structuralist' paradigm, on the other hand, attributes vulnerability to disempowerment of the victims through political-economic structures that favour the elite at the expense of the mass of population. The denial of resources by either national or transnational concerns means that the affected populations can do little to improve their level of vulnerability. This view sees 'underdevelopment' in particular countries and regions as a product of 'development' in others. High levels of vulnerability in developing countries have also been attributed to dependence on external assistance either as disaster relief or in risk management programmes. It has been argued that these measures can override traditional coping mechanisms, suppress indigenous mitigation practices and reduce the ability or incentive to take independent measures to mitigate risk.

Landslide hazard and risk studies are clearly positioned at the nexus of social and scientific concerns – two cultures that have not always been perceived as having compatible agendas. The effective research and management of risk requires the integration of a wide range of interests. There are many stakeholders that are directly or indirectly affected by the identification of risk or the promulgation of measures to reduce risk. These include:

- The decision makers and managers, and officers responsible for executing and monitoring policy
- Directly affected property owners and those who rely on the property for income and livelihood
- Indirectly affected institutions, companies or private personnel affected by disrupted lifelines
- Financial institutions and insurance agencies
- Regulators and other government organizations that have authority over activities, including issuing consents and permits, and responsibilities for emergency management
- Politicians with electoral or portfolio interest
- Suppliers and service providers: scientists, technicians, consultants, engineers, valuers, contractors
- Public interest groups and non-government organizations such as aid agencies and environmental groups
- Media.

Balancing the interests of all the affected parties when evaluating risk or choosing risk treatment options is a fundamental consideration in risk management.

1.2 Landslide Risk Assessment and Risk Management

In most societies, the ultimate goal of landslide *hazard* (the definitions of terms in italics are given in Section 1.8 and are summarized in the glossary) and *risk* studies is an accurate assessment of the level of threat from landslides: an objective, reproducible, justifiable and meaningful measure of risk. The process of establishing such a measure of risk is referred to as *risk estimation*. The estimated level of risk can then be evaluated (*risk evaluation*) in the light of the benefits accrued from being exposed to that risk (*risk–benefit analysis*) and, as a result, decisions can be made on whether that level of risk is *intolerable, tolerable* or *acceptable*. Comparison of risks from sources other than landslides, if estimated in the same way, can be made, and priorities for *risk treatment* can be rationally established. An objective measure of risk can also be employed in terms of cost–benefit (or cost–risk reduction) analysis of proposed risk treatment measures. The full range of procedures and tasks that ultimately lead to the implementation of rational policies and appropriate measures for risk reduction are collectively referred to as *risk management*.

Figure 1.5 summarizes the components that constitute risk management and their hierarchical relationships. Each of these components is examined here in a logical sequence in order to identify some of the important issues. First, if a project were established to assess the risk from landslides, a number of fundamental questions would need to be

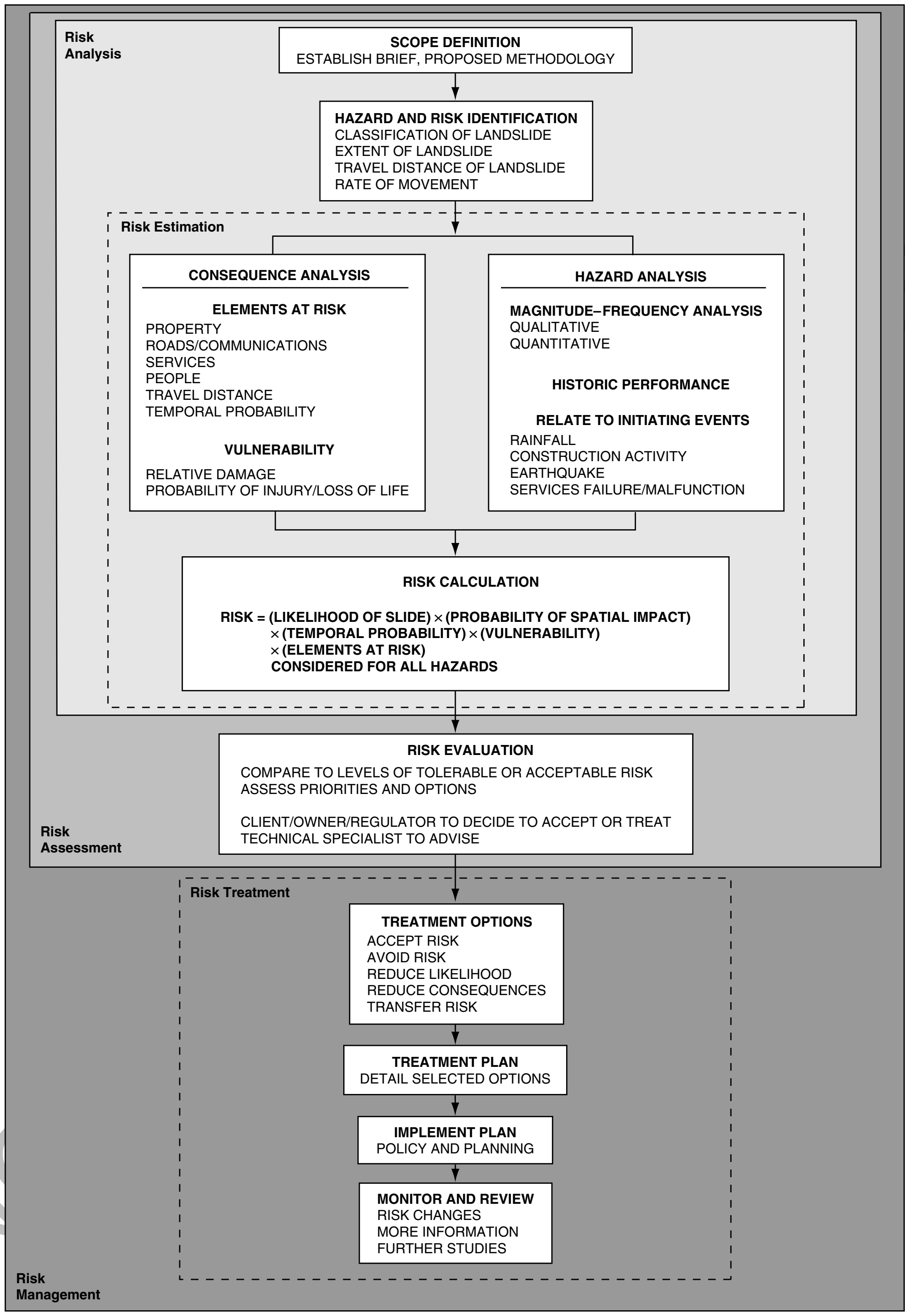

Figure 1.5 *Flow chart showing all the stages involved in landslide risk management (based on Australian Geomechanics Society, 2000)*

addressed from the outset. For example, what sort of information is required? What type of methodology should be employed? What resources are required, and, most importantly, what is the assessment to be used for? The resolution of these questions constitutes the scoping phase of the project. In practice, the scope is often dictated by scientific, economic, legal or social imperatives. It is likely to dictate the area or objects of concern; it may identify the time frame of interest, the resources available, and the degree of detail required by the assessment. In some respects, the success of an investigation may be measured against how it satisfies the identified scope or the prepared brief for the study. However, from a scientific and professional perspective, satisfaction of a brief may only partially address the question of risk (Dai *et al.*, 2002). If this is the case, it is incumbent on practioners to identify the shortcomings and point to ways of providing a more comprehensive and valuable answer.

Having identified the scope of the study, the next stage is *hazard and risk identification*. In one sense, this part of risk assessment is still very much a scoping exercise and should not be confused with the subsequent more detailed analyses of hazards and consequences. It should answer the question as to what types of physical processes exist. What might their impact characteristics be? At the same time, in order to identify potential risks it is essential to identify the possible *elements at risk*, their spatial and temporal relationship with the hazard, how they may be affected, as well as their possible levels of *vulnerability*.

The hazard and risk identification stage essentially identifies those factors that should be further investigated and taken into consideration in risk estimation. The process of *risk estimation* integrates the behaviour of the hazard (*hazard analysis*) with the elements at risk and their vulnerability (*consequence analysis*) in order to allow *risk calculation*, usually in the form of the generic hazard–risk equation:

$$\text{Risk} = \text{hazard} \times \text{vulnerability} \times \text{elements at risk} \qquad (1)$$

This is a simple but very powerful equation that identifies separately the principal factors contributing to risk. These include the probability of occurrence of a damaging landslide of a given magnitude (hazard), the valued attributes at risk (elements at risk) and the amount of damage expected from the specified *landslide magnitude*, expressed as the ratio of the value of damage to the total value of the element (vulnerability).

Although 'risk', identified as the expected loss in a unit of time, could in some instances be determined without accounting for the other factors in the equation (by simply analysing the history of loss), it would obfuscate the dynamic role of the factors causing the problem. Because of the limited length and quality of landslide impact records, consequence analysis alone would underestimate the risk emanating particularly from *high-magnitude–low-frequency* events (e.g. Figure 1.6). Calculation of risk by multiplication of the terms is also significant. It implies that if any one of the independent factors (terms on the right of the equation) is zero, the risk will be zero. Consequently, if a natural process occurs in an unpopulated area or if the structural vulnerability is very low, the risk is zero.

In some instances, it can be useful to carry out hazard analysis as a separate exercise. By doing this it is possible to identify not only the impact on existing elements but also the potential impact related to any future development, in other words potential hazard. Despite the rubric that 'there is no hazard if there is nothing at risk', the estimation of

Figure 1.6 *Rockfall near Randa in 1991, Matter Valley, Valais, Switzerland (photo by T. Glade), described by Schindler* et al. *(1993) in detail. The rockfall blocked the valley, hit lifelines and a lake was formed as a consequence. A large effort has been undertaken to reduce secondary effects, such as a flash flood resulting from a potential burst of the rockfall-dammed lake*

hazard, independent of existing human constructs, can in some instances be a powerful guide to future development decisions.

Hazard analysis (at a regional scale) requires three steps: first, the analysis of all identified landslides to determine their types and potential behaviour; second, the determination of those members of the landslide population that are capable of producing damage on the basis of an analysis of impact characteristics; and third, the determination of the location, magnitude, frequency and spatial extent of the potentially damaging landslides.

As well as a term representing hazard, the hazard–risk equation (1) requires identification and valuation of the elements at risk. The elements at risk are difficult to identify and even more difficult to quantify. In the broadest sense, they are all those attributes valued by mankind. They range from life, human well-being, through monetary values of property, lifelines, resources and means of production, to ways of life, religious, aesthetic and other values. The remaining term required for the calculation of risk in the hazard–risk equation is vulnerability. This factor is probably the most difficult to represent quantitatively (see Chapter 2). Very few data exist on the degree of damage to various elements at risk from landslides in general and even fewer for vulnerability with respect to different landslide types.

Calculated values of risk are of course the product of objective scientific investigation and are of little value until their significance can be determined by those affected. The evaluation of risk is a cultural exercise. Until an estimated level of risk can be evaluated, compared to other risks, and placed in the context of the benefits derived as a function of facing that risk, few rational decisions can be made. It is on the basis of the evaluated level of risk that risk treatment options can be exercised. These may range from the simple acceptance of the risk, education and avoidance, to various measures of control, encompassing legislative and engineering solutions affecting the hazard, vulnerability or the elements at risk.

Management of risk thus involves actions that instigate, regulate and control the identification and monitoring of hazard and risk, the estimation and evaluation of risk, as well as the options for reducing risk. In turn, the reduction of risk may involve the acceptance, avoidance, prevention, mitigation or sharing of risk. The means may include engineering solutions, legislative or regulatory edicts, education, common sense, insurance, aid, preparedness and planning (see Chapter 11).

1.3 Approaches to Landslide Hazard Analysis

The approaches taken to analyse landslide hazard depend greatly on the scope of the problem and the physical and social context. A regional assessment, for example, is likely to differ markedly from the assessment of a high-value or potentially high-risk site. The nature of information used to assess hazard may also differ depending on whether the site involves a natural slope, artificially cut slope or constructed earthworks. The presence of existing landslides also allows the application of a different set of methodologies compared to those employed in areas where no landslides exist and the hazard from first-time landslides is being assessed. The nature of existing databases and the ability to obtain relevant surface and subsurface information also dictate the approach. Whichever approach is adopted, the initial concern is to characterize the problem by determining what physical hazards exist (hazard identification) and how they are likely to behave with respect to elements at risk.

1.3.1 Landslide Hazard Identification

The first step in hazard assessment, then, is the identification of the nature of hazard likely to be encountered in the area of concern. Initially, the type of landslide has to be determined, based on internationally accepted terminology of landslides such as that proposed by Cruden and Varnes (1996) or by Dikau *et al*. (1996). A detailed review of landslide types is given in Chapter 2. After having assessed landslide type, the extent of landslide activity has to be investigated. Spatial scales of investigation can range from a few m^2 for a single landslide to several km^2 for a large number of failures (Figures 1.7 and 1.8).

The hazard identification stage also needs to investigate the potential velocities of movement. At one extreme, velocities may accelerate up to m/s for rock falls and slides. On the other hand, extremely slow, creeping landslides may move at rates of only cm/year (refer to Chapter 2 for details). Appropriate investigation techniques need to be chosen with respect to potential velocities. However, most landslides do not move continuously; instead they tend to move episodically, commonly as a response to changed environmental conditions such as elevated porewater pressures. If long-term movements need to be analysed or if early warnings need to be issued, for example in the case of debris flows, measuring devices are indispensable. However, such devices generally provide information for only short periods; thus information on long-term behaviour needs to be obtained by using other techniques.

Investigations generally cover one of two general scales: site-specific analysis or regional-based investigations. Analysis of single landslides at a particular site has a long tradition and includes field mapping, soil sampling and testing, and slope stability

__Figure 1.7__ A large, deep-seated rockslide that occurred in 1965, Hope, British Columbia (photo by M.J. Crozier)

modelling by a wide range of techniques. In contrast, regional analysis tends to be less precise and more indicative in nature. While the first approximations of hazard at the regional scale generally involve inventory maps of old landslides, recent failures, or a combination of both, new approaches include statistical analysis and process-based methods. Depending on the sophistication of the database and methods employed, 'hazard'

Figure 1.8 *Shallow earth slides and earth flows, triggered by the rainstorm of February 2004, Manawatu-Wanganui, New Zealand. Note the stabilizing effect of forest plantation (photo by G. Hancox)*

may be ultimately represented by spatial distributions, derived landslide susceptibility and, in some instances, probability of occurrence. These different types of assessment are summarized by Turner and Schuster (1996).

The overall aim of landslide hazard identification (as opposed to the larger task of hazard estimation) is to scope the nature of the potential threat. Hazard identification is the initial requirement of any programme designed to estimate the risk from landslides. This initial stage of an investigation should set out to determine the physical nature of the threatening process. Is it continuous or episodic? Is it fast or slow? Is it a localized site problem or is it a regional condition? With respect to the type of movement, will displacement be slow or catastrophic; will the displacement be in the form of disrupted blocks or single units; and over what distance will the material travel (Figure 1.9)? This stage of assessment should also anticipate any likely impacts to elements at risk. For example, are the landslides likely to affect the drainage system (Figure 1.10), infrastructure, or human settlements? It is on this basis that a programme of hazard analysis can be appropriately designed.

Identification of the hazard is a small but important step towards the overall goal of hazard analysis and risk estimation. Those responsible for making decisions with respect to the landslide risk will ultimately need a much more refined statement of the problem. They need to know not only the nature of the physical threat, but also how frequently it

Figure 1.9 A long-runout, rapid earthflow triggered by the rainstorm of February 2004, Manawatu-Wanganui, New Zealand (photo by G. Hancox)

will be manifest in a given location. The scientists involved in providing such information need to be aware of the range of methodolgies currently employed to determine hazard and risk. The following sections of this chapter cover the various approaches used to solve these problems.

1.3.2 The Geomorphological and Geotechnical Context

A large amount of information of value to hazard and risk assessment can be gained if the existing and potential landslide hazards are considered within their geomorphological and geotechnical context. Landslides are a geomorphological process intricately linked to the landform, material, structural, hydrological, climatic and vegetative conditions within which they occur. Careful study of these relationships can reveal patterns and thresholds that differentiate stable from unstable conditions. On the assumption that the combination of factors that has led to landsliding in the past will operate in the future, the analysis of pre-existing landslides (referred to as the precedence approach) provides a useful means of assessing not only the degree of future stability but also landslide behaviour. Essential to this approach is the ability to recognize evidence of past geomorphological processes and to distinguish the landslide signature from those of other less hazardous processes. Slope form, microtopography, lineaments, and depositional form and fabric, particularly when placed in the spatial context by geomorphological mapping, can provide evidence

Figure 1.10 *Deep-seated rockslide triggered by the rainstorm of February 2004, Manawatu-Wanganui, New Zealand (photo by G. Hancox)*

of current activity, velocity, age, type and extent of past landslides (Crozier, 1984). The correlation of dated landslides with changes in environmental conditions, as indicated by other geomorphological evidence, can also reveal the nature and intensity of conditions leading to landslide initiation (Hutchinson, 2000). The advantage of the precedence approach over a lab and desktop assessment is that geomorphological evidence has the potential to record the influence of a wide range of factors (including climate and hydrology) experienced by the slope (Crozier, 1997). In some instances, however, the conditions that prevailed in the past may be significantly altered by factors such as climate change, earthworks and land use activity (e.g. Figure 1.11). In particular, landslide events themselves can change the susceptibility of the terrain to future events, commonly by removing susceptible material and thereby increasing the resistance of the terrain (Crozier and Preston, 1999; Bovis and Jakob, 1999; Dykes, 2002; Glade, 2004a; Zimmermann and Haeberli, 1992; Zimmermann *et al*., 1997). These changes strongly influence hazard, and thus a comprehensive geomorphological and geotechnical assessment of their influence is an indispensable requirement for any sustainable landslide hazard scheme.

Understanding the interrelationships between the hillslope system and associated fluvial or coastal systems can provide valuable information not only on the magnitude and frequency of landslides but also on the implications of slope protection and stabilization measures. In one example from the unstable coastal cliffs of North Yorkshire, England,

Figure 1.11 Landslide occurrence following a rainstorm in 2002, Gisborne area, New Zealand. Note the differences in landslide coverage, which can be attributed to land use (photo by M.J. Crozier)

Moore *et al*. (2002) demonstrate the close links not only between marine erosion, landsliding, cliff and coastline movements (both seaward and landward), but also the relationship between landsliding and the supply of beach sediment. Stabilization measures to protect cliff top property need to be viewed alongside their potential to affect the maintenance of the beach, which in itself is a valuable recreational asset (Figure 1.12).

Careful reading of the ground can indicate the stress history of the slope. Evidence of past erosion may indicate the presence of overconsolidated material, indications of former movement can reveal that material strength has been reduced below its original peak strength, while fault evidence may point to the presence of crushed and myolinite zones. Groundwater conditions may be anticipated by spring seeps or soil precipitates, and the potential for perched water tables or artesian pressure can be signalled by stratigraphic conditions.

1.3.3 Determining Landslide Susceptibility and Hazard

Methodologies for analysing hazard range from theoretical determinism based on slope physics, through empiricism, to historical description. As mentioned before, each of these approaches may be treated quantitatively or qualitatively and many can be validated and explored through computer- or lab-based physical simulation. Deterministic methods may

Figure 1.12 *Stabilized landslide site at a coast near Ventnor, Isle of Wight. Stabilization is integrated in recreational usage of the coast (photo by T. Glade)*

be argued through geomechanical principles and mathematical solutions, while stochastic attributes and statistical association validate other methods.

Theoretical deterministic methods depend on understanding the causes of landslides. Causes, or factors conducive to instability, can be recognized at various levels of abstraction from the slope itself. There are those factors such as cohesion or porewater pressure that directly control the magnitude of stress within the slope. These direct factors can be influenced by other factors recognized at successively more remote levels of abstraction. For example, porewater pressure may be related to the rate of rainfall infiltration through the ground surface, which in turn may be related to the density of the vegetation cover. Similarly, the vegetation cover may be subject to change as a result of climate conditions or land use activity. Such chains of relationships may be critical in reducing the stability of a slope over time to a point where triggering of movement may occur.

Landslide susceptibility is thus a function of the degree of the inherent stability of the slope (as indicated by the factor of safety or excess strength) together with the presence and activity of causative factors capable of reducing the excess strength and ultimately triggering movement. The identification of causative factors is the basis of many methods of susceptibility/stability assessment. The factors may be dynamic (e.g. porewater pressure), or passive (e.g. rock structure), and may also be considered in terms of the roles they perform in destabilizing a slope (Crozier, 1989). In this sense, the factors recognized are preconditioning factors (e.g. slope steepness), preparatory factors (e.g. deforestation) and triggering factors (e.g. seismic shaking). For a full discussion see Chapter 2.

1.3.3.1 Susceptibility assessment

An initial stage of hazard analysis based on the deterministic approach is susceptibility assessment and mapping. This provides a measure of the propensity of a site or area to produce landslides based on the presence of known causative factors, the history of slope behaviour (precedence approach) or the comparison of shear and resisting stresses (factor-of-safety).

Factor (parameter) mapping. Factor mapping is commonly employed as an initial stage of regional stability assessments. It involves identifying the spatial distribution of one or more of the causative factors or their combined effect and the subsequent ranking of unit areas on the anticipated interrelated influence these may have on susceptibility (e.g. rock type and slope angle). A comprehensive list of stability factors commonly employed in this approach is given by Crozier (1989), Turner and Schuster (1996) and Guzzetti *et al.* (1999). Factor mapping can be carried out both in areas with landslides and in areas with no previous landslide history. However, if landslides are present, they can be used subsequently to determine the relative importance of factors employed in this form of susceptibility assessment.

A good example of this approach has been produced for assessing debris-flow risk (Moon *et al.*, 1991). The range of techniques that can be applied is discussed by Hansen (1984) and Gee (1992).

Precedence approach. If landslides or evidence of former landslides are present in an area, a useful first approach to the determination of susceptibility can be gained by discriminating between those factors associated with landslides and those factors associated with stable ground (Rice *et al.*, 1969). For example, it may be possible to identify slope angle and height combinations above which landslides are always found and below which conditions appear stable. The application of such spatial thresholds beyond the area within which they were established needs to done with great care, as critical conditions may vary between sites. In addition, as with all assessments based on historical conditions, subsequent changes in conditions that may affect stability need to be taken into account.

Factor of safety. A more sophisticated approach represents the terrain in terms of differences in inherent stability based on the factor of safety (FoS). The FoS is the ratio of shear strength to the shear stress mobilized. In simple terms, the value of the FoS is assumed to be 1.0 at the moment of failure and values successively greater than 1.0 represent increasing stability and hence lower susceptibility to failure. This approach can be pursued with a wide range of available methods (Duncan, 1996), depending on the nature of the anticipated failure. Simple methods such as the infinite approach require little information on the geometry of the potential displaced mass, while others partition the mass into components and may involve two-dimensional or three-dimensional stress analysis. Recently, finite element models that predict deformations within the slope are becoming increasingly used to inform engineering solutions.

In order to account for the stresses operating in a slope, a considerable amount of information is required, relating to such factors as the shape of the potential failure surface, the geometry of the slope, porewater pressure conditions, and material properties including friction and cohesion (determined for the appropriate drainage conditions), stress and strain history and likely rate of failure. Determination of the FoS permits limiting equilibrium analysis of a slope and is particularly useful in the design of the type and magnitude of remedial measures required to achieve an acceptable FoS. Because of the detailed data requirements, generally obtainable only by subsurface exploration and rigorous laboratory testing, limiting equilibrium analysis is generally only employed on a site-by-site basis, and then only where potential risk is high. If limiting equilibrium analysis is linked to the behaviour of potential triggering factors, it has the potential to convert a static FoS into a statement of hazard. For example, if a critical factor, such as rise in porewater pressure, is successfully correlated with rainfall conditions, it may be possible (with reference to the rainfall record) to determine the probability with which porewater conditions exceed a critical threshold and initiate failure.

Physically based simulation models. Dynamic modelling of hydrology and resultant slope strength conditions can be achieved using sophisticated computer simulation programs. One such model, the Combined Hydrology Slope Stability Model (CHASM™) can simulate the changes in slope stability during the course of a rainstorm and anticipate the factors of safety during the course of the event (Anderson *et al*., 1988). In critical situations, this can lead to a prediction of the time and size of failure during a rainstorm. Such models require information on rainfall intensity, antecedent hydrological conditions, soil properties, and saturated and unsaturated hydraulic conductivities. The CHASM model employs both unsaturated flow and groundwater flow as factors determining porewater pressure throughout the slope. Factors of safety are iteratively determined while conventional slope stability methods are used to isolate the most likely failure surface. Similar approaches have been used for distributed catchment hydrology modelling and slope stability (Burton and Bathurst, 1998; Montgomery and Dietrich, 1994) and have the advantage of being able to simulate areas of drainage convergence and divergence based on upslope surface morphological conditions derived from a digital elevation models.

Deterministic physical lab modelling. There have been a number of attempts to set up hardware, scale models of slopes and landslides in the laboratory environment and to determine empirically the conditions that control initiation and behaviour of landslides. This approach has been used successfully for debris flows (Tognacca *et al*., 2000). As with all scale modelling there are difficulties in scaling down all field parameters. Furthermore, in controlled laboratory conditions, it is difficult to account for dynamic changes in the geomorphic environment that occur in reality at initiation sites.

Susceptibility and stability assessments, while useful contributions to hazard analysis, do not generally provide a direct assessment of magnitude and frequency of occurrence. Increasingly, stability analyses that can link critical dynamic changes of geotechnical properties to behaviour of external triggering conditions are capable of providing an estimate of probability of occurrence and magnitude of movement (van Asch *et al*., 1999) and therefore a representation of hazard.

1.3.3.2 Historically determined frequency and magnitude

Sources for historically determining frequency–magnitude relationships are based either on natural archives from the field (e.g. hillslope evidence – morphology, deposits; dendrogeomorphology; varved lake sediments) or on human archives (e.g. church chronicles, postcards, newspaper, letters).

Field evidence. Evidence of former landsliding can be determined from slope morphology, sedimentary deposits, or impact features (e.g. deformed trees). As this type of evidence deteriorates or is obliterated progressively with time, care has to be taken in establishing long-term trends in occurrence. Off-site landslide deposits may be better preserved in the lacustrine sedimentary record. While careful dating of landslide-derived strata can provide an accurate measure of frequency, the actual magnitude and character of the formative landslide activity is less easy to establish. An excellent illustration of the use of lacustrine records to establish the frequency and magnitude of landsliding is provided by Page *et al.* (1994). A wide range of both relative and absolute methods has been employed for dating of field evidence (Lang *et al.*, 1999; Bull, 1996). A number of papers dealing with the determination of frequency and magnitude of occurrence from field evidence can be found in Matthews *et al.* (1997).

Historic archives. Another important source of past landslide activity is historical information. In this context, the term 'historical' refers to information recorded either intentionally or unintentionally by humans. Such sources may include maps, newspaper articles, church chronicles, and even postcards, drawings and personal letters. When using these data, it has to be remembered that not all events will have been recorded. Despite the fact that the quality of historical evidence is strongly dependent on recording procedures and available records, this approach provides an indication of at least the minimum level of landslide activity in an area. The issue of using historical data in natural hazard assessments is discussed by Guzzetti *et al.* (1994), Glade *et al.* (2001), and Petrucci and Polemio (2002) and is specifically addressed to landslides by Glade (2001), Bozzano *et al.* (1996) and Guzzetti (2000).

There are problems associated with all historically based approaches if they are to be used to estimate existing or future hazard. First, the historically based frequency–magnitude record may be a response to environmental conditions that no longer pertain in the area. Second, longevity of evidence is a function of time and magnitude of event. This means that the record may give a false impression, indicating, for example, that in the distant past there were fewer but bigger landslides compared with more recent periods of the record. However, this approach has the capability of including the influence of critical slope stability factors that may be missed by the inaccuracies of sampling and laboratory analyses.

1.3.3.3 Triggering threshold analysis

Analysis of the influence and behaviour of landslide-triggering agents can be used to assess the frequency and sometimes frequency–magnitude behaviour of landslides. This can be a useful approach because, in some cases (e.g. climate records), the triggering agent record is much longer and more reliable than the record of actual landslide occurrence. Despite the stability status of a given slope or catchment, a trigger (usually extrinsic) is needed to initiate the movement. In nature, these triggers can be identified as: rainfall, earthquakes, volcanic eruptions, or the undercutting of slopes by fluvial, coastal or weathering processes. Human-induced triggers may include explosions, slope cutting, slope loading (with buildings, material or water) or drainage systems that lead to a change of soil moisture regime. While human-induced triggers are difficult to assess – in particular with respect to determination of the probability of occurrence and a consequent triggering threshold – investigation of natural triggers has been successfully used to estimate landslide hazard. Triggering threshold analysis involves identifying the critical conditions associated with the initiation of landslides in the past and the comparison of these with the conditions that did *not* initiate movement. Based on the assumption that the triggering conditions and environmental setting are constant, a threshold analysis can be carried out. Such analyses are strongly dependent on a number of factors, including: the quality of the database, the quantity of items in the database, and standardization of record-keeping techniques. Another issue is the representation of a region by point-source data. For example, landslide locations and rainfall recording sites are commonly some distance apart. Thus care has to be taken when extrapolating rainfall conditions over wide areas.

Rainfall as trigger has been extensively investigated by various authors (e.g. Wieczorek and Glade, in press; Wieczorek and Guzzetti, 2000; Polemio and Petrucci, 2000; Toll, 2001; Zêzere, 2000). While some studies focus on specific locations (e.g. Finlay *et al.*, 1997), regional assessments have been performed for the USA (e.g. Larson, 1995; Wilson *et al.*, 1993; Wilson and Wieczorek, 1995), for Italy (e.g. Polloni *et al.*, 1996), and for New Zealand (e.g. Glade, 2000), to name only a few. In areas where there is a comprehensive database, it has been possible to develop triggering models to provide early warning schemes (e.g. Crozier, 1999; Wilson *et al.*, 1993). Some authors have developed rainfall thresholds for landslides and floods (Aleotti *et al.*, 1996; Reichenbach *et al.*, 1998). Inherent in all of these methods is their empirical, somewhat 'black-box' approach, leading to some uncertainty as to which stress conditions are actually critical in the triggering process (Chowdhury and Flentje, 2002).

In contrast, studies on earthquakes as landslide triggers are not as extensive (e.g. Bommer and Rodriguez, 2002). Wilson and Keefer (1985) suggested a method to predict spatial limits of earthquake-induced landslides, based on earthquake magnitude and intensity. More recently, Jibson and Keefer (1993) investigated earthquakes and related thresholds for the Madrid region, while the Northridge earthquake in 1994, which triggered numerous landslides, has been studied by Harp and Jibson (1995). A regional method for relating landslide occurrence and earthquake activity has been proposed by Jibson *et al.* (1998). As with rainfall triggers, these studies involve empirical methods and thus numerous data are required. The basis of the relationships established by these methods can be location-specific and therefore application of derived models to other regions is limited.

1.4 Techniques Employed in Obtaining Information of Value to Hazard Estimation

Landslide occurrence is a complex, multivariate problem. The accuracy with which landslide hazard can be represented varies depending on the quality and quantity of data available. The quality of the database in turn can often be a function of the availability of time, money and other resources. At the scoping stage of any landslide hazard and risk investigation, important decisions need to be made on the nature of the solution sought and the consequent detail and techniques required with respect to data acquisition. In general, investigation types can be differentiated, including:

- Surface investigations
- Subsurface investigations

- Laboratory analysis
- Modelling approaches
- Dating techniques
- GIS techniques.

Commonly, each field study starts with a detailed mapping campaign. Depending on the study design, this may incorporate topographic characteristics, geotechnical information, geomorphological features, lithological and structural information, hydrological conditions and so on. These can be registered on a base map, or dominant positions can be determined by tachymetry or GPS. Both techniques have the advantage that fixed ground-control points can be regularly revisited to provide information on surface movement (e.g. Malet *et al*., 2002). Present-day movement can also be monitored by a range of recording devices (e.g. extensiometers as described in Angeli *et al*., 1999). In addition, remote sensing techniques allow spatial information to be accessed for even remote areas. These techniques include airborne-derived data such as aerial photography and oblique photography, and satellite imagery (e.g. Zhou *et al*., 2001). Where a suitable vegetation cover exists, dendrogeomorphological investigations can be used to determine the record of surface movements (e.g. Gers *et al*., 2001).

Subsurface movement is generally monitored using inclinometer tubes. These measurements are often used in conjunction with borehole drillings, drop-penetration tests and geophysical investigations (e.g. seismic reflection and refraction, georadar and geoelectric sensing; refer to Mauritsch *et al*. (2000) for a typical case study). In addition, soil hydrology can be monitored using tensiometers, piezometers and pressure cells installed at different depths.

Age of events can also be assessed using a range of methods. Generally, these refer to either indirect techniques such as relative dating (e.g. by stratigraphic position of landslide sediment) or to direct approaches such as lichenometry, radiocarbon dating (C^{14}), luminescence (TL or OSL), or nucleide dating of exposed surfaces (Lang *et al*., 1999). Recently, spatial analysis using GIS techniques has become common. Point-derived data can be coupled with spatial data sets (e.g. Digital Terrain Model, geology, soil, vegetation, etc.) in order to gain additional information of relevance to landslide distribution and movement. An introduction to GIS techniques of different complexities is given by Soeters and van Westen (1996) and by Carrara and Guzzetti (1995). It has to be emphasized, however, that spatial analysis may involve large errors due to data uncertainty. Therefore, any spatial analysis should be verified by a range of independent validation techniques (e.g. Chung and Fabbri, 1999). A valuable source of information on techniques and methods available for landslide hazard assessment has been compiled by Turner and Schuster (1996).

1.5 Approaches to Risk Estimation

A simple approach to risk estimation might involve just a frequency analysis of past *consequences*. For example, the number of deaths resulting from aircraft incidents per unit distance travelled could provide a measure of risk from air travel. However, because aircraft are becoming safer and patterns of air travel change, the measure of risk produced in this way has limited temporal significance. While safer aircraft mean that there are fewer fatalities per air mile travelled and thus on average *individual risk* may be less, *societal risk* has increased because there are more people flying and more air miles being flown. Clearly, both the dynamics of the source of the problem (hazard) and elements at risk also need to be assessed. Similarly, landslide risk cannot be adequately represented by consequence analysis alone. The main reason for this is that the record of landslide impact is often too short or too obscure to have captured the very high-magnitude–low-frequency events that constitute a major component of landslide risk. Thus a comprehensive risk assessment should involve the sequential identification and analysis of a number of components that influence risk.

There are two sources of uncertainty in risk estimation: first, the uncertainty attached to both the hazard and consequence components of risk; and second, the accuracy (margin of error) of the estimate itself. Estimates of risk can be arrived at and expressed both qualitatively and quantitatively. No matter which approach is taken, the value of the estimate depends on the accuracy of initial hazard and risk identification. That initial stage of investigation should be widely scoped to include not just direct and immediate impacts but also consequential hazards, indirect and delayed impacts. For example, episodes of landsliding in parts of New Zealand have ultimately led to downstream aggradation, loss of channel capacity and severe flooding. In some cases this has resulted in abandonment of farming operations or the installation of expensive flood protection works (Page *et al.*, 2001). Thus landslide impacts can be direct or indirect, immediate or delayed, and in some instances generate consequential hazards.

1.5.1 Vulnerability Assessment

Vulnerability relates to the Latin verb *vulnerare*, 'to wound' or 'to be susceptible', and is explained in the dictionary as 'liability to be damaged or wounded; not protected against attack'. Hence the vulnerability relates to the consequences, or the results of an impact of a natural force, and not to the natural process or force itself (Lewis, 1999). In practice, vulnerability and consequences are irrevocably linked. Two fundamentally different perspectives for examining vulnerability exist: investigations based on natural science and those based on social science methods and assumptions.

Unfortunately, there exists no uniform definition of 'vulnerability' in social sciences. Numerous definitions are reviewed and listed by Weichselgartner (2001). Wilches-Chaux (1992) summarized different views of vulnerability and differentiates between natural, physical, ecological, technical, economical, social, political, institutional, ideological, cultural and educative vulnerability. Also Cutter (1996) states that there are no unique definitions of vulnerability in social sciences. Chambers (1989) refers to both internal and external dimensions affecting vulnerability. While the internal dimensions include defencelessness and insecurity of threatened people, the external dimension refers to exposure to risk, shock and stress (Bohle, 2001). Hence vulnerability is determined by factors closely related to both external conditions, and to whether humans and their resources are able to withstand or cope with a natural disaster, or not (Hewitt, 1997; Smith, 2001).

Commonly, vulnerability assessments in landslide risk research are based on natural science approaches such as Liu *et al.* (2002). In contrast to other natural processes such as flooding and earthquakes, it is very difficult to assess vulnerability to landslides due to the complexity and the wide range of variety of landslide processes (Leroi, 1996). As Glade (2004b) summarizes, diverse effects have to be considered:

- Vulnerability of different elements at risk varies for similar processes.
  Fell (1994: 263) states that 'a house may have similar vulnerability to a slow- and a fast-moving landslide, but persons living in the house may have a low vulnerability to the slow-moving landslide (they can move out of the way) but a higher vulnerability to the fast-moving landslide . . .' because they cannot escape. If the scale of investigation is increased, there are also differences within a single house. For example, rooms facing towards the slope are more vulnerable to debris flows than valley-facing rooms. Furthermore, the larger the windows, the more vulnerable is the room and the respective content. Even people sleeping in this room will have a higher probability of death than other occupants of the house (Fell, 1994; Fell and Hartford, 1997).
- Temporal probability for a person of being present during the landslide event is variable.
  While a house is fixed to the ground, a car or inhabitants are mobile and might not be present during the event. For example, at night, a family is sleeping in the house whereas during the day, children are at school and the parents are working; hence the house would be empty. In contrast, fewer people are in commercial buildings at night; hence the potential consequences would be less severe, although property damage might be extensive.
- Different groups of humans have different coping potentials.
  In contrast to most adults, children might not be able to react adequately to endangering processes. Similarly, elderly or handicapped people might not have the possibility to escape, although the endangering process is correctly judged. This is one example of different coping potentials that has been addressed for landslide risk analysis by Liu *et al*. (2002).
- Early warning systems affect the vulnerability of people.
  If a warning system is installed, people might be able to escape (Smith, 2001), or at least reach safe places (Fell and Hartford, 1997) and thus change their vulnerability to given event magnitudes.
- Spatial probability of landslide occurrence varies.
  The spatial probability of the occurrence of a potentially damaging event at a given location has to be considered. For example, although a landslide occurs in the predicted zone, the probability that a small item or an individual human is affected is significantly different for a single rockfall compared with a widespread debris-flow. Hence it is important to differentiate landslides by type, such as rockfall, debris-flow, or translational earth slides, to name a few only (Fell, 1994).

Although this list could be extended, it gives an indication of potential factors that have to be considered in vulnerability assessment within landslide risk analysis. Despite all these limitations and complex, sometimes even unsolved problems, it is an economic and political necessity to assess vulnerability to landslides. Various attempts have been made. For preliminary studies, vulnerability is commonly set to 1, referring to a total damage as soon as the element at risk is hit by a landslide (e.g. Carrara, 1993; Glade *et al*., submitted). More detailed investigations apply damage matrices (Leone *et al*., 1996) based on either qualitative (e.g. Cardinali *et al*., 2001) or quantitative approaches (e.g. Fell, 1994; Finlay and Fell, 1997; Heinimann, 1999; Leone *et al*., 1996; Michael-Leiba *et al*., 2000; Ragozin, 1996). Vulnerability assessment is a complex issue, which is regularly not considered in an appropriate and thoughtful manner.

1.5.2 Qualitative Risk Estimation

While the ultimate aim of risk estimation is the derivation of some reproducible standard measure of risk that can be compared and evaluated along with other similarly estimated risks, this is not always achievable. Resource and data constraints or preconceived notions of risk may dictate that quantitative estimations are neither warranted nor achievable. In such cases, risk may be determined by judgement and experience and expressed in qualitative terms. Intuition and professional judgement have long been defended as a legitimate approach to risk assessment, particularly among the engineering fraternity. If this approach is adopted, it needs to be explained and supported by ample reasons and statement of significance. Some examples of qualitative assessment of frequency, consequences and risk with respect to property are given in Tables 1.2, 1.3 and 1.4.

The subjectivity, latitude and cultural specificity of the terms used in qualitative estimation of risk lend themselves to a diversity of interpretation. Whereas intuitive estimates of risk, calling on judgement and experience, may be entirely appropriate

Table 1.2 *Qualitative measures of likelihood (Australian Geomechanics Society, 2000)*

Level	Descriptor	Description	Indicative annual probability
A	Almost certain	The event is expected to occur	$>= 10^{-1}$
B	Likely	The event will probably occur under adverse conditions	$= 10^{-2}$
C	Possible	The event could occur under adverse conditions	$= 10^{-3}$
D	Unlikely	The event might occur under very adverse circumstances	$= 10^{-4}$
E	Rare	The event is conceivable but only under very exceptional circumstances	$= 10^{-5}$
F	Not credible	The event is inconceivable or fanciful	$<= 10^{-6}$

Table 1.3 *Qualitative measures of consequences to property (Australian Geomechanics Society, 2000)*

Level	Descriptor	Description
1	Catastrophic	Structure completely destroyed or large-scale damage requiring major works for stabilization
2	Major	Extensive damage to most of the structure, or extending beyond site boundaries requiring significant stabilization works
3	Medium	Moderate damage to some structure, or significant part of the site requiring large stabilization works
4	Minor	Limited damage to part of structure, or part of site requiring some reinstatement/stabilization works
5	Insignificant	Little damage

Table 1.4 *Qualitative risk-level implications (Australian Geomechanics Society, 2000)*

Risk level	General guide to implications
Very high risk	Extensive detailed investigation and research planning and implementation of treatment options essential to reduce risk to acceptable levels: may be too expensive and not practicable
High risk	Detailed investigation, planning and implementation of treatment options required to reduce risk to acceptable levels
Moderate risk	Tolerable provided plan is implemented to maintain or reduce risks. May be accepted. May require investigation and planning of treatment options
Low risk	Usually accepted. Treatment requirements and responsibility to be defined to maintain or reduce risk
Very low risk	Acceptable. Manage by normal slope maintenance procedures

and even the best approach in some circumstances, they can sometimes be difficult to reproduce and substantiate by other parties. Where possible, a universal estimate of hazard and risk is best addressed in standard, objective, quantitative terms. The derived values can then be appropriately placed and evaluated within the relevant social context.

1.5.3 Quantitative Risk Calculation

Quantitative risk calculation is carried out by expressing hazard frequency and consequences in measured, numerical terms and determining their product. For example, the risk from property can be calculated (Australian Geomechanics Society, 2000) from:

$$R_{(Prop)} = P_{(H)} \times P_{(S:H)} \times V_{(Prop:S)} \times E \tag{2}$$

where:

$R_{(Prop)}$ is the risk to property (annual loss of property value)

$P_{(H)}$ is the annual probability of the hazardous event (the landslide)

$P_{(S:H)}$ is the probability of spatial impact by the hazard (i.e. of the landslide affecting the property and, for vehicles, for example, the temporal probability)

$V_{(Prop:S)}$ is the vulnerability of the property to spatial impact (proportion of the property value lost)

E is the element at risk (e.g. the value or net present value of the property)

Because the areal unit used in assessing hazard and risk is not always identical to the area specifically affected by the landslide, the term 'probability of spatial impact' [$P_{(S:H)}$] is included in the above equation. Spatial probability is the ratio of the area affected by the landslide to the assessment area multiplied by the ratio of the area of the element of interest to the assessment area. Similarly, some elements at risk are mobile and have only temporary presence in the area affected by the landslide. The probability of presence can be taken into account by including the term temporal probability [$T_{(P:S)}$]. For example, a person may occupy a threatened building for only part of the time or a vehicle may be in the location only for a proportion of the time. It should be stressed that a quantitative approach such as indicated in equation (2) provides only a very limited estimate of risk, dealing with only one component, essentially direct damage to property in economic terms. There are likely to be many other indirect consequences associated with property damage. For example, in the case of damage to an industrial plant, this may involve loss of profit, loss of clients, loss of employment and earnings, as well as the adverse effects experienced by retailers and suppliers of raw materials associated with that industrial plant.

1.6 Approaches to Risk Evaluation

Risk evaluation is the processes of determining the significance of a risk to the individual, organization or community. Only after significance of risk is assessed can an appropriate response be determined. Essentially the risk needs to be judged as *acceptable, tolerable*, or *intolerable* (Fell, 1994; Finlay and Fell, 1997). These judgements are, however, hugely influenced by psychological, social and cultural values (Fischhoff *et al*., 1981). Therefore it is important that risk is understood, evaluated and response options determined by those that live with the risk. Perception of risk involves an intuitive evaluation by an individual or group and perceptions can vary widely between individuals even within the same community (refer to Chapter 6 for more details). Perception is influenced by a multitude of factors, including: education, acquired knowledge, experience of previous hazards, gender, age and so on, and has been the subject of extensive psychological and sociological research (Garrick and Willard, 1991). From a management perspective, it is important that the variability of perception is reduced and that, through education and communication, the margin between reality and perception is narrowed. The terminology used to express risk is also difficult for the non-expert to understand. Difficulty may be experienced in interpreting and differentiating between expressions such as ‘highly likely’, or a ‘probability of 10^{-2}’, or a chance of occurrence of ‘10% in fifty years’. One of the ways of improving the understanding of risk is by risk comparison; that is, comparing risk estimates with those of more familiar, easily understood risks. Risk comparison and ranking is also a useful means of prioritizing response (Table 1.5).

The nature of response to risk depends on the judgements of whether the risk is acceptable, tolerable or intolerable. As with perception, these judgements are highly subjective and influenced by psychological, sociological and cultural perspectives. Judgements can also be influenced by the nature of the risk. For example, people are more likely to accept a given level of risk emanating from a natural hazard as opposed to risk associated with

Table 1.5 *Comparison of individual risk of death from hazards in New Zealand (population ~3.5 million). Annual average between 1840 and 1990*

Hazard	Deaths per year	Probability of death per person per year
Smoking	4000	1.1×10^{-3}
Road accident	600	1.7×10^{-4}
Suicide	380	1.1×10^{-4}
Falls	300	8.6×10^{-5}
Drowning	120	3.5×10^{-5}
Homicide	50	1.4×10^{-5}
Fire	32	9.0×10^{-6}
Natural hazards	6	1.6×10^{-6}

an artificial source such as a nuclear power plant. Similarly, attitudes toward risk vary, depending on whether the risk is localized or widespread throughout the community or whether it is voluntary (such as rock climbing) or involuntary (such as earthquakes).

Despite the subjectivity involved in risk judgement, some authorities and industries have set standards used to determine the acceptability of risk. For example, interim guidelines set by the Geotechnical Engineering Office of the Hong Kong Government for landslides and boulder falls on natural terrain indicate, in terms of annual loss of life, an 'acceptable' individual risk level at 1×10^{-5} for new developments and 1×10^{-4} for existing developments (Moore *et al.*, 2001).

Acceptability of societal risk, on the other hand, is sometimes based on the use of the FN diagram, which shows the ratio of frequency of events to the severity of the consequences of those events, expressed in terms of fatalities (Figure 1.13).

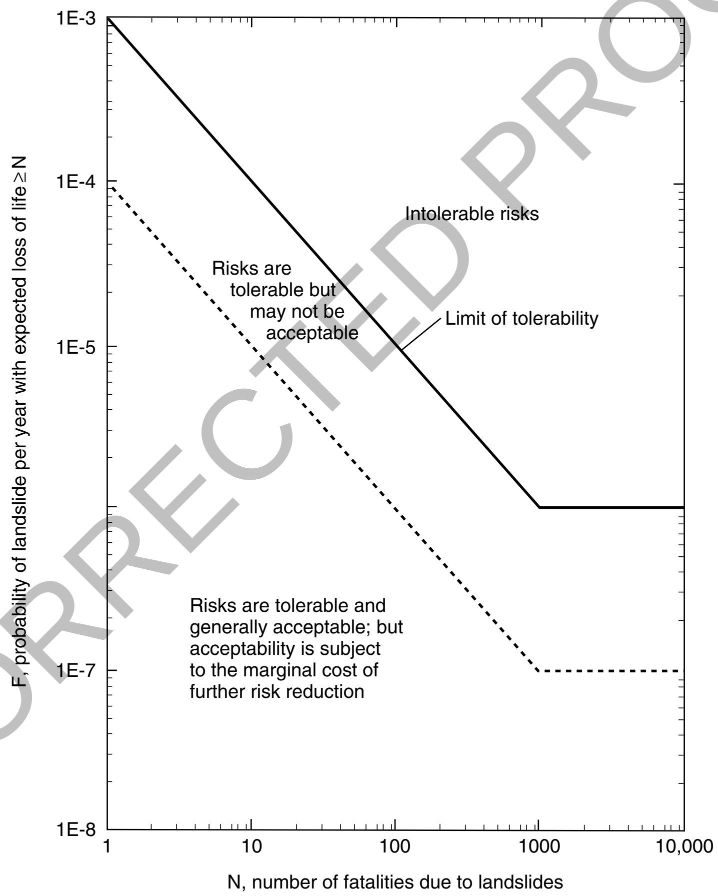

Figure 1.13 *The frequency of events of given magnitude (number of deaths) plotted against the number of deaths represented by those events (adapted from Australian Geomechanics Society, 2000). These diagrams are referred to as FN diagrams*

Implicit or explicit in any decision on acceptability of risk, whether as an individual or government authority, is the exercise of risk–benefit analysis. This is the comparison of the level of risk with benefits associated with being exposed to that risk. Even though there might be a relatively high risk, the associated benefits are sufficient to accept or tolerate the risk. For example, living on the top of a coastal cliff may expose the inhabitants to landslide risk but the view and other attributes may be considered to outweigh that risk (see Chapter 11 for discussion of this issue).

1.7 Risk Treatment

The risk management cycle (Figure 1.14) provides a generic ideal representation of the range and relationships of all the components of management aimed at managing and reducing risk and responding to emergencies (refer to Chapter 11 for further details). Landslide risk management is fully discussed in Part 3 of this book and mentioned here are only those aspects of management that are directly hazard-specific, namely mitigation and prevention (treatment options).

The risk/benefit ratio and the absolute level of risk strongly influence not only the acceptability of risk but also the nature of the response. High levels of risk may warrant

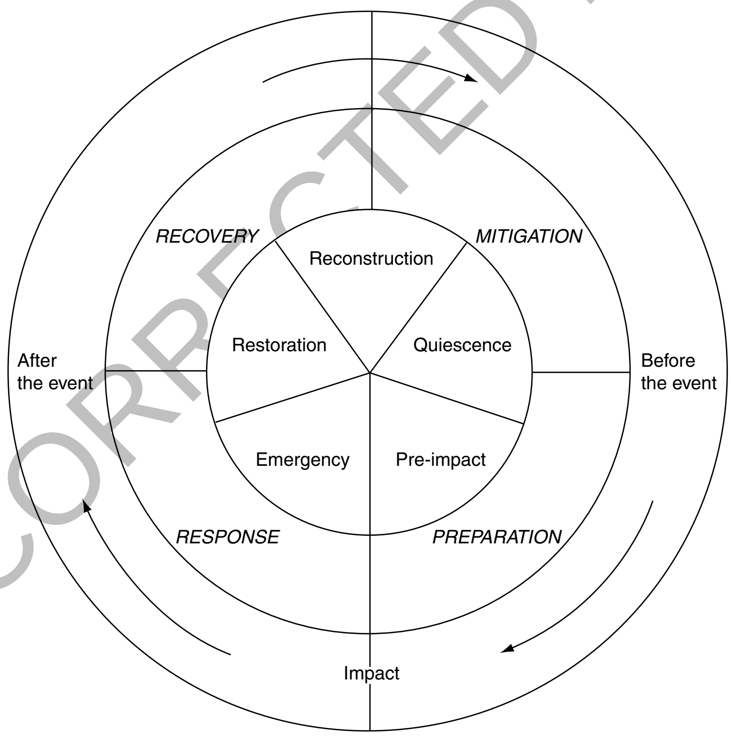

Figure 1.14 *The general risk management cycle as described by Alexander (2000; 2002)*

a legislative or sophisticated engineering response, while low levels of risk may be accepted or treated by common sense and education. The physical characteristics of the hazard also dictate the type of treatment measures adopted. For example, the hazard from shallow soil landslides may be prevented or reduced by tree planting, whereas with deep-seated landslides trees may produce very little benefit. If landslides are of the type that recur in specific locations, for example debris-flow tracks, alarm systems, warning information or zoning may be employed. The type of material, size, rate, type and depth of movement can all be matched with a range of appropriate engineering slope control measures. Determination of the factors critical to the onset of movement can also point to appropriate remedial solutions. For example, if movement relates to high groundwater levels, slope drainage becomes an option. In areas where toe erosion instigates movement, buttressing and toe reinforcement are appropriate measures.

The range of options available for reducing landslide risk can be grouped as follows:

- Hazard modification: usually engineering solutions aimed at modifying the impact characteristics and reducing the frequency – in other words, keeping the hazard away from people.
- Behaviour modification: reducing the consequences by options such as avoidance, warning systems, reduction of vulnerability, development planning, education, regulations and economic incentives.
- Loss sharing: including systems for insurance, disaster relief, development aid and compensation.

1.8 Definitions

Because hazard and risk studies in general have been approached from so many different discipline perspectives there is inevitably a level of confusion in the terminology employed. This lack of standardization and consistency of use of the terminology has also found its way into the study of landslide hazard and risk. Listed below are definitions for many important terms that are fundamental to communication and understanding of landslide hazard and risk, although many of the definitions offered are sufficiently generic to apply to other forms of hazard. Wherever possible the definitions have been expressed initially in the most broadly applicable generic sense and where necessary subsequently explained with reference to landslides. Most but not all of the definitions are in accord with those proposed by Australian Geomechanics Society (2000) and Fell and Hartford (1997).

Acceptable risk: level of risk that a given society is prepared to accept because of the marginal cost of any further risk reduction. Risk management may aim to reduce all risks to this level.

Consequences (impacts): the effects, usually but not always negative or adverse, resulting from hazard. Negative consequences may be referred to as losses or costs involving both economic and non-economic values.

Consequence analysis: identification and analysis of adverse effects or potential adverse effects arising from landslides, including immediate and delayed effects from direct landslide impact or indirectly through the disruption of other systems.

Consequential landslide hazard: a hazard (type I or type II) resulting not directly from the landslide itself but as a result of a consequential process set in train by the landslide. For example, a wave set up by a catastrophic landslide entering a water body would be considered a consequential hazard in this context.

Dynamic hazard: hazard resulting from the active, generally episodic behaviour of the natural process.

Elements at risk: all valued attributes threatened by the hazard (the landslide); may include structures, land, resources, social and physical infrastructure productive and non-productive activities, environmental qualities, life and physical and mental well-being. Some of these attributes are quantifiable, some can be expressed in economic terms and others defy ready quantification.

Frequency: a measure of the likelihood expressed as the number of occurrences of an event in a given time. For many natural hazards, including landslides, the basic unit of time used in frequency analysis is the year. For example a frequency of five events (*n*) recorded in a 100-year period (*t*) can also be expressed as an average frequency (*n*/*t*) of one event every 20 years on average. The term *n*/*t* (in this example 20 years) is referred to as the **recurrence interval** or return period. The reciprocal of the return period expressed in years provides the annual *probability*; in this example 1/20 yields an annual probability of 0.05. In other words, there is a 5% chance of the event occurring in any one year, on average.

Hazard: in natural hazard usage, there are two accepted definitions of 'hazard'. The first (Hazard I) refers to an actual physical entity (process or situation) that has the potential to cause damage (e.g. a large rockslide or a long runout debris-flow). This is the common non-technical understanding of hazard. However, this use of the term hazard is also found in some legal and statutory documents, with statements of the form: 'It is council policy to record the date and location of hazards. These include landslide, debris-flow, surface flooding, subsidence etc. . . .'. The second definition (Hazard II) is more technical and refers not to a process but rather to a threatening condition resulting from the behaviour of that process, expressed as the probability of occurrence of a damaging landslide.

Hazard I: a hazard is a potentially damaging process or situation (the landslide), for example an earthquake above a certain intensity or a landslide of sufficient size, depth, or displacement to cause damage or disruption or, as an example of a situation, the presence of weak foundation material.

Hazard II: the probability of a potentially damaging event (a landslide) occurring in a unit of time. This probability varies with the magnitude of the event (generally small landslides occur more frequently than large landslides). Consequently hazard is often expressed as the probability of occurrence of a given magnitude of event (see *magnitude–frequency relationship*). Defined in this way, hazard represents a state or condition and is assessed and applied to a particular place, for example site, unit area of land surface, region or object, lifelines, hydro dams, and so on.

Hazard analysis: the process of identifying the probability of occurrence of a damaging event.

Hazard identification: the process of recognizing and accounting for all possible hazards that might occur within the place and time period of interest. For landslides this involves identifying landslide type, *landslide impact characteristics* and *consequential hazards*. The process needs to consider the types of element at risk as well as the relationship in time and space between landslides and *elements at risk*.

Individual risk: total risk divided by the population at risk. For example, if a region with a population of one million people experiences on average 5 deaths from landslides per year, the individual risk of being killed by a landslide in that region is 5/1 000 000, usually expressed in orders of magnitude as 5×10^{-6}.

Intolerable risk: level of risk that society is not prepared to live with and which must be reduced, removed, or avoided.

Landslide impact characteristics: characteristics of the landslide that may control the potential impact, including: degree of disruption of the displaced mass, areal extent and distance of runout, depth, area affected, velocity, discharge per unit width, and kinetic energy per unit area. Collectively these have been considered to represent **'landslide intensity'**.

Landslide magnitude: a measure of landslide size generally taken as the mass or volume of material displaced. With many other natural hazards the standard magnitude parameter (e.g. Richter magnitude for earthquakes or peak discharge for floods) is directly related to potential impact. Landslide magnitude, however, is a less reliable index of impact potential – other characteristics of the movement may be more important in determining impact (see *landslide impact characteristics*).

Landslide susceptibility: the propensity of an area to undergo landsliding. It is a function of the degree of inherent stability of the slope (as indicated by the factor of safety or excess strength) together with the presence of factors capable of reducing the excess strength and ultimately triggering movement.

Magnitude–frequency relationship: the relationship between the size of landslides and the frequency with which they occur in time or space. Essentially, big events are rare and small events are common. Some form of declining exponential or power-law function generally represents the relationship between magnitude and frequency.

Probability: the likelihood of a specific outcome, measured by the ratio of specific outcomes to the total number of possible outcomes. Probability is generally expressed as a number between 0 and 1, with 0 indicating an impossible outcome, and 1 indicating that an outcome is certain.

Risk: a measure of the probability and severity of loss to the *elements at risk*, usually expressed for a unit area, object, or activity, over a specified period of time.

Risk analysis: the overall process involving scoping, *hazard and risk identification* and *risk estimation*.

Risk assessment: the combined processes of risk analysis and risk evaluation, leading to the stage where personal judgements and treatment decisions can be rationally made.

Risk estimation: the process of deriving a measure of the probability and severity of loss to the *elements at risk* by the integration of hazard and consequence analysis. This can be carried out quantitatively (involving risk calculation, sometimes referred to as Quantitative Risk Analysis [QRA]) or qualitatively.

Risk evaluation: the process of determining the importance and relevance (significance) of the results of *risk analysis* with reference to the social and physical context within which they occur. This process determines whether risk is tolerable or acceptable. Risk evaluation may involve considerations of risk perception, risk communication and risk comparison with the aim of developing some appropriate level or form of response. It generally implicitly or explicitly balances the risk with the benefits associated with exposure to that risk.

Risk management: the process of developing and applying policies, procedures and practices to the tasks of assessment, monitoring, communication and *treatment of risk*.

Risk treatment: actions taken to address the results of risk; may involve acceptance, avoidance, reduction of frequency or intensity of hazard, reduction of consequences or the transferral of risk.

Risk–benefit analysis: the process of relating the level of risk to the level of benefits associated with exposure to that risk.

Societal risk: the total risk attributed to the society responsible for bearing that risk.

Specific risk: hazard probability × vulnerability for a given element at risk and/or for a given type of process.

Static hazard: hazard arising not through episodic behaviour of the natural agent but by human actions leading to the encounter of static hazardous conditions, for example building on weak foundation material. Hazard in this case is determined from the probability of human encounter or the number of damaging incidents per unit of time associated with the deposit.

Tolerable risk: level of risk that a society is prepared to live with because there are net benefits in doing so, as long as that risk is monitored and controlled and action is taken to reduce it.

Total risk: the expected consequences (loss) resulting from the level of hazard in a place, over a specified time period. It depends not only on the different hazardous process involved but also on elements at risk and their vulnerability.

Vulnerability: the expected degree of loss experienced by the elements at risk for a given magnitude of hazard.

References

Alcántara-Ayala, I., 2002, Geomorphology, natural hazards, vulnerability and prevention of natural disasters in devloping countries, *Geomorphology*, **47**, 107–124.

Aleotti, P., Baldelli, P. and Polloni, G., 1996, Landsliding and flooding event triggered by heavy rains in the tanaro basin (Italy) Internationales Symposium

AQ: Pls provide publication details

Alexander, D., 1995, *Natural Disasters* (London: UCL Press).

Alexander, D.E., 2000, *Confronting Catastrophe* (New York: Oxford University Press).

Alexander, D.E., 2002, *Principles of Emergency Planning and Management* (New York: Oxford University Press).

Anderson, M.G., Kemp, M.J. and Lloyd, D.M., 1988, Applications of soil water finite difference models to slope stability problems, in C. Bonnard (ed.), *Proceedings of the* 5th *International Symposium on Landslides*, 10–15 July 1988, Lausanne, Switzerland (Rotterdam: A.A. Balkema), 525–530.

Angeli, M.G., Pasuto, A. and Silvano, S., 1999, Towards the definition of slope instability behaviour in the Alvera mudslide (Cortina d'Ampezzo, Italy), *Geomorphology*, **30**, 201–211.

AQ: Pls provide volume no

Australian Geomechanics Society, 2000, Landslide risk managamenet concepts and guidelines, *Australian Geomechanics*, 49–92.

Bell, F.G., 1999, *Geological Hazards – Their Assessment, Avoidance and Mitigation* (London and New York: E & FN Spon).

Bohle, H.-G., 2001, Vulnerability and criticality: perspectives from social geography. *IHDP Update*, **2**, 1–5.

Bommer, J.J. and Rodriguez, C.E., 2002, Earthquake-induced landslides in central America, *Engineering Geology*, **63**, 189–220.

Bovis, M.J. and Jakob, M., 1999, The role of debris supply conditions in predicting debris-flow activity, *Earth Surface Processes and Landforms*, **24**, 1039–1054.

Bozzano, F., De Pari, P. and Mugnozza, G.S., 1996, Historical data in evaluating landslide hazard in some villages in Southern Italy in K. Senneset (ed.), *Landslides – Glissements de Terrain* (Rotterdam: A.A. Balkema) vol. 1, 159–164.

Brand, E.W., 1989, Occurrence and significance of landslides in Southeast Asia, in E.E. Brabb and B.L. Harrod (eds), *Landslides – Extent and Economic Significance* (Rotterdam: A.A. Balkema) 303–324.

Bull, W.H., 1996, Prehistorical earthquakes on the Alpine fault, New Zealand, *Journal of Geophysical Research*, **101**, 6037–6050.

Burton, A. and Bathurst, J.C., 1998, Physically based modelling of shallow sediment yield at catchment scale, *Environmental Geology*, **35**, 89–99.

Cardinali, M., Reichenbach, P., Guzetti, F., Adrizzone, F., Antonini, G., Galli, M., Cacciano, M., Castellani, M. and Salvati, P., 2001, A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy, *Natural Hazards and Earth System Sciences*, **2**, 1–16.

Carrara, A., 1993, Uncertainty in evaluating landslide hazard and risk, in J. Nemec, J.M. Nigg and F. Siccardi (eds), *Prediction and Perception of Natural Hazards, Proceedings Symposium*, 22–26 October 1990, Perugia, Italy. (Dordrecht: Kluwer Academic Publishers), vol. 2, 101–109.

Carrara, A. and Guzzetti, F. (eds), 1995, *Geographical Information Systems in Assessing Natural Hazards: Advances in Natural and Technological Hazards Research* (Dordrecht: Kluwer Academic Publishers).

Chambers, R., 1989, Vulnerability, coping and policy, *IDS Bulletin*, **20**, 1–7.

Chowdhury, R. and Flentje, P., 2002, Uncertainties in rainfall-induced landslide hazard, *Quarterly Journal of Engineering Geology and Hydrogeology*, **35**, 61–69.

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

Crosta, G.B., Imposimato, S. and Roddeman, D.G., 2003, Numerical modelling of large landslide stability and runout, *Natural Hazard and Earth System Science*, **3**, 523–538.

Crozier, M.J., 1984, Field assessment of slope instability, in D. Brunsden and D.B. Prior (eds), *Slope Instability* (London: John Wiley & Sons Ltd), 103–142.

Crozier, M.J., 1989, *Landslides: Causes, Consequences and Environment* (London: Routledge).

Crozier, M.J., 1995, Landslide hazard assessment: a review of papers submitted to theme G4, in D.H. Bell (ed.), *Proceedings of the Sixth International Symposium*, 10–14 February 1992, Christchurch, New Zealand (Rotterdam: A.A. Balkema), 1843–1848.

Crozier, M.J., 1996, Runout behaviour of shallow, rapid earthflows, *Zeitschrift für Geomorphologie (Supplementband)*, **105**, 35–48.

Crozier, M.J., 1997, The climate–landslide couple: a southern hemisphere perspective, in J.A. Matthews, D. Brunsden, B. Frenzel, B. Gläser and M.M. Weiß (eds), *Rapid Mass Movement As a Source of Climatic Evidence for the Holocene* (Stuttgart: Gustav Fischer) vol. 19, 333–354.

Crozier, M.J., 1999, Prediction of rainfall-triggered landslides: a test of the antecedent water status model, *Earth Surface Processes and Landforms*, **24**, 825–833.

Crozier, M.J., and Preston, N.J., 1999. Modelling changes in terrain resistance as a component of landform evolution in unstable hill country. In: S.Hergarten and H.J> Neugebauer (Editors), Process Modelling and Landform Evolution. Lecture Notes in Earth Sciences. Spring-Verlag, Heidelberg, pp. 267–284.

Cruden, D.M. and Varnes, D.J., 1996, Landslide types and processes, in A.K. Turner and R.L. Schuster (eds), *Landslides: Investigation and Mitigation* (Washington, DC: National Academy Press), Special Report 247, 36–75.

Cutter, S.L., 1996, Vulnerability to environmental hazards, *Progress in Human Geography*, **20**, 529–539.

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

Dikau, R., Brunsden, D., Schrott, L. and Ibsen, M. (eds), 1996, *Landslide Recognition: Identification, Movement and Causes* (Chichester: John Wiley & Sons Ltd).

Duncan, J.M., 1996, Soil slope stability analysis, in A.K. Turner and R.L. Schuster (eds), *Landslides: Investigation and Mitigation* (Washington, DC: National Academy Press), Special Report 247, 337–371.

Dykes, A.P., 2002, Weathering-limited rainfall-triggered shallow mass movements in undisturbed steepland tropical rainforest, *Geomorphology*, **46**, 73–93.

Erickson, G.E., Ramirez, C.F., Concha, J.F., Tisnado, G.M. and Urquidi, F.B., 1989, Landslide hazards in the central and southern Andes, in E.E. Brabb and B.L. Harrod (eds), *Landslides: Extent and Economic Significance* (Rotterdam: A.A. Balkema), 111–118.

Fell, R., 1994, Landslide risk assessment and acceptable risk, *Canadian Geotechnical Journal*, **31**, 261–272.

Fell, R. and Hartford, D., 1997, Landslide risk management, in D.M. Cruden and R. Fell (eds), *Landslide Risk Assessment – Proceedings of the Workshop on Landslide Risk Assessment*, Honolulu, Hawaii, USA, 19–21 February 1997 (Rotterdam: A.A. Balkema), 51–109.

Finlay, P.J. and Fell, R., 1997, Landslides: risk perception and acceptance, *Canadian Geotechnical Journal*, **34**, 169–188.

Finlay, P.J., Fell, R. and Maguire, P.K., 1997, The relationship between the probability of landslide occurrence and rainfall, *Canadian Geotechnical Journal*, **34**, 811–824.

Fischhoff, B., Lichtensetin, B.S., Slovic, P., Derby, S.L. and Kenney, R.L., 1981, *Acceptable Risk* (Cambridge: Cambridge University Press).

Flageollet, J.C., 1989, Landslides in France: a risk reduced by recent legal provisions, in E.E. Brabb and B.L. Harrod (eds), *Landslides: Extent and Economic Significance* (Rotterdam: A.A. Balkema), 157–168.

Garrick, B.J. and Willard, C.G. (eds), 1991, *The Analysis, Communication and Perception of Risk* (New York: Plenum Press).

Gee, M.D., 1992, Classification of landslide hazard zonation methods, in D.H. Bell (ed.) *Proceedings of the Sixth International Symposium*, 10–14 February 1992, Christchurch, New Zealand (Rotterdam: Balkema), 947–952.

Gers, E., Florin, N., Gärtner, H., Glade, T., Dikau, R. and Schweingruber, F.H., 2001, The application of shrubs for dendrogeomorphological analysis to reconstruct spatial and temporal landslide patterns – A preliminary study, *Zeitschrift für Geomorphologie, Supplement Band*, **125**, 163–175.

Glade, T., 2000, Modelling landslide triggering rainfall thresholds at a range of complexities, in E. Bromhead, N. Dixon and M.-L. Ibsen (eds), *Landslides in Research, Theory and Practice* (Cardiff: Thomas Telford), 633–640.

Glade, T., 2001, Landslide hazard assessment and historical landslide data – an inseparable couple? in T. Glade, F. Frances and P. Albini (eds), *The Use of Historical Data in Natural Hazard Assessments* (Dordrecht: Kluwer Academic Publishers) vol. 7, 153–168.

Glade, T., 2004a, Linking natural hazard and risk analysis with geomorphology assessments, *Geomorphology*, in press.
Glade, T., 2004b, Vulnerability assessment in landslide risk analysis, *Die Erde*, **134**, 121–138.
Glade, T. and Dikau, R., 2001, Gravitative Massenbewegungen – vom Naturereignis zur Naturkatastrophe, *Petermanns Geographische Mitteilungen*, **145**, 42–55.
Glade, T., Frances, F. and Albini, P. (eds), 2001, *The Use of Historical Data in Natural Hazard Assessments: Advances in Natural and Technological Hazards Research* (Dordrecht: Kluwer Academic Publishers).
Glade, T., von Davertzhofen, U. and Dikau, R. (submitted) GIS-based landslide risk analysis in Rheinhessen, Germany *Natural Hazards*.
Guzzetti, F., 2000, Landslide fatalities and the evaluation of landslide risk in Italy, *Engineering Geology*, **58**, 89–107.
Guzzetti, F., Cardinali, M. and Reichenbach, P., 1994, The AVI Project: A Bibliographical and Archive Inventory of Landslides and Floods in Italy, *Environmental Management*, **18**, 623–633.
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**, 181–216.
Hansen, A., 1984, Landslide hazard analysis, in D. Brunsden and D.B. Prior (eds) *Slope instability* (Chichester: John Wiley & Sons Ltd), 523–602.
Harp, E.L. and Jibson, R.W., 1995, Inventory of landslides triggered by the 1994 Northridge, California earthquake Denver, *US Geological Survey*, **17**.
Heinimann, H.R., 1999, *Risikoanalyse bei gravitativen Naturgefahren – Methode*. Bern.
Hewitt, K., 1997, *Regions of risk: A geographical introduction to disasters* (Harlow: Addison Wesley Longman Limited).
Hsu, K.J., 1975, Catastrophic debris streams (sturtzstrom) generated by rockfalls. *Geological Society of America Bulletin*, **86**, 128–140.
Hungr, O., 1995, A model for the runout analysis of rapid flow slides, debris flows, and avalanches, *Canadian Geotechnical Journal*, **32**, 610–623.
Hutchinson, J.N., 2001. Reading the ground: morphology and geology in site appraisal. The Fourth Glossop Lecture. *Quarterly Journal of Engineering Geology and Hydrogeology*, **34**: 7–50.
Jibson, R.W. and Keefer, D.K., 1993, Analysis of the seismic origin of landslides: examples from the New Madrid seismic zone, *Geological Society of America Bulletin*, **105**, 521–536.
Jibson, R.W., Harp, E.L. and Michael, J.A., 1998, A method for producing digital probabilistic seismic landslide hazard maps: an example from Los Angeles, California, area Los Angeles, *US Geological Survey*, **21**.
Lang, A., Moya, J., Corominas, J., Schrott, L. and Dikau, R., 1999, Classic and new dating methods for assessing the temporal occurrence of mass movements, *Geomorphology*, **30**, 33–52.
Larsen, M.C., Wieczorek, G.F., Eaton, S. and Sierra, H.T., 2001, The Venezuela landslide and flash flood disaster of December 1999, in Mugnai, A. (ed.), *2nd Plinius Conference on Mediterranean Storms*, 16–18 October 2000. Siena, Italy, EGS.
Larson, R.A., 1995, Slope failures in southern California: rainfall threshold, prediction, and human causes, *Environmental and Engineering Geoscience*, **1**, 393–401.
Leone, F., Asté, J.P. and Leroi, E., 1996, Vulnerability assessment of elements exposed to mass-movement: working toward a better risk perception, in K. Senneset (ed.), *Landslides – Glissements de Terrain* (Rotterdam: A.A. Balkema) vol. 1, 263–270.
Leroi, E., 1996, Landslide hazard – Risk maps at different scales: objectives, tools and development, in Senneset, K. (ed.), *Landslides – Glissements de Terrain, 7th International Symposium on Landslides*, (Rotterdam: A.A. Balkema), 35–51.
Lewis, 1999, *Development in disaster-prone places – studies of vulnerability* (London: Intermediate Technology Publications Ltd).

AQ: Pls provide initials

Liu, X.L., Yue, Z.Q., Tham, L.G. and Lee, C.F., 2002, Empirical assessment of debris-flow risk on a regional scale in Yunnan province, southwestern China, *Environmental Management*, **30**, 249–264.
Malet, J.P., Maquaire, O. and Calais, E., 2002, The use of Global Positioning System techniques for the continuous monitoring of landslides: application to the Super-Sauze earthflow (Alpes-de-Haute-Provence, France), *Geomorphology*, **43**, 33–54.

Matthews, J.A., Brunsden, D., Frenzel, B., Gläser, B. and Weiß, M.M. (eds), 1997, *Rapid mass movement as a source of climatic evidence for the Holocene*: *Paläoklimaforschung Paleoclimate Research* (Stuttgart, Jena, Lübeck and Ulm: Gustav Fischer Verlag).

Mauritsch, H.J., Seiberl, W., Arndt, R., Römer, A., Schneiderbauer, K. and Sendlhofer, G.P., 2000, Geophysical investigations of large landslides in the Carnic region of southern Austria, *Engineering Geology*, **56**, 373–388.

Michael-Leiba, M., Baynes, F. and Scott, G., 2000, Quantitative landslide risk assessment of Cairns, Australia, in Bromhead, E., Dixon, N. and Ibsen, M.-L. (eds) *Landslides in Research, Theory and Practice* (Cardiff: Thomas Telford), 1059–1064.

Montgomery, D.R. and Dietrich, W.E., 1994, A physically based model for the Topographic control on shallow landsliding, *Water Resources Research*, **30**, 1153–1171.

Moon, A.T., Olds, R.J., Wilson, R.A. and Burman, B.C., 1991, Debris-flow risk zoning at Montrose, Victoria, in D.H. Bell (ed.), *Landslides* (Rotterdam: Balkema), vol. 2, 1015–1022.

Moore, R., Hencher, S.R. and Evans, N.C., 2001, An approach for area and site-specific natural terrain hazard and risk assessment, Hong Kong Geotechnical Engineering Meeting Society's Needs, *Proceedings of the 14th Southeast Asia Geotechnical Conference*, Hong Kong, December 2001, 155–160.

Moore, R. and Mclnnes, R.G., 2002. Cowes to Gurnard costal stability: providing the tools and information for effective planning and management of unstable land. In: R.G. Mclnnes and J.Jakeways (Editors), Instability Planning and Management. Proceedings of the International Conference. Thomas Telford, Isle of Wight, pp. 109–116.

Müller, L., 1964, The rockslide in the Vaiont valley, *Felsmechanik und Ingenieurgeologie*, **2**, 148–212.

Münchner Rückversicherung, 2000, *Topics 2000: Naturkatastrophen – Stand der Dinge München* (Münchner Rückversicherung), 126.

Nussbaumer, J., 1998, *Die Gewalt der Natur. Eine Chronik der Naturkatastrophen von 1500 bis heute*, ed. Grünbach Sandkorn.

Oyagi, N., 1989, Geological and economic extent of landslides in Japan and Korea, in E.E. Brabb and B.L. Harrod (eds), *Landslides: Extent and Economic Significance* (Rotterdam: A.A. Balkema), 289–302.

Page, M.J., Trustrum, N.A. and DeRose, R.C., 1994, A high-resolution record of storm induced erosion from lake sediments, New Zealand, *Journal of Paleolimnology*, **11**, 333–348.

Page, M.J., Trustrum, N. and Gomez, B., 2001, Implications of a century of anthropogenic erosion for future land use in the Gisborne – East Coast region of New Zealand, *New Zealand Geographer*, **56**, 13–24.

Petley, D., 1996, The Mechanics and Landforms of Deep-Seated Landslides, in M.G. Anderson and S.M. Brooks (eds), *Advances in Hillslope Processes* (Chichester: John Wiley & Sons Ltd) vol. 2, 823–835.

Petrucci, O. and Polemio, M., 2002, Hydrogeological multiple hazard: a characterisation based on the use of historical data, in J. Rybár, J. Stemberk and P. Wagner (eds), *Landslides: Proceedings of the First European Conference on Landslides, Prague*, June 2002 (Lisse: Balkema), 269–274.

Polemio, M. and Petrucci, O., 2000, Rainfall as a landslide triggering factor: an overview of recent international research, in E. Bromhead, N. Dixon and M.-L. Ibsen (eds), *Landslides in Research, Theory and Practice, Proceedings of the 8th International Symposium on Landslides* (Cardiff: Thomas Telford), 1219–1226.

Polloni, G., Aleotti, P., Baldelli, P., Nosetto, A. and Casavecchia, K., 1996, Heavy rain triggered landslides in the Alba area during November 1994 flooding event in the Piemonte Region (Italy), in Senneset (ed.), *Landslides – Glissements de Terrain* (Rotterdam: Balkema), vol. 3, 1955–1960.

Ragozin, A.L., 1996, Modern problems and quantitative methods of landslide risk assessment, in K. Senneset (ed.), *Landslides – Glissements de Terrain* (Rotterdam: A.A. Balkema), vol. 1, 339–344.

Reichenbach, P., Cardinali, M., De Vita, P. and Guzzetti, F., 1998, Regional hydrological thresholds for landslides and floods in the Tiber River Basin (central Italy), *Environmental Geology*, **35**, 146–159.

Rice, R.M., Corbett, E.S. and Bailey, R.G., 1969, Soil slips related to vegetation, topography, and soil in Southern Caifornia, *Water Resources Research*, **7**, 647–659.

Schindler, C., Cuenod, Y., Eisenlohr, T. and Joris, C.L., 1993, The events of randa, April 18th and May 9th, 1991 – an uncommon type of rockfall, *Eclogae Geologicae Helvetiae*, **86**, 643–665.

Smith, K., 2001, *Environmental Hazards: Assessing Risk and Reducing Disaster* (London: Routledge).

Smith, R.P., Jackson, S.M. and Hackett, W.R., 1996, Paleoseismology and seismic hazards evaluations in extensional volcanic terrains, *Journal of Geophysical Research – Solid Earth*, **101**, 6277–6292.

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

Soldati, M., 1999, Landslide hazard investigation in the Dolomites (Italy): the case study of Cortina d'Ampezzo, in R. Casale and C. Margottini (eds), *Floods and Landslides: Integrated Risk Assessment* (Berlin: Springer-Verlag), 281–294.

Tianchi, L.C., 1989. Landslides: Extend and economic significance in China In: E.E. Brabb and B.L. Harrod (Editors) Landslides: Extent and Economic Significance. A.A. Balkema, Rotterdam, pp. 271–288.

Tognacca, C., Bezzola, G.R. and Minor, H.-E., 2000, Threshold criterion for debris-flow initiation due to channel bed failure, in G.F. Wieczorek and N.D. Naeser (eds), *Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment*, 16–18 August 2000, Taipei, Taiwan (Rotterdam: A.A. Balkema), 89–98.

Toll, D.G., 2001, Rainfall-induced landslides in Singapore. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering*, **149**, 211–216.

Turner, A.K. and Schuster, R.L., 1996, *Landslides: Investigation and Mitigation*, Transportation Research Board Special Report 247 (Washington, DC: National Academy Press).

van Asch, T.W.J., Buma, J. and Van Beek, L.P.H., 1999, A view on some hydrological triggering systems in landslides, *Geomorphology*, **30**, 25–32.

Weichselgartner, J., 2001, Disaster mitigation: the concept of vulnerability revisited, *Disaster Prevention and Management*, **10**, 85–94.

AQ: Pls update

Wieczorek, G. and Glade, T., in press, Climatic factors influencing occurrence of debris flows, in M. Jakob and O. Hungr (eds), *Debris-Flow and Debris Avalanches – A Practically-oriented Overview of the State-of-the-Art* (Heidelberg: Springer).

Wieczorek, G.F. and Guzzetti, F., 2000, A review of rainfall thresholds for triggering landslides, *Mediterranean Storms – Proceedings of the EGS Plinius Conference*, Maratea, Italy, October 1999, 407–414.

Wilches-Chaux, G., 1992, The global vulnerability, in Y. Aysan and I. Davis (eds), *Disasters and the Small Dwelling*, 30–35.

Wilson, R.C. and Keefer, D.K., 1985, Predicting areal limits of earthquake-induced landsliding, *US Geological Survey*.

Wilson, R.C. and Wieczorek, G.F., 1995, Rainfall thresholds for the initiation of debris flows at La Honda, California, *Environmental and Engineering Geoscience*, **1**, 11–27.

Wilson, R.C., Mark, R.K. and Barbato, G., 1993, Operation of a real-time warning system for debris flows in the San Francisco Bay Area, California Hydraulic Engineering, ASCE (San Francisco, CA: Hydraulics Division, ASCE), 1908–1913.

Zêzere, J.L., 2000, Rainfall triggering of landslides in the area north of Lisbon (Portugal), in E. Bromhead, N. Dixon and M.-L. Ibsen (eds), *Landslides in Research, Theory and Practice, Proceedings of the 8th International Symposium on Landslides* (Cardiff: Thomas Telford), 1629–1634.

Zhou, C.H., Yue, Z.Q., Lee, C.F., Zhu, B.Q. and Wang, Z.H., 2001, Satellite image analysis of a huge landslide at Yi Gong, Tibet, China, *Quarterly Journal of Engineering Geology and Hydrogeology*, **34**, 325–332.

Zimmermann, M. and Haeberli, W., 1992, Climatic change and debris-flow activity in high-mountain areas – a case study in the Swiss Alps, *Catena Supplement*, **22**, 59–72.

Zimmermann, M., Mani, P. and Romang, H., 1997, Magnitude–frequency aspects of alpine debris flows, *Eclogae Geologicae Helvetiae*, **90**, 415–420.