3

A Review of Scale Dependency in Landslide Hazard and Risk Analysis

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3.1 Introduction

Landslides occur at various spatial and temporal scales. They are a natural part of landscape evolution, and differ greatly in their contribution to slope-forming processes in different environmental settings. When landslides occur, they can move quickly downslope at rates of several m/s, or they can creep slowly at rates of only a few mm/year. On the one hand, they can move instantaneously following a specific trigger such as an earthquake, an intense rainfall event, an explosion, or undercutting event. On the other hand, they may show a delayed response to critical triggering conditions, for example after a prolonged rainfall event with a gradual rise in porewater pressures. The range of spatial and temporal scales covered by different landslide types is shown schematically in Figure 3.1.

The wide range of both spatial and temporal scales distinguishes landslide processes significantly from other natural processes such as floods, earthquake shaking or tsunamis. Some examples of the range of landslide occurrences are given in Figure 3.2. The relative spatial and temporal coverage of these examples is indicated in Figure 3.1. Despite these extreme variations, some general patterns of occurrences can be recognized.

The spatial and temporal behaviour of landslides and the occurrence of specific types of landslide can be linked to particular environmental domains, but only in the most general terms (Figure 3.2). For example, all types and scales of movement can be found in mountainous terrain. However, rock avalanches (Bergsturz) and instantaneous rock

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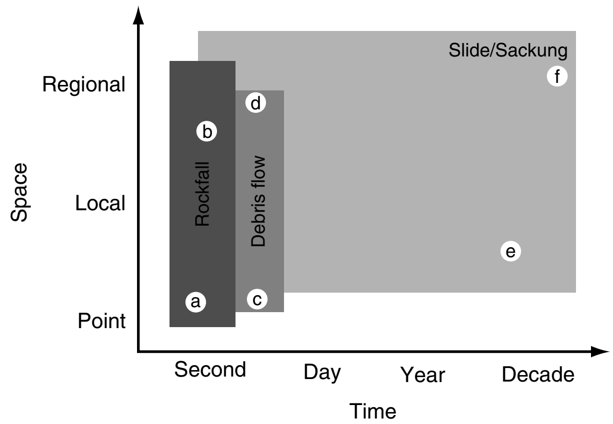

Figure 3.1 *Schematic diagram of scales of landslide occurrence. Letters refer to examples shown in Figures 3.2(a–f)*

and debris falls, slides, and flows with long runouts are generally restricted to these steep mountainous areas. Such areas provide the potential and kinetic energy requirements by having high relief and steep slopes, as well as providing large rock-dominated slopes, and sources of mechanically weathered debris. Nevertheless, rotational failures (slumps) require rock and soil conditions that are massive and free from structural control in order to achieve their full development. Typically, such conditions are met in softer rock in more gentle terrain. Large failures, however, are not restricted to any terrain. Block slides, rotational failures (slumps) and lateral spreading of large dimensions have been recorded in areas of very low slope angle as well as low relative relief. Critical in these instances is the presence of weak or failure-prone material. The slump flows in the quick clay of Scandanavia and North America are prime examples (e.g. Larsen *et al.*, 1999). Other problem situations are commonly found in areas where slopes have been actively and recently destabilized, usually by active undercutting such as on river banks and coasts or where human construction has taken place. All forms of movement are possible in these locations and their magnitude and behaviour are largely dictated by the available relief and slope angle. Regolith and soil failures are, by definition, characteristic of areas that are of sufficiently low angle or sufficiently susceptible to weathering to have produced and retained a regolith mantle (for example rolling hill country). The soil and debris slides and flows that eminate from these areas are supply-constrained. Their frequency of occurrence is dependent not only on triggering forces but also on the availability of material. These failures become most threatening in areas where they can become channelized. Thus moderate to steep terrain, retaining a regolith and drained by high-angle valleys, provides the potential for high-velocity, high-magnitude events.

The character of magnitude and frequency distributions can also be related to the nature of the triggering event. Earthquake shaking and extreme climatic conditions (including intense rainfall) can trigger movements over areas of many square kilometres in extent (Crozier and Preston, 1999; Eyles *et al.*, 1978; Keefer, 2002). These situations commonly produce multiple-occurrence events with up to thousands of landslides occurring over hundreds of square kilometres in the range of a few minutes or hours. Their impact can

Figure 3.2a Examples of landslides occurring at different temporal and spatial scales. Rockfall in the Ahr Valley, Germany (photo by T. Glade)

Figure 3.2b *Vaimont rockslide/Bergsturz (photo by E. Bromhead)*

Figure 3.2c *Debris flow in the Matter Valley, Switzerland (photo by H. Gartner)*

Figure 3.2d *Debris and earthslides and flows in Makahoni, New Zealand (photo by M.J. Crozier)*

Figure 3.2e *Coastal landslides in the south of the Isle of Wight, UK (photo by T. Glade)*

Figure 3.2f *Large rock slumps in King Country, New Zealand (photo by M.J. Crozier)*

be registered in all types of terrain, from gentle relief to mountainous terrain. Analysis of such events has indicated difficulities in differentiating the landslide signature arising from earthquake- and rainfall-triggered events. Crozier (1997) suggests that climatically triggered events have a predominance of small to medium-size landslides, with only the rare large event, whereas he concludes that earthquake-triggered events are capable of producing a high proportion of large failures. Alternatively, Guzzetti *et al.* (2002b) suggest that the magnitude–frequency distribution of events triggered by rainfall and earthquakes are indistinguishable.

Irrespective of the triggering mechanism, on most slopes, landslides will occur where inherent susceptibility (excess strength) is lowest. However, failure sites for climatically triggered events will normally occur where surface and groundwater concentrate or where sufficient depth of susceptible material occurs (e.g. hillslope hollows, Crozier *et al.*, 1990). In some situations, prevailing antecedent soil-water conditions may be related to slope aspect, consequently dictating the distribution of landslide occurrence during an event (Crozier *et al.*, 1980). In contrast, seismically triggered failures may occur preferentially on ridge crests where topographic enhancement of earthquake waves occurs or within material susceptible to liquefaction. Other triggering mechanisms such as undercutting by geomorphic process occur in predictable locations such as the outside bends of stream channels and exposed coastal cliffs. Triggering by human action is indiscriminate (Baroni *et al.*, 2000), generally confined to areas of undercutting, mining or oversteepening or to areas that have been loaded by material or excess drainage. However, human action as a preparatory factor (see Chapter 2) can exert its influence over wide areas, such as in the case of deforestation (e.g. Glade, 2003a; Guthrie, 2002;

Marden and Rowan, 1993; Montgomery *et al*., 2000; Vanacker *et al*., 2003; Wu and Swanston, 1980).

3.2 Philosophy of Spatial Modelling

The temporal and spatial behaviour of landslides dictates the method of hazard and risk analysis as well as the treatment of the problem. While individual landslides may be treated with site investigations and possibly advanced numerical stability models, spatial distributions require other techniques. Generally, it can be assumed that with increasing spatial resolution more data are available to analyse the phenomenon, hence the system complexity also increases. Accordingly, the model generalizing reality expands in its complexity. Consequently, the more data available, the higher is the model complexity, and the predictive potential of the result is more robust. This dependency has been described to determine spatial patterns of catchment hydrology by Grayson and Blöschl (2000) as well as Grayson *et al*. (2002) and is transferred to spatial landslide observations in Figure 3.3.

The conceptual relation between data availability, model complexity and predictive capacity shows that there is an 'optimum model complexity' (bold dashed line in Figure 3.3) best describing the relation of these three variables. The following example demonstrates this dependency for a given data set (bold line in Figure 3.4). Analysis of a medium-sized data set shows a decreasing model performance after having passed the line of 'optimum model complexity'. Even better and more advanced models describe the data set with less predictive capacity. This relation can be attributed to the fact that a specific data set allows only the application of specific models; more advanced models do not necessarily increase the accuracy of prediction. Similarly, a model with a given complexity can only be used to predict a data set of a given quality. Even better data sets (in quality, quantity, resolution, etc.) do not significantly enhance the prediction given by the similar model complexity. Although the general trend shown in this figure is reasonable, some problems are inherent in details. The line of 'optimum model complexity' is not necessarily as straight as shown in Figure 3.3. Another possible relation is a step-wise increase in prediction accuracy, which is given when the data availability increases, but model complexity and the predictive surface stay constant. In contrast,

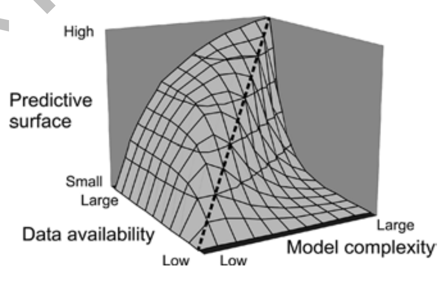

Figure 3.3 *Schematic diagram showing one relation between data availability, model complexity and predictive capacity of the result (based on Grayson and Blöschl, 2000 and Grayson* et al.*, 2002). The 'optimum model complexity' (Grayson* et al.*, 2000) is marked as a bold dashed line and described in the text*

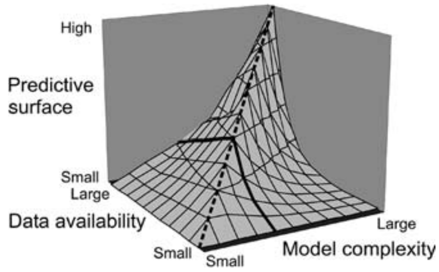

Figure 3.4 *Schematic relation between data availability, model complexity and predictive capacity of the result. This figure gives a probable relation of current reality. The bold line indicates a decrease of the predictive surface after exceeding the line of 'optimum model performance' (bold dashed line) although the data availability increases*

models with increasing complexity applied to the same data set do not necessarily change the predictive surface. In addition, often the accuracy of results (or predictive surface) from different models with increasing complexity *decreases* after exceeding the line of 'optimum model complexity' (bold line in Figure 3.4). This can be related to the fact that the more variables included in a data set, the more uncertain are the interrelationships, and positive or negative feedback loops between the variables exist. Larger model complexities cannot address these interrelations and loops adequately. Consequently, more data do not necessarily allow better predictive surfaces, as indicated in Figure 3.3. Therefore, the minimum set of information that best explains the system behaviour with current methods and techniques has to be determined. It must be asked whether the most accurate predictive result is better modelled using smaller data sets than applying additional data to a similar model. In addition, the simpler black-box models (i.e. models where only input and output are known and no knowledge on internal links is available) are often more robust than advanced numerical models. Hence, after exceeding the line of 'optimum model complexity' there is no constant prediction surface associated with increasing data sets for similar models as shown in Figure 3.3; rather the prediction surface decreases again with larger data sets. This dependency is given schematically in Figure 3.4.

To summarize, Figure 3.3 gives theoretical relations, but these relations can often not be verified by analysis for the reasons explained in the previous paragraph. Independent of the previously mentioned constraints, however, research should aim to move towards a relation such as given in Figure 3.3.

For practical application (e.g. planning purposes), it is most important to consider the cost of the analysis, and the benefit of the proposed measures. Such cost–benefit considerations are often the driving force of practical solutions and thus the line of 'optimum model complexity' helps to define which method describes the available data set with highest precision for which resolution. Consequently, it is most important to be sure that the result of the applied method meets the requirements of the study aim.

Having this schematic concept of data availability, model complexity and prediction capacity in mind, the following sections review approaches for local investigations and spatial analysis. Three distinct different landslide types have been selected: rockfall, debris flow and translational/rotational earth- and soil slides. These three groups are the most common landslide types and are thus briefly reviewed with respect to susceptibility, hazard and risk.

3.3 Landslide Susceptibility and Hazard Analysis

3.3.1 Site-based Stability and Hazard Analysis

3.3.1.1 Rock slope analysis

Rock slope failures, rockfalls and rock topples can occur in any size. Worldwide examples are summarized by Evans and DeGraff (2002). Analytical techniques for rockfalls and rock slopes have been developed since the beginning of the twentieth century. Albert Heim (1932) analysed rockfalls systematically in the European Alps. This work has been extended by Abele (1974) to produce one of the most comprehensive monographs on rockfalls in the European Alps. On the basis of this type of information various other authors have continued to develop the empirical methods. Many of these methods use, in particular, fall height and rock volume to establish empirical estimates of runout distance (e.g. Scheidegger, 1973, 1984). Mapping of field evidence and the characterization of different terrain along with landslide attributes are common to many empirical models of this type (e.g. Li Tianchi, 1983). In contrast, detailed rock slope monitoring is often required in order to give predictions for rockfall occurrences (e.g. Monma *et al*., 2000). These studies require more advanced models.

A summary of those various analytical methods and techniques is given in Giani (1992) and Erismann and Abele (2001). Following Coggan *et al*. (1998), Moser (2002) differentiates between conventional techniques and numerical methods for rock slope analysis. The conventional methods include stereographic and kinematic analysis, limit equilibrium analysis and physical modelling, including the use of rockfall simulators. Stereographic and kinematic analyses aim at determining critical slope, discontinuity geometry and approximate shear strength characteristics. Limiting equilibrium analysis focuses on determining the degree of stability of a slope and requires information on slope geometric and material characteristics, rock mass shear strength parameters (cohesion and friction), as well as groundwater conditions (Stead *et al*., 2001). Physical models use material characteristics at appropriate scaling factors. Rockfall simulators are based on slope geometry, rock block sizes, shapes along with density, and on the coefficients of restitution (Moser, 2002). Examples of such models widely applied for practical use include the Colorado Rockfall Simulation Program CRSP (Jones *et al*., 2000) and the 'Rockfall' model developed by Spang and Sönser (1995), which additionally considers the influence of vegetation characteristics (Ploner and Sönser, 1999). A similar ROCKFALL model, developed by Evans and Hungr (1993), is based on a random collision lumped mass modelling approach. The ROCKFALL model uses two restitution coefficients and a transition to rolling criterion (Evans and Hungr, 1993). A comparison of some rockfall models is given by Guzzetti *et al*. (2002a).

Numerical models may include continuum modelling (e.g. finite-elements, finite-difference), discontinuum modelling (e.g. distinct-elements, discrete-elements) (e.g. Yamagami *et al*., 2001), and hybrid/coupled modelling (Moser, 2002). In general, advantages of these numerical approaches are: a basis on general physical laws, a deformation and stability consideration performed within one model only, any kind of support or construction is incorporated, and dynamic impacts such as vibrations or earthquakes can be modelled. These models are mainly used in mining and civil engineering situations. Specific applications include tunnel constructions, foundations, and surface excavations

(Kliche, 1999). The main disadvantage is, however, the high demand for precise data, which are often not available in view of the cost involved or the high complexity of the slopes.

3.3.1.2 Debris-flow analysis

Debris flows are complex mass movement processes determined by hydraulic flow behaviour, which is strongly dependent on the composition of the solids (Hungr, in press; Hungr *et al.*, 2001). One of the first monographs specifically devoted to debris flows was published by Stiny (1910). The most recent textbook on debris flows and debris avalanches is edited by Jakob and Hungr (in press). The methods used to assess debris flows on a site-specific scale range from general geometric relations to advanced numerical modelling. Current research on debris flows is summarized in Chen (1997), Wieczorek and Naeser (2000), Rickenmann and Chen (2003) as well as within the proceedings of the International Symposium INTERPRAEVENT (proceedings of last symposia are INTERPRAEVENT, 2000a, b, c, 2002a, b).

Relatively simple empirical and semi-empirical methods commonly relate geometric parameters to debris-flow characteristics. Due to practical demands, one of the most common debris flow characteristics to be modelled is the runout distance (e.g. Rickenmann, 1999; Wieczorek *et al.*, 2000). Although originally developed for rockfalls (as suggested by Heim, 1932 and further developed by Scheidegger, 1975, Li Tianchi, 1983 and others), the empirical model describing the relationship between volume and travel distance, and in some cases relief (height difference between the starting and deposition point) has also been widely applied to debris flows (e.g. Cannon, 1989; Corominas, 1996; Mark and Ellen, 1995; Rickenmann, 1999; Wong and Ho, 1996; Zimmermann *et al.*, 1997). Other studies using statistical analysis of slope geometry to predict landslide travel distances are limited to cut slopes, fill slopes, retaining walls and boulder falls (e.g. Finlay *et al.*, 1999). However, there are some drawbacks in these empirical approaches. First, some models do not consider slope breaks within the longitudinal channel profile (e.g. Cannon, 1993; Fannin *et al.*, 1997). Second, some models give statistical relationships between various factors which have been calculated for specific regions only, and are therefore not easily applicable to other regions. Additionally, it is impossible to model or include complex flow mechanisms involved in the equations. Despite all of these limitations, Rickenmann (1999) has shown a surprisingly good fit of general and global trends for these empirical models.

Rheological and physical-based modelling of debris flows needs detailed information on rheologic, hydrologic and hydraulic properties (e.g. Coussot *et al.*, 1998). For example, Hungr (2000) analysed debris-flow surges using the theory of uniformly progressive flow. Numerous authors are working with such physical models (e.g. Costa and Wieczorek, 1987; Iverson, 1997a, b; Major and Iverson, 1999; Revellino *et al.*, 2002). A recent review of different approaches is given by Hutter *et al.* (1996), Jan and Shen (1997), Chen and Lee (2000) and within Rickenmann and Chen (2003).

3.3.1.3 Slide stability investigations

Slide stability analysis have a long history going back to Terzaghi (1925), Terzaghi and Peck (1948), Skempton and Northey (1952), and Skempton (1953). Besides modelling the stability of unfailed slopes, it is also of interest to get more information on the importance of certain stability factors of previous events, which can be verified by back-analysis. For example, a large event which interests researchers until today is the Vaiont slide (e.g. Kiersch, 1980; Müller, 1964; Petley, 1996; Skempton, 1966; Voight and Faust, 1992). Most recently, Vardoulakis (2002) performed a dynamic analysis and presented two early stages of the earth slide considering two mechanically coupled substructures: (a) the rapidly deforming shear band at the base of the slide, and (b) the accelerating (rotating) rigid body.

Most recent reviews of slope stability concepts and techniques have been reviewed by Bromhead (1996, 1997). Applications of numerical modelling tools to slope stability assessments for single landslides are given in Bandis (1999). Additionally, the use of neural networks for slope stability modelling is becoming popular (e.g. Mayoraz *et al*., 1996), and some authors also used this method to predict slope movements (e.g. Fernández-Steeger and Czurda, 2001). Collections of most recent approaches of slope stability modelling are within the conference proceedings edited by Anderson and Brooks (1996), Li *et al*. (1998), especially by Ho and Li (2003).

Actual research tries to extend sophisticated models originally developed for two-dimensional approaches to the third dimension (e.g. Bromhead *et al*., 2002; Wang *et al*., 2001). One example is CHASM in its latest version 4.0. Within this Combined Hydrology And Stability Model, geometrical characteristics, geotechnical properties, hydrologic conditions and vegetation-related information are defined for squares with three dimensions. In combination with triggering conditions, both rainfall events and earthquakes, slope stability calculations give most likely failure surfaces with respective factor-of-safety values, and runout distance can be obtained (Lloyd *et al*., in press). Another recent method is the Energy Approach (EA) developed by Ekanayake and Phillips (1999). The newly proposed approach incorporates, within the stability analysis, the ability of soil with roots to withstand strain, based on a consideration of the energy consumed during the shearing process of the soil-root system (Ekanayake and Phillips, 1999). All these new promising approaches cannot be used at larger spatial scales, because neither data are available in the required detail nor does the computational capacity exist. However, with further development of computer technology, these approaches have the potential to be applied within the next years.

3.3.1.4 Conclusion

Rock slope analyses are commonly based on empirical estimates, conventional stability analysis techniques, and more sophisticated numerical methods. The more advanced the models, the higher the input data requirement and thus, the more complex the assessment. Hence empirical and conventional techniques are applied either for back-analysis or for preliminary assessments. Detailed site-specific investigations require numerical models based on continuum modelling, discontinuum modelling, or hybrid/coupled modelling. The last models, in particular, are used in mining and civil engineering applications.

Debris-flow analysis is strongly determined by hydraulic-flow behaviour. Empirical and semi-empirical methods relate geometric parameters to debris-flow characteristics. Despite restrictive assumptions these relatively simple methods have proven their potential in practical applications. Rheological and physical-based modelling approaches have been further developed over the last decades. Although these approaches allow a detailed modelling of debris flows, data requirements are very high and thus such models applied to practical applications are limited.

Slide stability analysis usually provides a statement of site susceptibility in terms of a factor-of-safety. In the case of first-time failures, the magnitude of event is largely unknown. However, modelling multiple potential failure surface permits some estimate, usually in a two-dimensional sense, of the likely magnitude involved. Moreover, the magnitude of movement associated with pre-existing failures can be addressed by locating the boundary shear surfaces within the slope. In addition, if the significance of dynamic stability factors (such as porewater pressure) can be determined through sensitivity analysis, then the behaviour of such critical factors may be linked to external triggering factors (such as rainfall). An examination of the climatic record may then reveal the frequency with which critical conditions may be reached within the slope. In some instances, the importance of certain stability factors can be verified by back-analysis of previous events.

For site-based analysis, irrespective of the process types and the applied method, the main objective should be the determination of both the magnitude and frequency of landslide occurrence, in order to properly estimate the hazard. By definition, the general location and, in some cases, the actual landslide itself is predetermined in site-based analyses. If no information on frequency is available, then it is only possible to determine the susceptibility of a given location towards the respective process. In some cases, frequency–magnitude information may be obtained by using historical archives or field evidences to approximate temporal landslide occurrence (e.g. Glade *et al*., 2001a).

3.3.2 Spatial Susceptibility and Hazard Analysis

Investigations of numerous landslides extending over large regions have been performed for decades. Many of the first regional assessments carried out were based on mapping techniques as part of extensive field survey campaigns (e.g. Brabb and Pampeyan, 1972). With the development of new computer technologies, particularly GIS techniques (e.g. Carrara and Guzzetti, 1995), controlled automated mapping procedures are becoming more popular (e.g. McKean and Roering, 2004). These techniques are commonly based on remote sensing data and use either aerial photography or satellite images to obtain spatial information on landslide occurrence and movement (e.g. Hervás *et al*., 2003). These automated procedures are constantly being developed with new computer generations, along with the availability of remote sensing imagery with increased resolution and accuracy. The main advantage of any GIS technique is its capacity for spatial analysis of large data sets. Different spatial information can be linked and coupled, new data sets can be created, and additional information can be obtained. Thus these recent advances provide a powerful tool for spatial landslide assessment.

Within the last decade, techniques of spatial landslide analysis have been greatly improved (e.g. summarized in Carrara and Guzzetti, 1995). Based on the scale classification for engineering geology maps (International Association of Engineering Geology, 1976), Soeters and van Westen (1996) have carried out extensive assessments of spatial landslide hazard. They slightly modified the original classification to produce the following classes ranging from large scales (<1:10 000), medium scales (1:15 000–1:100 000), regional scales (1:125 000–1:500 000), to national scales (>1:750 000). A typical method of analysis can be assigned to each investigation scale. This classification is summarized in Table 3.1.

Table 3.1 *Recommended scales for different spatial landslide analysis (extended from Soeters and van Westen, 1996)*

Scale	Qualitative methods		Quantitative methods		
	Inventory	Heuristic analysis	Statistical analysis	Probabilistic prediction analysis	Process-based and numerical analysis
<1:10 000	Yes	Yes	Yes	Yes	Yes
1:15 000–1:100 000	Yes	Yes	Yes	Yes	Probable
1:125 000–1:500 000	Yes	Yes	Probable	Probable	No
>1:750 000	Yes	Yes	No	No	No

Two main types of investigation can be differentiated on the basis of methodology: qualitative and quantitative. Landslide inventories plus heuristic approaches are grouped within the qualitative methods. In nearly all spatial investigations, landslide inventories are the basis for developing and/or verifying the method. Even if the chosen method does not use landslide locations for model development (e.g. numerical models), information on locations is needed for verification and validation of the results (e.g. Santacana *et al.*, 2003). These inventories are thus of great importance, and provide a potential source of information for future developments in spatial analysis (Guzzetti *et al.*, 1999). Consequently, a high proportion of project resources should be allocated for the development of inventories, because only high-quality inventories allow a reliable proof for spatial analysis. A second qualitative method is the heuristic approach. Based on *a priori* knowledge, local experiences, as well as expert judgement, are included. The heuristic approach also uses spatial information in explaining landslide occurrence. Commonly, such information includes topographic, hydrological, geologic, geotechnical, or geomorphic factors, and often vegetation coverage along with land use is considered, too. These factors are determined by either field campaigns or aerial photograph interpretation. In particular, spatial geomorphic factor maps offer a first approximation of the activity degree regarding the respective landslide processes (e.g. Cardinali *et al.*, 2002). In addition to inventories and other factor maps, this geomorphic information is an important basis for any further assessment (e.g. Glade and Jensen, 2004). Experts weight the importance of different environmental factors based on personal knowledge and experience, thus providing an initial assessment of landslide susceptibility. Indeed, qualitative weightings are heavily dependent on the experience of the person or expert group responsible for the analysis. Criteria for the assessments are not always identifiable by others, which is a major limitation of the heuristic approach. Thus the objectivity is not measurable, and consequently the reproducibility is often difficult. However, if the expert has a profound understanding of the processes involved and knows the study region in detail, such assessments can also be accurate and applicable, in particular for first approximations of landslide susceptibility.

In contrast, approaches using quantitative methods are generally based on objective criteria and are thus, in theory at least, repeatable, producing identical results for similar data sets. The quantitative methods include statistical, probabilistic prediction, process-based, or numerical approaches. The statistical methods are the most popular ones. Factor maps such as geology, soils, or topographic conditions (e.g. slope angle, horizontal and vertical curvature, aspect, distance to divide, etc.) are compared with landslide distribution from inventory maps and landslide density is calculated. Initially bivariate statistical analysis may be used to compare each factor separately with landslide locations, and weighting factors are computed on this basis for each factor. However, using multivariate statistics, any combination of factor maps can be related to landslide locations and the resulting matrix is then analysed using statistical tests, such as multiple regression or discriminant analysis (e.g. Chung *et al.*, 1995). The statistical tests then provide information on which factor or which combination of factors best explains landslide occurrence. The areas with factor scores equivalent to those for areas associated with landslides, but without former landslide occurrence, are thus considered prone to future landslides. Resulting maps give only spatial landslide susceptibility, because they do not contain any direct information on the hazard, that is, temporal variation of magnitude and frequency of landslides. Other statistical methods providing probabilistic prediction models (e.g. Bayesian probability, fuzzy logic) can also be used to produce landslide susceptibility maps (e.g. Binaghi *et al.*, 1998; Chung and Fabbri, 1999; Fabbri *et al.*, 2002; Fernández-Steeger *et al.*, 2002; Pistocchi *et al.*, 2002). For example, the fuzzy method simply applies 'if-then' rules to the different factor sets, and is thus based on a decision tree approach (e.g. Ercanoglu and Gokceoglu, 2002; Mackay *et al.*, 2003). The result is still a susceptibility map. Basic assumptions in both statistical approaches are static environmental and triggering boundary conditions. Considering the ongoing debate on the effects of climate change on landslide occurrence (e.g. Dehn, 1999; Schmidt and Glade, 2003), on changes of catchment conditions following each landslide event (e.g. Crozier and Preston, 1999), and on human impact on environmental conditions through, for example, land use change (e.g. Frattini and Crosta, 2002), it is obvious that these assumptions strongly influence the interpretation of the result.

The use of different data sets for spatial analysis requires a good deal of caution. First, large data sets are required which are difficult to assess for some remote regions. Second, the input data need to be of identical quality and resolution. For example, generating a 10 m raster resolution from a 1:2 750 000 soil map using downscaling techniques provided in any GIS is very easy. This downscaled high-resolution raster can be used for large-scale analysis, for example at a scale of 1:25 000. However, the information stored with the 10 m raster pixel still relates to the original scale, and is thus of little value for comparison with more detailed data sets, for example landslide locations. Although this pitfall is obvious, one might be tempted to apply this procedure in order to gain a result; but when analysing data sets with two different resolutions, the result can lead to an incorrect conclusion. As a general rule-of-thumb, spatial analysis can only be carried out at the scale of the data set with the coarsest resolution. Nevertheless, despite all these potential pitfalls and limitations, the beauty of this approach is its simplicity and reproducibility. And for numerous applications, the derived information on landslide susceptibility is sufficient.

The second group of quantitative methods includes the empirical and deterministic, process-based methods. Within this set of methods, topographic attributes (e.g. slope angle, vertical and horizontal curvatures, slope aspect, distance to divide or channel, contributing area, etc.) are coupled with hydrological conditions (e.g. soil saturation, permeability, hydraulic conductivity) and generalized geotechnical information on soil properties (e.g. cohesion, angle of internal friction, specific weight) in order to perform a stability analysis. Most of the available models are based on the infinite slope approach (e.g. Vanacker *et al.*, 2003).

Verification of modelled results, however, is an important task which is not always carried out (Chowdhury and Flentje, 2003). One example of a spatial application of the infinite slope approach is the SHALSTAB model, which has been developed by Montgomery and Dietrich (1994) and Dietrich *et al.* (1995) and was applied to various sites in the United States (e.g. Dietrich and Sitar, 1997; Montgomery *et al.*, 2000; Montgomery *et al.*, 1998) and in Rio de Janeiro (e.g. Fernandes *et al.*, 2004). A recent development is the application of numerical cinematic approaches to spatial analysis (e.g. Günther *et al.*, 2002a, b).

After having addressed major issues in site-specific and spatial landslide analysis, the final part of this chapter focuses on spatial landslide assessments. Due to the numerous demands from agencies responsible for spatial planning and to the increasing numbers of studies published in recent years, it is important to give an overview of spatial assessments. Consequently, the following sections give some examples of different kinds of spatial landslide susceptibility and hazard, but also risk investigations.

3.4 A Review of Spatial Landslide Susceptibility and Hazard Investigations

Qualitative methods and approaches are popular for providing a preliminary estimation of landslide susceptibility and hazard. While some investigations do not distinguish between the different types of landslide, others treat specific types separately. To illustrate different types of analysis, some examples of the many studies that have been carried out are given below. Whenever possible, the studies have been classed in the two groups of 'catchment and regional scale' and 'national scale' analysis.

3.4.1 General Landslide Information

Table 3.2 lists sources providing information on the spatial distribution of landslides. These sources treat landslides collectively and do not provide an analysis on the basis of landslide type. The nature of the data provided (whether in the form of general information, landslide distribution, or inventory) is noted for each entry. For some sources, it was difficult to determine which form of spatial information was used. If no details on the spatial data set were available, the label 'information' was added. Table 3.2 shows that numerous spatial landslide studies have been carried out. These data sets provide a rich information base for future detailed analysis.

Table 3.3 includes references to those spatial data sets providing estimations of landslide susceptibility and hazard. None of these, however, differentiates between different types of landslide. These sources of information have been classified in the table as susceptibility, hazard, zonation, or qualitative assessment. This table demonstrates the performance of numerous spatial analyses throughout the world and the availability of spatial landslide susceptibility and hazard estimates for numerous catchments and regions.

Table 3.2 *Sources of information on spatial landslide distribution and inventories for different regions worldwide*

Continent	Country	Region	Type	Reference(s)
Catchment and regional scale				
Africa	Nigeria	General	Information	Schoeneich and Bouzou (1996)
		Southern Nigeria	Distribution	Okagbue (1994)
	Southern Africa	General	Distribution	Paige-Green (1989)
Asia	China	Yunnan Province	Inventory	Tang and Grunert (1999)
		Gansu region	Distribution	Derbyshire *et al.* (1991)
		Hong Kong	Inventory	Brand *et al.* (1984); Chan *et al.* (2003); King (1999); Pun *et al.* (2003); Wong and Hanson (1995)
	India	Darjeeling	Inventory	Basu (2001); Jana (2000); Sarkar (1999)
		Northeastern India	Susceptibility	Gupta (2000)
	Japan	Hokkaido	Inventory	Yamagishi *et al.* (2002)
		Kobe	Distribution	Sassa *et al.* (1999)
	Jordan	Northern & Central	Distribution	Farhan (1999)
	Korea	Gyeonggi Province	Susceptibility	Kim *et al.* (2001)
	Taiwan	Western Foothills	Frequency and spatial distribution	Chang and Slaymaker (2002)
		Central Range	Inventory	Hovius *et al.* (2000)
Europe	Croatia	Medvednica Range	Distribution	Jurak *et al.* (1998)
	Czech Republic	Vizovická vrchovina Highland	Distribution	Kirchner (2002)
	France	Mercantour Massif, French Riviera	Inventory	Julian and Anthony (1996)
	Germany	Bonn Region	Inventory	Grunert and Schmanke (1997); Hardenbicker (1994)
		Rheinhessen	Inventory	Dikau and Jäger (1995)
		Hessen, Thüringen	Inventory	Schmidt and Beyer (2001), (2002)
		Schwäbische Alb	Inventory	Bibus and Terhorst (1999); Schädel and Stober (1988); Thein (2000)
		Fränkische Alb	Inventory	Moser and Rentschler (1999); Streit (1991)
		Bavarian Alps	Inventory	Mayer *et al.* (2002); von Poschinger and Haas (1997)

Great Britain	Isle of Wight	Distribution	Hutchinson and Bromhead (2002)
	Scotland	Distribution	Ballantyne (1997)
	South coast	Temporal and spatial distribution	Brunsden and Ibsen (1994)
	South Kent	Distribution	Bromhead *et al*. (1998)
Hungary	Danubian Bluffs	Inventory	Kertész and Schweitzer (1991)
	Hernád Valley	Distribution	Szabó (1999)
Italy	Calabria	Distribution	Sorriso-Valvo (1997)
	Cardoso T. basin	Inventory	D'Amato Avanzi *et al*. (2000)
	Cortina d'Ampezzo	Inventory	Panizza *et al*. (1996), (1997); Pasuto and Soldati (1999)
	Naples	Distribution	Calcaterra *et al*. (2002)
	Northern Calabria	Inventory	Carrara and Merenda (1976)
	Central Calabria	Distribution	Antronico and Gullà (2000)
	Pizzo d'Alvano	Distribution	Gudagno and Zampelli (2000)
	Sicilia & Southestern	Distribution	Nicoletti *et al*. (2000); Pantano *et al*. (2002)
	Umbria region	Inventory	Guzzetti and Cardinali (1990); Guzzetti *et al*. (1994); (2002b)
Poland	Carpathians	Inventory	Alexandrowicz (1993); Alexandrowicz (1997); Margielewski (2002); Ostaficzuk (1999); Starkel (1997)
Portugal		Distribution	Zezere *et al*. (1999)
Romania	General	Inventory	Ielenicz *et al*. (1999); Rosenbaum and Popescu (1996)
Slovakia	Orava region	Distribution	Janova (2000)
Spain	Asturias, Meredela valley	Distribution	Cuesta *et al*. (1999); Sánchez *et al*. (1999)
	Barranco de Tirajana basin, Gran Canaria	Distribution	Lomoschitz (1999)
	Izbor basin, Granada	Inventory	El Hamdouni *et al*. (2000)
	Los Guajares Mountains, Granada	Inventory	Fernandez *et al*. (1996); Irigaray *et al*. (1996)
	La Pobla de Lillet area	Inventory	Santacana *et al*. (2003); Santacana and Corominas (2002)

Table 3.2 *(Continued)*

Continent	Country	Region	Type	Reference(s)
Catchment and regional scale				
		Río Serpis basin	Inventory	van Beek (2002)
		Sorbas	Inventory & Distribution	Hart and Griffiths (1999)
		Southeastern Pyrenees	Distribution	Moya *et al*. (1997)
	Sweden	Kärkevagge	Distribution	Jonasson *et al*. (1997)
	UK	Broadway area	Distribution	Whitworth *et al*. (2000)
		Scarborough coast	Distribution	Lee and Clark (2000)
Northern America	Canada	Alberta	Inventory	Cruden (1996)
		Capilano Watershed, British Columbia	Inventory	Brardinoni *et al*. (2003)
		Queen Charlotte Islands	Inventory	Martin *et al*. (2002)
		Vancouver Island	Inventory	Guthrie (2002)
	Puerto Rico	Tropical region	Inventory	Larsen and Torres-Sanchez (1998)
	USA	New Mexico	Inventory	Brabb *et al*. (1989); Dikau and Jäger (1995); Reneau and Dethier (1996)
		Northridge, California	Inventory	Harp and Jibson (1995)
		San Fransisco Bay	Inventory	Ellen and Wieczorek (1988); Wieczorek (1984)
		Utah	Inventory	Hylland and Lowe (1997)
		Lewis County, Washington	Inventory	Dragovich *et al*. (1993)
Southern America	Brazil	Rio de Janeiro	Inventory	Amaral and Palmeiro (1997); Amaral *et al*. (1996); Jones (1973)
	Chile	Antofagasta	Distribution	Van Sint Jan (1994)
		Rinihue	Distribution	Erickson *et al*. (1989)
	Colombia	Cudinamarca	Inventory	Forero-Duenas and Caro-Pena (1996)
		Paez region	Distribution	Martinez *et al*. (1995)
		Different regions	Inventory	van Westen (1994)
	Ecuador		Distribution	Schuster *et al*. (1996); Tibaldi *et al*. (1995)

	El Salvador	Corillera Costera	Distribution	Agnesi *et al.* (2002a)
	Peru	Nevados Huascaran	Distribution	Keefer (1984); Plafker *et al.* (1971)
Pacific	Fiji	Viti Levu, Wainitubatolu Catchment	Distribution	Crozier *et al.* (1981)
	Philippines	Luzon	Distribution	Arboleda and Punongbayan (1999)
	Salomon Island	MISSING	Distribution	Trustrum *et al.* (1990)
South Pacific	Australia	Bumbunga Hill	Distribution	Twidale (2000)
	New Zealand	Hawke Bay	Inventory	Glade (1997); Harmsworth *et al.* (1987); Page *et al.* (1994)
		Taranaki	Distribution	Crozier and Pillans (1991); DeRose *et al.* (1993)
		Waipaoa	Distribution	Page *et al.* (1999)
		Wairarapa	Inventory	Crozier *et al.* (1980); Glade (1997); Trustrum and Stephens (1981)
		Wairoa	Distribution	Douglas *et al.* (1986)
		Wellington	Inventory	Brabhaharan *et al.* (1994); Crozier *et al.* (1978); Eyles *et al.* (1974), (1978); Glade (1997)
National scale				
Asia	Armenia		Distribution	Boynagryan *et al.* (2000)
	China		Inventory	Yin *et al.* (2002)
Europe	Austria		Inventory of large landslides	Moser (2002)
	France		Inventory	Asté *et al.* (1995)
	Hungary		Distribution	Juhász (1997)
	Italy		Inventory	Guzzetti *et al.* (1994)
	Spain		Distribution	Ferrer and Ayala-Carcedo (1997)
	United Kingdom		Inventory	Jones and Lee (1994); Lee *et al.* (2000)
North America	USA		Inventory	Brabb *et al.* (1999); Eldredge (1988); Wieczorek (1984)
South Pacific	New Zealand		Inventory	Glade (1996); Harmsworth and Page (1991)

Table 3.3 *Sources of information on spatial landslide susceptibility and hazard for different region of the world*

Continent	Country	Region	Type of analysis	Reference(s)
		Catchment and regional scale		
Africa	Ethiopia	Blue Nile Basin	Susceptibility	Ayalew (2000)
Asia	China	Gansu Province	Hazard	Meng *et al*. (2000)
		Hong Kong	Susceptibility	Dai and Lee (2001), (2002); Lee *et al*. (2001)
		Lawngthlai, Southern Miziram	Susceptibility	Khullar *et al*. (2000)
	India	Darjiling, Himalaya	Susceptibility	Basu (2000)
		Garhwal Himalaya	Susceptibility	Anbalagan *et al*. (2000)
		Munipur River basin	Susceptibility	Nagarajan (2002)
		Rakti Basin	Susceptibility	Bhattacharya (1999)
	Iran	Jiroft watershed	Susceptibility	Uromeihy (2000)
		Khorshrostam area	Susceptibility	Mahdavifar (2000)
		Shahrood drainage basin	Susceptibility	Feiznia and Bodaghi (2000)
	Japan	Amahata River basin	Susceptibility	Aniya (1985)
		Fukushima Pref.	Susceptibility	Sasaki *et al*. (2002)
		Hanshin district	Susceptibility	Kamai *et al*. (2000)
		Higashikubiki region	Susceptibility	Iwahashi *et al*. (2003)
		MISSING	Susceptibility	Kubota (1994)
		MISSING	Susceptibility	Massari and Atkinson (1999)
	Jordan	Wadi Mujib Canyon	Susceptibility	De Jaeger (2000)
	Korea	Yanghung area	Susceptibility	Lee *et al*. (2002)
		Yongin	Susceptibility	Lee and Min (2001)
	Nepal	Kulekhani watershed	Susceptibility	Dhakal *et al*. (2000)
	Ukraine	Southern region	Susceptibility	Cherkez *et al*. (2000)
Europe	Austria	Bad Ischl	Susceptibility	Fernández-Steeger *et al*. (2002)
	Belgium	Manaihant	Susceptibility	Demoulin and Chung submitted
	Czech Republic	North Bohemia	Susceptibility	Hroch *et al*. (2002)
	Germany	Bonn region	Susceptibility	Schmanke (2001)
		Rheinhessen	Susceptibility/ hazard	GLA (1989); Jäger (1997)
		Schwäbische Alb	Susceptibility	Thein (2000)
		Hessen and Thüringen	Susceptibility	Schmidt and Beyer (2001); Schmidt and Beyer (2002)
		Bratica T. Basin	Susceptibility	Clerici (2002)

	Great Britain	Barbados, Scotland	Susceptibility	Hodgson *et al*. (2002)
		Starkholmes, Derbyshire	Susceptibility	Thurston and Degg (2000)
	Italy	Calabria Region	Susceptibility	Carrara *et al*. (1977b)
		Centenora catchment, Northern Apennines	Susceptibility	Casadei and Farabegoli (2003)
		Corniglio	Hazard	Froldi and Bonini (2000)
		MISSING	Susceptibility	Carrara (1989)
		Mignone basin	Hazard	Del Monte *et al*. (2003)
		Forlì-Cesena, Emilia Romagna	Susceptibility	Pistocchi *et al*. (2002)
		Lecco province, Lombardy region	Susceptibility	Frattini and Crosta (2002)
		Messina Straits Crossing site	Susceptibility	Baldelli *et al*. (1996)
		Orcia drainage basin	Hazard	Del Monte *et al*. (2003)
		Potenza region	Susceptibility	Ferrigno and Spilotro (2002)
		Trionto basin	Hazard	Del Monte *et al*. (2003)
		Umbria, Marche Regions	Susceptibility and hazard	Carrara *et al*. (1995); Guzzetti *et al*. (1999)
	Portugal	Coimbra region	Susceptibility	Tavares and Soares (2002)
		Fanhoes-Trancao Region	Susceptibility	Fabbri *et al*. (2002); Zêzere *et al*. (2000)
	Slovak Republic	Handlovská kotlina Basin	Susceptibility	Paudits and Bednárik (2002)
		Kosice region	Susceptibility	Petro *et al*. (2002)
	Spain	Deba Valley, Province Guipuzoa	Susceptibility	Fabbri *et al*. (2002)
		Rio Aguas	Susceptibility	Griffiths *et al*. (2002)
		Malorca Island	Susceptibility	Mateos Ruiz (2002)
		La Pobla de Lillet area	Susceptibility	Baeza and Corominas (1996); Santacana *et al*. (2003)
		Jerte Valley	Susceptibility	Carrasco *et al*. (2000)
	Turkey	Mengen	Susceptibility	Gökceoglu and Aksoy (1996)
		Yenice	Susceptibility	Ercanoglu and Gokceoglu (2002)
North America	Canada	Hull-Gatineau region, Quebec	Susceptibility	Clouatre *et al*. (1996)
		Lilloet River watershed, British Columbia	Susceptibility	Holm *et al*. (2004)

Table 3.3 *(Continued)*

Continent	Country	Region	Type of analysis	Reference(s)
			Catchment and regional scale	
	USA	Anchorage	Susceptibility	Dobrovolny (1971)
		Cincinnati, Ohio	Hazard	Bernknopf *et al.* (1988)
		Coos Bay, Oregon	Susceptibility	Casadei and Dietrich (2003)
		Oregon Coast Range	Susceptibility	Schmidt *et al.* (2001)
		San Mateo County	Susceptibility	Brabb (1993); Brabb *et al.* (1978) Roth, (1983) #2940
		Travis County, Texas	Susceptibility	Wachal and Hudak (2000)
		Washington State	Hazard	Harp *et al.* (1997)
	Jamaika	St. Andrew	Susceptibility	Maharaj (1993)
	Argentina	Mendoza province	Susceptibility	Moreiras (2004)
South America	Brazil	Rio de Janeiro	Susceptibility	Barros *et al.* (1991); Fernandes *et al.* (2004)
	Colombia	Chinchina region	Hazard	Chung *et al.* (1995); Chung *et al.* (2003); van Asch *et al.* (1992)
	El Salvador	Corillera del Balsamo	Susceptibility	Agnesi *et al.* (2002b)
Pacific Islands	Fiji	Viti Levu	Susceptibility	Crozier (1989); Greenbaum *et al.* (1995)
	Papa New Guinea	Ok Tedi	Susceptibility	Crozier (1991)
South Pacific	Australia	Southeast Queensland	Susceptibility	Hayne and Gordon (2001)
	NewZealand	Hawke Bay	Susceptibility	Glade (2001)
		Wairarapa	Hazard	Wilson and Crozier (2000)
			National scale	
Africa	South Africa		Zonation based on expert judgement	Paige-Green (1985)
Asia	China		Hazard mapping and management	Tianchi (1996)
Europe	Germany		Qualitative assessment	Dikau and Glade (2003); Glade *et al.* in prep. a

3.4.2 Rock Slope Analysis

Spatial rock slope analysis focuses mainly on rockfalls and rock slides, the latter mostly of large dimension. Information on spatial studies on rockfalls, topples, slides and avalanches is summarized in Table 3.4. Inventories give spatial distributions (e.g. Gardner, 1983; Luckman, 1972; McSaveney, 2002). Other inventories have been further analysed using statistical approaches (e.g. Bartsch *et al.*, 2002) and apply empirical models to spatial rockfall analysis (e.g. Dorren and Seijmonsberegen, 2003; Meißl, 2001; Wieczorek *et al.*, 1998). Most recently, numerical models have been developed to calculate spatial movement patterns (e.g. Guzzetti *et al.*, 2002a). Although a few general national inventories provide information on rockfalls and topples (e.g. Guzzetti *et al.*, 1994), no nationwide inventory has been carried out specifically for rock slope events.

3.4.3 Debris-flow Analysis

In contrast, debris flows have been investigated at catchment, regional and national scales (Table 3.5). Such investigations have been focused on general inventories of spatial debris-flow occurrence (e.g. Calcaterra *et al.*, 1996a) or on distributions following distinct triggering events (e.g. Del Prete *et al.*, 1998; Pareschi *et al.*, 2000; Rickenmann, 1990; Villi and Dal Pra', 2002). Statistical techniques along with numerical approaches to assess debris-flow susceptibility and hazard have been applied in various regions worldwide (e.g. D'Ambrosio *et al.*, 2003a; D'Ambrosio *et al.*, 2003b; Lorente *et al.*, 2002; Mark and Ellen, 1995). Besides the catchment and regional analysis, national scale investigations have also been carried out. For example, maps showing the reported debris flows, debris avalanches and mudflows (Bert, 1980), as well as inventory and regional susceptibility for Holocene debris flows and related fast-moving landslides (Brabb *et al.*, 1999), are available for the USA or for Switzerland (Zimmermann *et al.*, 1997).

3.4.4 Slide Analysis

References related to spatial assessments of soil and earth flows and slides are summarized in Table 3.6. While some authors record deep-seated landslides only (e.g. Yamagishi *et al.*, 2002), others focus on shallow translational slides. Several papers employ infinite limiting equilibrium slope stability analysis. This method has been applied in particular to shallow landsliding (e.g. Dietrich *et al.*, 1995; Montgomery and Dietrich, 1994; Montgomery *et al.*, 2000; Wu and Abdel-Latif, 2000) to estimate the factor of safety and probability of failure. Derived from hydrological response units, soil mechanical response units have been suggested by Möller *et al.* (2001) for application to the infinite slope model. Some authors also include soil root strength (e.g. Ekanayake and Phillips, 1999). Simple heuristic techniques are also applied to national scale investigations (e.g. Fallsvik and Viberg, 1998; Viberg *et al.*, 2002). In addition, Perov *et al.* (1997) presented a global distribution of mudflows. Although this analysis is based on expert judgement, it gives a first approximation of mudflow distributions, thus providing a starting point for further, more detailed analysis applying more advanced models.

3.4.5 Summary

Tables 3.2 to 3.6 demonstrate the wide application of spatial landslide analysis over the last thirty years. Types of information range from landslide distributions and inventories to

Table 3.4 *Selections of spatial assessments of rock topple, fall, slide and avalanche for different regions of the world*

Continent	Country	Region	Type of analysis	Reference(s)
Asia	Pakistan	Karakoram Himalaya	Distribution of large failures	Hewitt (2002)
Europe	European Alps		Distribution of large failures	Abele (1974); Heim (1932); von Poschinger (2002)
	Austria	Innsbruck	Process-based modelling	Meiβ l (2001)
		Gaschurn, Montafon	Numerical modelling of rock falls	Dorren *et al*. (2004); Dorren and Seijmonsberegen (2003)
		Vorarlberg	Process-based modelling	Ruff *et al*. (2002)
	Germany	Oker basin	Rock slide modelling	Günther *et al*. (2002a)
	Ireland	Co. Antrim	Rock fall distribution	Douglas (1980)
	Italy	Camonica Valley, Lombardi region	Numerical modelling of rock falls	Guzzetti *et al*. (2002a)
		Valle San Giacmo	Rock fall modelling	Mazzoccola and Sciesa (2000)
	Spain	Northern Spain	Rock fall susceptibility	Duarte and Marquinez (2002)
	Sweden	Kärevagge	Rock fall – statistical analysis	Bartsch *et al*. (2002)
North America	Canada	Canadian Cordillera	Distribution of large failures	Cruden (1985)
		Surprise Valley, Jasper National Park	Rock fall inventory	Luckman (1972)
		Highwood Pass Area, Alberta	Rock fall and slide inventory	Gardner (1983)
	USA	Yosemite Valley	Rock fall hazard	Guzzetti *et al*. (2003); Wieczorek *et al*. (1998)
		Tully Valley Area, Finger Lakes Region, New York	Rock fall susceptibility	Jäger and Wieczorek (1994)
South America	Argentinia	Puna Plateau	Inventory of rock avalanches	Hermanns *et al*. (2002)
South Pacific	New Zealand	Mount Cook National Park	Rock fall and avalanches	McSaveney (2002)

Table 3.5 Selections of spatial susceptibility and hazard analysis of debris flow for different regions of the world

Continent	Country	Region	Type of analysis	Reference(s)
			Regional and catchment scale	
Asia	Japan	Miyakejima volcano	Distribution	Yamakoshi *et al*. (2003)
	Kazakstan	Southeast	Susceptibility	Medeuov and Beisenbinova (1997)
	Nepal	Kulekhani watershed	Distribution	Dhital (2003)
	Taiwan	Chen-You-Lan River basin	Hazard	Lin *et al*. (2000)
		Central taiwan	Distribution	Cheng *et al*. (2003)
Europe	Austria	Salvensen valley	Distribution	Becht and Rieger (1997)
	Germany	Faltenbach valley	Susceptibility	Becht and Rieger (1997)
	Iceland	Gleidarhjalli area	Hazard	Decaulne and Saemundsson (2003)
		Northwestfjords region	Susceptibility	Glade and Jensen (2004)
	Italy	Serre Massif – Calabria	Distribution	Calcaterra *et al*. (1996a)
		Circum-Vesuvian areas & Sarno Mountains	Distribution / Hazard	Calcaterra *et al*. (2000); Cinque *et al*. (2000); D'Ambrosio *et al*. (2003a); (2003b); Del Prete *et al*. (1998); Fiorillo *et al*. (2001); Pareschi *et al*. (2000)
		Isarco valley	Distribution	Villi and Dal Pra' (2002)
		Lecco area, Lombardy	Susceptibility	Bathurst *et al*. (2003)
		Versilia, Garfagnana	Susceptibility	Martello *et al*. (2000)
	Spain	Upper Aragón and Gállego valley, Central Pyrenees	Bivariate Statistics	Lorente *et al*. (2002)
	Switzerland	Mattertal, Wallis	Distribution	Dikau *et al*. (1996)
North America	USA	Honolulu of Oahu, Hawaii	Hazard	Ellen and Mark (1993); Ellen *et al*. (1993); Reid *et al*. (1991)
		Madison County, Virginia	Hazard	Wieczorek *et al*. (2003)
		Mount Rainier, Washington	Hazard	Hoblitt *et al*. (1995); Iverson *et al*. (1998); Schilling and Iverson (1997); Scott *et al*. (1995)

Table 3.5 *(Continued)*

Continent	Country	Region	Type of analysis	Reference(s)
		Regional and catchment scale		
		Northwestern California	Distribution	Reid *et al*. (2003)
		Noyo watershed, California	Susceptibility	Dietrich and Sitar (1997)
		Oakland, California	Susceptibility	Campbell and Bernkopf (1997); Campbell *et al*. (1994)
		Oregon	Inventory & Susceptibility	Hofmeister (2000); Hofmeister and Miller (2003)
		San Mateo County, California	Susceptibility	Mark (1992)
		Santa Cruz Mountain, California	Inventory	Wieczorek (1984)
		Blue Ridge of Central Virginia	Hazard	Wieczorek *et al*. (2000)
		Wasatch Front, Utah	Distribution	Wieczorek *et al*. (1989)
South America	Ecuador	Pichincha massif	Hazard	Canuti *et al*. (2002)
	El Salvador	San Salvador, San Vicente & San Miguel volcanoes	Hazard	Major *et al*. (2003)
	Venezuela	Northern region	Distribution	Lopez *et al*. (2003)
South Pacific	Australia	Montrose, Victoria	Hazard	Fell and Hartford (1997)
		Wollongong	Distribution	Flentje *et al*. (2000)
		National scale		
Europe	Austria		Distribution	Andrecs (1995)
	Switzerland		Distribution	Rickenmann (1990); Zimmermann *et al*. (1997)
North America	USA		Inventory of debris flow, avalanches, and mud flows	Bert (1980); Brabb *et al*. (1999)

Table 3.6 *Selections of spatial assessment of shallow translational and rotational earth and soil slides for different regions of the world*

Continent	Country	Region	Type of analysis	Reference(s)
		Catchment and regional scale		
Asia	Japan	Hokkaido	Inventory	Yamagishi *et al.* (2002)
		Taiyo-no Kuni	Inventory	Chigira (2002)
		Sasebo district	Numerical 3d modelling	Xie *et al.* (2001)
Europe	Bulgaria	Baltchik area	Distribution	Koleva-Rekalowa *et al.* (1996)
	Germany	Rheinhessen	Physically based modelling	Möller *et al.* (2001)
	Italy	MISSING	Physically based modelling	Ekanayake and Phillips (1999)
		Lemezzo basin, Piemonte region	Physically based modelling	Campus *et al.* (2001)
		Serre Massif, Calabria	Distribution	Calcaterra *et al.* (1996b)
North America	Canada	Grondines and Trois Rivieres areas, Quebec	Distribution	Karrow (1972); Mollard and Hughes (1973)
		Lemieux, Ontario	Distribution	Evans and Brooks (1999)
	USA	Northern California	Physically based modelling	Dietrich *et al.* (1995)
		Van Duzen River basin, California	Distribution	Kelsey (1978)
		Seattle, Washington	Hazard	Savage *et al.* (2003)
		South Fork of Tilton River, Cascade Mountains, Washington State	Mechanics based approach	Wu and Abdel-Latif (2000)
		MISSING	Physically based modelling	Montgomery and Dietrich (1994); Montgomery *et al.* (2000)
South America	Ecuador	Gordeleg catchment	Physically based modelling	Vanacker *et al.* (2003)
South Pacific	New Zealand	Otago	Distribution	Crozier (1968), (1969), (1996)
		National scale		
Asia	USSR		Qualitative assessment	Perov and Budarina (2000); Sidorova (1997)
	Central & Southeast		Qualitative assessment	Belaia *et al.* (2000)
Europe	Sweden		Qualitative assessment	Fallsvik and Viberg (1998); Viberg *et al.* (2002)
World				
			Qualitative assessment	Perov *et al.* (1997)

advanced mathematical modelling of spatial data sets at catchment, regional and national scales. At regional scales, statistical models have been widely applied to assess landslide susceptibility (e.g. Baeza and Corominas, 2001; Carrara, 1983, 1989; Carrara *et al*., 1977a; Fernandes *et al*., 2004; Griffiths *et al*., 2002; Jäger, 1997) and hazard (e.g. Guzzetti *et al*., 1999; van Asch *et al*., 1992). Also statistical techniques such as the fuzzy approach (e.g. Ercanoglu and Gokceoglu, 2002; Pistocchi *et al*., 2002) as well as different probabilistic prediction models (e.g. Pistocchi *et al*., 2002 or most recently Chung, Chapter 4 in this book) have been applied recently to assess landslide susceptibility. At national scale, Paige-Green (1985) has produced a classification of different susceptibility classes based on expert judgement. Information on landsliding in Great Britain was summarized by Jones and Lee (1994) and a comprehensive landslide inventory is provided by Guzzetti *et al*. (1994) for Italy. For Germany, a national landslide susceptibility map was estimated based on lithology and slope geometry (Dikau and Glade, 2003). The latter examples show, despite the fact of landslide occurrence at distinct locations or within restricted regions, the large potential for analysis at the national scale. Any available local or regional landslide information can be used to validate and verify the results gained at national scale analysis. Although major differences in the resolution and quality of basic data sets and in the type of analysis appear, spatial landslide information is available and provides a valuable source for further analysis, for example to estimate regional landslide risk by combination with elements at risk and respective socio-economic attributes. For some regions, such regional landslide risk estimates have already been carried out. Some examples are given in the following section.

3.5 Landslide Risk Assessments

The history and basic concepts of landslide risk assessments and analysis are explained in Chapters 1 and 2 of this book (refer also to Chowdhury, 1988; Evans, 1997; Kong, 2002). The following section summarizes regional examples of landslide risk assessment. Due to limited information, Table 3.7 does not distinguish between different landslide types, nor between different methods used to assess the elements at risk and the respective consequences. Methods may involve different spatial resolution of elements at risk (e.g. single houses versus 'urban settlement') and different depth of quality and quantity of socio-economic data (e.g. monetary value of a building including its content or of an industrial site including goods, number of persons of different ages in a house versus 'population density', population per km^2). Such socio-economic data are fundamental to an accurate assessment of vulnerability (Romang *et al*., 2003). Comprehensive expressions of vulnerability involve not only structural measures (e.g. the degree of damage to a building hit by a given magnitude debris flow), but have also a social dimension (e.g. coping capacity (resilience) of the affected person/family/community) as described by Solana and Kilburn (2003).

Once landslide hazard maps have been produced and further spatial information on potential consequences is available, landslide risk can be estimated (e.g. Wu *et al*., 1996). Thus the consequences of the natural hazard occurring are the product of the elements at risk and the vulnerability. A measure of vulnerability is essential for the determination of consequences and is defined as the degree of loss for a given element at risk, or set

Table 3.7 *References on spatial landslide risk assessments for different regions of the world*

Continent	Country	Region	Type	Reference(s)
			Catchment and regional scale	
Asia	China	Yunnan Province	Debris flow risk	Liu *et al.* 2002
		Hong Kong	Analysis; Quantitative risk assessments	Hardingham *et al.* (1998); Ho and Wong (2001); Moore *et al.* (2001); Papin *et al.* (2001); Pinches *et al.* (2001); Reeves *et al.* (1998); Smallwood *et al.* (1997)
	India	Kumaun Himalaya	Assessment	Anbalagan and Singh (1996)
	Taiwan	Fong-Chui area	Debris flow risk	Lin (2003)
Europe	Germany	Rheinhessen	Analysis	Glade *et al.* in prep.-b
	Iceland	Bíldudalur	Analysis	Bell and Glade (2004)
	Italy	Italian Alps	Assessment	Eusebio *et al.* (1996)
		Northern Calabria		Ragozin (1996)
		Piedmont region	Risk assessment	Aleotti *et al.* (2000)
		Sarno region	Debris flow risk	Toyos *et al.* (2003)
		Umbria region	Qualitative risk assessment	Cardinali *et al.* (2002)
	Switzerland	La Veveyse and Veveyse de Figre valleys	Risk assessment	Sarkar *et al.* (2000)
Northern America	Canada	Vancover	Debris flow risk	Morgan *et al.* (1992)
	USA	Alameda County, California	Landslide damage	Godt *et al.* (2000); Godt and Savage (1999)
		Montrose, Victoria	Debris flow risk zoning	Moon *et al.* (1991)
		Seattle, Washington	Debris flow risk	Gori *et al.* (2003)
Southern America	Argentinia	Rio Grande Basin	Zonation mapping	Espizua and Bengochea (2002)
	Ecuador	Precupa	Hazard and vulnerability map	Basabe and Bonnard (2002)
Pacific	Indonesia	Yogyakarta	Lahar risk assessment	Lavigne (1999)
South Pacific	Australia	Cairns	Quantitative landslide risk assessment	Michael-Leiba *et al.* (2000); Michael-Leiba *et al.* (2003)
		Wollongong	Risk assessment	Flentje *et al.* (2000)
			National scale	
Europe	Italy		Assessment	Guzzetti (2000)

of elements at risk, resulting from event occurrence of a given magnitude (Newman and Strojan, 1998). Vulnerability is commonly expressed on a scale of 0 (no loss) to 1 (total loss) and is expressed either in monetary terms, such as the loss experienced by a given property, or to loss of life. The vulnerability concept has been reviewed for landslide risk assessments by Alexander (Chapter 5 in this book) and Glade (2004).

The risk concept ($hazard \times elements\,at\,risk \times vulnerability$) (UNDRO, 1982) has been transferred to landslides issues by various authors (Brabb, 1984; Einstein, 1988; Fell, 1994; Gill, 1974; Hearn and Griffiths, 2001; Hicks and Smith, 1981; Leone *et al*., 1996; Leroi, 1996; Stevenson, 1977; Stevenson and Sloane, 1980; Wu and Swanston, 1980). One comprehensive publication summarizing various attempts to address landslide risk is the proceedings of a workshop on landslide risk assessment edited by Cruden and Fell (1997). Since then, various case studies have been published on landslide risk (e.g. Cardinali *et al*., 2002; Dai *et al*., 2002; Finlay *et al*., 1999; Guzzetti, 2000; Hardingham *et al*., 1998; Hearn and Griffiths, 2001; Michael-Leiba *et al*., 2000). A comprehensive and generalized definition of landslide risk has been proposed by the Australian Geomechanics Society by Fell (2000) and adopted by the IUGS Working Group on Landslides – Committee on Risk Assessment (1997). This report refers not only to the definitions given in Chapter 1 and in the glossary of this book, but also focuses on the notions of 'acceptable', 'tolerable', 'single' (individual) and 'collective' (societal) risk. As a conclusion, however, the majority of landslide hazard and risk literature is based on natural science approaches to assess landslide risk (Aleotti and Chowdhury, 1999). Social science studies looking at coping strategies or resilience capacities of affected communities for landslide occurrence are rather limited in contrast to those available for other natural processes such as floods or earthquakes.

Table 3.7 gives an overview of various spatial landslide risk assessments for different regions worldwide. While some authors present landslide hazard and risk zonation based on mapping procedures (e.g. Espizua and Bengochea, 2002), others propose empirical assessments for specific landslide types, for example debris flows (Liu *et al*., 2002), or use probabilistic methods to analyse landslide risk (e.g. Chung and Fabbri, 2002; Rezig *et al*., 1996). Common to all approaches is the attempt to relate socio-economic data to spatial landslide hazard information in order to gain more informative data on the potential consequences of landslide occurrence. Numerous publications are available which use 'risk' in their title and text, but do not cover the risk concept as previously defined. Such studies have not been included in the presented tables. In order to demonstrate the different depth of analysis, the following section gives examples of local and spatial landslide risk assessments at varying levels of generalization.

3.6 Examples of Landslide Risk Analysis

Spatial landslide risk analysis provides a valuable tool for gaining risk estimates at the regional scale. As with any spatial assessment, the choice of model type and the performance of the model are strongly dependent on the data sets available for analysis. Two examples of varying depth of analysis and data sets of different resolution give some idea on the variety of details in spatial landslide risk analysis. Hence the focus of the following examples is not on the calculation of the hazard using advanced methods (e.g. Guzzetti *et al*., 2003); rather it aims to demonstrate the application of different information on elements at risk and potential consequences for spatial landslide risk analysis.

3.6.1 A Quantitative Rockfall Risk Analysis in Bíldudalur, Iceland

A comprehensive, object-oriented assessment of landslide risk has been carried out by Glade and Jensen (2004) for Bíldudalur in the northwest fjord region of Iceland (Figure 3.5). To illustrate the result of the applied methodology of risk analysis, the following description focuses on rockfalls. A detailed report of environmental settings of Bíldudalur, local rockfall history along with the method and results of calculating runout zones for rockfalls are described in detail in Glade and Jensen (2004).

Based on this report, Bell and Glade (2004) developed a methodology for landslide risk analysis as part of a general landslide risk assessment. For this methodology, the approach of Heinimann (1999) was applied, which determines the vulnerability of buildings according to building structure and their resistance to rockfalls of different magnitude. Historical data could not be used to prove the reliability of vulnerability values because suitable information was not available. Within the whole historical record, no fatalities have been caused by rockfall events (Glade and Jensen, 2004). Although there is no previous evidence of serious consequences, there still is an inherent risk to life which needs to be calculated to support responsible administration to take appropriate countermeasures. Therefore the probability of loss of life in a building for both individuals (individual risk of life) and all people living or working inside a house (object risk to life, thus a risk to life considering all the people staying inside one building) has been calculated.

Rockfall runout zones determined by Glade and Jensen (2004) have been transformed into hazard zones by attributing a return period to each rock size used within the runout calculations. Rockfall risk was calculated using these hazard zones in combination with potential damage values and respective vulnerabilities of the elements at risk. The spatial distribution of one set of elements at risk (number of residents and employees per building) are shown in Figure 3.6. The consequence analysis was carried out considering the vulnerability, the probability of spatial and temporal impact, as well as the probability of seasonal impact of the rockfall at any given location in the study area. Resulting risk maps include individual risk to life and object risk to life, which are given in Figure 3.7. On these maps, areas with different probabilities of loss of life can be identified (refer to Bell and Glade, 2004 for a comprehensive description).

The individual risk to life due to rockfalls ranges between 1.1×10^{-5}/year and 5.6×10^{-5}/year and is thus relatively low (Figure 3.7a). Of the total area, 92% belong to low risk and 8% to very low risk. Taking the total number of people in a building into account (object risk to life), the risk increases (Figure 3.7b) and ranges between 1.6×10^{-3}/year and 2.1×10^{-5}/year. For the total region, 4% relate to very low risk, 27% to low risk, 58% to medium risk, and 11% to high risk. The calculated total risk to life is 0.009 deaths per year.

Similar procedures can be used to calculate the monetary risk of the community. One of the main advantages of such an approach is that this type of analysis can be performed for just about any natural processes (e.g. rockfall, debris flow, snow avalanches, tsunami) and a combined multi-risk analysis can be derived (Bell and Glade, 2004). Whether appropriate countermeasures have to be organized is the decision of the responsible

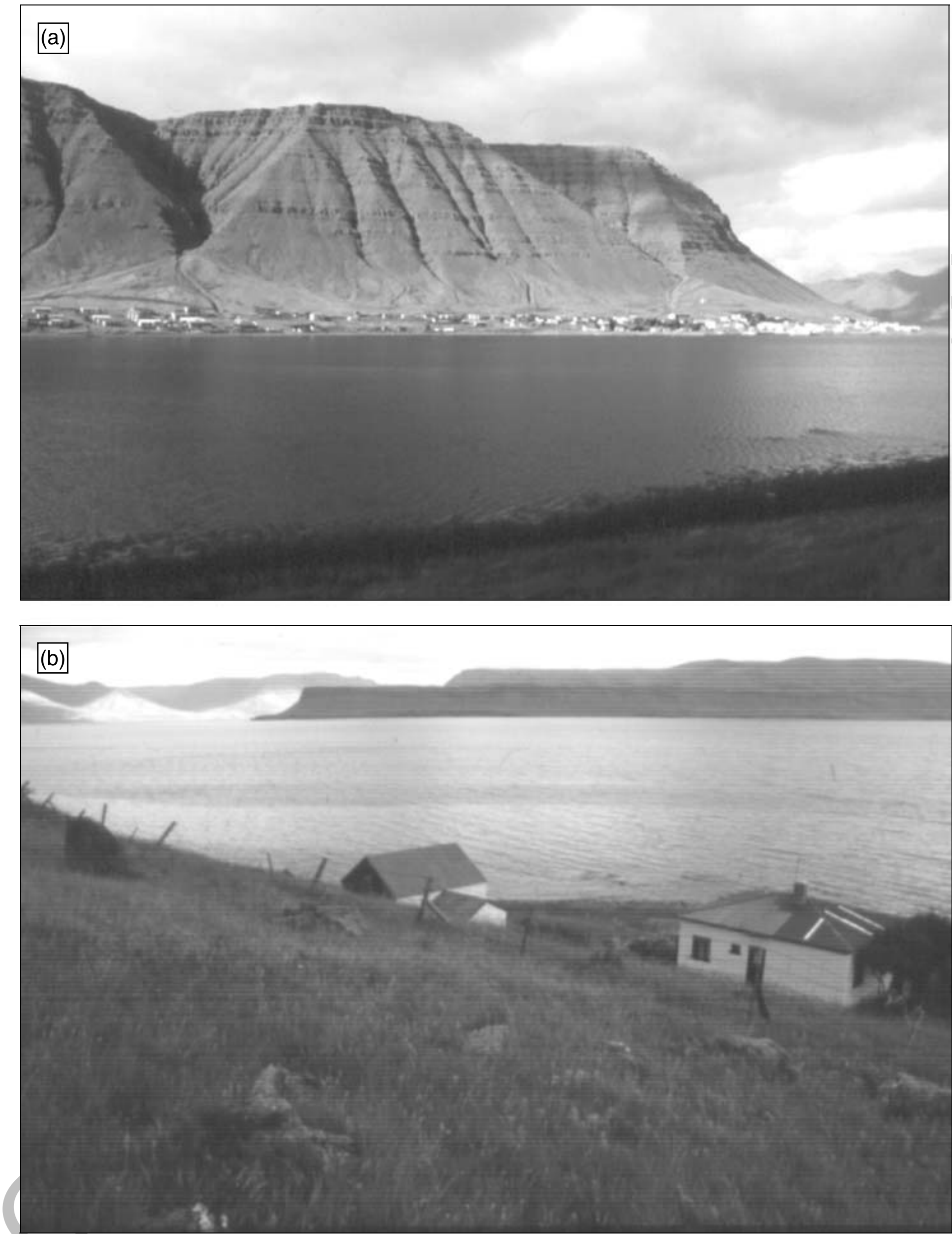

Figure 3.5 *(a) Northwards view to Bíldudalur, Northwest Iceland. Relief difference is approx. 400 m. (b) Rock with diametres up to 1.7 m above a house in Bíldudalur (photos by T. Glade)*

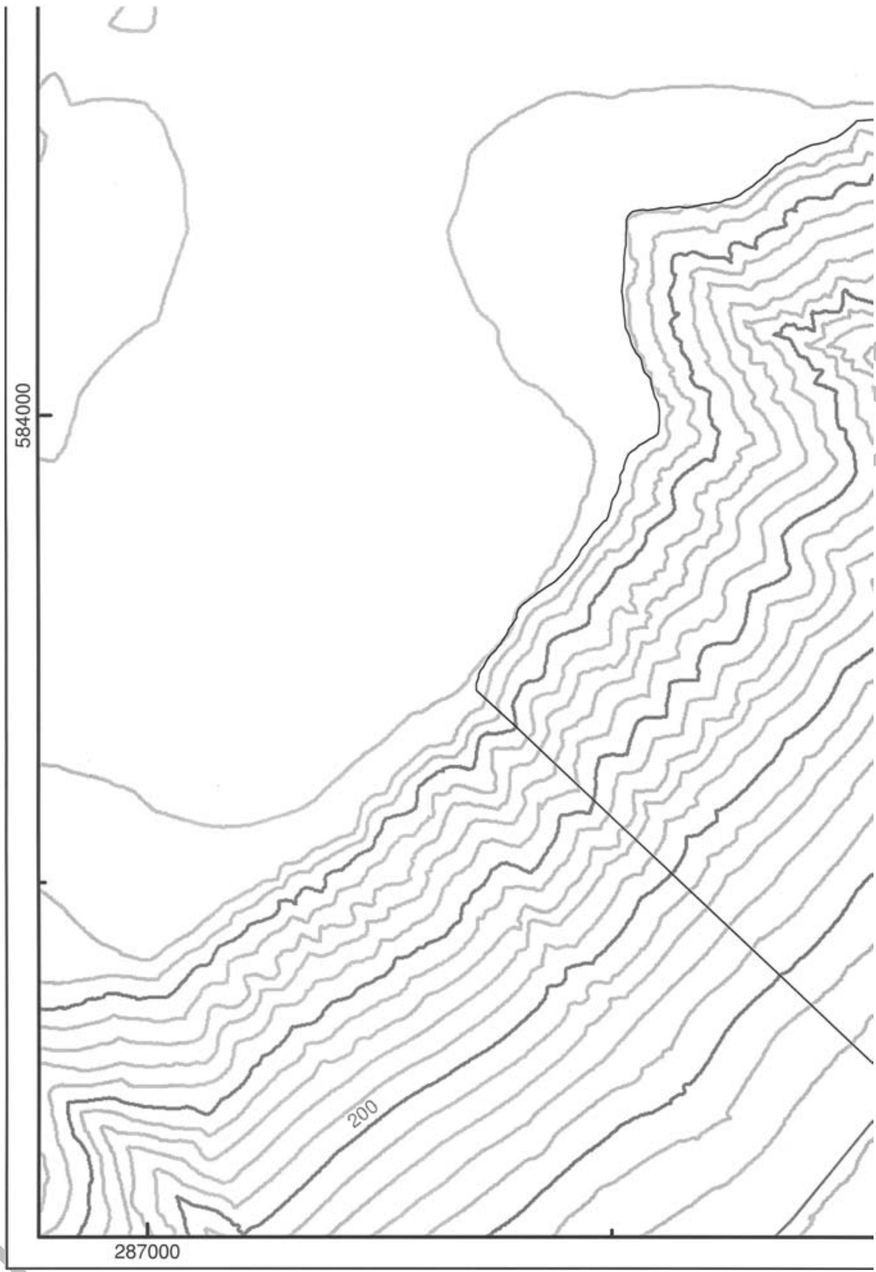

Figure 3.6 *From all elements at risk, the number of residents and employees per building are given using the four classes of residents: 'no', 'few' (1–2 persons), 'some' (3–6 persons), and 'many' (>7 persons). Eighty-nine buildings are garages and barns and are grouped as 'no' persons, 'few' persons reside in 26 buildings, 46 buildings accommodate 'some' persons, and only two buildings belong to the largest class (Bell and Glade, 2004)*

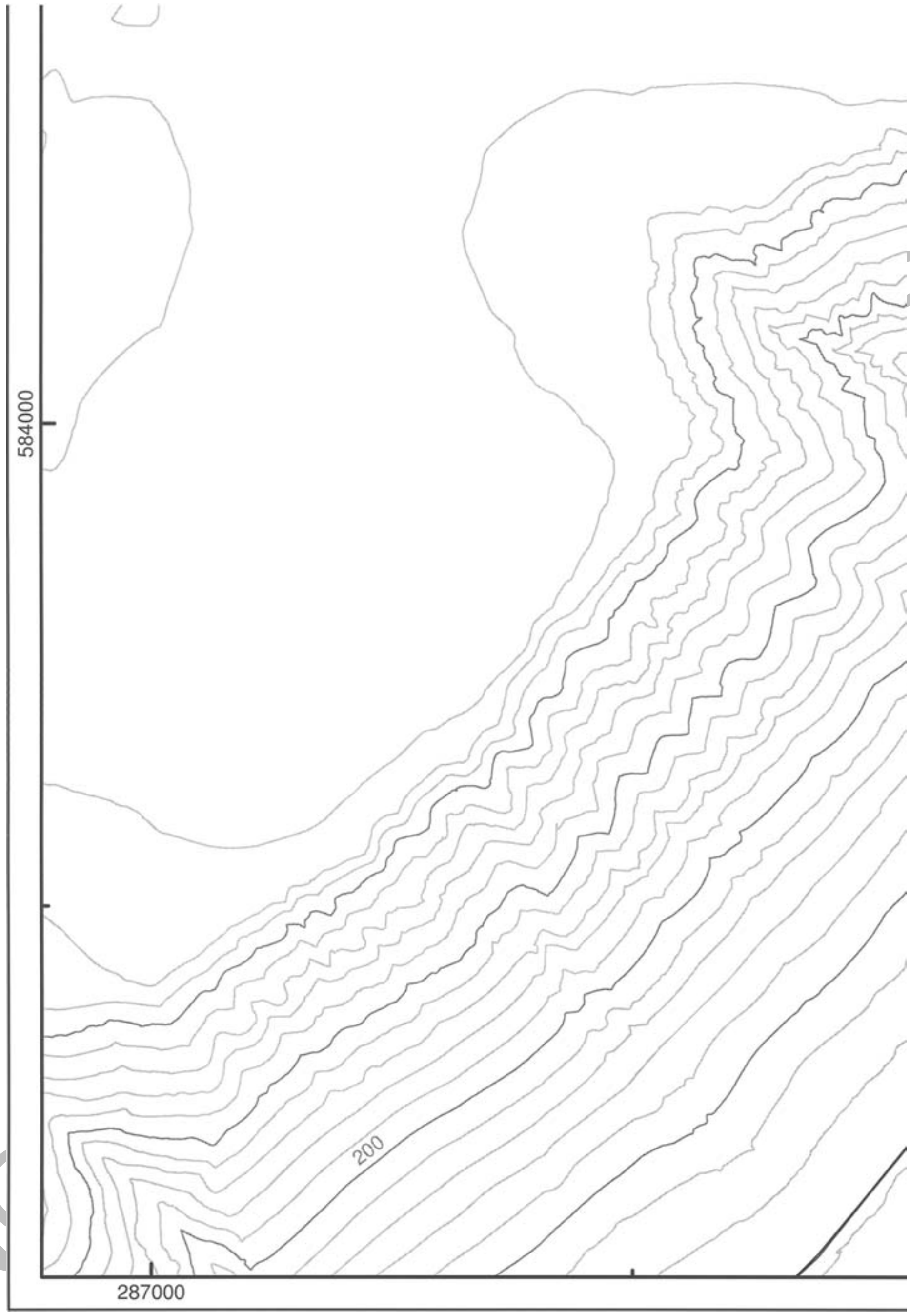

Figure 3.7 *The rockfall risk map gives two different types of risks in buildings. (a) refers to the individual risk to life for each person. (b) gives the object risk to life considering all people in a building, and hence is an average risk to life (Bell and Glade, 2004)*

Figure 3.7 *(Continued)*

administration. This type of analysis, however, provides the local administrations with important information.

3.6.2 A Regional Approach to Address Regional Landslide Risk

The Rheinhessen study was designed to provide a landslide risk analysis by applying simplified vulnerability values and generalized monetary values based on regional mean values. Regional details and the general background of slope instability in Rheinhessen are given in Glade *et al.* (2001b) and Glade *et al.* (in prep.b). Dominant landslide types are shallow translational failures and rotational slides (Figure 3.8).

First, landslide risk analysis is based on landslide hazard map derived by Jäger (1997), but extended resolution using a 20 m DTM instead of the original 40 m. Second, elements at risk have been determined for different land use groups and digitized from official land use plans. Afterwards, for each element at risk, a damage potential has been defined based on literature review and on data from national statistics yearbooks (Table 3.8). For this region, no information on vulnerability of elements at risk from landslide initiation was available. Therefore it was assumed that if an element at risk is affected by a landslide, it is totally destroyed. Consequently, vulnerability has been assigned as 1 to all elements at risk. Due to the low probability that a person will be injured or even killed from a landslide event, risk to life has been excluded from the analysis. Details on methods, analysis and results are given by Glade *et al.* (in prep.b).

The classified elements at risk are summarized in Table 3.8. Respective damage potentials have been assigned to enable a calculation of economic value for each class.

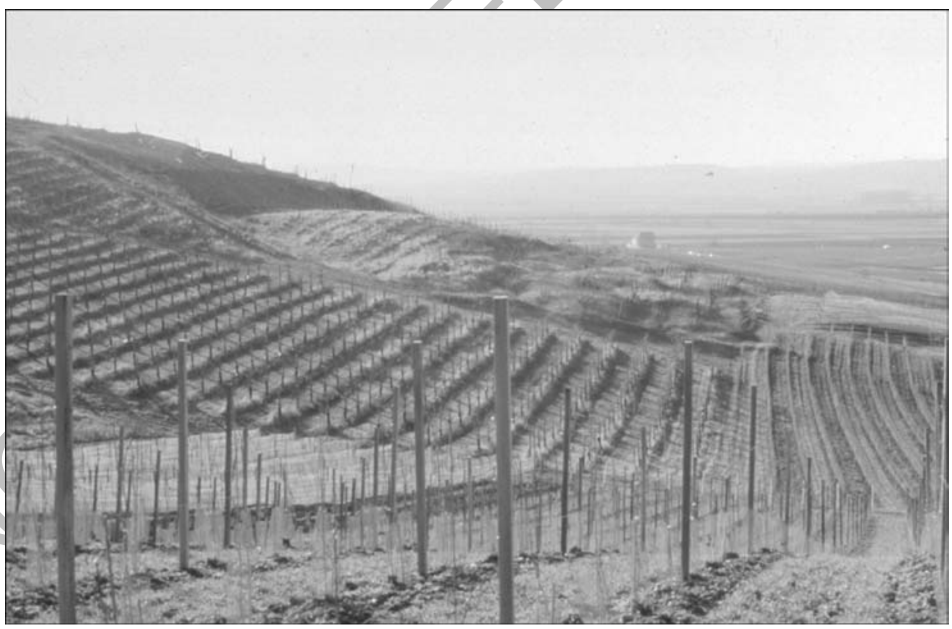

Figure 3.8 Example of the rotational landslide OCK3 in northwest Rheinhessen, view to east (photo by T. Glade)

Table 3.8 *Elements at risk with attributed damage potential in* (€/m^2) *(refer to Glade* et al. *(in prep.b) for details of sources and calculations)*

Risk element	Monetary value (€/m^2)	Risk element	Monetary value (€/m^2)
Residential Area	255	Pasture	0.5–0.7
Mixed usage	255–410	Agricultural areas	0.3
Industrial Region	205–255	Viniculture	10
Specialized Region	205	Forest	2
Road	13–15	Highway	85–128

These classes have been combined with natural hazard information and the elements at risks. A qualitative matrix of the combination of these parameters resulted in different landslide risk classes, which are shown in the landslide risk map (Figure 3.9 – see also Colour Plate section Plate 1).

The landslide risk map includes 'low', 'medium', 'high' and 'very high' risk classes. Of the total area, 90% has been classified as 'low', 8% as 'medium', 2% as 'high', and 0.2% as 'very high' landslide risk. In general, 'low' risk areas refer to flat or moderately steep slopes with pasture. In contrast, 'high' and 'very high' risk classes represent the steep slope segments with either buildings or vineyards. This result highlights the importance of the potential effects of landslides in the study area, which is representative for the whole Rheinhessen area. Due to its generalized input data, the resulting risk map cannot be used by local administration for detailed planning, but it is of great value for both local and regional governments to locate areas prone to landslide risk and to organize more detailed analysis in the identified 'hot spot' areas.

3.6.3 Summary

Both examples demonstrate the potential of landslide risk assessments at various scales and with different levels of analysis. While detailed risk assessments are indispensable for site-specific problems, more generalized risk analysis is also of major importance to gain an overview of a large area. Besides the scale of interest of the administrative authorities, detail of analysis is also highly dependent on numerous other factors such as financial resources, time constraints, data availability and quality. However, it is important to use the resources in the most profitable way to provide methods and concepts which can be applied to gain the most benefit from lowest costs.

3.7 Influence of the Triggering Agent

The previous discussion on local and spatial landslide investigations gave no details of the respective landslide triggering agents. Nearly all reviewed landslide investigations are related either to rainfall and subsequent soil moisture regimes or to earthquake triggers. In terms of establishing an inventory or a susceptibility map, the landslide trigger is of minor importance. Irrespective of the cause, the principal interest of these investigations is the landslide location and the environmental factors, which give some indication of landslide susceptibility. Indeed, some environmental factors are more important for earthquakes

Figure 3.9 *Regional landslide risk in Rheinhessen, Germany (Glade* et al., *in prep.b). Vulnerability to elements at risk is assumed to be 1, referring to total loss if an element is affected by a landslide*

than for rainfall (e.g. orientation of geologic structure and landforms, distance to tectonic lineaments). But most other factors are important for both triggers (e.g. slope geometry, soils, vegetation). In any case, if the analysis extends further to address hazard, for a specific landslide type, information on the triggering agent can be extremely valuable as a component of the analysis.

Generally, it is easier to establish a temporal record of rainfall-triggered landslides than of earthquake-triggered failures. Rainfall records coupled with historical landslide information allow the calculation of the temporal probability of rainfall-triggered landslides. In contrast, information on landslide occurrence related to recurrence intervals of different-sized earthquakes is more difficult to assess due to the low return periods of these events. Despite these constraints, attempts to model the spatial extent of both triggers using empirical and/or numerical approaches are in progress. These scenarios of probable future triggers have the potential to be linked with empirical or numerical models of landslide movement. This procedure allows an approximation of the change of landslide hazard for different trigger magnitudes. Thus it enables a shift from static to dynamic conditions. This scenario modelling is a powerful tool for any landslide hazard assessment.

The consequences of a landslide event are also not dependent on the nature of the trigger. Structural damage of elements at risk results purely from the landslide types and expected magnitudes and intensities. Direct damage from earthquakes is not within the scope of this work. Possibly, some elements at risk may already have been weakened by foreshocks or an earlier earthquake (e.g. cracks in foundations, etc.) and are thus more vulnerable to the subsequent landslides, while other elements at risk might become less vulnerable. For example, foreshocks or the first few seconds of an earthquake might allow people to be better prepared for the subsequent landslides, for example by moving into other rooms in the case of debris flows, leaving the house in the case of large rotational slides, or seeking shelter in the case of small rockfalls. In general, it is rather difficult to forecast the consequences of a trigger and thus their consideration within the landslide risk analysis is complex.

3.8 Summary and Conclusion

The review of inventory, susceptibility and hazard analysis has shown the wide range of studies and applications. Despite the numerous studies from worldwide examples, many other regions are also affected by landslides. These also need to be examined in detail. It is demonstrated that landslide inventories are of major value for any susceptibility, hazard and risk analysis. Such inventories can be used as input data for the direct calculation of susceptibility. Moreover, if there is temporal and magnitude information available in the inventory, the probability of landslide occurrence of a given magnitude in a specific time period and a predefined location can also be estimated, and thus landslide hazard estimates delineated. Another application of landslide inventories is their use for verification and validation of calculated susceptibility or hazard. If inventories need to be used for both analysis and validation of results, the data sets can be split in two groups, one for analysis and one for validation (Chung and Fabbri, 1999). This is a major and fundamental issue which is often ignored.

Independent of scale, the concepts and approaches to landslide hazard and risk analysis outlined in this chapter allow a standardized and, in some cases, objective assessment of potential consequences of an assumed triggering event. As well as the ultimate determination of a level of risk, decision makers and planners should also be aware of the concepts, assumptions, methods or limitations involved in its computation. As with any modelling procedure, limitations of the approach have to be appreciated when using the information for making subsequent decisions on policy and management:

- Any spatial landslide information contains uncertainties that are difficult to evaluate (e.g. Ardizzone *et al*., 2002; Carrara *et al*., 1992).
- The resolution and quality of the socio-economic data influence the accuracy of the resulting risk.
- In most cases, the vulnerability of structures and of societies can only be roughly estimated or approximated (e.g. Glade, 2003b).
- The risk model is always a generalization of reality, and the model performance is strongly dependent on data constraints.
- The calculated landslide risk is a stationary expression of reality at the time of analysis.

Alternatively, there are many advantages of landslide risk assessments (e.g. Petrascheck and Kienholz, 2003). These are, in particular:

- Risk values and information are transparent and comprehensible.
- Scenarios allow assessment of the consequences of future developments.
- Reliability of the model performance is strongly dependent on data quantity and quality; thus with increasing data availability, the reliability of the risk estimate increases.
- Most models of landslide risk can be adapted to significant changes in the environment, such as vegetation changes or changes in land use or suburban developments. Therefore the potential exists to regularly update the static risk information.
- The conceptual approach and established methods allow a comparison not only of risk from different landslide types, but also from other natural hazards.

These advantages can be used to trace the evolution of landslide risk. Change of landslide risk is not only dependent on the change of the underlying landslide processes. Even while the level of landslide hazard remains constant, the risk may change as a result of human activity. Landslide risk is consequently not only an expression of the natural environment, but is also related to human interference with nature.

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