4 Mountain hazards

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4.1 Introduction to mountain geomorphic hazards

4.1.1 Mountain geomorphic hazards defined

A geomorphic hazard results from any landform or landscape change that adversely affects the geomorphic stability of a site or drainage basin (Schumm, 1988) and that intersects the human use system with adverse socio-economic impacts (White, 1974). If there are no people affected, there is no hazard and if the landform or landscape is unchanged there is no geomorphic hazard. Barsch and Caine (1984) have described the distinctive relief typologies of major mountain systems. Mountain geosystems are not exceptionally fragile but they show a greater range of vulnerability to disturbance than many landscapes (Körner and Ohsawa, 2005) and their recovery rate after disturbance is often slow. During the past three decades, the world's population has doubled, the mountain regions' population has more than tripled and stresses on the physical and biological systems of mountain regions have intensified many fold. The combination of extreme geophysical events with exceptional population growth and land use modifications underlines the urgency of better understanding of these interactions and working out the implications for adaptation to and mitigation of the effects of drivers of change on landforms and landscapes. Geomorphic hazards intensify and risks multiply accordingly.

4.1.2 The major drivers of change and 'key' vulnerability

The three drivers of environmental change in mountains are relief, as a proxy for tectonics (Tucker and Slingerland, 1994), hydroclimate and runoff (Vandenberghe, 2002) and human activity (Coulthard and Macklin, 2001). Not only are they important in themselves but they are commonly so closely interrelated that it becomes difficult to rank their relative importance and, indeed, their status, whether dependent or independent. One of the greatest challenges facing mountain scientists is to separate environmental change caused by human activities from change that would have occurred without human interference (Marston, 2008).

Unfortunately, there has been inadequate representation of the interactive coupling between relief, land use and climate in the climate change discussions to date (Osmond *et al*., 2004). Based on a number of criteria in the literature such as magnitude, timing, persistence/reversibility, potential for adaptation, distributional aspects of the impacts, and likelihood and importance of the impacts, some of these vulnerabilities have been identified as 'key' (Füssel and Klein, 2006). It is the point of exceedance of thresholds, where non-linear processes cause a system to shift from one major state to another, that expresses this key vulnerability. From the perspective of geomorphologists, these key vulnerabilities are often expressed as increasing magnitude and/or frequency of geomorphic hazards.

4.1.3 The scale question

To enhance the complexity of the puzzle, the three drivers of change (relief, hydroclimate and human activity) operate variably at different spatial scales

For the purpose of the following discussion we have adopted a scale typology as follows:

a. Site scale hazards ($<10^{-1}$ km^2)
b. Drainage basin scale hazards (10^{-1} to 10^3 km^2) and
c. Global scale hazards ($>10^3$ km^2)

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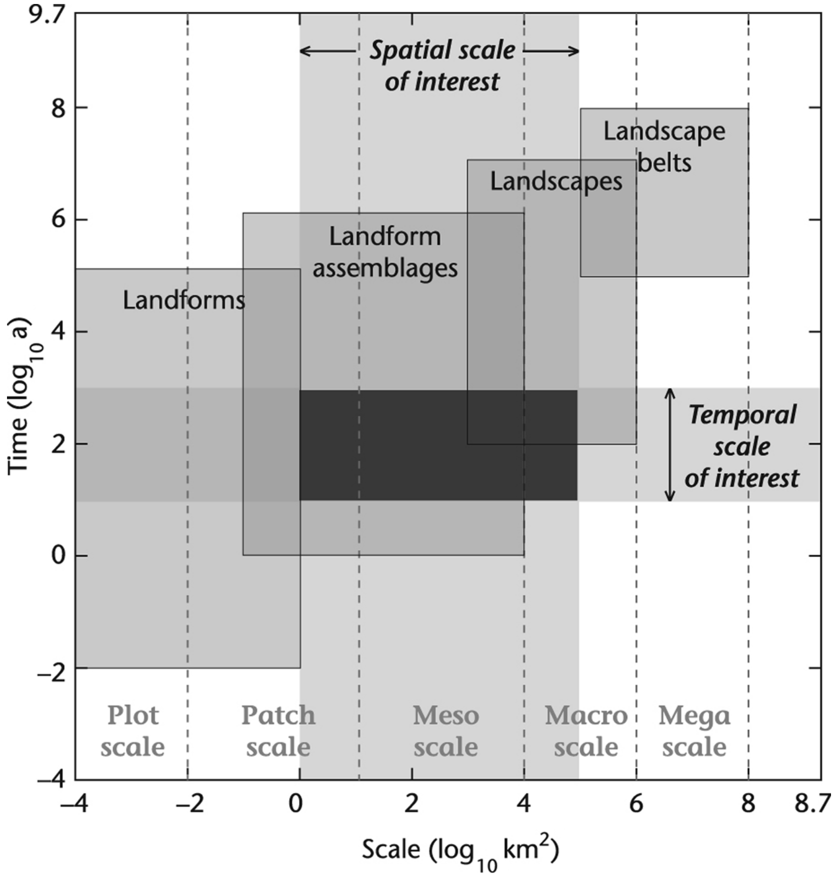

FIGURE 4.1. Spatial and temporal scales in geomorphology. On the *x* axis, the area of the surface of the Earth in km^2 is expressed as 8.7 logarithmic units; on the *y* axis, time since the origin of the Earth in years is expressed as 9.7 logarithmic units. (Slaymaker *et al*., 2009.)

We do not know where the breaks in the hierarchy should come. An example of the difficulty of establishing a scale typology for the study of landscapes under global environmental change is introduced as Figure 4.1. Motivation for defining preferred spatial and temporal scales of study can be found in Slaymaker *et al*. (2009), but in the present context it is sufficient to note that we have no theoretical justification for the separation of these scales of enquiry.

4.2 Site scale

4.2.1 Relief

The tradition of process geomorphology has focused most of its attention at smaller scales. In part, this is because site scale analysis is most amenable to quantitative treatment and, in part, because the geomorphic response to site scale disturbance is rapid. In mountains, relief is a major driving force, alongside of hydroclimate and human activity.

The driving forces associated with relief include: absolute elevation (which controls temperature and precipitation); gradient (which controls the erosional force $g \sin \alpha$); concave slopes (which tend to concentrate water) and convex slopes (which tend to shed water). Aspect controls the amount of radiant energy received at the surface and leads to highly contrasted slope climates. The resisting forces associated with strength of surficial materials can be defined in numerous ways, such as cohesive and frictional strength, erodibility and modes of deformation (rheological properties defined by strain–time and stress–strain rate graphs).

4.2.2 Hydroclimate and runoff

Site scale hydroclimate is influenced by relief (see above) and also by the nature of the regolith. The regolith controls the preferred pathways of movement of water and sediment. The relative importance of weathering, sediment transport and depositional processes depends on the hydroclimate. Precipitation, snow storage, glacier storage, available soil moisture, groundwater storage, actual evapotranspiration and surface runoff are the components of the hydrological cycle that influence and respond to environmental change. The magnitude, frequency and duration of storm events is vital information that often does not exist because the usual presentation of precipitation data is in the form of daily totals (Barry, 1992).

4.2.3 Human activity

Timber harvesting is a major land management practice whose precise influence on slope stability depends on the method of harvesting, density of residual trees and understory vegetation, rate and type of regeneration, site characteristics and patterns of water inflow after harvesting (Sidle *et al*., 2002). Roads can be the focus of the highest rates of denudation in the landscape. Humans do accelerate slope failures through road building, especially when roads are situated in mid-slope locations instead of along ridge tops (Marston *et al*., 1998). Roads in eastern Sikkim and western Garhwal have caused an average of two major landslides for every kilometer constructed. Road building in Nepal has produced up to 9,000 cubic meters of landslide per kilometer, and it has been estimated that, on average, each kilometer of road constructed will eventually trigger 1,000 tons of land lost from slope failures (Zurick and Karan, 1999).

4.2.4 Site scale hazards

Sites of initiation of rilling and gullying, the uppermost finger-tip tributaries of river networks, zero order basins (or colluvial bedrock depressions) and sites of mass movement initiation are all sites at which a threshold safety factor has been exceeded. The initiation of snow avalanches and debris avalanches are specific cases of such hazards.

Steep slopes and heavy snowfall at high elevations are the main factors affecting avalanche incidence. In countries such as Canada, Switzerland, Austria, France, Italy and Norway expenditures involve tens of millions of dollars annually. No clear trends have been identified in the frequency and number of avalanches in the Alps in the past century (Agrawala, 2007), but in many avalanche-prone areas the density of buildings and other investments has increased.

Permafrost degradation is likely to contribute to rockfall activity (Behm *et al*., 2006) and may well trigger higher debris flow activity, but research into this link so far remains inconclusive. A recent study showed that frequency of debris flows originating from permafrost areas in Ritigraben (Swiss Alps) has been decreasing, although a lower frequency may also be associated with more intense events due to larger accumulation of materials between events (Stoffel and Beniston, 2006). Fischer *et al*. (2006) have identified permafrost degradation as a cause of slope instabilities on Monte Rosa; and Gruber and Haeberli (2007) provide a comprehensive review of permafrost and slope instability.

Road systems are often critical in hazard generation; removal of vegetation from forest to agriculture to urban; removal of soil for urban and mining purposes; and gravel extraction all have potential for generating site scale hazards.

4.3 Drainage basin scale

4.3.1 The sediment cascade in mountains

The greater complexity of the drainage basin scale is expressed through emergent properties that do not exist at site scale. Some of these emergent properties are linear erosion, slope and channel coupling, and preferred surface and sub-surface pathways for movement of sediment and water. The literature has traditionally used such variables as basin area and drainage density to act as surrogates for these integrated effects.

The sediment cascade that results can be characterized in terms of four environments (after Caine, 1974) which are differentiated by dominant processes and forms as:

a. the mountain cryosphere system;
b. the coarse debris system;
c. the fine-grained sediment system; and
d. the geochemical system.

Note that the categories overlap and they are identified only in terms of their dominant characteristics.

Each of these components of the mountain geosystem is sensitive to environmental change, whether in response to relief, temperature, precipitation, runoff, sediment transport or land use changes. The cryosphere stores water and changes the timing and magnitude of runoff which erodes and transports sediment. Snow responds to environmental changes on a daily time scale; lake and river ice on an annual time scale; permafrost and glaciers on annual to century time scales; associated ecosystem responses are measured in decades to centuries; and sediment systems may take decades to millennia to respond (Figure 4.2)

4.3.2 Basin area

At the drainage basin scale, runoff intensity reaches a maximum within basins whose dimensions approximate those of the extreme event producing storm cells. Partly for this reason and also because, at smaller basin scales, slopes and

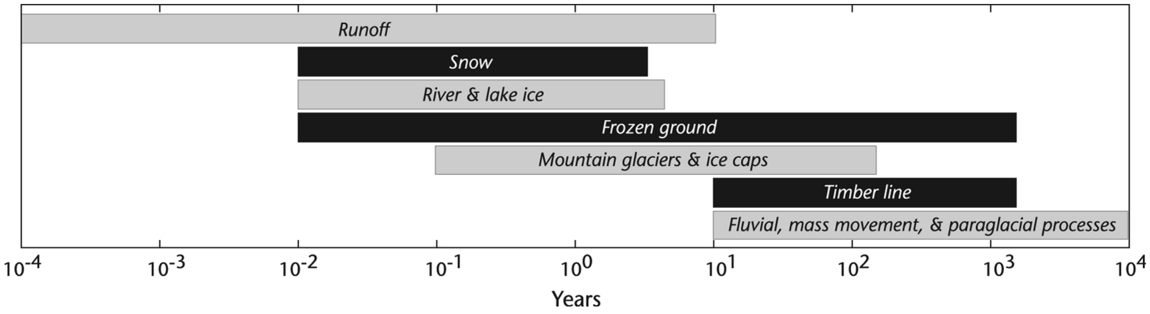

FIGURE 4.2. Components of the mountain cryosphere, ecosphere and sediment cascade and their response times following disturbance by hydroclimate or by human activity. (Slaymaker and Embleton-Hamann, 2009.)

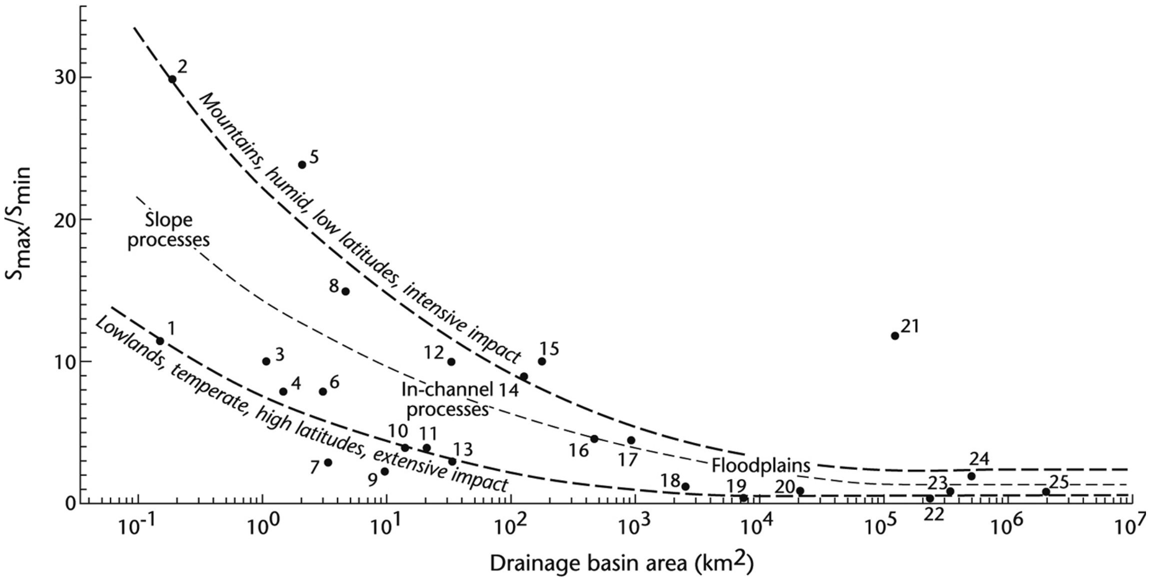

FIGURE 4.3. Relative magnitude of change between low or baseline sediment flux and maximum sediment flux (dimensionless ratio S_{max}/S_{min}) plotted against lake-catchment area (km^2). (Dearing and Jones, 2003.)

channels are often coupled, debris torrent basins tend to average between 0.5 and 5 km^2. When basins reach 5 km^2 or greater, most slopes and channels are uncoupled and the sediment response time after extreme hydroclimatic events increases substantially. Systematic analysis of the relative magnitude of change in sediment flux in basins of different size shows that relative changes diminish with increasing basin size (Figure 4.3). This is because smaller basins are more sensitive and vulnerable to environmental change than the larger basins.

4.3.3 Drainage density

Drainage density (*Dd*) is influenced by mean annual precipitation, precipitation intensity, lithology, soil characteristics, relief, vegetation, human activity and stage of drainage network development. Although there are many ambiguities in the calculation of *Dd* (Schumm, 1997), data available suggest that values of *Dd* between 1 and 10 km^{-1} are representative for maturely dissected fluvial landscapes.

There is a wide range of values of drainage density reported in the literature. They range from the very high drainage densities recorded in the badlands of Perth Amboy, New Jersey (*c*. 600 km km^{-2}) (Schumm, 1956) to less than 1 on undissected plateau or plains surfaces. The influence of lithology and stage of network development has been clearly demonstrated in many studies but, as Chorley *et al*. (1984) point out, contemporary hydroclimate and surface properties seem to be dominant in controlling

TABLE 4.1. *Theoretical characteristics of basins with variable ruggedness number*

Dd (km * km^{-2})	*Ht* (m)	R^a	Coupling	Geomorphic process	Incidence of hazards
Mountains					
>10	>1000	>10	High	Debris flows	High
1–10	300–1000	*c*. 1	Intermediate	Fluvial	Intermediate
<<1	>>1000	<1	Low	Mass movement	High
Non-mountains					
>>10	<300	>3	High	Badlands	High
<1	<300	<0.3	Low	Desert	Low

[a] *R* is ruggedness number, defined as $Dd \times Ht$, a dimensionless number.

differences of drainage density. There is a range of drainage density values from the American Southwest (Melton, 1957), Sri Lanka (Madduma Bandara 1971), the eastern Caribbean mountainous islands (Walsh 1985); the Seychelles (Walsh, 1996) and the continental USA (Hadley and Schumm, 1961; Chorley and Morgan, 1962). These variations reflect the direct and indirect influence of climatic variables. The direct influence is that of large rainstorm magnitude–frequency, as it is only the large runoff events associated with such rainstorms that are capable of eroding finger-tip sections of the drainage net. The indirect influence of climate is exerted via the influence of annual rainfall, rainfall seasonality and vegetation on soil characteristics.

Walsh (1996) suggests that there are three major questions outstanding: (1) what return period of rainstorm/runoff event is responsible for controlling the drainage network? (2) what are the processes responsible? and (3) how quickly do networks develop or adjust to changes in climate? Various drainage density models appear to be applicable. Different slope runoff processes and their spatial patterns, inheritance from collapsed pipe networks, channel development in landslide scars (Chorley *et al*., 1984) or even the simultaneous operation of uncoupled pipe collapse and erosion by overland flow may be the dominant process. The essential point in this present discussion is that there would appear to be strong evidence for the relation between drainage density and hydrogeomorphological hazards, especially the incidence of large rainstorm and runoff events, whatever the precise mechanism involved.

4.3.4 The ruggedness number

The ruggedness number, *R*, defined as the product of drainage density (km^{-1}) and basin relief (m), ($Dd * Ht$) is one of the three dimensionless numbers that describe the dynamics of drainage basin evolution (Church and Mark, 1980). It seems reasonable to suppose that the incidence and intensity of geomorphic hazards would also be related to the ruggedness number. Originally defined by Strahler (1952), the ruggedness number has been used in various guises by many students of morphometry, such as Schumm (1956) and Melton (1957) as an indicator of the relative dynamism of the basin, but rarely in the context of hazard studies. Kovanen and Slaymaker (2008) showed a strong relation between the Melton ruggedness number ($Ht * A^{-0.5}$) and debris fan slope; an inverse relation between debris fan slope and basin area, and a modest relation between basin area and debris fan area in the Nooksack basin, Cascade Ranges, USA. The fans, which are active at present, have a documented history of >7000 years of debris flow activity. The drainage basin ruggedness number is then a potential indicator of the hazardousness of a basin, especially of those hazards that are related to water movement and sediment mobilization, erosion on slopes and fluvial erosion.

In Table 4.1 we have postulated a direct relation between ruggedness number and extreme geomorphic events and an inverse relation between basin area and extreme geomorphic events.

4.3.5 Climate change

One of the most significant impacts of climate change (see also Chapters 5, 8 and 20) in glacierized basins may be the changing pattern of glacier melt runoff (Walsh *et al*., 2005). Glaciers will provide extra runoff as the ice disappears. In most mountain regions, this will happen for a few decades and then cease. For those regions with very large glaciers the effect may last for a century or more. Kotlyakov *et al*. (1991) have provided estimates of change for Central Asia, which give a threefold increase of runoff from glaciers by

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2050 and a reduction to two-thirds of present runoff by the year 2100. In the short term, a significant increase in the number of flood events in Norway is projected (Bogen, 2006). Bogen found that suspended sediment concentrations and volumes were dependent on the availability of sediments, the type and character of the erosion processes and the temporal development of the flood. In the Norwegian case, it appears that the glacier-controlled rivers are unlikely to respond dramatically in terms of sediment transport because of limited sediment availability. Nevertheless, in global sediment yield terms, Hallet *et al.* (1996) have conclusively demonstrated the importance of glacier melt waters. The global data and the regional Norwegian data demonstrate the difficulty of making generalizations about the probable effects of climate change on sediment transport in glacierized basins. Changing patterns of snowmelt resulting from climate change are also complex (Woo, 1996) and are sensitive both to elevation and to the seasonal and event distribution of temperature change and precipitation.

4.3.6 Human activity

There is growing evidence since the Third Assessment Report (IPCC, 2001b.) that adaptations that deal with non-climatic drivers are being implemented in both developed and developing countries. Examples of adaptations to land use change, such as construction, decommissioning and management of reservoirs, and adaptations to extreme sediment cascades and relief, as well as their interactions with climate include the following:

a. partial drainage of the Tsho Rolpa glacial lake in Nepal was designed to relieve the threat of GLOFs (glacial lake outburst floods) (Shrestha and Shrestha, 2004);
b. Sarez Lake in Tajikistan and the so-called ‘quake lakes’ in Szechwan Province, China are commanding national and international funding;
c. increased use of artificial snow making by the alpine ski industry in Europe, Australasia and North America.

Glacial retreat favors the formation of glacial lakes and ice avalanches, and disastrous events such as glacial lake outburst floods (GLOFs). GLOFs are the most destructive hazards originating from glaciers due to the large water volume and large areas covered. Luckily, glacial lakes, from which GLOFs originate, usually form slowly and can be monitored. McKillop and Clague (2007) have estimated the probability of the occurrence of GLOFs in southern British Columbia.

In mountain landscapes, extreme geophysical events interact with social systems in dramatic ways. The May 12, 2008 earthquake in Szechwan, China, which generated hundreds of large landslides and which blocked more than 30 large lakes, killing 75,000 people and causing millions of dollars in damage, is a case in point. Earthquakes and floods, which are not exclusively mountain hazards, account for more than 50% of the damage caused by natural hazards globally; and the highest damage in recent years in Switzerland, Austria and France, for example, was due to floods and windstorms (Agrawala, 2007).

The country of Tajikistan is part of the Pamir-Alai mountain system. Ninety-two percent of its land area of *c.*140,000 km^2 is mountainous; nearly 50% lies above 3,000 m and is classified as dry, cold desert. It is drained by the headwaters of the Amu Darya and Syr Darya rivers, the major feeders of the Aral Sea. This is a zone of intensive seismic activity and steeplands that are geomorphically highly active. Earthquakes with magnitudes exceeding 5 on the Richter scale have a recurrence interval of 75 days and the region is well known for the earthquake-triggered natural dams that have blocked large lakes, holding as much as 17 km^3 of water in the case of Sarez Lake, and presenting a permanent risk of catastrophic draining (Alford *et al.*, 2000). Rock falls and massive rock slides have accounted for the deaths of more than 100,000 victims during the twentieth century, and this in a country of barely 6 million people. Thirty-one percent of the country is said to be agricultural land and 13% is under forest, but overgrazing of the rangelands by sheep and rapid deforestation has encouraged widespread erosion on slopes and more frequent occurrence of mudflows and landslides.

4.3.7 Drainage basin scale hazards

High drainage densities have implications for slope profiles. A logical implication of fine dissection by the stream network is that slope angles will be steeper (and slope lengths shorter), even in areas of moderate altitudinal relief, than in other humid environments with lower drainage densities. This makes landsliding more likely and rainsplash erosion (heavily dependent on slope angle) more effective.

Japan is well known for its debris flow hazards (Figure 4.4) associated with the volcanic mountain landscapes and high drainage densities.

By contrast with the site scale hazards, drainage basin scale hazards involve coupled debris avalanches and debris flows and coupled slopes and channels in the headward parts of the basins, which is one degree of complexity. As drainage basins grow, slopes and channels are gradually decoupled and the rate at which this decoupling occurs is specific to the hydroclimate and nature of the regolith in

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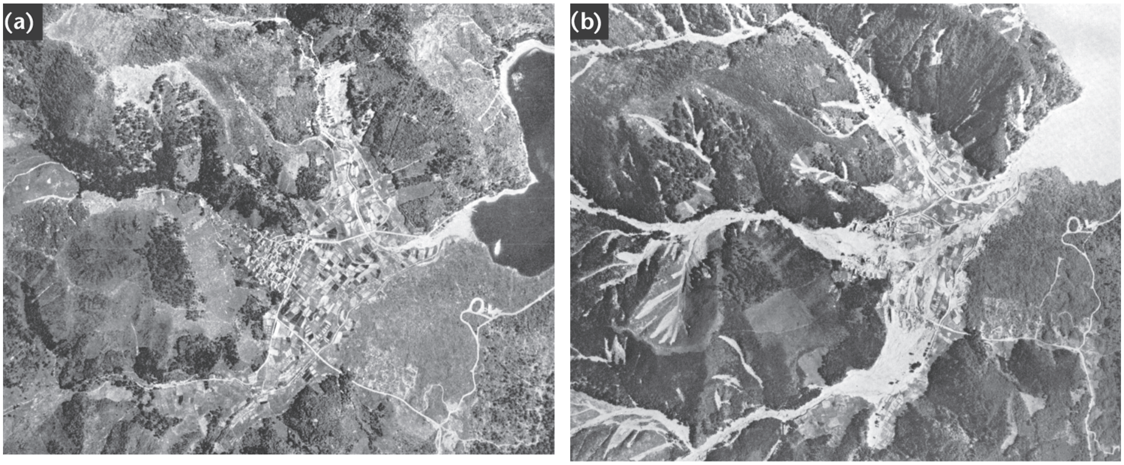

FIGURE 4.4. Debris flows as geomorphic hazard, illustrated from the effects of an intense rainstorm in 1966 at Ashiwada in Yamanashi Prefecture, Japan: (a) pre-1966; (b) post-Typhoon 26, 1966. (From Akagi, 1973.)

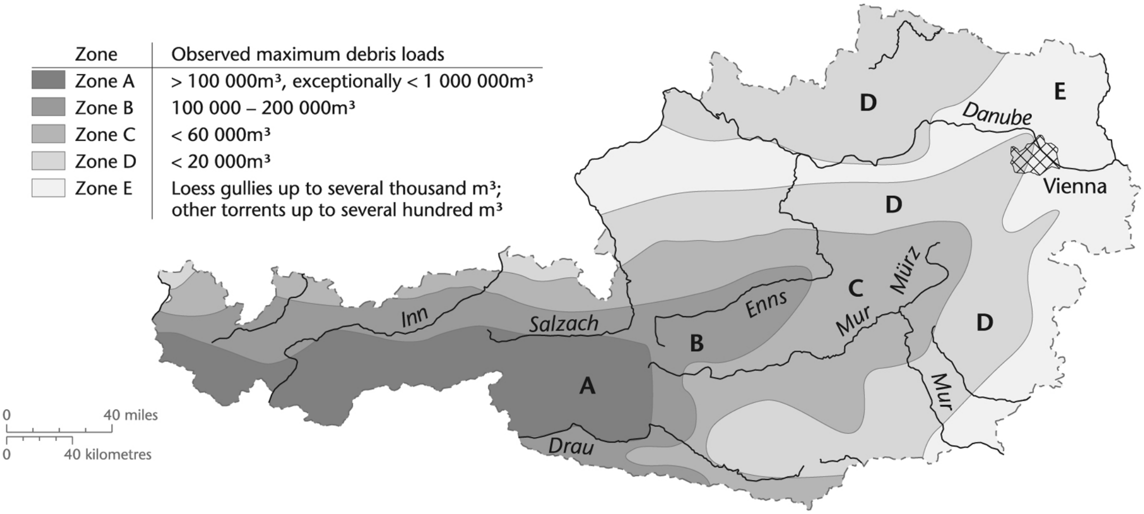

FIGURE 4.5. Regional distribution of torrent and debris flow hazard in Austria, based on observed maximum debris load. (From Kronfellner-Kraus, 1989; Embleton-Hamann, 2007.)

each basin. The relative importance of hydroclimate, relief, regolith and land use is difficult to establish.

The debris flow hazard in Austria is instructive in this regard. Debris loads involved in about 2,000 torrent disasters from catchments up to 80 km^2 in size have been calculated and mapped (Figure 4.5).

The regional pattern of debris flow loads (declining from west to east) reflects rather closely the influence of relief and hydroclimate. However, individual torrent basins with intensive land use have a higher hazard and risk rating simply because of the scale and nature of socio-economic investment in the valley bottoms. Land use has become more important in determining the magnitude of the hazard and the dimensions of the risk. It is also important to observe that land use in the form of afforestation can mitigate and even enhance the landscape (Figure 4.6)

If climate warming continues, destabilized mountain walls, increasing frequency of rock fall, incidence of rock avalanches, increase and enlargement of glacial lakes and destabilization of moraines damming these lakes are expected to accompany increased risk of outburst floods.

Geomorphic hazards associated with glacier retreat include rock avalanches, deep-seated slope sagging (sackung), debris flows, debris avalanches, debris slides, rock

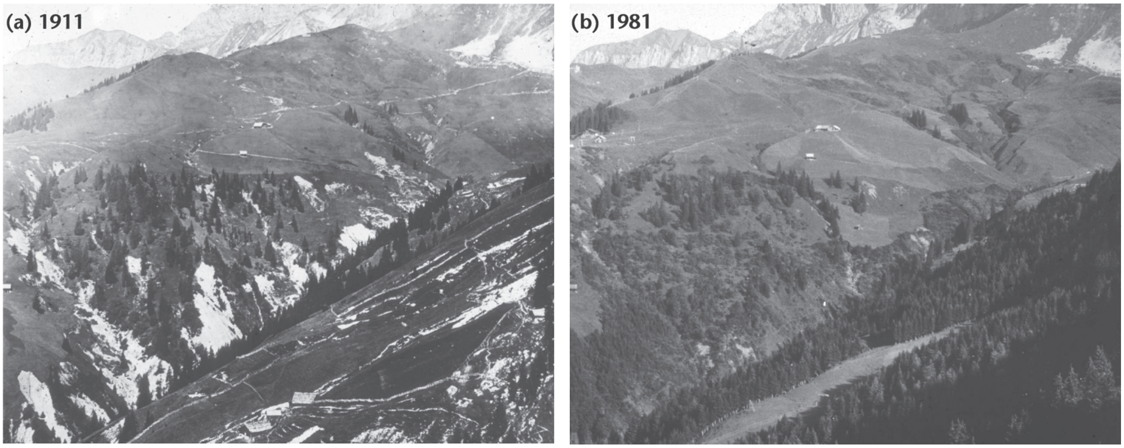

FIGURE 4.6. Source area of the Gangbach. In the foreground is Aebnenegg, Canton Uri, near Altdorf, Switzerland. (a) A 33-hour rainfall event in June 13–14, 1910 caused extensive debris flow activity. (b) The same landscape in 1981 after the completion of afforestation between 1932 and 1960. (R. Kellerhals, personal communication, 2008.)

fall, moraine dam failures and glacier outburst floods (Geertsema *et al*., 2006). The effects of glacier retreat on sediment transport are controversial. Schiefer *et al*. (2006) identified three periods of accelerated sedimentation in a montane lake in the Coast Mountains over the past 70 years: a period of intense rainstorms, a year of massive slope failure and a period of rapid glacier retreat between 1930 and 1946. The present period of rapid glacier retreat does not seem to be generating exceptional sedimentation events.

If climate warming is accompanied by increasing storminess (IPCC, 2007b) and intense rainfall, then peak stream discharges will increase and erosion, sediment transport and sediment deposition downstream will presumably also increase. Hazards will include flooding, possibly increasing both magnitude and frequency of floods and increased lateral instability of stream banks. A prominent indication of a change in extremes is the observed evidence of increases in heavy precipitation events over the mid-latitudes in the last 50 years, even in places where mean precipitation amounts are not increasing. (Kunkel, 2003). In Central and Southwest Asia the 1998–2003 drought provides an example of unanticipated effects of extreme events. Flash flooding occurred over hardened ground desiccated by prolonged drought in Tajikistan, central and southern Iran, and northern Afghanistan leading to accelerated erosion in early 2002 (IPCC, 2007a). In terms of impact on the landscape it is the extreme events (both high and low) and the freshet flows that mobilize most of the sediments and, to a lesser extent, the solutes. More frequent/intense occurrences of extreme weather events will exceed the capacity of many developing countries to cope.

The growth of cities in the mountain world places further stress on mountain stability. In Latin America, the Caribbean and countries in transition, nearly half of the mountain population lives in urban areas. In the case of tropical mountains by contrast, the towns are in the uplands and roads are often in ridge top locations. In the case of temperate mountain areas, the only space for urban agglomerations and transport routes is on the flat floor of broader valleys and mountain basins (Bätzing *et al*., 1996). These used to be flood-prone wetland areas. Therefore all rivers needed to be turned into artificial channels in these areas. The consequence is that geomorphic hazards have been enhanced: concreting of the riverbanks and the waterproofing of urban areas represent aggravating factors for floods.

4.4 Global scale

4.4.1 Relief

At the larger mountain system and global scales, elevation and gradient are the most important relief elements insofar as they influence temperature, and precipitation. Elevation controls the incidence and intensity of freeze–thaw events as well as orographic precipitation, and many associated climatic effects. Gradient defines the gravitational driving force ($g \sin \alpha$) and influences radiation and precipitation receipt, wind regimes and snow. Erosion rates reported for the Nanga Parbat massif are among the highest measured (22 ± 11 m per 1,000 years) and reported rates of uplift for the Himalayas vary from 0.5 to 20 m per 1,000 years (Owen, 2004). Ahnert (1970) developed an equation relating denudation and local relief:

$$D = 0.1535h \tag{4.1}$$

where D is denudation in mm/1,000 yrs and h is local relief in m/km.

Summerfield and Hulton (1994) analyzed 33 basins with an area >500,000 km^2 from every continent except Antarctica. Total denudation (suspended plus dissolved load) varied from 4 mm ka^{-1} (Kolyma in the Russian Far East) to 688 mm ka^{-1} (Brahmaputra). They found that more than 60% of the variance in total denudation was accounted for by basin relief ratio and runoff.

4.4.2 Disturbance regimes

There is an increasing sense that almost all mountain landscapes are transitional from one landscape-forming regime to another. This condition has been described by Hewitt (2006) as a disturbance regime landscape. By this, he meant that disturbances occur so frequently that the landscape gets no chance to equilibrate with contemporary processes. Mega-landslides in the Himalayas are the regional example that Hewitt has described. Note contrast with models of Brunsden (1993).

Mountain societies contain a higher incidence of poverty than elsewhere, and therefore have a lower adaptive capacity and a higher vulnerability to environmental change. Mountain peoples have been made more vulnerable to natural extreme events by vast numbers being uprooted and resettled in unfamiliar and more dangerous settings (Hewitt, 1997).

Many studies suggest that at least until 2050 land use change will be the dominant driver of change in human-dominated regions (UNEP, 2002). Not only are there geosystem disturbance regimes, such as those discussed by Hewitt (above), but land use change, fire and insect outbreaks can also be analyzed as disturbance regimes, using a shorter response time scale (Sala *et al*., 2005). Similarly, over-grazing, trampling and vegetation destabilization have been analyzed in this way in the Caucasus and Himalayas (IPCC, 2001b).

4.4.3 A conditionally unstable landscape

The landscape of British Columbia (B.C.) is in transition between the Last Glacial Maximum (LGM) and present and illustrates a specific kind of geosystem disturbance regime. The Cordilleran Ice Sheet covered almost the whole of the province before 14,500 BP and since that time the process of transition towards a fluvially dominated landscape has been on-going. Nevertheless, B.C.'s mountains still contain over 29,000 km^2 of glaciers and ice caps, in spite of warming since the Little Ice Age and marked glacier retreat. Schiefer *et al*. (2007) estimate total ice loss of 22.5 km^3 a^{-1} between 1990 and 2005.

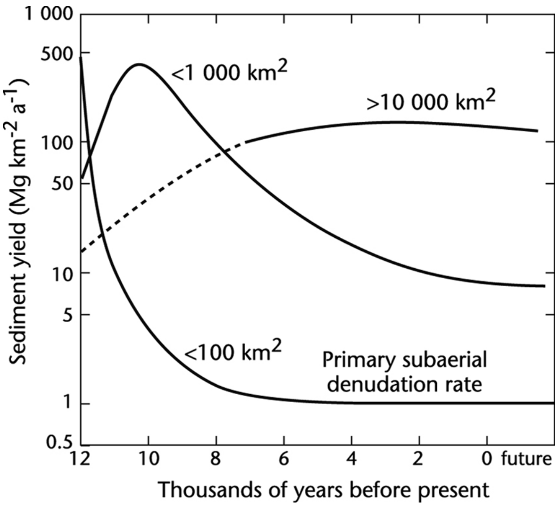

FIGURE 4.7. Temporal pattern of paraglacial sediment yield in formerly glaciated upland and valley sites in coastal British Columbia and Alaska. Values are for basins of order 100, 1000 and 10 000 km^2 based on the contemporary spatial pattern of sediment yield. (From Church, 1998.)

The suite of landforms that evolved was characterized by 'non-glacial processes that are directly conditioned by glaciation' (Church and Ryder, 1972). A distinctive pattern of sediment yield (Figure 4.7) is interpreted as evidence of a transitional landscape with a relaxation time of the order of 10 ka (Slaymaker, 1987; Church and Slaymaker, 1989). This transitional landscape lasts until the glacially conditioned sediment stores are either removed or attain stability (Schumm and Rea, 1995). The landscape of B.C. is a disturbance regime landscape in so far as the post-glacial landscape has had insufficient time to recover from the effects of the last major disturbance, namely the LGM.

In B.C., and indeed in most of Canada, larger geomorphic systems have not yet achieved a form that is adjusted to the contemporary fluvial landscape (Church *et al*., 1999). The implication of this conclusion is that the B.C. mountain landscape is conditionally unstable and it can be anticipated that small changes in hydroclimate and/or land use may cause landscape change.

The regional climate projection of the Fourth Assessment Report (IPCC, 2007a) anticipates for B.C. a mean annual temperature increase and a mean annual precipitation increase, incorporating a summer decrease and a winter increase in precipitation. If this larger volume of moisture comes in the form of high magnitude, low frequency rainfall events, debris flow hazard may increase markedly. A decrease in snow season length and snow depth is also projected. The general tendency under climate warming will be an upslope shifting of hazard zones and widespread reduction in stability of formerly glaciated or perennially frozen slopes (Barsch, 1993; Ryder, 1998).

4.4.4 Human activity, population and land use

Human activity, in the form of population density and land use, is a direct driver of environmental change in mountains (Vorosmarty *et al*., 2003; Syvitski *et al*., 2005). It is not, however, the sheer numbers of people but aspects of population composition and distribution, especially the level of urbanization and household size, that exercise the greatest demands on the land (Lambin *et al*., 2001). High population densities in the developing world, for example, may lead to better management, such as in Kenya and Bolivia, described by Tiffen *et al*. (1994) as cases where the presence of more people has led to less erosion. The creation of infrastructure, especially roads, is a crucial step in triggering land use intensification. In developing countries, the largest mountain populations are found in the mid-elevation zones. In developed and transitional countries, by contrast, the lowest mountain zones are most heavily populated.

4.4.5 A typology of mountain systems sensitive to relief, hydroclimate and land use changes

If one is to get a realistic view of the incidence and source of geomorphic hazards, mountain systems should be differentiated not only in terms of relief and hydroclimate but in ways that reflect demography and land use. In this simplistic typology, we incorporate population density as a proxy for the intensity of the human signature on the landscape. Higher population densities lead to a higher pressure on land resources and intensified land use and therefore the human signature (though not necessarily a negative one) will be higher.

Polar mountains (population density <0.1/km²)
Svalbard, for example, has few permanent residents (around 2,300 as of 2000) and a few isolated mining activities, but it is estimated that *c*. 40,000 tourists visit each year (as of 2007). Sixty-five percent of the surface of Svalbard consists of protected areas. Climate and relief are the dominant drivers of change and hazards associated with permafrost degradation and glacier retreat are most evident.

Low population density temperate mountains (population density 0.1–25/km²)
Mountains with a history of less dense settlement retain more of their traditional agriculture and forestry. Relief and hydroclimate are the most important drivers of environmental change. Formerly glaciated mountains are strongly controlled by the historical legacy of glaciation.

High population density temperate mountains (population density 25–75/km²)
In western Europe and Japan, mountain regions are experiencing increasing land use pressures because of competition between conservation use, mineral extraction and processing, recreation development and market oriented agriculture, forestry and livestock grazing. The human impact (both positive and negative) on these mountains far exceeds the documented effects of relief and hydroclimate.

Tropical mountains (population density 50–100/km²)
Many developing countries (defined as having a relatively low standard of living, an undeveloped industrial base and a moderate to low human development index) are located in tropical and semi-arid environments. In those regions, the mountain areas are usually cooler and/or wetter than the lowlands and more hospitable for living and commercial exploitation. They also have deeper soils and fewer diseases. Human encroachment has reduced vegetation cover, increasing erosion and siltation, thereby adversely affecting water quality and other resources. Direct anthropogenic influence on these mountain regions appears to greatly surpass climate effects.

4.4.6 Global scale hazards

Global scale geomorphic hazards necessarily involve a consideration of tectonic and historical legacy. Hovius *et al*. (1998) emphasizes geomorphic hazards controlled by tectonic activity in earthquake-dominated landscapes. Scaled for drainage basin area, sediment yields increase through almost five orders of magnitude from tectonic cratons (typical sediment yields of 100 t km^{-2} a^{-1}) to contractional mountains (up to 10,000 t km^{-2} a^{-1}). Tectonically active mountain belts not only provide relief to drive erosion processes but they also combine high regolith loss with the rapid uplift of new bedrock into the weathering zone to continually refresh these erosion processes and maintain high sediment yields. On the rapidly uplifting (5–7 mm a^{-1}) island of Taiwan, erosion appears driven by interaction of erodible substrates, rapid deformation in the form of frequent earthquakes and typhoon-driven runoff variability. Earthquakes produce sediment by rock mass shattering and landsliding, and landslides and debris flows are also triggered by typhoon-generated storm runoff which flushes sediments from the mountains (Dadson *et al*., 2003). Thus changes in the frequency, magnitude and track positioning of typhoons in the Philippine Sea, western North Pacific Ocean, consequent upon climate change will have consequences for denudation rates; these processes are more important than simple relief and average precipitation controls (e.g. Andes: Aalto *et al*., 2001; Himalayas: Finlayson *et al*., 2002).

One of the implications of the fact that many mountain landscapes are disturbance regime landscapes is that they are exceptionally sensitive to environmental change and are in this sense geomorphically vulnerable. Geomorphic vulnerability is expressed not only by the frequent incidence of earthquake-triggered landslides, but, for example, by the fate of Himalayan glaciers, which cover 17% of the mountain area, and are predicted to shrink from the present 500,000 to 100,000 km^2 by 2035 (WWF, 2005). The glaciers on Mt. Kilimanjaro are likely to disappear by 2020 (Thompson *et al*., 2002) and Bolivian glaciers are heading for the same fate (Thompson *et al*., 1998).

Climate change can be expected to alter the magnitude and frequency of a wide variety of geomorphic processes (Holm *et al*., 2004). Increased triggering of rock falls and landslides could result from increased groundwater seepage and pressure. Large landslides are propagated by increasing long-term rainfall whereas small landslides are triggered by high intensity rainfall. These tendencies will probably lead to enhanced sediment transport. Increased sediment input to glacier-fed rivers may lead to increased channel instability, erosion and flooding. The hazard zones related to most of these fluvial processes will extend a long way beyond the limits of the mountain area (Ashmore and Church, 2002). Rainfall amounts and intensities are the most important factors in water erosion and they affect slope stability, channel change and sediment transport. Increased precipitation intensity and variability is projected to increase the risk of floods and droughts in many areas. Changes in permafrost will affect river morphology through destabilizing of banks and slopes, increased erosion and sediment supply (Vandenberghe, 2002).

Agriculture has been the greatest force of land transformation on this planet (Lambin and Geist, 2006). Nearly a third of the Earth's land surface is currently being used for growing crops or grazing cattle (FAO, 2007). Much of this agricultural land has been created at the expense of natural forests, grasslands and wetlands. In Africa, for example, most of the mountains are under pressure from commercial and subsistence farming activities. In unprotected areas, mountain forests are cleared for cultivation of high altitude adapted cash crops such as tea, pyrethrum and coffee. Grazing and forestry are the predominant uses of mountain land in all regions. Extensive grazing has little impact on slope processes, but overgrazing can have severe impacts.

4.5 Conclusion in light of accelerating environmental change

It is possible to learn from ecology, where recent models have placed environmental change and system collapse as central to an understanding of contemporary change and where there are similar complexity problems. Panarchy is a metaphor designed to describe systems of ecosystems at varying spatial and temporal scales. The terminology developed for panarchy (Holling, 2001) is entirely ecological and needs to be translated for the needs of geomorphology. Holling suggests that complex systems are driven through adaptive cycles which exist at a range of spatial scales. The term adaptive is self-evident in ecological systems; in geomorphic systems we often speak of self-regulating systems (Phillips, 2003). Adaptive cycles are defined as consisting of four phases, namely exploitation (the environmental disturbance regime), conservation (the response), collapse (threshold exceedance and unpredictable behavior of the system) and reorganization (recovery). A geomorphic analogue would be a disturbance regime landscape characterized by both orderly evolution and system collapse. The duration of these phases of adaptation depends on the intrinsic strength of the system, the connectivity of the system and the time required for the recovery of the system (resilience).

The panarchy metaphor has a fascinating flexibility in dealing with complex systems. Although there are evident differences between geophysical systems and ecosystems, there are many parallels in the behavior of self-organizing systems that can assist in improving attempts to understand and manage the environment sensitively. The concepts and terminology of the panarchy model are consistent with geomorphic concepts such as complex response (Schumm, 1973), threshold exceedance, landscape sensitivity and barriers to change.

Many mountain hazards can be viewed in terms of scale, ruggedness number, lithologic strength and connectivity (criticality of the adaptive system). The risks and losses associated with these hazards depend on how close to a

TABLE 4.2. *Mountain hazards classified according to scale, ruggedness number, lithologic strength, connectivity and vulnerability (H is high and L is low)*

Scale	**Resilience**		**Connectivity**	**Vulnerability**	**Hazard types**	**Risks**
	Ruggedness	Lithology	Drainage density			
Site	H	L	H	H	Slope failure	Human life
	L	H	L	L	Debris flows	Structures
Drainage Basin	H	L	H	H	Extreme events	Community
	L	H	L	L	Land degradation	Infrastructure
Global	H	L	H	H	Human activity	Ways of life
	L	H	L	L	Climate change	Economic systems
					Eutrophication	Ecological integrity

condition of collapse the adaptive system is allowed to proceed (Table 4.2).

4.6 Conclusions

There appears to be a hierarchy of mountain hazards and in Holling's (2001) terms this is a panarchy of adaptive systems. Each adaptive system, at its own spatial scale, evolves towards a critical condition leading either to collapse (hazard) or to self-reorganization (adaptation or mitigation in socio-economic context). Climate change is just one of the drivers that operates on the adaptive system.

If the IPCC definition of vulnerability is seriously engaged, then geomorphologists also have to investigate adaptive systems. Reliance on reactive, autonomous adaptation to the cumulative effects of environmental change is ecologically and socio-economically costly. Planned and anticipatory adaptation strategies can provide multiple benefits. But there are limits on their implementation and effectiveness. Enhancement of adaptive capacity reduces the vulnerability of landscapes to environmental change, but adaptive capacity varies considerably among regions, cultures, and socio-economic groups. Improved understanding of geomorphic hazards at many temporal and spatial scales is urgently needed.

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