18 Hazard assessment for risk analysis and risk management

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18.1 Approach

The focus in this chapter is on the client – what is it that hazard and risk managers want from geomorphologists and what do geomorphologists believe that their science can constructively offer hazard and risk management? However, communicating skills and requirements can be difficult because scientists and practitioners come from different backgrounds and work within different constraints. On the one hand, the geomorphologist primarily needs to satisfy the research community, while the manager, on the other hand, has to deal with their client base and the public in general, often within a strict statutory, regulatory, policy and financial framework. Clearly, the basic information demands of hazard assessment, of *where* (location), *what* (type of event), *when* (how often) are fundamental to reducing risk but the manager might also legitimately ask 'which areas are free from hazard?', 'what type of mitigation might be appropriate?', 'what sort of monitoring should be undertaken?', 'what changes can we expect in the future?' and 'what is the cost effectiveness of different management options?'.

In post-event situations, geomorphologists may also be required for forensic investigation. In many cases this will be to establish the cause, apportion weight to the causative factors, and to determine the relative importance of human versus natural factors in creating both cause and consequences.

By understanding the geomorphic system, not only in space but also through time, the geomorphologist should be capable of predicting or at least indicating the hazardous characteristics of processes and places within the system, at a range of spatiotemporal scales. They should be able to identify the 'hotspots' in the system, the direction of system change, where and when the intrinsic or extrinsic thresholds might be met but more importantly how those thresholds may change in time and space. For high-risk situations, there will always be a need for further detailed investigations often by a range of specialists. The geomorphologist, however, should be able to identify the important issues in the light of interconnections within the geosystem and consequently to guide those investigations, and pose the critical questions that need to be pursued in greater detail on site.

While this chapter is intentionally confined to the 'hazard assessment' component of the wider framework of risk management, it is important for the geomorphologist to recognise that authorities involved with hazards are ultimately concerned with assessment, evaluation and treatment of risk (that is the expected losses associated with hazard). Risk itself is not just a function of the hazard (probability of occurrence of a given magnitude of event in a given region/location and period) but also the elements of value exposed to the hazard and their vulnerability (Crozier and Glade, 2005). A general problem in any hazard or risk study is, however, that uncertainty is commonly not well addressed or communicated in hazard and risk assessments.

18.2 Basic concepts and issues

18.2.1 Behaviour of geomorphic processes: what makes them hazardous

The characteristics of geomorphic processes that make them hazardous include a wide range of parameters including: volume (mass), velocity, depth, mechanisms, duration, areal extent, and speed of onset. The relevance and damage capability (referred to here as *intensity*) that can be attached to these parameters varies with the type of hazard, the magnitude of these *intensity parameters* at the time of occurrence, and with the frequency with which

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they can be expected to occur in a given place. Unfortunately, only some of these critical parameters are recorded in historic data bases in a systematic way conducive to risk assessment. For example, floods may have a good record of peak discharge but little on the duration or residence time of flood water (which may be more important than peak discharge in causing economic loss). Frequency–magnitude analysis (Crozier, 1996, 1999; Crozier and Glade, 1999), which is at the heart of hazard assessment, is often restricted to conventional representations of magnitude, e.g. volume of landslide or snow avalanche, depth of precipitation, discharge of floods, rather than the parameters which more accurately represent the damage potential of the hazard. Additionally, there are three other hazard parameters of importance that are as much a function of the human condition as the physical process. These are predictability, controllability and lethality. Whereas they are not necessarily the domain of the geomorphologist, an appreciation of such parameters is essential to the hazard manager in choosing appropriate mitigation and risk reduction options.

The losses associated with the occurrence of a hazard are rarely confined solely to the event itself or to the specific locality of initial impact (Glade and Crozier, 2005a). It is important for management purposes to view hazard impact at a variety of scales and form (Glade and Crozier, 2005b). The impacts may be direct or indirect, acute (immediate) or chronic (delayed) or may lead to the development of consequential hazards. *Direct impacts* are those consequences incurred by direct physical contact with the hazard process itself. *Indirect impacts*, on the other hand, are changes brought about in the properties and behaviour of other natural systems as a result of hazard activity. Some of these induced changes may give rise to consequential hazards, e.g. a wave being generated by a landslide entering a reservoir, biological hazards arising from stagnant water left in the aftermath of flooding, or a flash flood resulting from a bursting lake formed by a surging glacier. Indirect impacts can be immediate or delayed, occur in the proximity of the initial hazard impact or at some distance from the impact site. For example, a tsunami consequent on submarine fault displacement may have its maximum impact delayed by many hours and manifest hundreds of kilometres away from the site of origin. Similarly, a large debris flow event caused by heavy precipitation in mountain ranges may cause extensive damage tens of kilometres away from the site of initiation (e.g. Lopez *et al*., 2003). *Acute impacts* are short lived while *chronic impacts* may be manifest over a longer period of time, as for example economic losses attendant upon damaged infrastructure or loss of means of production.

Our understanding of the complexity of hazard and risk very often depends on analysis of existing records. However, one has to be cautious. The knowledge of past events and possible consequent damage is only available if these incidences have been reported. Thus, no information on former events does not automatically imply that there were no events in the past, it might just be an expression of missing records (Glade *et al*., 2001). Although a trivial aspect, this is often disregarded in hazard and risk analysis and consequent interpretation.

18.2.2 Non-linearity and frequency–magnitude assessment

There is a variety of approaches used to assess magnitude and frequency including: the use of physically based modelling (Brooks *et al*., 2004), analysis of the instrumental, historic, oral, secular or documentary record (Kemp, 2003), as well as the interpretation of geo archives such as sedimentary stratigraphy (Page *et al*., 1994). It is in the last approach that geomorphologists, using a full range of increasingly sophisticated dating techniques (Walker, 2005; Gartner, 2007), make a distinctive contribution, particularly in the area of determining trends and shifts in the state of geosystem equilibria.

Our understanding of frequency–magnitude behaviour of physical processes has often been achieved indirectly by establishing the relationship between the behaviour of a forcing agent (triggering agent) and the associated geomorphic response (e.g. the relationship between river discharge and sediment movement, wind velocity and sediment entrainment, rainfall intensity and landsliding (Glade *et al*., 2000), or earthquake shaking intensity and landsliding (Keefer, 1984; Keefer and Wilson, 1989)). Analysis of this relationship is designed to obtain the triggering (critical) threshold for a given response – thus allowing the record of the triggering agent (often much more complete than that of the hazard itself) to be examined in order to determine the frequency with which the critical threshold is likely to be equalled or exceeded. Many such studies (Wolman and Miller, 1960; Wolman and Gerson, 1978) have established frequency–magnitude relationships on the assumption of steady state or dynamic equilibrium conditions – assuming, for example, that process response is purely power constrained (Richards, 1999). However, in certain situations, the condition of the ambient environment can change sufficiently to alter the critical threshold, thus inducing changes in frequency and magnitude of hazard events, independent of the behaviour of the geomorphic agent. For instance, the relationships established between channel degradation, soil erosion

(Favis-Mortlock and Boardman, 1995) or wind erosion and the behaviour of the triggering agent may not be temporally stable and can readily break down with, for example, the development of bed armouring or lag deposits. In the case of landsliding, synergistic relationships derived from repeated episodes in a given place can increase thresholds and decrease event frequency in relatively short periods of time. For example, the removal of available material by repeated episodic shallow landsliding has been shown to increase overall catchment stability (referred to as *event resistance* (Crozier and Preston, 1999; Brooks *et al*., 2002)). Similarly, repeated deep-seated bedrock landslides can also induce negative feedback by depleting the availability of susceptible sites – an effect referred to as *site exhaustion* (Cruden and Hu, 1993). Such synergistic changes need to be taken into account in landslide hazard mapping, which conventionally views the presence of landslides as indicators of future landslide susceptibility (referred to as the *precedence approach*).

Assessment of reactivation of existing landslides, on the other hand, may need to consider the possibility of the positive feedback conditions induced by initial movement. In certain cases, movement can reduce material strength from a peak to a weaker residual condition and poorly evacuated landslides can develop a morphology that inhibits drainage and enhances water entry into the slope, both lowering activation thresholds.

Non-linear relationships resulting from response-induced changes make frequency–magnitude assessment a difficult task, calling for an understanding of landform evolution at a range of temporal and spatial scales.

18.2.3 Vulnerability

Vulnerability (the expected degree of loss associated with a given level of hazard intensity) can be viewed as a function of both social and physical conditions. It can be expressed in terms of structural damage (damage ratios), or in terms of human, economic, cultural and environmental loss (Birkmann, 2006; Douglas, 2007; refer also in this book to Chapter 19 by Hufschmidt and Glade).

One of the least understood issues in hazard and risk assessment is the development of damage ratios and physical vulnerability indices with respect to different types of hazard and their intensity (e.g. Fuchs *et al*., 2007). While damage ratios are well defined for different building materials and design with respect to earthquake shaking (which by definition incorporates different ground conditions (Dowrick, 1996)), there is little such information available for most other hazardous processes. Table 18.1, for example, treats physical vulnerability as a function of degree of exposure, and the nature of the physical process impact. However, the vulnerability ratios listed in this table are very tentative and could clearly be further qualified by degree of structural integrity and type of design. The degree of exposure considered in this table is static and, in order to calculate risk of a population likely to be affected, it is necessary to introduce a dynamic exposure term (e.g. the proportion of the time a person is likely to be in a location exposed to such a hazard).

TABLE 18.1. *Vulnerability of a person to landsliding under different degrees of exposure – the value 1.0 indicating a 100% probability of death*

		Vulnerability of a person		
Location	Description	Data range	Recommended value	Comment
Open space	Struck by rock fall	0.1–0.7	0.5	May be injured but unlikely to cause death
	Buried by debris	0.8–1	1	Death by asphyxia
	Not buried, but hit by debris	0.1–0.5	0.1	High chance of survival
Vehicle	Vehicle is buried/crushed	0.9–1	1	Death almost certain
	Vehicle is damaged only	0–0.3	0.3	High chance of survival
Building	Building collapse	0.9–1	1	Death almost certain
	Inundated building with debris and person is buried	0.8–1	1	Death is highly likely
	Inundated building with debris, but person is not buried	0–0.5	0.2	High chance of survival
	Debris strikes the building only	0–0.1	0.05	Virtually no danger

Modified by Glade (2003) after Wong *et al*. (1997)

Vulnerability as a function of social conditions is a complex concept involving aspects of coping capacity, adaptive capacity, and resilience, which in turn may be related to fundamental developmental and socio-political structural issues of the affected society (Alcántara-Ayala, 2002; Birkmann, 2006).

18.2.4 Hazard assessment

Hazard assessment (hazard analysis) in this context focuses on the physical behaviour of natural processes, particular at their extremes where the magnitude and frequency is such that those affected have been unwilling or unable to make the adaptations and adjustments that would allow nullification of the impacts. *Hazard*, by definition, is the probability of a damaging event and, expressed as such, has the implicit element of prediction and a requirement for exceedence of a notional damage threshold. The concept of probability, however, can be used in two different ways in hazard assessment. First, in the sense of *susceptibility*, i.e. the probability that the pre-conditions at a site will allow occurrence. Commonly, susceptibility assessments simply rank terrain on its likelihood of ever experiencing a hazard event, often in the form of a red (yes), orange (maybe) and green (never) zonation for different spatial expressions and resolutions (e.g. pixel by pixel or polygons, expressing slope segments or even catchments). Second, probability can refer to recurrence in time, i.e. the probability that a hazard event will recur. This latter characterisation of probability provides an expression of frequency that allows the statement of recurrence intervals (return periods). One main drawback in most temporal probability studies is that there is commonly little information on the spatial variation of temporal probability available. While hazard framed in these terms is much more useful for management purposes, it has more rigorous data requirements (van Westen *et al*., 2006). Many of these issues have been recently addressed in a comprehensive set of international standards for defining, analysing and representing susceptibility and landslide hazard (Fell *et al*., 2008).

It is critical that assessments of hazard provided to managers have taken into account future likely changes in frequency and magnitude. Such changes result from either culturally related reduction of the damage threshold or from physical causes related to changes in the variability, and/or magnitude of physical processes or from changes in environmental susceptibility (Crozier, 2008). Herein lies the danger of using historical data and empirical models and of treating hazard established at one point of time as a constant for a location. Hazard as well as risk is as dynamic and evolutionary as the physical system itself (Hufschmidt and Crozier, 2008).

As indicated in Figure 18.1, hazard analysis is only one component of the risk management system and can be carried out at different levels of sophistication, depending on the scope and objectives of the project undertaken and the value of elements at risk that may be threatened. Assessments can range from regional to site scales or to specific object assessments such as buildings or life-line infrastructure (Glade and Crozier, 2005b). They may be required in areas where there is abundant evidence of former hazard events or, on occasions, in areas where there is no previous evidence of hazard occurrence. Hazard assessments may be a component of ‘greenfields’ planning projects, where considerable options are available for avoidance and mitigation or they may be conducted in high value, densely populated areas, where there are few opportunities for avoidance and technological treatments are the predominant options. Such considerations form part of the scoping phase and will strongly influence the detail and methodology of assessment as well as ultimately the choice of risk reduction solutions.

18.3 The contribution of geomorphology to hazard assessment

18.3.1 Location

Answering the ‘*where*’ question in hazard assessment addresses the question of susceptibility and, while not providing a statement of hazard in itself, it is an essential first step of the assessment process. Geomorphic hazards can be loosely assigned to two groups, on the basis of locational preference. First, those where the required set of critical geomorphic conditions are repeatedly met at the same locality, thus hazard recurrence is expected in the same location (*location specific*), and second, those where the terrain requirements are less specific and can be met over a wide range of locations (*non-location specific*). For example, fault rupture (*location specific*) is confined to linear fault zones whereas ground shaking (*non-location specific*) may be manifest at a wide range of terrain types over a relatively large area. Non-location specific hazards, of course, are much more difficult to manage from a planning perspective, while location specific hazards represent geomorphic hazard ‘hot spots’ and can be targeted by a range of treatments. Although geomorphic hazard hot spots are well recognised by the geomorphic community, they are not always fully appreciated by planners, managers and the public at large. An obvious example of a hazard hotspot is represented by debris flow and alluvial fans. To the lay

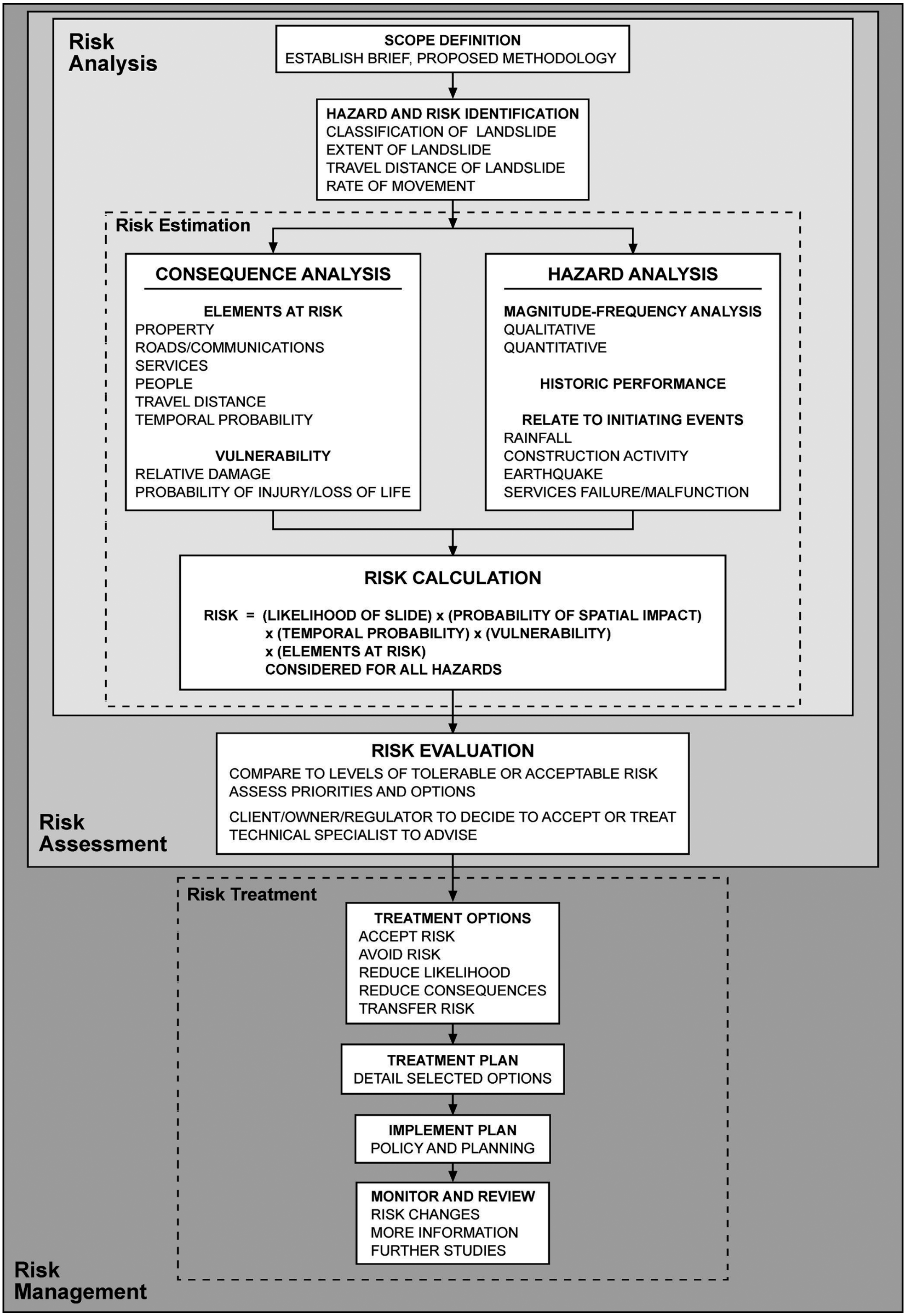

FIGURE 18.1. Flow chart showing all the stages involved in landslide risk management. (Based on Australian Geomechanics Society, 2000.)

FIGURE 18.2. Rakia River fan, New Zealand, showing avulsion pathways of different ages (Note: homestead on the true left of the active channel). (Photo: Jan Thompson.)

person, these landforms can appear to be the best building sites (relatively gently sloping land above the flood plain, below mountain slopes, and easy to use building ground – Figure 18.2), yet they are notorious for channel avulsion, gullying, and complex response (Davies and Korup, 2007), even on parts of the fan that have been dormant for many decades (Gartner, 2007).

Floodplains are perhaps more widely understood hazard 'hotspots' but are in high demand globally for their productivity, easy terrain and trafficability. The geomorphologist can provide information on their mode of formation, frequency of inundation and whether they are contemporary or relict (e.g. Pelletier *et al*., 2005). In terms of volcanic hazards, lahars tend to be location specific, recurring within well-defined pathways (Lecointre *et al*., 2004). Volcanic ash showers, on the other hand, are not specific to any particular location and the place affected depends on wind direction and strength at the time of the eruption.

Major hotspots for landslides are 'oversteepened' slopes. These constitute slopes that have been brought into a state of *marginal stability* (Crozier, 1986) through increase in height and/or slope angle, as a result of coastal, fluvial, glacial, tectonic or human action. At marginal stability, even small perturbations can trigger adjustment by slope failure and these highly susceptible conditions can persist for decades or even hundreds of years, until a stable angle of repose with respect to landsliding is reached and slower, more benign, slope process begin to assume dominance. While these slopes are easily recognisable when the erosional activity is still taking place (e.g. contemporary coastal cliffs), after they have been abandoned they are much less identifiable and yet the adjustment process will still continue to operate (Figure 18.3).

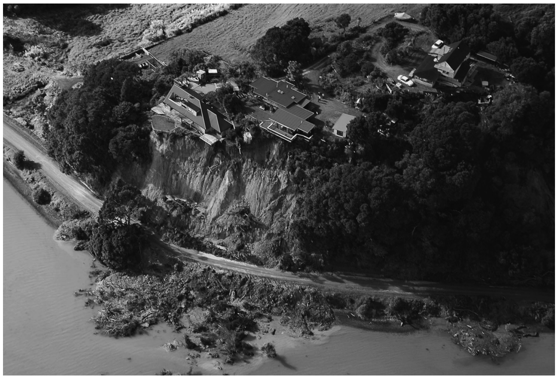

FIGURE 18.3. Former sea cliff still actively adjusting by landsliding, Orewa, New Zealand, 2006. (Photo: Graham Hancox.)

FIGURE 18.4. Multiple occurrence regional landslide event. These phenomena can occur almost anywhere in New Zealand hill country, depending on intensity and location of storm rainfall. Gisborne, New Zealand, 2002. (Photo: Michael Crozier.)

Multiple occurrence regional landslide events (Crozier, 2005) are common non-location specific landslide phenomena. They involve the essentially simultaneous occurrence of hundreds to thousands of rainfall- or earthquake-triggered landslides occurring over vast areas of varied terrain (Figure 18.4). The density of landslide occurrence is closely related to the intensity of the triggering agent. While broad terrain thresholds for their occurrence can be recognised, their location is determined by the passage of intense rainfall cells or the epicentre of earthquake energy release, the location of which at any one time is essentially random.

Site specific hazards have the potential of being avoided by the use of planning tools and regulation, including coastal and floodplain marginal set-back zones. Indeed, in some cases of fault rupture, avoidance is the only option, because of the magnitude of ground deformation (for example, the

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Wairarapa fault in Wellington, New Zealand, has a characteristic displacement of 13 m horizontal and 2.7 m vertical), thus engineering solutions are simply not feasible (Grapes, 1999). From a management perspective, mitigation of non-location specific hazards is best addressed by generic tools such as education, building design, preparedness and warning. On the other hand, the fact that many hazards are associated with specific landforms indicates that appropriately constructed geomorphic maps can provide a very important role in susceptibility identification (van Westen *et al.*, 2003).

18.3.2 Frequency–magnitude

By definition, frequency and magnitude analysis is the core of hazard assessment. This is conventionally established empirically from the inventory of occurrence or, less directly, by the frequency with which triggering agents are likely to surpass critical thresholds for hazard occurrence. Frequency–magnitude distributions can be established from a temporal record or from a spatial distribution of morphological or sedimentary evidence arising from one or more events (Hovius *et al.*, 1997; Malamud *et al.*, 2004; Guzzetti *et al.*, 2008). For the purpose of hazard prediction it is sometimes assumed (questionably) that spatial frequency–magnitude distribution faithfully represents temporal probabilities. For example, if a spatial inventory of a multiple occurrence landslide event indicates that 10% of the landslides are of a magnitude sufficient to cause damage, then this ratio is transferred to established annual frequencies – an annual frequency of 10 landslides a year would thus suggest an occurrence of one damaging landside per year. As noted earlier, synergistic changes and consequent non-linearity in process–response relationship demand that a sound understanding of geomorphic system behaviour is required if empirical methodologies are to be employed. In particular, empirical approaches also need to factor in the impact of climate and land use change, both of which have the potential to dramatically affect the incidence of hazard occurrence (Haerbeli *et al.*, 1993; Collison *et al.*, 2000; Dehn *et al.*, 2000; Ashmore and Church, 2001; Van Beek, 2002; Goudie, 2006; Crozier, 2008; Clague, 2009).

Hazard assessments may also be required in situations where historical inventories do not exist or where there is no evidence of hazards having occurred in the past. This situation commonly applies in the case of river impoundment and reservoir formation, which have the potential to induce shoreline landslides. The catastrophic consequences associated with large rapid landslides entering a reservoir are such that a planner requires a statement of hazard in order to evaluate the environmental and risk effects of the project. If there is no existing evidence, then the probability of first-time failure needs to be addressed. Whereas some information may be gained from analogues from other reservoirs in similar terrain and rock condition, the only feasible approach is to use a theoretically based stability analysis, employing scenarios based on the expected changes in slope hydrology related to reservoir filling and proposed operating levels. Probabilities then are usually based on the variability of input parameters and their ability to bring the slope to a factor of safety of 1.0 or less.

While most geomorphic hazards are dynamic, some important ones are static and require a different form of frequency analysis for risk assessment. For example, areas of weak foundation material such as organic-rich deposits, bentonitic clays or sinkholes can represent a substantial hazard to building development. In such situations, frequency can be represented by area ratios or more realistically by *encounter probabilities*. The latter are commonly employed to determine the risk to motorists from site specific landslides and avalanches and involve such factors as the number of vehicles and their speed. Fitzharris and Owens (1980) used such factors in calculating avalanche hazard and risk as follows:

Encounter probability for moving traffic (P_m)

$$P_\mathrm{m} = \frac{T \times (L + D) \times F}{V \times 3600 \times 24},$$

where:

P_m = number of moving vehicles hit by avalanches per annum
T = average daily traffic volume (vehicles/day)
V = average speed of traffic (m/s)
L = length of road covered by avalanche (width of avalanche)
D = stopping distance on a snow-covered road for a vehicle with speed V
F = frequency of avalanche occurrence (average number per year).

Encounter probability for stationary traffic (P_w)

$$P_\mathrm{w} = Ps \times F \times N,$$

where:

P_w = number of stationary vehicles hit per annum
P_s = probability of another avalanche occurring at the same or adjacent site to one that has forced traffic to stop
N = number of vehicles in the avalanche track.

The *hazard index* (I) is then calculated as:

$$I_{\mathrm{X1}}^{\mathrm{X4}} = \sum W(P_\mathrm{m} + P_\mathrm{w}),$$

where W is a weight applied to each category of avalanche X1–X4. The weightings reflect the cost and consequences of an avalanche from a particular category, and in the case of the Milford Road, New Zealand, were chosen to be:

X1 (Powder snow) = 1
X2 (light snow) = 4
X3 (deep snow) = 10
X4 (plunging snow) = 12.

Indeed, additional possibilities to calculate the hazard and risk exist (e.g. McClung, 2005; Zischg *et al*., 2005: refer also in this book to Chapter 5 by Bründl *et al*.), however, the basic principle remains the same.

18.3.3 Geomorphology and reconstruction of hazard intensity parameters

Geomorphologists have used a variety of physically based techniques to reconstruct the intensity parameters associated with a range of different hazardous processes. For example, the velocity of rapid earth flows and debris flows can be reconstructed from super-elevation debris run-up on the outside of bends, by the following relationship (Takihashi 2007):

$$E_{\max} = \frac{U^2}{2r_{\mathrm{co}}g}(2mh_{\mathrm{o}} + b),$$

where:

$E_{\max}$ = maximum super-elevation above elevation of channel midpoint
U = cross-sectional mean velocity
r_{co} = radius of curvature for channel centre line
g = acceleration due to gravity
h_{o} = is mean depth
b and m = constants, in the case of turbulent debris flows $b = 0$ and $m = 3$.

Similarly, Reneau and Dietrich (1987) have estimated debris flow velocity from the difference in elevation between the debris marks on the upstream and downstream faces of mid-channel obstacles.

Nott (1997, 2003) has developed a series of equations for estimating wave height required to move boulders in different positions based on boulder and water density, weight, and friction. These have been applied together with dating techniques to establish frequency and magnitudes of both tsunami and storm waves (Figure 18.5), which differ largely in terms of wave period and celerity (Kennedy *et al*., 2007). Similar approaches can be used to reconstruct velocity from the maximum size of particles in flood deposits using Hjulström or similar size/velocity entrainment relationships, or from bedform analysis (Simons and Richardson, 1966).

Flood discharges can be reconstructed by identification of the highest flood marks and rack deposit to define channel area and then application of considerations such as Manning's formula.

FIGURE 18.5. Tsunami deposit of imbricated boulders used to determine size of emplacement wave. The overlying sand and loess deposit were dated to provide a minimum age for the event. Shag point, Otago, New Zealand. (Photo: David Kennedy.)

There are also well-established relationships between fault displacement, length of fault rupture, and earthquake magnitude. For example, Bonilla *et al*.'s (1984) relationship between surface wave magnitude (M_{s}) and fault rupture length (L) in kilometres is

$$M_{\mathrm{s}} = 6.04 + 0.704(\log L);$$

whereas for maximum surface displacement in metres ($D_{\max}$) per event the relationship with earthquake magnitude (M_{s}) is

$$M_{\mathrm{s}} = 7.0 + 0.782(\log D_{\max}).$$

Identification of displacement by successive disruption of dated fluvial or lacustrine deposits can then be used to establish the earthquake frequency and magnitude record for given faults.

Wilson and Keefer (1985) have also established relationships between earthquake magnitude and the ellipsoidal area within which earthquake-triggered landslides occur and also with the distance of the furthermost landslide or liquefaction feature from the earthquake epicentre. Hancox *et al*. (1997) using a similar approach have established that the magnitude of an earthquake can be determined by

$$M = 1.04 \log_{10} A + 3.85,$$

where M is Richter magnitude and A is area (km^2) affected by landslides.

In this way, identification of previous earthquake events through landslide evidence and other earth deformation features can assist in establishing the frequency–magnitude record of an area over long periods of time (Crozier *et al*. 1995).

http://dx.doi.org/10.1017/CBO9780511807527.018

The examples given here (although far from complete) have been derived from studies of geomorphic processes carried out to determine their behaviour, causative factors, and their role in landform evolution, and not necessarily with the aim of reconstructing magnitude and frequency for hazard assessment purposes. However, they serve to illustrate that geomorphology can play an important part in understanding hazard behaviour of natural systems.

18.4 Conclusions and perspectives

The previous examples have shown the importance of geomorphic hazard assessments for risk analysis and risk management. This contribution, in particular, focuses on 'hazard assessment' and demonstrates the need for detailed process studies viewed as part of the geosystem as a whole, as a basis for any risk decision. The advantages of the geomorphic approaches can be summarized as follows:

Within a geomorphic assessment, not only currently monitored process intensities are of importance, but also the record of former events determined by sedimentary archives or documentary archives is indispensable. Geomorphic studies are capable of extending the hazard record and thus allowing the full range of energy fluctuations and responses to be appreciated as well as helping to distinguish between variability and change within the system.

Temporal probabilities are often related to single catchments only, but respective spatial information is also required most importantly for spatially extrapolating these relationships and allowing the development of comprehensive planning strategies.

Accordingly, the investigation of interconnections and linkages between processes, earth materials, landforms and land use is a major geomorphic contribution to hazard assessment.

Additionally, a geomorphic assessment considers the current criticality status of the investigated system, thus addressing whether the system is in a stable state, or is near an exceedence threshold, requiring only small trigger magnitudes (e.g. fully saturated slopes).

The limitations of these assessments are in line with restrictions of other hazard and risk assessment approaches and include the following considerations:

Not enough information on former events is available, either for general occurrence or for detailed event characteristics (especially the critical intensity parameters).

The associated uncertainty is commonly not addressed. This error includes not only the error (and its propagation) within the analysis, but also in the completeness and accuracy of the available data.

Although conceptually addressed, the linkage between different geomorphic systems (e.g. sediment routing from slopes to flood plains), the importance of triggers (e.g. required earthquake magnitude to cause landform response) as well as the threshold conditions are not sufficiently understood for the full range of terrain types and conditions.

Besides the already addressed advantages and limitations of geomorphic assessments in hazard analysis, it is evident that the social component needs much more integration into relevant hazard and risk research. A selection of major research issues required to address these concerns is represented in the following questions:

How much do humans influence the geomorphic systems directly (e.g. deforestation) and indirectly (e.g. climate change)? Can the ultimate drivers of these influences such as socio-economic conditions, population growth and urbanisation, be factored into future hazard and risk predictive models?

How does the rate of change in the human environment relate to the condition of the geomorphic environment; thus, how large are environmental buffer capacities, what is the human driving force, and how can this be influenced?

Can we predict hazard and risk with sufficient confidence in order to allow sustainable development?

How do we cope with errors, error propagation, and related uncertainty in hazard and risk assessments?

Geomorphology takes hazard assessment beyond the realm of a specific site or a specific moment in time. It uses a range of discipline tools, methodologies and concepts to explore variability and change in time and space. In so doing, it has established that robustness, accuracy and value of hazard assessments can only be met by addressing the interconnections between both physical and human systems at a range of spatial and temporal scales.

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