1 Landslide hazard and risk

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ABSTRACT

Each year, landslides are responsible for hundreds of millions of dollars' worth of damage and, on average, claim more than 1000 lives around the world. Although most common in mountainous areas, landslides can occur anywhere with enough local relief to generate gravitational stresses capable of causing rock or soil to fail. In recent decades, research rooted in engineering and the physical sciences, new technologies, and improvements in computational power have greatly advanced our understanding of the causes, triggers, and mechanics of landslides. However, these improvements and advances bear on only part of the landslide risk equation – hazard and exposure; other factors that affect risk are much less understood. Notably, vulnerability and coping capacity, two concepts most developed in the social sciences, play an important – but poorly understood – role in landslide risk. We provide an example of an attempt to estimate landslide risk, which illustrates the difficulty of adequately quantifying vulnerability. We also argue that landslide risk will almost certainly increase over the rest of this century, due to a large increase in global population, settlement and development of previously sparsely populated landslide-prone regions, and climate change.

1.1 INTRODUCTION

Landslides are one of the most damaging and deadly of natural hazards. Data from the Centre for Research on the Epidemiology of Disasters (CRED) suggest that landslides were responsible for over 10,000 deaths and left 2.5 million people homeless over the past decade (2001–2010) (CRED, 2011). However, the true loss of life and incidence of injury may be much larger, due to the under-reporting of small events in many parts of the world, the exclusion of events in the database that are below predefined loss thresholds, and the misattribution of some landslide events to the seismic or hydrologic events that triggered them.

Although most common in mountainous areas, landslides are by no means restricted to them. They also occur in incised valleys in areas of otherwise low relief and are common in many lakes, in fjords, and on the seafloor at the edges of continental shelves. Irrespective of relief, water, and discontinuities in earth materials are critical determinants of slope stability.

Any discussion of landslide hazard and risk must recognize the variety of mass-movement processes and the range of geologic, topographic, and climatic environments in which they occur. Geoscientists distinguish landslides that occur in rock from those that occur in fine- and coarse-textured unconsolidated sediments (soils). They further categorize landslides according to failure mechanisms (falls, topples, slides, spreads, and flows), water content, and speed (Fig. 1.1; Varnes, 1978; Cruden and Varnes, 1996). A large percentage of landslides, however, do not lend themselves to being pigeonholed into these groups. Varnes (1978) terms these "complex landslides": mass movements that have a particular initial failure mechanism but one or more different styles of subsequent movement (Fig. 1.1). Examples include rockfalls that evolve into rock avalanches, and rockslides that transform into large debris flows (Hungr and Evans, 2004). The only commonality to landslides is captured in their generally accepted definition: the downslope movements of earth material under the influence of gravity. Some researchers exclude from the definition of "landslides" debris flows and creep; the latter occurs at very low velocities (millimeters per year). We will not dwell on the semantics of "landslides" here, but instead point out that they encompass a wide variety of phenomena and thus constitute a diverse group of hazards, with major implications for the risk they pose to people and property.

Landslides: Types, Mechanisms and Modeling, ed. John J. Clague and Douglas Stead. Published by Cambridge University Press.

MOVEMENT TYPE	MATERIAL TYPE: Rock (bedrock)	Debris (predominantly coarse soil)	Earth (predominantly fine soil)
Fall	Rockfall	Debris fall	Earth fall
Topple	Rock topple	Debris topple	Earth topple
Slide*	Rockslide	Debris slide	Earth slide
Spread	Rock spread	Debris spread	Earth spread
Flow	Solifluction flow	Debris flow	Earth flow
Complex	e.g. rock avalanche	e.g. debris slide-debris flow	e.g. earth slide -earth flow

* Slide includes translational and rotational slides. Slumps are rotational slides.

Fig. 1.1. Landslide classification scheme (adapted from Cruden and Varnes, 1996).

In this chapter, we explore issues of landslide hazard and risk, the latter from both physical science and social science perspectives. We forecast trends in both hazard and risk over the remainder of this century and briefly consider strategies for reducing landslide risk.

1.2 HAZARD AND RISK

Before discussing the issues related to landslide hazard and risk, we define the key terms that we use.

- *Hazard* is the probability that a specific damaging event will happen within a specific area in a particular period of time (ISO/TMB/RMWG, 2007). This definition of hazard is common to both the natural and social sciences, but natural hazard analysis lies largely within the fields of engineering and the physical sciences, specifically geology and physical geography.

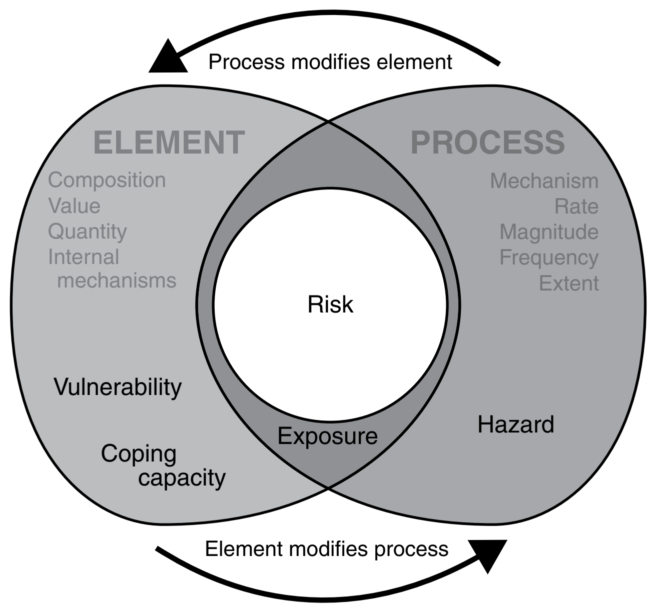

Fig. 1.2. Conceptual model of risk, showing its four components and their relationships. Risk occurs at the interface (exposure) between a process producing hazard and an element or elements characterized by vulnerability and coping capacity. The process and elements can influence each other.

- *Risk*, on the other hand, is more commonly a subject of the social sciences, because it is rooted not only in hazard but also in vulnerability and coping capacity (Fig. 1.2; O'Keefe *et al.*, 1976; Chambers, 1989; United Nations Department of Humanitarian Affairs, 1992; Watts and Bohle, 1993; Bohle, 2001; International Strategy for Disaster Reduction, 2004; Birkmann, 2006; Villagrán de León, 2006). Definitions of risk are legion, but for our purposes, it can be expressed by the following function:

$$\text{Risk} = f\,(\text{hazard, exposure, vulnerability, coping capacity}). \quad (1.1)$$

Although risk can be conceptualized as a function of these four components, their interrelationships cannot be described in mathematical terms or even fully understood. Vulnerability and coping capacity are latent states of an element at risk and are only manifested through the occurrence of a hazardous event (ISO/TMB/RMWG, 2007). Here we define "element" as a physical or social feature that can be affected by a process to which it is exposed.

- *Vulnerability* is the susceptibility of an element to a hazardous event and is commonly thought of as having technological and human dimensions. Technological aspects include damage and loss of life, which are subjects studied by engineers and geoscientists. Human aspects relate to a wide range of social issues, including, in addition to loss of life, loss of livelihood, physical displacement, and psychological and environmental impacts of hazardous events.
- *Coping capacity* is the ability of an element to respond to and reduce the negative effects of a hazardous event.

- *Exposure* is the overlap in space and time of a hazardous process and infrastructure or population.

The physical and social sciences each have strengths in conceptualizing and evaluating certain components of risk, but separately they are likely to oversimplify other components. The focus in the physical sciences is on hazard and exposure. In this paradigm, the human system is typically viewed as static or passive. In most engineering literature, the role of human behavior in mediating the consequences of hazards is not considered. In contrast, the focus in social sciences is on vulnerability and coping capacity, and hazard is viewed as a static process that reveals vulnerability and coping capacity. In reality, all four components of risk – hazard, exposure, vulnerability, and coping capacity – are dynamic and can vary greatly over a range of temporal and spatial scales.

In the social sciences, attention is directed to factors that limit the ability of individuals and society to contend with hazardous processes, rather than the negative impacts following a disaster. In studies carried out by the United Nations (Birkmann, 2007) and the World Bank (Arnold *et al.*, 2006), vulnerability is assessed based on socio-economic indicators, for example gross domestic product (GDP) per inhabitant, human poverty index (HPI), inflation rate, and population characteristics such as density, growth, age, life expectancy at birth, and literacy rate. Arguably, however, these indicators are poor measures of vulnerability and coping capacity. Perhaps it is for this reason that engineers and physical scientists focus on hazard and exposure, which are more easily quantified.

1.3 EVALUATING HAZARD

The first step in assessing landslide risk[1] is to understand and, if possible, quantify the hazard. Landslide hazard is analyzed first by understanding, as well as possible, the process that gives rise to the hazard, and second by deriving a frequency–magnitude model for the hazard (Moon *et al.*, 2005).

Different types of landslides pose different hazards. Most rockfalls affect relatively small areas directly below their source cliffs, which can be delineated using the "rockfall shadow" concept (Evans and Hungr, 1993) or numerical models of specific rockfall scenarios (Agliardi *et al.*, 2012, Chapter 18, this volume). Most rainfall-triggered debris flows also affect small areas, typically fans or cones onto which streams with steep, debris-laden channels flow. It is possible to identify areas that are likely to be affected based on the geology and topography of the watersheds that generate the debris flows and on sediment availability (Hungr *et al.*, 2005). Slow-moving earthflows may damage roads, buildings, and other engineered structures located on them, but they rarely injure or kill people because of their very low speeds; exceptions are slow-moving rock slopes that spawn rockslides or rock avalanches. Large rapid mass movements, including rockslides and rock avalanches, are much more difficult to forecast than smaller landslides, mainly because the state of stress deep within a slope prior to failure cannot yet be easily or reliably determined. Furthermore, the area impacted by a large rockslide or rock avalanche depends critically on the failure location, volume of the failed rock mass, and topography. Nevertheless, reasonable estimates of scenario landslide runouts can be made with state-of-the-art numerical codes, assuming that failure locations and volumes can be determined (McDougall *et al.*, 2012, Chapter 16, this volume).

The second step in landslide risk assessment is to establish a reliable frequency–magnitude model. Historic records on which such a model might be based generally do not extend far enough back in time to establish a robust and statistically reliable relationship, particularly for less frequent, larger magnitude events. The alternative is to supplement historic records with geologic data. The latter, however, are generally incomplete and temporally biased, limiting the frequency–magnitude analyses on which they are based. Nevertheless, records based on tree damage over several centuries may yield good estimates of magnitude and frequency for small debris flows (Stoffel *et al.*, 2005; Stoffel, 2006; Jakob and Friele, 2010). Similarly, the frequency of large landslides whose scars and deposits persist in the landscape (Guthrie and Evans, 2007) may also be reasonably estimated. In contrast, the deposits of medium-sized landslides are easily eroded or buried, and their frequency is commonly underestimated. As records of past events are nearly always incomplete, the formulation and use of frequency–magnitude plots must involve expert judgment.

1.4 FROM HAZARD TO RISK

An analysis of risk can proceed once a reliable frequency–magnitude model has been established. The frequency–magnitude model is only useful, however, if the hazardous process is well understood. It is not sufficient, for example, to know that, at a particular site, a 10^6 m^3 landslide has an average recurrence of 1000 years. The type of landslide (e.g., debris flow, rockslide, or rock avalanche) and the area of impact must be known. Only then can the next component of risk – exposure – be incorporated. Probabilities of injury and loss of life, and estimates of property damage are associated with a given hazardous event, which has a defined likelihood of occurrence, albeit with considerable and inevitable uncertainties. Potential impacts from all hazardous events in the frequency–magnitude model can then be examined to identify the events that carry the greatest risk. It is these events that are the basis for possible mitigation measures, within the context of both a cost–benefit analysis and a consideration of societally acceptable risk. It is common to

[1] *Risk analysis* is the process of formal risk characterization involving estimation and analysis of hazard, exposure, vulnerability, and coping capacity. *Risk assessment* is the process of comparing risk analysis results for risk mitigation (International Society for Soil Mechanics and Geotechnical Engineering, 2004).

find that the greatest risk reduction is achieved by planning for moderate-sized events with intermediate return periods. Very large events, although highly destructive, are rare; and very small events, although much more common, may cause little or no loss.

At this point in risk analysis, the physical scientist considers his job done. The analysis, however, is far from complete, because two other components that are critical to all considerations of risk and that are dynamic properties of a social system have not been considered – human vulnerability and coping capacity. As mentioned earlier, these two components have traditionally been examined within the social sciences.

Conceptual models of vulnerability may explain and communicate the process and components of risk. They can also facilitate the choice of appropriate indicators of vulnerability and, therefore, are integral to vulnerability analysis. Chambers (1989) introduced an early formal definition of vulnerability with a social science context: "exposure to contingencies and stresses and the difficulty which some communities experience while coping with such contingencies and stresses." He also identified two general types of vulnerability: external vulnerability, which relates to external shocks (that is, impacts due to sudden-onset events and stresses); and internal vulnerability, which relates to defenselessness or the inability to cope. Watts and Bohle (1993) examined vulnerability within the economic, political, and institutional capabilities of people, and concluded that it results from three factors: exposure, coping capacity, and recovery potential. Bohle (2001) later provided a clearer graphic representation of the model, in which coping capacity is explicitly included as a component of vulnerability. Exposure in the Bohle model is not equivalent to the concept of technological vulnerability inherent in the natural science paradigm. Rather, it represents people's ability to resist initial impact of stresses or shocks, and is determined by population dynamics and capacities, entitlement (ability to access and manage assets), and social and economic inequalities. The Bohle model thus places exposure under the umbrella of vulnerability. Within the so-called "disaster risk community," vulnerability is considered within the broader context of risk; vulnerability, coping capacity, and exposure are separate components that, together, produce risk and, potentially, disasters (Birkmann, 2006).

A difficulty in applying these concepts is that they are virtually impossible to quantify. How does one quantify human vulnerability or coping capacity? Clearly, individuals or societies with a limited ability to absorb external shocks are more vulnerable and less able to cope with hazardous processes, but most social measures of quality of life, such as per capita income, access to health assistance, equality, and access to social resources, are only rough indicators of vulnerability and coping capacity. These issues are intimately linked to the concept of individual and societal "acceptable risk" or risk tolerance. In developed countries, notably Japan, New Zealand, Australia, and those of North America and Europe, societal tolerance of injury from landslides and other hazardous phenomena is far lower than that in countries with a low standard of living. A consequence is that governments in developed countries invest heavily in mitigation to minimize hazard (e.g., slope stabilization) and vulnerability (e.g., public education). In addition, coping capacity after disasters in developed countries is generally high due to access to resources, although it also depends on social capital such as social networks. Accordingly, risk in developed countries is much lower than that in less developed countries. Nevertheless, coping capacity and vulnerability cannot yet be integrated in a quantitative way with the more easily measured factors – hazard and exposure. Thus, in the example that follows, we present a quantitative estimate of landslide risk based largely on hazard and exposure.

1.5 AN EXAMPLE OF LANDSLIDE RISK EVALUATION

Friele *et al*. (2008) evaluated the debris-flow risk to the communities of Pemberton and Mount Currie in Lillooet River valley, southwest British Columbia, Canada (Fig. 1.3). The hazard derives from large landslides at Mount Meager, a Quaternary volcano in the upper part of the watershed.

The settled area of Lillooet Valley can be divided into two zones with different population densities. Pemberton Meadows, 32–55 km downstream from Mount Meager, is primarily agricultural and has a population of about 200 people (average population density 5 persons/km^2). Pemberton and Mount Currie, 55–75 km downstream, have about 3800 and 1000 residents, respectively (average population density of 125 persons/km^2).

Drilling in Lillooet River valley has documented valley-wide sheets of debris-flow deposits derived from Mount Meager that are of Holocene age, 2–8 m thick, and 32–55 km downstream from the source (Friele *et al.*, 2005; Simpson *et al.*, 2006). The debris flows that left these deposits had velocities of 10–15 m s^{-1} in the upper Pemberton Meadows area and 3–6 m s^{-1} at Pemberton (Friele *et al.*, 2008). A hyperconcentrated flow or debris flow traveling at these velocities would destroy most residential buildings in the valley. Some people might survive a class 8 (10^7–10^8 m^3) debris flow by climbing into large standing trees or reaching higher ground, but death would be likely for class 9 (10^8–10^9 m^3) events.

Friele *et al.* (2008) established a frequency–magnitude model for debris flows from Mount Meager based on historic events and on prehistoric events inferred from a rich body of geologic evidence (Fig. 1.4). They used the method of Fell *et al.* (2005) to analyze the landslide risk of residents in the Lillooet River valley. They restricted their analysis to loss of life. The variables used in their analysis are:

P_H the probability of the hazard
P_{LOL} the annual probability of loss of life for an individual
$P_{S:H}$ the spatial probability that the event will reach the individual
$P_{T:S}$ the temporal probability of impact (the percentage of time the individual occupies the hazard area, in this case the affected part of the valley)

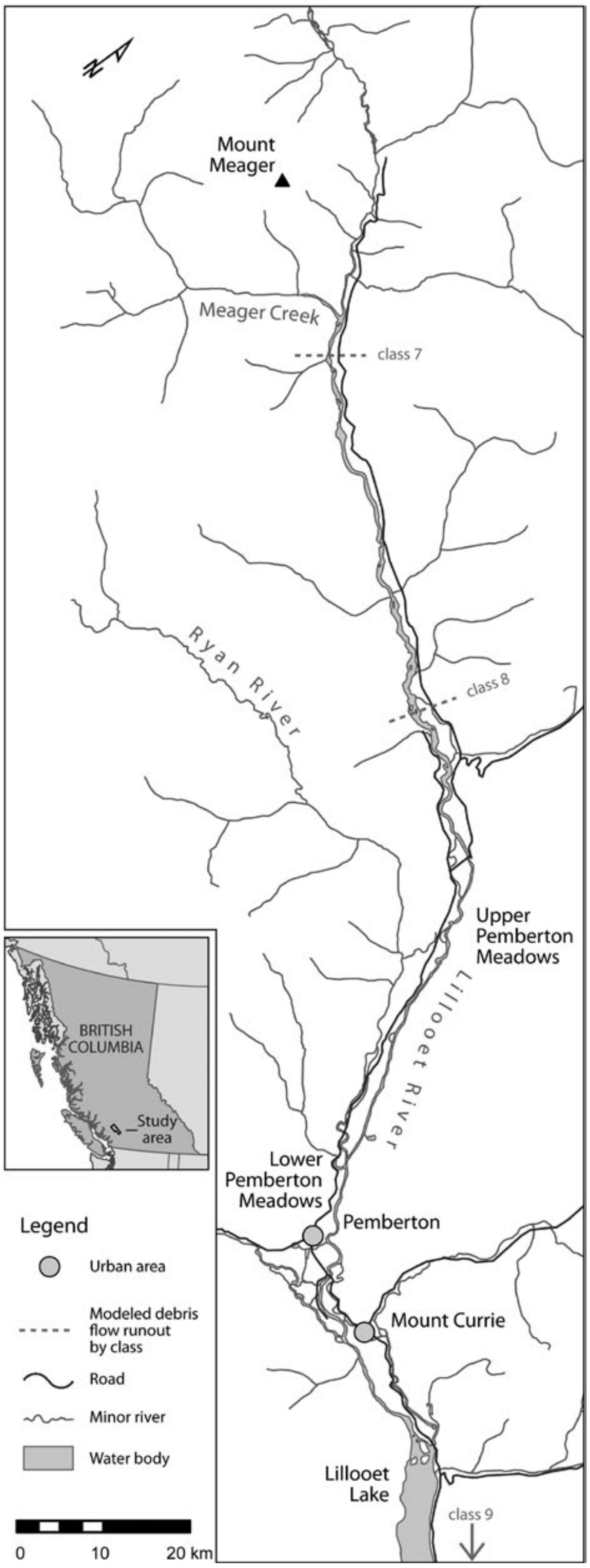

Fig. 1.3. Map of Lillooet River valley showing the location of Mount Meager, the communities of Pemberton and Mount Currie, and downstream limits of class 7 (10^6–10^7 m^3), class 8 (10^8–10^9 m^3), and class 9 (10^9–10^{10} m^3) debris flows from the Mount Meager massif.

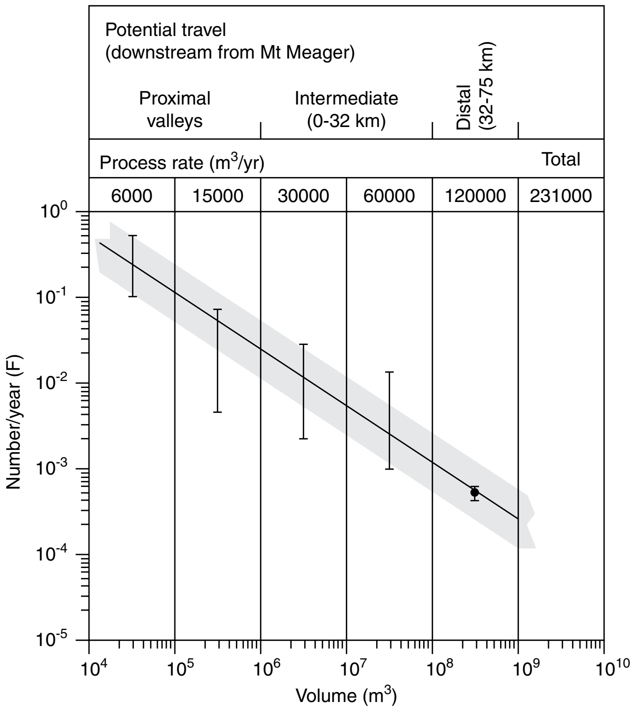

Fig. 1.4. Frequency–magnitude diagram for landslides at the Mount Meager massif, British Columbia (figure 4 in Friele *et al.*, 2008). Uncertainty limits (black bars) for landslides are derived from the historic record (upper bound) and geologic data (lower bound). The gray band represents the most likely uncertainty bounds for the frequency–magnitude model and takes into account data censoring.

V the likelihood of loss of life should the individual be affected by the hazardous phenomenon, which is a function of the intensity of the process at that location

E the element of concern, in this case the number of lives potentially at risk.

Risk can be quantified for individuals or for groups. Risk to individuals is commonly related to the person most at risk. Individual risk is generally compared to some socially accepted or tolerable risk threshold. Friele *et al.* (2008) estimated annual risk of loss of life to an individual (P_{LOL}) from the relation:

$$P_{LOL} = P_H \times P_{S:H} \times P_{T:S} \times V. \quad (1.2)$$

Societies are more tolerant of individual loss of life than to the simultaneous death of a large number of people (Ale, 2005). Group risk can be estimated by plotting the annual frequency (*F*) of one or more deaths from a particular hazard or suite of hazards against the expected number of fatalities (*N*), where *F* is defined, according to Fell *et al.* (2005), as:

$$F = P_H \times P_{S:H} \times P_{T:S} \quad (1.3)$$

and *N* is the product of the number of elements at risk (*E*) and their vulnerability (*V*) to the hazard under consideration. On the *F*/*N* plot of Friele *et al.* (2008), the total risk is the sum of partial risks from different magnitude classes.

Field evidence (Friele *et al.*, 2005) and modeling (Simpson *et al.*, 2006) show that only the largest debris flows (classes 8–9; 10^7–10^9 m^3) reach settled areas of Lillooet Valley, thus Friele *et al.* (2008) referred only to those events. For class 8 events, $P_{H(min)}$ and $P_{H(max)}$ are taken to be 0.001 and 0.005, respectively; for class 9 events, the corresponding values are, respectively, 0.0004 and 0.0006.

Inundation areas and travel distances of debris flows of different size were estimated using the LAHARZ model developed by Iverson *et al.* (1998). The results indicate that a 10^7 m^3 debris flow is unlikely to directly impact settled areas of the Lillooet River valley. A 10^8 m^3 debris flow could just reach Pemberton Meadows, which Friele *et al.* (2008) represented as low probability of impact ($P_{S:H}$ = 0.1). A 10^9 m^3 debris flow would reach Lillooet Lake ($P_{S:H}$ = 1.0). Thus, $P_{S:H}$ ranges from 0.01 to 0.1 for class 8 debris flows, and from 0.1 to 1.0 for class 9 debris flows.

In the case of class 8 debris flows, the temporal probability ($P_{T:S}$) is high for the inhabited part of the impacted area. This area is agricultural; the majority of the adult residents spend their time in the home or fields, while children commute daily to school in Pemberton. Thus, $P_{T:S}$ for class 8 debris flows was assigned a value of 0.9 for the person most at risk. Assuming a family of two adults and two children, with the children present at school 8 hours per day, $P_{T:S}$ for the average individual is 0.8. Class 9 debris flows travel farther, reaching areas occupied by farmers, First Nation residents, and service sector workers, some of whom commute daily to Whistler. Lacking detailed occupational statistics, Friele *et al.* (2008) assumed that 50 percent of those people live and work/school locally, and 50 percent commute out of the valley and are absent 12 hours per day. $P_{T:S}$ for those staying in the valley was assumed to be 0.9, and for commuters 0.5; the average value is 0.7.

Friele *et al.* (2008) defined vulnerability as the likelihood of death should a building or site be impacted directly by a debris flow or debris flood. They acknowledged that any estimate of vulnerability has a large degree of uncertainty, because it is affected by parameters that are poorly known or highly variable, for example the location of individuals within a building, the intensity of impact, and the ability of a building to withstand impact without incurring structural damage that could lead to death. Uncertainty is built into the vulnerability estimate by defining lower and upper bounds, V_{min} and V_{max}. Allowing for some possibility of survival, V_{min} was assumed to be 0.5 for a class 8 debris flow and 0.9 for a class 9 debris flow. V_{max} was assigned a value of 1.0.

The range of estimated annual debris-flow risk to an individual residing in Lillooet Valley is 5×10^{-6} to 5.0×10^{-4} deaths per year. Governments in Australia, Hong Kong, and England have defined the tolerable landslide risk level to be 10^{-4} annual probability for existing development and 10^{-5} annual probability of death for new development (Fell *et al.*, 2005; Leroi *et al.*, 2005). For Lillooet Valley, individual risk is up to 5.4 times higher than acceptable levels for Australia, Hong Kong, and the UK, and up to 54 times higher than acceptable risk for individuals in the Netherlands (Ale, 2005). In the Netherlands,

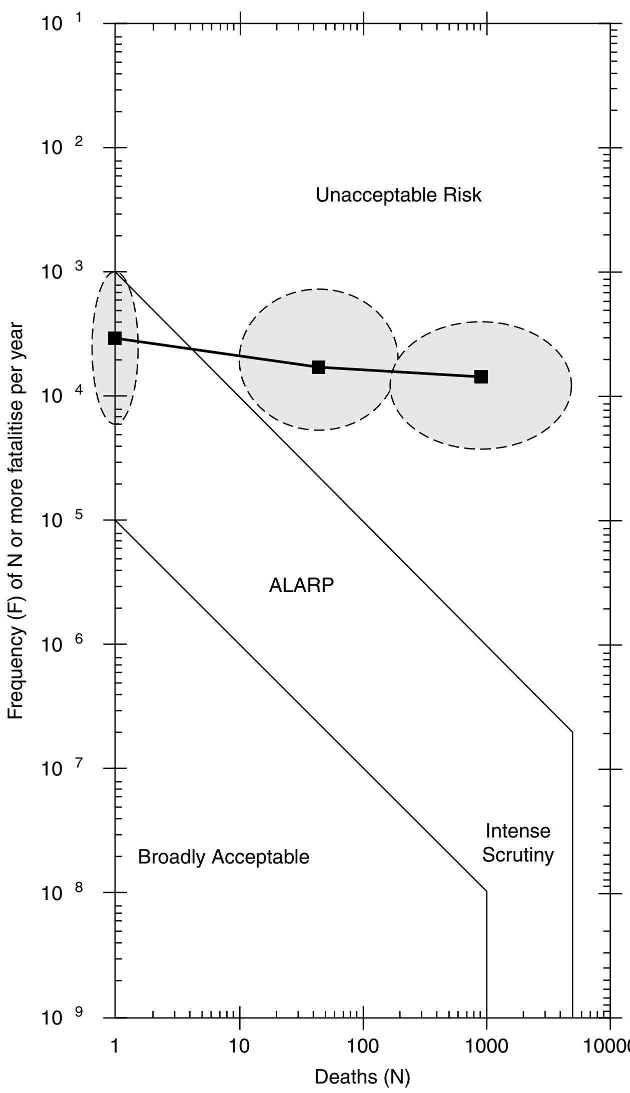

Fig. 1.5. *F*/*N* plot for societal risk in Lillooet Valley for three categories of large debris flows from the Mount Meager massif (10^6–10^7, 10^8–10^9, and 10^9–10^{10} m^3) (figure 7 in Friele *et al.*, 2008). The results are plotted as dashed circles, reflecting uncertainties incorporated into the risk calculations. ALARP is "as low as reasonably practical." *F*/*N* threshold lines are based on standards adopted by Hong Kong, the Netherlands, Denmark, and Britain.

however, the principle of "as low as reasonably practical" does not apply, which is contrary to Anglo-Saxon Common law. Common Law in most European countries encodes the principle of "as low as reasonably practical," while encouraging additional risk reduction. For new development, the tolerable landslide risk levels in Australia, Hong Kong, and the UK are one order of magnitude lower than the values cited above; thus, without adequate mitigation, the risk values that Friele *et al.* (2008) estimated are up to 36 times higher than acceptable levels.

Societal risk is quantified for each debris-flow class as *F–N* pairs in Figure 1.5. This figure shows evaluation criteria that are gaining acceptance in Australia, the UK, and recently in

Canada (Fell *et al*., 2005; Porter *et al*., 2007). The *F–N* plot is subdivided into four zones:

1. *unacceptable* – risk is generally considered unacceptable by society and requires mitigation;
2. *as low as reasonably practical* – risk from a hazard should, wherever possible, be reduced;
3. *broadly acceptable* – risk from a hazard is within the range that society can tolerate;
4. *intense scrutiny region* – the potential for large loss of life is low, but careful consideration is required.

In the Lillooet Valley study, uncertainties in hazard, exposure, and vulnerability required that the risk for each class be plotted as a zone rather than a point (Fig. 1.5). The plot shows that risk to groups in Lillooet Valley is unacceptable for both class 8 and 9 debris flows, based on international standards. Friele *et al.* (2008) therefore recommended that mitigation measures be taken to reduce risk to the "as low as reasonably practical" region of the *F–N* plot. They further recommended restricting development to areas where risk could be reduced to the "acceptable" level.

1.6 LANDSLIDE RISK IN THE FUTURE

We hypothesize that societal landslide risk will increase in the future and offer three reasons for this assertion. First, the human population will increase, perhaps by as much as 50 percent over the remainder of this century. Second, and more specifically, populations will increase in landslide-prone regions, notably in mountainous areas. Third, forecast climate change may increase the incidence of landslides in many areas. Collectively, these three factors will more than offset risk reductions achieved through improved scientific understanding of landslides and better-informed land-use decisions.

Global population reached 7 billion in 2011 and will exceed 9 billion by the middle of this century. Forecasts for the remainder of the twenty-first century are less certain, but a population of around 10 billion by the year 2100 is possible. Most of the additional 3 billion people will live in Asia and Africa, but almost all countries in North America and Europe will also experience population increases due to a combination of domestic growth and immigration. Development pressures related to larger populations and improved standards of living may result in the settlement of hazardous land. The percentage of the global population living in cities will rise, such that the total urban population will exceed the rural population by the middle of this century. Even with the concentration of people in large urban areas, more remote mountainous areas will also experience substantial absolute increases in population, due in part to the increase in the areas of cities and in part to recreational and resource opportunities that mountainous areas afford. Notable large metropolitan areas that will occupy more space and thus expand within or into mountainous areas include Vancouver, Calgary, Seattle, Portland, Denver, Mexico City, San Salvador, Bogotá, Quito, Santiago, La Paz, Chengdu, Kabul, Tehran, Rawalpindi, Dushanbe, Tashkent, Katmandu, Ankara, Milan, Turin, Addis Ababa, and Nairobi. However, as noted earlier, landslides also occur outside mountainous areas, thus increased damage and injury can be expected in cities built on lower-relief surfaces as their footprints increase.

It is widely recognized that water plays a definitive role in most landslides. All other things being equal, landslides are more frequent in humid environments than in dry ones. Until recently, however, the possibility that climate change might alter the frequency of landslides within a specific region had not been widely considered. It is now evident that climate has changed significantly over the past century, and the scientific community has achieved consensus that it will change even more over the remainder of this century (Solomon *et al.*, 2007). Since the late nineteenth century, the average surface temperature of Earth has increased about 0.8°C, and it is forecast to increase by 2–5°C over the next 90 years (Solomon *et al.*, 2007). Temperature increases at high latitudes and in many mountain ranges are likely to increase considerably more than the global average. Two consequences of such change are the melting of alpine glaciers and thawing of permafrost, both of which may destabilize slopes. Of greater significance for slope stability, however, are the attendant spatial and temporal redistribution of precipitation and a possible increase in extreme precipitation events. A warmer atmosphere will hold more moisture, and warmer oceans are likely to produce stronger cyclonal storms. Long-term or seasonal increases in rainfall, especially in coastal mountains, would lead to more frequent landslides, probably resulting in increased damage and loss of life.

An increase in landslide risk can be partially countered through land-use planning and hazard mitigation. Expansion into mountainous areas and onto slopes outside mountains can be controlled in order to reduce the exposure of people and infrastructure to landslides. Engineered protective works can be built to provide protection when such slopes are developed. Engineering, however, cannot eliminate all risk and is generally ineffectual in stabilizing large, unstable rock slopes and in protecting people from large landslides. Furthermore, engineered reductions in the risk of life loss are only possible in societies with low vulnerabilities due to their wealth and access to resources. Countries with limited resources are less able to implement policies and other measures required to significantly lower risk.

Although we are not confident that landslide risk, or for that matter risk from most other hazardous natural processes, can be significantly reduced in the short term, considerable progress could be made by increasing the coping capacity of the most vulnerable populations, specifically those of impoverished countries that have limited resources to support their citizens. Economic and social equity among nations would go a long way in reducing the loss of life from natural disasters, not to mention easing many seemingly intractable problems that we face today.

1.7 CONCLUSIONS

Landslides are natural processes that shape the Earth's surface and redistribute mass from high elevations to lower ones. They also pose threats to people and infrastructure. Physical scientists and engineers have spent considerable time, energy, and resources studying landslide processes, partly in order to provide better guidance for reducing landslide risk. Although the new scientific insights they have provided enable better estimates of the frequency, magnitude, and potential physical impacts of different types of landslides, this type of work is not adequate, on its own, to reduce risk. Rather, it must be integrated with research on the dynamic properties of social systems performed by social scientists. Specifically, the issues of vulnerability and coping capacity must be incorporated into hazard analysis.

Landslide risk is likely to increase through the remainder of the twenty-first century due to a 50 percent increase in global population, an increase in the number of people living in landslide-prone areas, and a warmer and locally wetter climate. These realities can be partially offset by using improving scientific knowledge of landslides in land-use decisions and by implementing targeted engineering mitigation measures to protect people and property. More fundamental, however, is the need to reduce the risk to the most vulnerable societies through social justice grounded in a more equitable distribution of global resources.

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2 Landslides in the Earth system

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ABSTRACT

Landslides convert potential energy into kinetic energy and are thus important agents of topographic change and landscape evolution. They are deformations of Earth's surface that reflect patterns of regional seismic, climatic, and lithospheric stress fields on sloping terrain. Landslides involve fracturing of the lithosphere ranging from microscopic rock fragmentation to giant submarine slope failures, thus spanning more than 26 orders of magnitude in volume. Here I synthesize major rate constraints on landslide distribution, size, and impacts that help gauge their relevance in the Earth system with a focus on the lithosphere, the hydrosphere, and the biosphere. Given sufficient size or frequency, landslides help sculpt local topography, trigger shallow crustal response, limit volcanic edifice growth, modulate bedrock incision as well as water and sediment flux in river systems, trigger far-reaching processes such as tsunamis or catastrophic outburst flows, condition rates of soil production, and alter hillslope and riparian habitats. Most importantly, landslides remain a significant hazard to people, housing, infrastructure, and land use in many parts of the world.

2.1 INTRODUCTION

Landslides are the downhill and outward movement of slope-forming materials under the influence of gravity and also, in most cases, water (Cruden and Varnes, 1996). Mostly triggered by earthquakes, rainstorms, snowmelt, and slope undercutting, they are among the prime producers of sediment and major agents of denudation. Landslides mobilize rock debris, regolith, soil, and biogeochemical constituents in all types of terrain, ranging from the highest peaks in tectonically active mountain belts to the margins of abyssal plains. The growing recognition that landslides play an important role in shifting mass across the Earth's surface, thus helping form and redistribute topography, suggests expanding the classic definition to one that accommodates landslides as deformations of the Earth's surface that reflect patterns of regional seismic, climatic, and lithospheric stress fields on sloping terrain. The objective of this chapter is to synthesize evidence for how the occurrence and consequences of landslides are relevant to Earth as a system, particularly the lithosphere, the hydrosphere, and the biosphere. The intention is to take a deliberate step back from the plethora of detailed landslide case studies and analyses at the hillslope scale and to review landslide impacts within a regional to global context.

2.2 LANDSLIDE DISTRIBUTION AND SIZE

Landslides may initiate almost anywhere within Earth's elevation range, but they abound in tectonically active mountain belts with young, rapidly exhuming, and mechanically weak rocks. There, strong earthquakes and orographically enhanced precipitation fed by monsoonal and cyclonic storms frequently trigger slope instability (Fig. 2.1; Lin *et al.*, 2008). More than half of the largest known terrestrial landslides occur in the steepest 5 percent of Earth's land surface, where the inferred rates of denudation exceed 1 mm per year (Korup *et al.*, 2007). Tectonic fault zones (Strecker and Marrett, 1999; Osmundsen *et al.*, 2009), volcanic arcs (Coombs *et al.*, 2007), rocky coasts (Hapke and Green, 2006), and the edges of continental shelves (Weaver, 2003) are other settings where landslides cluster. Yet even in such highly susceptible terrain, the observed number of landslides per unit area or time ranges through 3–11 orders of magnitude (Fig. 2.2). This variation attests to the broad spectrum of ways in which hillslopes can adjust to external perturbations to their stability through rate changes in landsliding. It

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