14

Climatic factors influencing occurrence of debris flows

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14.1 INTRODUCTION

A wide variety of climatic factors influence the occurrence of debris flows, which include mudflows and lahars (see Chapter 2). Climatic factors are an important subject for a better understanding of hydrologic response of soils and of how global climate change can influence debris-flow activity. In addition, climatic factors are essential for developing debris-flow warning systems. Climatic factors have extreme spatial and temporal variability. Rapid infiltration of prolonged intense rainfall, causing soil saturation and a temporary increase in pore-water pressure, is generally believed to be the mechanism by which most shallow landslides, and more specifically debris flows, are generated during rainstorms (Iverson, 2000).

This chapter focuses on the primary and secondary climatic factors that influence the occurrence of debris flows. Primary climatic influences are those that directly trigger debris flows, such as intense rainstorms or rapid snowmelt. Secondary climatic influences are those, such as antecedent rainfall or antecedent snowmelt, that influence whether debris flows are triggered during an earthquake, volcanic event, or intense rainstorm. Thresholds for the triggering of debris flows will also be discussed, including application of rainfall thresholds for hazards assessment and mitigation such as warning systems. In addition to short-term climatic influences, the possible effects of longer term climatic changes are examined. This chapter does not attempt to present new scientific material on this subject, but does try to summarize the extent of worldwide research to gain a better understanding of this complex subject.

14.2 PRIMARY CLIMATIC FACTORS

Intense rainstorms and rapid snowmelt are two primary climatic factors that are recognized as directly associated with near-immediate triggering of debris flows.

M. Jakob and O. Hungr (eds), *Debris-flow Hazards and Related Phenomena.*

14.2.1 Intense rainstorms

The relationship of high-intensity rainfall in the triggering of shallow landslides that transform into debris flows was first noted by Campbell (1975) in the Santa Monica Mountains of southern California. He postulated that after sufficient antecedent rainfall, infiltration of intense storm rainfall created temporary perched aquifers with positive pore-water pressures that reduced the effective strength of surface soils and initiated shallow landslides (Figure 14.1). Starkel (1979) conceived a critical rainfall threshold as a combination of rainfall intensity and duration. Storms of very high intensity, but relatively short duration, such as less than one hour, may cause high surface runoff, but generally insufficient infiltration for high pore-water pressures for triggering shallow landslides. Conversely, low-intensity, lengthy storms, lasting a few days, may increase deep groundwater levels, but often result in insufficient pore pressure within near surface soils for triggering shallow landslides. Although the instability effects of rainfall intensity and duration depend on thickness, porosity, and permeability of the local regolith, the measure of the combination of rainfall intensity-duration is useful for comparing regional triggering of debris flows. Caine (1980) assembled worldwide rainfall data to further support the concept of thresholds of rainfall intensity and duration for the

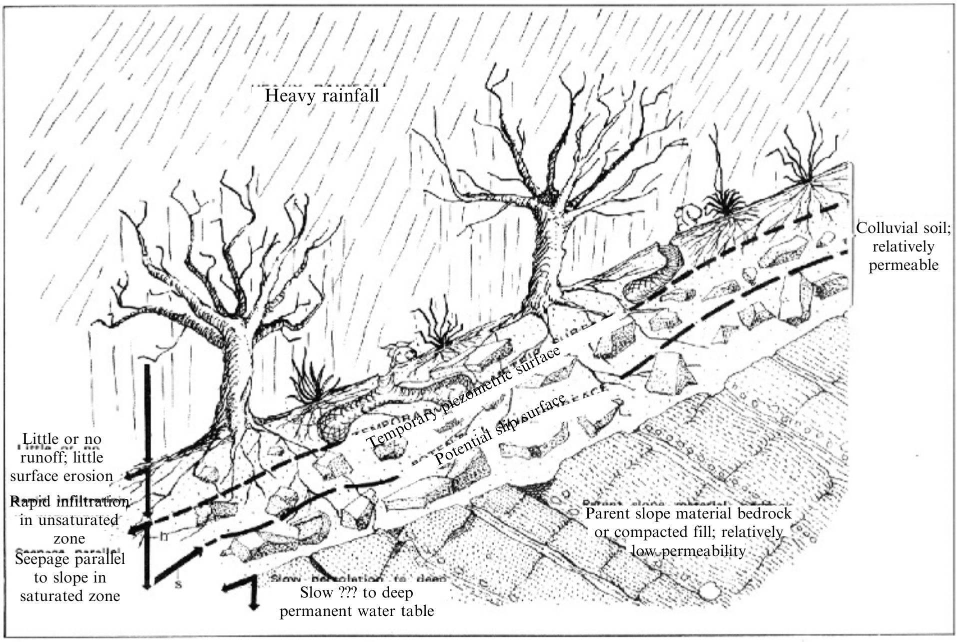

Figure 14.1. Conceptual model for intense rainfall, infiltration and temporary aquifers in shallow hillside soils.

Campbell (1975).

triggering of debris flows. Subsequently, studies from many parts of the world have documented different intensity and duration of rainfall for the triggering of debris flows in different regions.

Worldwide observations have identified the minimum and maximum rainfall over various periods of time critical for triggering debris flows. A minimum rainfall threshold defines the lowest amount of rainfall capable of initiating a landslide (i.e., below which no landslide has occurred). What we here call a maximum threshold defines the amount of rainfall that has always triggered landslides historically (Crozier, 1997). The probability of debris-flow occurrence increases as rainfall progresses from the minimum threshold towards the maximum threshold.

Caine (1980) developed a minimum rainfall intensity–duration threshold using published rainfall data from 73 worldwide storm events, with durations up to 10 days associated with the triggering of different types of shallow landslides. Only landslide triggering events were used to obtain the threshold; rainfall conditions which did not trigger landslides were not considered, and so the definition of the threshold incorporates only part of the evidence. Subsequent studies, however, have included both triggering and non-triggering events in the analysis, and thresholds obtained in this manner have been applied for a single drainage in the Italian Alps (Marchi et al., 2002), in New Zealand (Crozier, 1997), and in southern British Columbia (Jakob and Weatherly, 2003).

Govi and Sorzana (1980) used the timing of mudflow and debris flows in combination with hourly rainfall data to characterize rainfall thresholds in a variety of geologic settings in north-western Italy. They found that the spatial density of debris flows within a 30-year period did not correlate to bedrock and soil type. However, they discovered that the rainfall threshold varied from one region to another mainly as a function of the mean annual precipitation.

During January 1982, an intense storm lasting for about 32 hours triggered more than 18,000 mainly shallow landslides (mostly debris flows) in soil and weathered rock in the San Francisco Bay region (Ellen and Wieczorek, 1988) (Figure 14.2). Documentation of initiation times of debris flows, coupled with continuous measurements of rainfall, permitted the identification of rainfall thresholds (Wieczorek and Sarmiento, 1983; Cannon and Ellen, 1985; Wieczorek, 1987; Cannon, 1988; Wieczorek and Sarmiento, 1988).

Subsequent to the 1982 storm in the San Francisco Bay region, a real-time landslide warning system was established. It was operated by the US Geological Survey and the National Weather Service (NWS) between 1986 and 1995 (Wilson et al., 1993; Wilson, 2005). Using a real-time rainfall monitoring system and NWS satellite-based quantitative rainfall forecasts, regional landslide warnings were issued using the rainfall thresholds during storms in 1986, 1991, 1993, and 1995. The times of landslide warnings in the storms of February 1986, which were based on the thresholds of Cannon and Ellen (1985) were found to correspond with documented times of shallow landslides (Keefer et al., 1987) (Figure 14.3). Organizational changes and decreases in funding and staffing forced the termination of the USGS/NWS debris-flow warning system in December 1995 (Wilson, 2005).

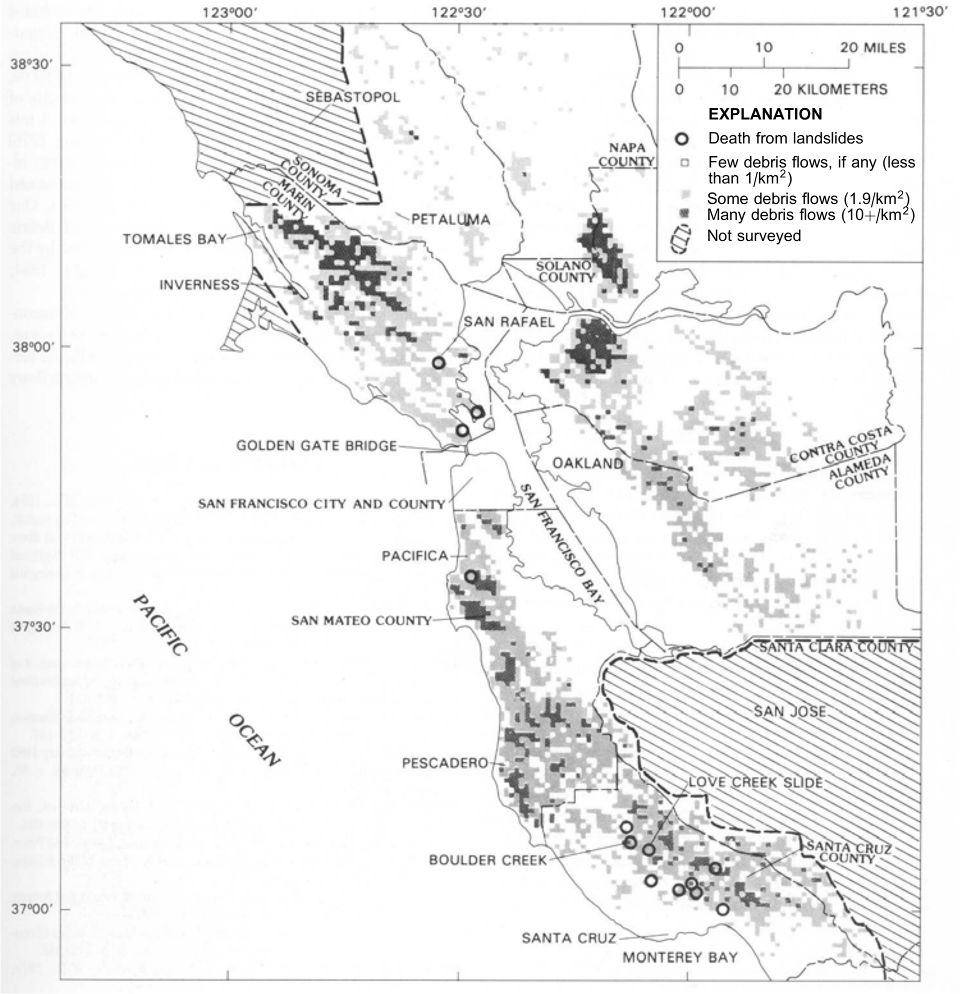

Figure 14.2. Distribution and spatial density of debris flows during the 3–5 January, 1982 storm in the San Francisco Bay region.

Ellen and Wieczorek (1988).

On 9–11 March, 1988 Tropical Cyclone Bola hit the east coast of the North Island of New Zealand dropping 753 mm of rain within a four-day period. Thousands of landslides were triggered, mostly earth flows, debris flows, and debris slides. Similar triggering events hit New Zealand frequently (e.g., near Wairarapa during 1977 and in Gisborne during 2002) (Figure 14.4, see also color section for 14.4(b)). Within an area of approximately 50 km^2 more than 19,000 landslides were mapped (Glade, 1997), resulting in an average spatial density of 380 landslides per square kilometer. A comparison of the landslide history with climate measurements in this region showed that a rainfall threshold could be estab-

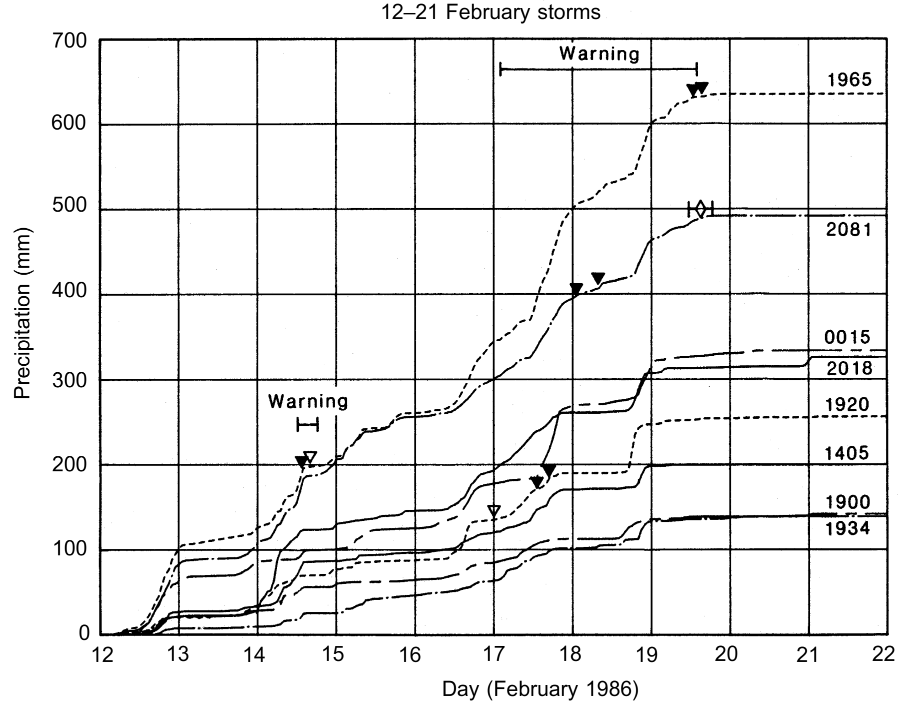

Figure 14.3. Timing of debris-flow warnings in San Francisco Bay region during the storms of 12–21 February, 1986 and documented debris flows (filled triangles), slump (diamond), and undetermined types of landslides (open triangles) at locations near specific numbered rain gauges.

Keefer et al. (1987).

lished (Page et al., 1994). Of added interest, Page et al. also demonstrated that a smaller rainstorm in 1938 (692 mm of rain within a four-day period) had produced more sediment from landslides than the larger 1988 storm, resulting in much larger environmental impact. They concluded that conditions in the drainage basin had been changed by the removal of a large amount of surficial materials, so that by 1988 the slopes had still not recovered from previous events (Preston, 1999).

In some areas, rainfall from intense storms infiltrates and percolates quickly into the regolith. This often results in the saturation of soils, development of perched aquifers, and rapid rise in groundwater levels. The temporary creation of perched aquifers and resulting high pore-water pressures can trigger debris flows on steep hillsides by effectively reducing soil strength. However, positive pore-water pressure can reach high levels without triggering debris flows. In the San Francisco Bay region, California, Johnson and Sitar (1990) used tensiometers to measure both negative and positive pore-water pressures through several intense rainstorms with associated debris flows. These measurements substantiated the importance of antecedent rainfall, which reduced negative pore pressure and thereby facilitated

(a)

Figure 14.4. Spatial distribution of debris flows and other landslides following extreme rainstorm events in New Zealand. (a) Rainstorm in 1977, Kiwi Valley, Wairoa. See color section for 14.4(b).

Photograph of Hawke's Bay Catchment Board.

development of transient positive pore-water pressures during subsequent high-intensity rainfall. Pore pressures rose and fell quickly over a period of less than 24 hours, and the pore-pressure pulses slowly progressed downhill (Johnson and Sitar, 1990). Theoretically, during initial infiltration during a rainstorm, the dissipation of negative pore-water pressure, or capillary soil suction, reduces the soil strength and could result in shallow landslides which may transform into debris flows (De Campos et al., 1994). However, this concept, which has been proposed primarily in tropical environments, such as Brazil, has not been verified by field measurements of the dissipation of negative pore pressure temporally associated with the triggering of debris flows.

14.2.2 Rapid snowmelt

Snowmelt enhanced by rainfall or sudden temperature increase can also lead to increased water infiltration. Horton (1938) monitored and studied the infiltration

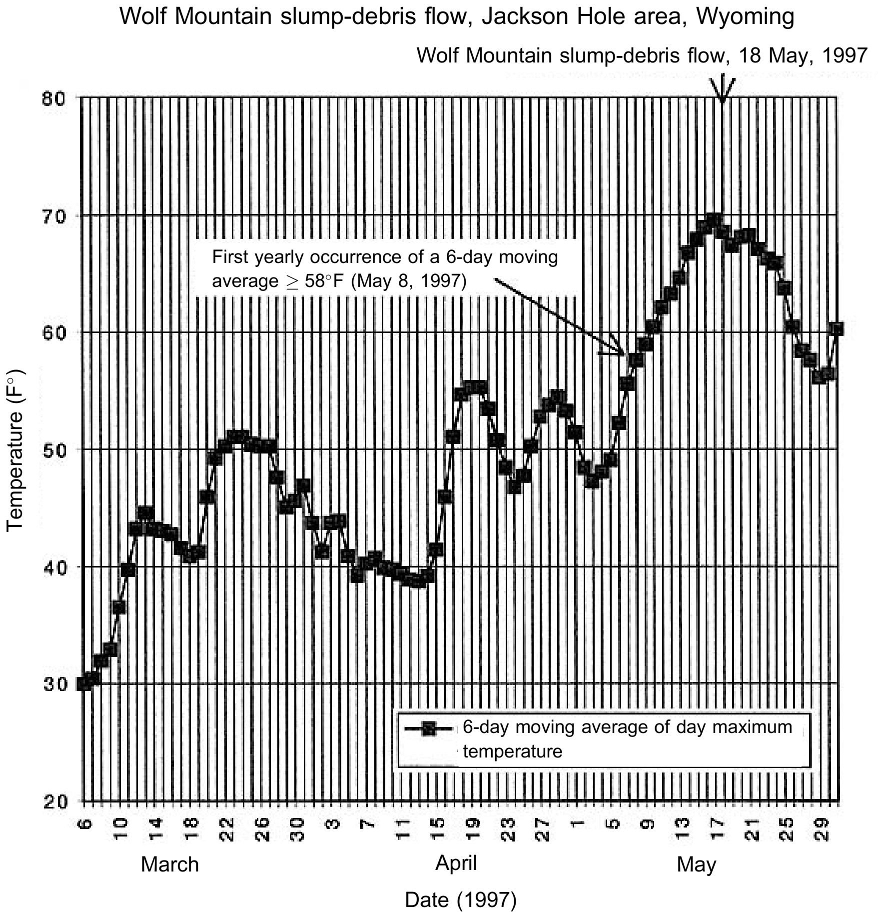

Figure 14.5. Temperature patterns for snowmelt triggering of a debris flow at Wolf Mountain, near Jackson Hole, Wyoming.

Chleborad (1998).

of melting snow into soil, including the case of the effects of rainfall on a snowpack. Horton found that the process of snowmelt provides a more continuous supply of water over longer time periods than infiltration from rain. Matthewson et al. (1990) found that snowmelt may also recharge shallow fractured bedrock and raise porewater pressures beneath shallow soils, thus triggering debris flows. Spatial variability from infiltration of snowmelt is not as high as that from intense rainstorm cells. The rate of snowmelt depends on air temperature, which in turn relates to the timing of debris flows (Chleborad, 1997, 1998). Chleborad et al. (1997) used a 6-day moving average of daily maximum temperature and 14.4°C as an optimum threshold of this average for anticipating the onset of snowmelt-generated landslides in the central Rocky Mountains of the USA (Figure 14.5). This threshold was used successfully to time the deployment of instrumentation prior to the occurrence of debris-flow activity at a site near Aspen, Colorado (Chleborad et al., 1997). Debris flows have also been found in south-western British Columbia to be associated with moderate rainfall with snowmelt, low intensity rainfall and heavy snowmelt, and heavy rainfall onto deeply frozen, thawing ground (Church and Miles, 1987).

14.3 SECONDARY CLIMATIC FACTORS

14.3.1 Antecedent rainfall

Campbell (1975) identified a seasonal antecedent rainfall threshold of 267 mm as necessary for debris flows to be produced by intense storms in the Santa Monica Mountains of southern California. This value of antecedent rainfall is an empirical representation of the minimum field moisture capacity required of slope materials for intense storms to trigger debris flows. A seasonal characterization of antecedent rainfall applies to regions, such as southern California, and the Pacific Northwest of the USA and Canada, where wet and dry seasons are distinct. For California, the wet season falls between late fall and early spring, generally during the months of November through to April.

The importance of antecedent, or pre-storm, seasonal rainfall for the triggering of debris flows was also demonstrated in northern California (Wieczorek and Sarmiento, 1988). Seasonal rainfall is defined as the total amount of rain beginning after the dry summer period, which in northern California usually ends in late October. A set of 22 storms between 1975 and 1984 were divided into three groups, based on the pre-storm seasonal rainfall and the ability of the storms to trigger debris flows in a study area near La Honda, California (Wieczorek, 1987, table 1). No storm, however intense, produced debris flows unless the seasonal antecedent rainfall exceeded 280 mm. The 10 intense storms in the first group, which occurred after a seasonal rainfall exceeding 280 mm, triggered debris flows; the intense storms in the second group, which occurred before 280 mm of seasonal rainfall, triggered no debris flows; and the storms in the third group, which occurred after a seasonal rainfall of 280 mm, but were of low intensity and short duration, triggered no debris flows.

The significance of pre-storm seasonal rainfall becomes clear when one examines the rainfall characteristics and the effects of the first and second group of storms. Even though the storms in the second group had storm rainfall totals, 24-h maximums, 1-hr maximums, and high intensity for durations of 2–8 hours exceeding most of the storms in the first group, the storms in the second group did not trigger debris flows, apparently because of insufficient pre-storm seasonal rainfall. Antecedent rainfall was evaluated for 2, 7, 15, and 30-day periods (Wieczorek and Sarmiento, 1988). Rainfall during the 7 and 15-day periods before the three storms which caused the greatest number of debris flows was significantly higher than for other storms, an observation suggesting that rainfall during the 1 or 2-week period preceding an intense storm may be more significant than the earlier pre-storm seasonal rainfall.

In regional contrast, comparison of storms in the Moscardo basin of the Italian Alps provides an example of the lack of importance of antecedent rainfall for the triggering of debris flows (Deganutti et al., 2000). In an examination of 73 storms, 15 of which triggered debris flows between late June and late September, antecedent rainfall of 24 hours, 5, 10, and 15 days showed no significant statistical correlation to debris-flow or non-debris-flow storm events. During the summer the melting of snow contributes to the high moisture content of soils and along with the presence of springs can account for the lack of significance of antecedent rainfall.

Other investigations have found that antecedent rainfall conditions contribute differently to debris-flow occurrence and distribution depending upon regional climate. Research in Italy (Wasowski, 1998) and New Zealand (Crozier and Eyles, 1980; Crozier, 1989, 1997) has demonstrated that antecedent climatic conditions play a vital role in determining debris-flow occurrence. In Korea, Kim et al. (1992) demonstrated that antecedent rainfall is significant in some climatic-terrain regions and not so important in others. In Hong Kong, Brand et al. (1984) and Brand (1989) found that antecedent climatic conditions are not important for the occurrence of debris flows and that rainfall intensity is the only critical triggering factor, despite the earlier contrary findings of Lumb (1975).

Although pre-storm rainfall is widely recognized as an important factor in the rainfall conditions that trigger debris flows, there is little agreement on the time period significant for the build-up of antecedent soil moisture (Cannon and Ellen, 1988). Lumb (1975), Eyles (1979), and Govi and Sorzana (1980) reported rainfall totals for time periods ranging from 2 to 45 days before a storm as contributing to the soil-moisture conditions that lead to debris flows. Other authors have defined the critical period of antecedent climatic conditions on soil saturation as 15 days in Italy (Pasuto and Silvano, 1998), 25 days in Colombia (Terlien, 1997, 1998), and 4 weeks in Seattle, Washington (Chleborad, 2000), and North Vancouver, British Columbia, Canada (Jakob and Weatherly, 2003). Seasonal variations of rainfall and temperature, affecting evapotranspiration could be significant to the importance of antecedent rainfall. For example, in the San Francisco Bay region, most intense storms occur during the cool fall and winter seasons. Evapotranspiration is minimal and soils would remain partly saturated for long periods of time. In contrast, in central Virginia, intense convective storms occur most often during the warm summer period when evapotranspiration could remove much of the soil moisture within days or a few weeks preceding another storm. Consequently, the significance of antecedent rainfall may vary depending upon the regional climate.

In November of 1998, intense rainfall from Hurricane Mitch triggered two catastrophic debris flows from the slopes of Casita volcano in Nicaragua. The first (larger) debris flow began as a landslide representing the collapse of a small flank (200,000 m^3) near the summit of an inactive volcanic edifice. The resulting large debris flow increased its volume by a factor of nine as it travelled 4 km, destroying several towns and killing more than 2,500 people (Scott, 2000). Intense rainfall of 750 mm over 83 hours between 26 October and the time of the Casita flank collapse at 10:30–11:00 a.m. on 30 October, probably increased pore pressure in the highly fractured, but only slightly altered, bedrock. In addition to the intense rainfall of

Mitch, antecedent rainfall was considered significant (Kerle et al., 2003) because of comparison of Hurricane Mitch (1,538 mm total rainfall) to 1982 Tropical Storm Alleta of similar magnitude (1457 mm). Whereas more than 1,900 mm of rain fell during the 6 months prior to Hurricane Mitch, the 1982 rainfall event, which occurred at the beginning of the rainy season with only 164 mm of antecedent rainfall over the same time interval, resulted in limited shallow debris flows causing only two fatalities (Kerle et al., 2003).

The influence of different lengths of antecedent conditions on landslide initiation has been investigated in Portugal by Zêzere et al. (1999) and in New Zealand by Glade (2000a). Whereas Zêzere et al. (1999) used cumulative rainfall over periods from 1–120 days, Glade (2000a) considered the loss from evapotranspiration and soil water drainage. Four antecedent periods (2, 3, 5, and 10 days) were applied in Glade's *Soil Water Status* model. Results show no significant changes in landslide occurrence with durations of antecedent rainfall beyond 2 days (Glade, 2000a). Thus, the length of record, in this case, is not very important. This result makes sense because the New Zealand study area consists of pasture lands that have shallow-rooted vegetation and coarse-grained soils developed on volcanic ash. In these conditions, rapid drainage and evapotranspiration can be expected to reduce the importance of long-term antecedent conditions. This example shows how local conditions affect the duration of significant antecedent conditions. In these examples, soil conditions, such as rainfall infiltration and soil water percolation, are generally not considered explicitly. For many regions, these data are not available. If values can be obtained, however, it is important to include them in modeling approaches.

Secondary climatic factors, such as antecedent rainfall or the melting of large snowpacks, increase soil moisture influencing the triggering of debris flows by earthquakes and volcanic events (Waldron, 1967; Waitt et al., 1983; Pierson et al., 1990; Schuster, 1991; Pierson, 1999; Scott et al., 2001; see also Chapter 10). Two earthquakes (M 6.1 and 6.9) on 5 March, 1987, which occurred shortly after a period of extended rainfall east of Quito, Ecuador, triggered thousands of earth slides, debris avalanches, and earth and debris flows that destroyed nearly 70 km of the Trans-Ecuadorian oil pipeline (Schuster, 1991). After a period of rainfall that saturated residual soils on steep slopes, a M 6.4 earthquake on 6 June, 1994 in the Rio Paez basin of Colombia triggered earth and debris flows that destroyed homes, a school, and other buildings (Martinez et al., 1999). A comparison of different earthquakes occurring in the same region can demonstrate the influence of antecedent rainfall on the earthquake triggering of debris flows. For example, the 16 April, 1906 San Francisco, California, earthquake ($M \sim 8.2$) triggered many large, deep-seated landslides throughout northern California, as well as several debris flows near Half Moon Bay (Youd and Hoose, 1978). In comparison, the 17 October, 1989 Loma Prieta earthquake (M 7.1), which affected a large portion of the same region, triggered mostly shallow landslides, but not any debris flows (Schuster et al., 1998). Although it had not rained for 17 days before the 18 April, 1906 earthquake (Youd and Hoose, 1978), the month of March 1906 was exceptionally wet. Cumulative rainfall for the region for the 1, 3, and 6-month periods before the 1906 earthquake was about 150–200% of normal. In comparison, regional rainfall in the month before the 17 October, 1989 earthquake was minimal; the earthquake occurred near the end of the dry summer season and since 1 June, only 30 mm of rain had fallen (Keefer and Harp, 1998). Thus, the timing of earthquakes in relation to seasonal rainfall can play a critical role in the triggering of debris flows. The timing of earthquakes with respect to climatic influence on groundwater levels and soil saturation is of importance to its impact on triggering landslides of any type.

On 13 November, 1985 a sequence of pyroclastic flows and surges interacted with snow and ice on the summit ice cap atop Nevado del Ruiz volcano in Colombia, triggering lahars that killed about 23,000 people living at the base of the volcano (Pierson et al., 1990). Combined with seismic shaking, the hot eruptive materials quickly melted about 10 km^2 of the snowpack and produced large volumes of meltwater that combined with new volcanic deposits to generate avalanches of snow, ice, and rock debris into the upper reaches of river valleys. Rapid incorporation of valley fill materials transformed the dilute flows and avalanches into debris flows. A total of about 9×10^7 m^3 of debris was transported up to 104 km from the source area before deposition. Key lessons related to climatic influences in this event included: (1) catastrophic lahars can be generated on ice and snow-capped volcanoes by relatively small eruptions; (2) the surface area of snow on an ice cap can be more critical than total ice volume; and (3) the mechanical mixing of hot rock debris with snow increases the rate of heat transfer and provides an efficient mechanism for generating lahars.

14.4 USE OF CLIMATIC DATA FOR FORECASTS AND WARNINGS

14.4.1 Rainfall thresholds

During the past two decades the concept of rainfall thresholds for the triggering of debris flows as presented by Caine (1980) has been widely applied worldwide. Within the USA, rainfall thresholds have been developed for many regions, including the San Francisco Bay region (Cannon and Ellen, 1985), Honolulu, Hawaii (Wilson et al., 1992), Puerto Rico (Jibson, 1989; Larsen and Simon, 1993), Seattle, Washington (Chleborad, 2000, 2003), and the Appalachian and Blue Ridge Mountains of the eastern USA (Neary and Swift, 1987; Wieczorek et al., 2000) (Figure 14.6). Rainfall thresholds for triggering shallow landslides or debris flows have also been developed in many other countries (Table 14.1). Some of these thresholds are based on abundant data and have been incorporated into early warning systems, for example in California (Keefer et al., 1987; Wilson, 2005), Italy (Iritano et al., 1998), Brazil (Ortigao et al., 2003), and Hong Kong (Brand 1985; Hansen et al., 1995). These examples show that debris-flow initiation follows some general trends in climatic conditions.

Rainfall thresholds are valuable for prediction and warning of landslide events, particularly for debris flows, which are high-velocity and high-hazard events. Such thresholds can be either derived for single catchments (e.g. Marchi et al., 2002) or on a regional scale (e.g. Cannon and Ellen, 1985; Glade, 1998; Jakob and Weatherly,

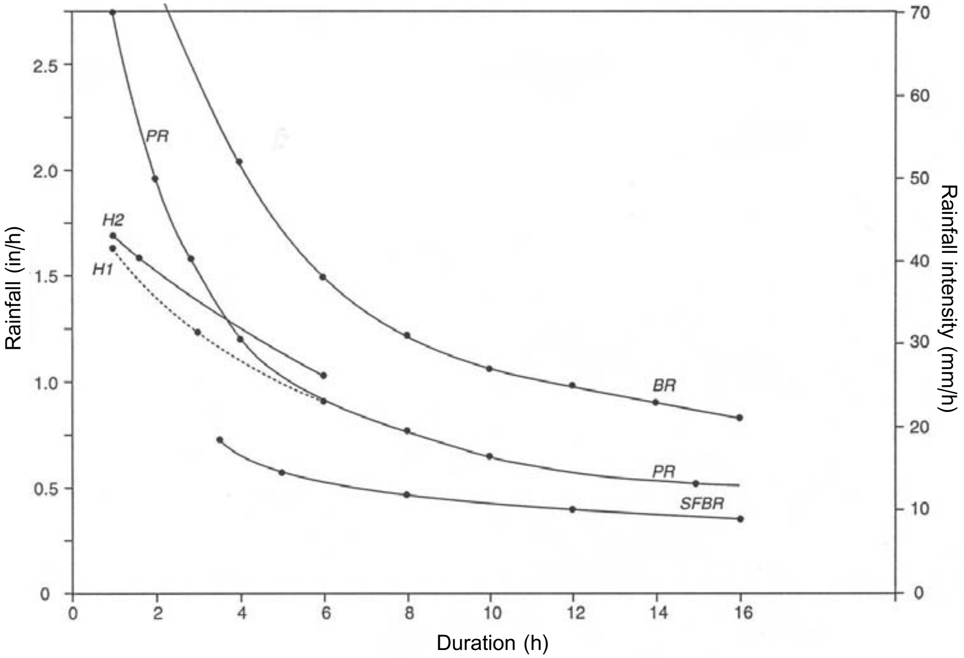

Figure 14.6. Comparison of rainfall thresholds for triggering of debris flows in Hawaii (H1, H2), Puerto Rico (PR), Blue Ridge Mountains of central Virginia (BR), and San Francisco Bay region (SFBR).

Wieczorek et al. (2000).

2003). As noted by Wilson (2000), successful regional rainfall thresholds are based on local conditions of geology, slope geometry, and climate.

Threshold models can be developed with a range of complexity. The simplest models compare only the rainfall amounts within a given period with landslide occurrence. For example, Glade (1998) compares daily rainfall magnitude with landslide occurrence (Figure 14.7). Other periods for which rainfall totals have been applied to determine rainfall thresholds include a single storm event (Corominas and Moya, 1999), a month (Flageollet et al., 1999), a season (Jäger and Dikau, 1994), and a year (Slosson and Larson, 1995; Cuesta et al., 1999).

Rainfall intensity is important in influencing the spatial distribution of debris flows as well as their timing. For several regions of Italy, Crosta and Frattini (2000) examined the correlation between the intensity vs. duration plots for different events and the number and spatial density of debris flows (Figure 14.8). These authors also compared worldwide thresholds using very detailed rainfall intensity information (Figure 14.9).

Regional variation in rainfall thresholds for the triggering of debris flows depends upon many factors, such as morphology, geology, hydrology, and vegetation. Most of the threshold models apply to debris flows triggered on slopes, and different models apply to debris-flow initiation in channel beds (Tognacca et al., 2000).

In examining the effects of climatic variation on rainfall thresholds along the Pacific Coast of the USA, Wilson (2000) noted the importance of the frequency of rainfall as well as mean annual precipitation (MAP). Although MAP is higher in the northern Pacific states of Oregon and Washington than in southern California, for example, the rainfall frequency is also higher in the north, so that the average daily rainfall is less than in southern California. Consequently, the rainfall threshold required to trigger debris flows is greater in the southern region than in the north. This result casts doubt on any simple relation between rainfall thresholds in different climatic regions and MAP.

The *Antecedent Daily Rainfall* model (Crozier and Eyles, 1980) provides a method to calculate the relation between daily rainfall and antecedent rainfall. In this model, triggering rainfall conditions are represented by a combination of antecedent rainfall and rainfall on the day of the event. A study applying this model was conducted in three regions susceptible to landslides on the North Island of New Zealand (Glade et al., 2000). A decay coefficient, derived for each region from the recessional behaviour of storm discharge hydrographs, was used to produce an index for antecedent rainfall. Statistical techniques were used to obtain the thresholds which best separate rainfall conditions associated with landslide occurrence from those associated with non-occurrence or a given probability of occurrence (Figure 14.10).

Modeling techniques have been developed in combination with physical measurements to relate antecedent rainfall to soil saturation and its influence on pore-water pressure. Wilson (1989) developed a numerical model, based on the simple physical concept of a "leaky barrel", which receives additional water from above at one rate, while losing water through leakage below at another rate. The model is used to represent the accumulation of infiltrated rainfall to form a zone of saturation. This *Leaky Barrel* model was tested using rainfall and piezometric data (Figure 14.11) collected at La Honda, California (Wilson and Wieczorek, 1995).

The *Leaky Barrel* model was subsequently used to develop a new threshold for the triggering of debris flows at La Honda based on cumulative rainfall and accounting for soil drainage and rainfall duration (Wilson and Wieczorek, 1995). This threshold identifies conditions for the triggering of single or isolated debris flows within this small area of high landslide susceptibility. In an area of historic debris-flow events in Campania, Italy, Chirico et al. (2000) developed a similar conceptual model of hydrological debris-flow initiation based on buildup of water levels within fractured bedrock and pyroclastic mantle incorporating rainfall, infiltration, surface runoff, evapotranspiration, and subsurface outflow.

Another method involves the weighting of antecedent climatic and soil moisture conditions preceding a rainstorm event (Glade, 2000a). Regional averages of soil depth, porosity, texture, and soil moisture capacity, which provide information on physical properties of soils for the specific regions, were established from the literature. In addition to rainfall inputs and water loss through drainage, the loss of water to the atmosphere through evapotranspiration and the ability of the regolith to retain water have to be taken into account. These factors are incorporated into the *Soil Water Status* model originally developed by Crozier and Eyles (1980) and

Table 14.1. A selection of worldwide criteria for debris-flow triggering threshold.

Continent	Country, location	Type(s) of threshold criteria	Reference(s)
North America	Canada, North Shore Mountains of Vancouver, British Columbia	Antecedent rainfall, rainfall intensity–duration, stream discharge	Jakob and Weatherly (2003)
	USA, San Francisco Bay region, California	Antecedent rainfall, rainfall intensity–duration	Cannon and Ellen (1985)
	USA, Santa Monica Mountains, southern California	Antecedent rainfall, rainfall intensity	Campbell (1975)
	USA, Blue Ridge Mountains, central Virginia	Rainfall intensity–duration	Wieczorek et al. (2000)
	USA, Puerto Rico	Rainfall intensity–duration	Jibson (1989), Larsen and Simon (1993)
	USA, Rocky Mountains, Colorado	Air temperature related to rate of snowmelt	Chleborad et al. (1997)
	USA, Seattle, Washington	Air temperature related to rate of snowmelt, antecedent rainfall, rainfall storm total	Chleborad (2000, 2003)
	USA, Honolulu District, Oahu, Hawaii	Rainfall intensity–duration	Wilson et al. (1992)
South America	Colombia, Manizales	Daily rainfall total	Terlien (1997, 1998)
	Brazil, Rio de Janeiro	Hourly rainfall	Ortigao et al. (2003)
Europe	Germany, Rheinhessen	Cumulative rainfall in specific time interval	Dikau and Jäger (1995), Glade et al. (2001)
	Germany, Bonn Area	Prolonged rainfall, groundwater, no thresholds have been derived	Hardenbicker and Grunert (2001)
	Iceland	Cumulative rainfall in specific time interval	Saemundsson et al. (2003)
	Italy, Piedmont region	Cumulative rainfall in specific time interval	Govi et al. (1985)
	Italy, Tiber River basin	Stream discharge	Reichenbach et al. (1998)

	Italy, Moscardo Torrent, Italian Alps	Total storm rainfall, maximum 1-hr rainfall intensity	Marchi et al. (2002)
	Italy, Cancia area, Dolomites	Rainfall intensity–duration	Bacchini and Zannoni (2003)
	Italy, Cordevola River basin, Dolomites	Antecedent rainfall, cumulative rainfall in specific time interval	Pasuto and Silvano (1998)
	Italy, Valtellina area, northern Italy	Rainfall intensity–duration	Polloni et al. (1992), Crosta (1998), Crosta and Frattini (2000)
	Italy, Calabria	Daily cumulative rainfall	Petrucci and Polemio (2000, 2002)
	Norway	Cumulative rainfall in specific time interval	Sandersen (1997)
	Portugal, north of Lisbon	Antecedent rainfall, rainfall intensity–duration	Zêzere et al. (1999), Zêzere and Rodrigues (2002)
	Poland, Carpathians	Rainfall intensity	Starkel (1996)
	Scotland	Antecedent rainfall, daily rainfall total	Ballantyne (2002)
	Spain, Llobregat River, Eastern Pyrenees	Daily rainfall total	Corominas and Moya (1999)
Asia	China, Hong Kong	Rainfall intensity	Brand et al. (1984), Brand (1989), Premchitt et al. (1994), Chan et al. (2003), Pun et al. (2003)
	India and Bhutan, Himalayas	Daily rainfall total, total storm rainfall	Starkel and Sarkar (2002)
	Japan, Higashi-Hiroshima	Antecedent rainfall, hourly rainfall	Kaibori et al. (2003)
	Japan, Ibi River, Gifu Prefecture	Stream discharge	Onda et al. (2003)
	Korea	Antecedent rainfall, rainfall intensity–duration	Kim et al. (1992)
	Malaysia, Kuala Lumpur, Karak	Rainfall intensity, antecedent preciptiation	Lloyd et al. (2003)
	Nepal	Rainfall intensity, hourly, daily, monthly, and annual rainfall totals	Gerrard and Gardner (2000)
	Taiwan, Nan-Tou County	Antecedent rainfall	Fan et al. (2003)
Australia	Australia, Illawarra area of New South Wales	Antecedent rainfall, daily rainfall total	Chowdhurry and Flentje (2002)
	New Zealand	Antecedent rainfall, rainfall intensity, rainfall storm total	Crozier and Eyles (1980), Crozier (1989, 1997), Glade (2000b)

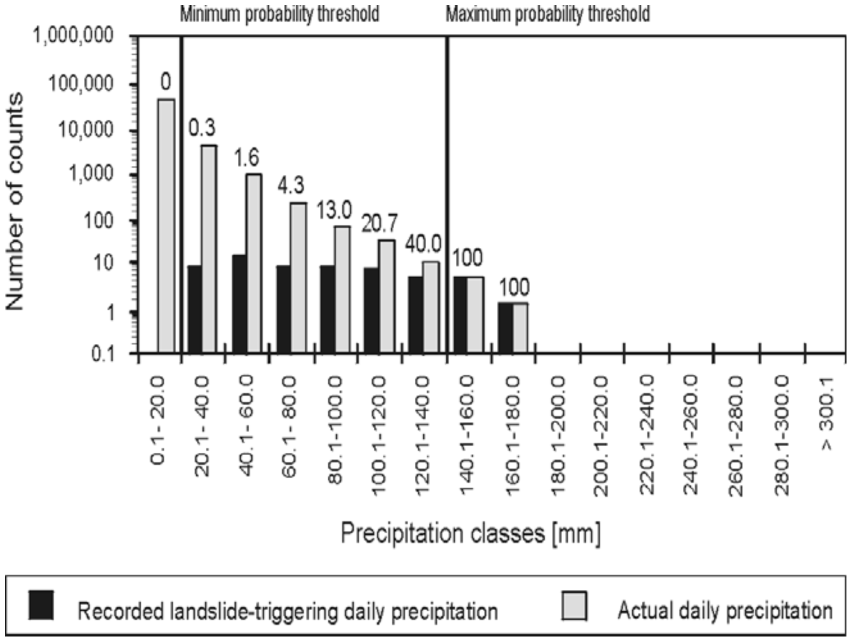

Figure 14.7. Rainfall probability thresholds established by applying the "*Daily Rainfall*" model (Glade, 1998) for the period from 1862 to 1995 for Wellington, New Zealand. The number of counts refers to the total number of rain days used in the analysis. An upper probability rainfall threshold of 140 mm and a lower threshold of 20 mm were established based on all past rainfall events. Any rainfall event greater than 140 mm triggered landslides, whereas no historical landslides were recorded for rainfall less than 20 mm.

further refined by Crozier (1999) and Glade (2000a). Glade determined a decay function for loss of water through drainage using recession curves from hydrographs of different streams with various catchment sizes within the study area. This method requires some assumptions. First, it is assumed that landslides are triggered by the maximum daily rainfall in the region. Second, the location of the triggered landslides is assumed similar to the position where the maximum daily rainfall was recorded. Further, it is assumed that the lowest values of potential evapotranspiration in the region are concurrent with maximum rainfall, and that a landslide is most likely to occur at the location where field moisture capacity is reached. Although the underlying assumptions seem restrictive, previous research in the two New Zealand regions of Wellington (Eyles et al., 1978) and Wairoa (Eyles and Eyles, 1981) support their validity. Crozier (1999) applied this model to the Wellington region and compared rainfall with landslide data from files provided by the Wellington City Council. The model provided a daily update of the soil water status and hence the amount of rainfall necessary to trigger landslides the following day. The probability of rainfall for the following day was calculated using frequency/magnitude statistics. The model results give a satisfactory level of landslide prediction, particularly during periods of intense landslide activity (Crozier, 1999). Despite its capability as an early warning

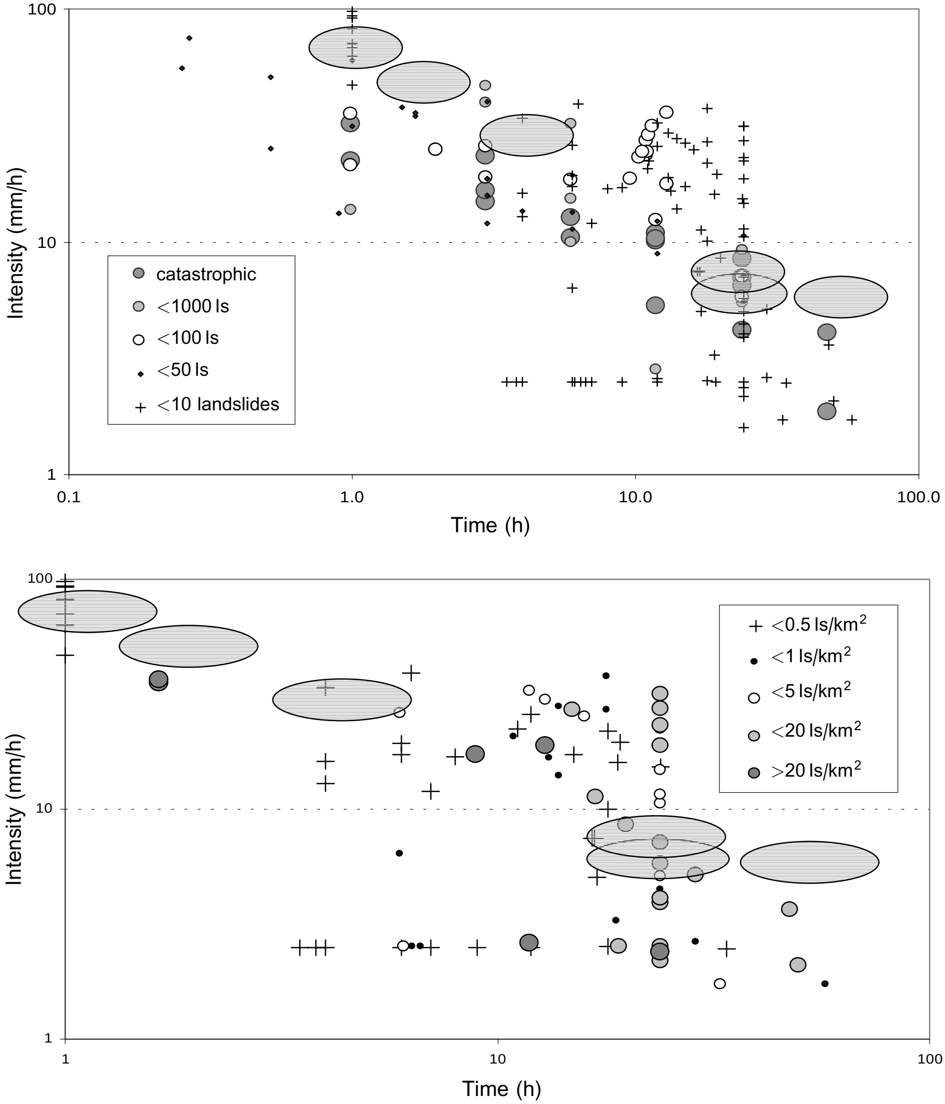

Figure 14.8. Number and spatial density of debris flows for rainstorms of different intensity and duration in the Alps, Prealps, and the Sarno regions of Italy. The gray ellipses indicate the position of the cluster of data points for major events in the Alps, Prealps, and the Sarno areas. From Crosta and Frattini (2000).

system on a daily basis and its successful application for an eight month period, the model has not yet been implemented as a hazard alert system.

The result of applying the *Soil Water Status* model is shown for the Wellington region (Figure 14.12). The graph shows that every landslide occurred with positive soil water status indices, indicating that the field capacity and consequent positive

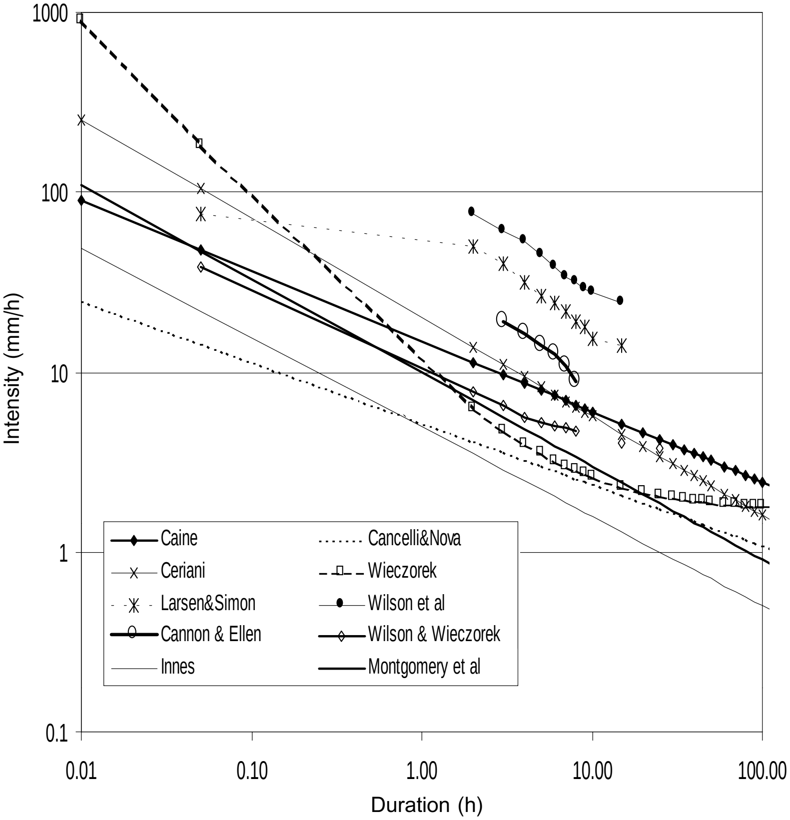

Figure 14.9. Worldwide rainfall thresholds from the literature. The thresholds by Caine (1980), Innes (1983), Cancelli and Nova (1985), and Ceriani et al. (1992) are of global type (i.e., they were prepared using all worldwide data available at the time) (Caine, 1980, Innes, 1983) or for large areas with different soil, morphologic and rainfall characteristics (Ceriani et al., 1992). Local or regional thresholds are from Larsen and Simon (1993), Cannon and Ellen (1985), Wieczorek (1987), Wilson and Wieczorek (1995), and Montgomery et al. (2000).

From Crosta and Frattini (2000).

pore-water pressures were reached (Glade 2000a). Rectilinear thresholds give the probability of landslide occurrence for a given combination of daily rainfall (horizontal line) and soil water status index (vertical line) (Figure 14.12). A similar decay function for soil drainage was used by Jakob and Weatherly (2003) for an application on the North Shore Mountains of Vancouver, Canada.

A worldwide model predicting the principal probabilistic periods of debris-flow danger depending upon the temporal variation of climatic factors in different climatic zones was developed by Belaya (2003). The systematic classification of regions with similar climatic conditions favourable to triggering debris flows has been conducted. The model uses monthly temperatures and precipitation data as well as documented times of rainfall-initiated debris flows occurring in the broad

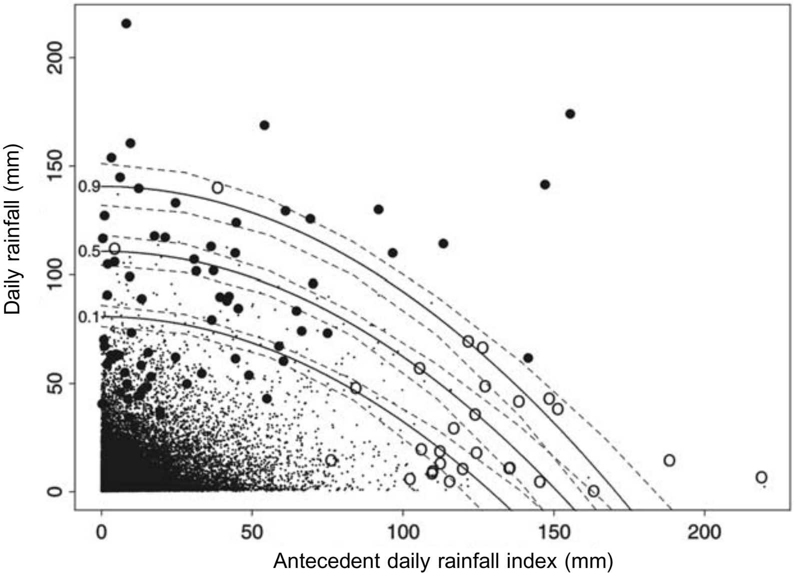

Figure 14.10. Rainfall probability thresholds established by applying the "*Antecedent Daily Rainfall*" model for the period 1862–1995 for Wellington, New Zealand (Glade et al., 2000). The antecedent daily rainfall index compromises the length of the antecedent rainfall period, including water loss to the atmosphere through evapotranspiration, and a decay factor representing the rate of soil moisture decrease in a specific period of time. Large dots relate to rainfall which triggered landslides, open circles relate to rainfall with probable landslide occurrence, and small dots relate to rainfall which did not trigger landslides. Confidence intervals are indicated for each probability curve by dashed lines.

climatic regions of permafrost areas, middle climate regions, and tropical areas. The Climate Research Unit (CRU) Global Climate Dataset, which consists of a mean monthly climatic database, with 0.5° latitude by 0.5° longitude resolution for global land areas, excluding Antarctica, was used for the period 1961–1990. The model characterizes three principal periods of debris-flow hazard: a debris-flow danger period (DFDP) as the part of the calendar year during which 100% of all debris flows occur; the main debris-flow danger period (MDFDP) within the DFDP and accounts for 90% of debris-flow events; and the extreme debris-flow danger period (EDFDP) accounting for 50% of debris-flow events (Figure 14.13). The number of debris flows per unit time increases progressively with each of these periods, from DFDP to MDFDP to EDFDP. The model was applied to all debris-flow regions in all continents to identify DFDP, MDFDP, and EDFDP months and the number of days of the DFDP for the present-day climate.

14.4.2 Forecasts and early warning

For practical applications, debris-flow forecasts, preferably coupled with early warning systems, are a major component of debris-flow risk management. The

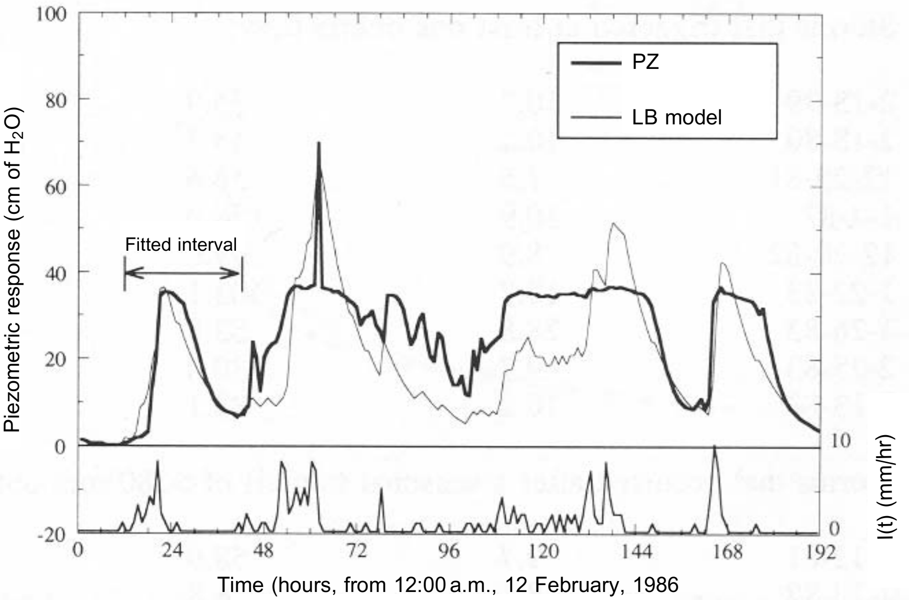

Figure 14.11. Piezometric (PZ) response (dark line) and "*Leaky Barrel*" (LB) modeling (gray line) vs. rainfall intensity for storm events starting at 12:00 a.m., 12 February, 1986 near La Honda, California.

Wilson and Wieczorek (1995).

various approaches include both regional forecasts and local early warnings. A regional forecast might issue a warning such as "*Tomorrow there will be a 50% probability of debris flows somewhere in the XY region*". No specific location can be identified. In contrast, local or site-specific warnings might be given through closure of railways, bridges, or roads to prevent damage from debris-flow impact.

In parts of the western USA, telemetered data on snowpack water equivalent, total precipitation, and air temperature are collected with the SNOTEL acquisition system (Crook, 1983). These data provide an indication of regional slope stability, which is useful for hazard evaluation and warning. Following the numerous debris-flow events of 1983 along the Wasatch Front in Utah (Wieczorek et al., 1989), several potential landslide sites were instrumented in 1984 to measure temperature, precipitation, and slope movement and to relay the data by telemetry to local officials (McCarter and Kaliser, 1985). After temperatures began rising and snowmelt was almost complete by late-May of 1984 in Rudd Canyon, near Salt Lake City, Utah, alarms generated by slow landslide movement gave advance warning of debris flows to local officials (McCarter and Kaliser, 1985).

Rainfall thresholds have been used for regional real-time landslide warning in the San Francisco Bay region, California (Keefer et al., 1987), Hong Kong, China (Hansen et al., 1995), and Rio de Janeiro, Brazil (Ortigao et al., 2003). These warning systems, which rely on nearly continuous ground-based rainfall measure-

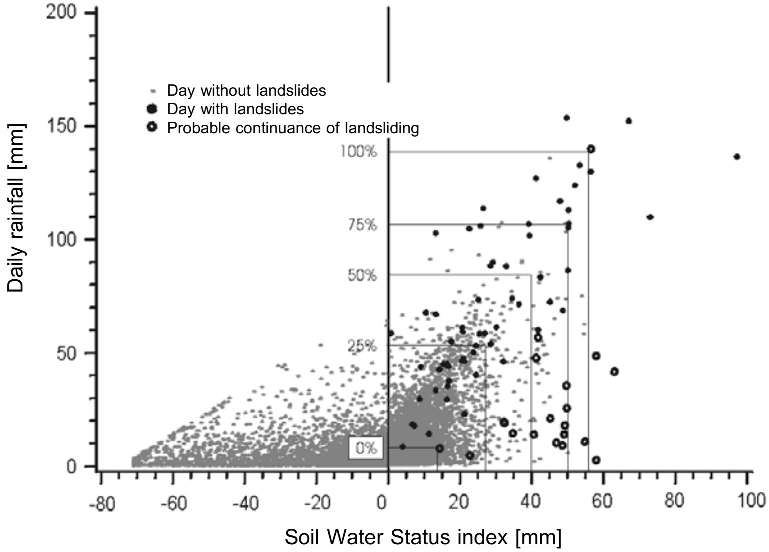

Figure 14.12. Rainfall thresholds established by applying the "*Soil Water Status*" model for the Wellington region, New Zealand (Glade, 2000a). The "*Soil Water Status*" index represents the soil water content critical for slope failure (Crozier and Eyles, 1980; Crozier, 1997).

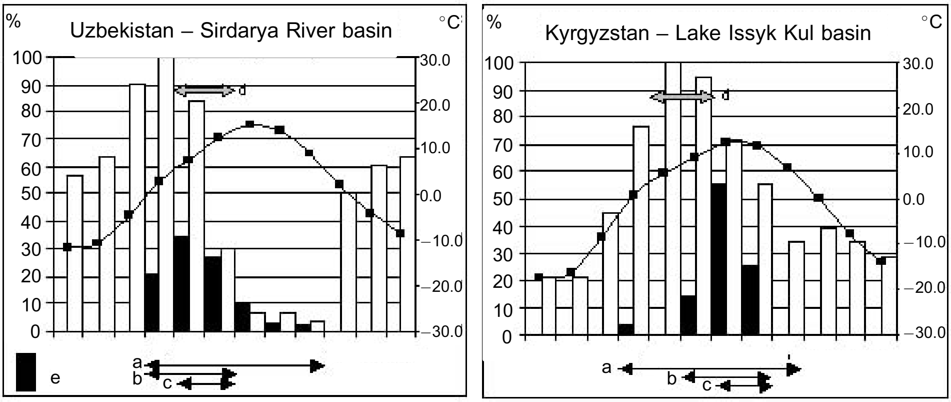

Figure 14.13. Distribution of debris-flow events among calendar months in percent of total (e). Periods of debris-flow danger: (a) DFDP, (b) MDFDP, (c) EDFDP, and (d) snow melt period. Solid lines with squares are monthly air temperature (°C); white bars are percent of maximum monthly precipitation.

Belaya (2003).

ments, can be very accurate temporally, but they may have serious spatial limitations related to the limited number and regional distribution of monitoring stations. Frequent temporal remote sensing of rainfall data, such as from Doppler radar, can provide the information necessary for assessing regional slope stability on a detailed spatial basis during near real time. Post-event comparisons of ground-based rainfall measurements with remote-sensed data for major storms are needed, particularly in areas with major topographic relief, to improve understanding of storm processes and to improve rainfall-estimating techniques based on remote sensing. Improved assessment of localized tropical storms is needed for providing accurate estimates of rainfall totals. Improved use of remote-sensing rainfall data for landslide hazard assessment and warning will depend upon shorter time intervals between measurements to allow sufficient time for analysis, communication of warning, and public response to warning (Wieczorek et al., 2003).

The regional landslide (debris-flow) warning system operated by the US Geological Survey and National Weather Service (NWS) from 1986 to 1995 in the San Francisco Bay region issued public advisories when rainfall conditions reached intensities likely to trigger debris flows from susceptible hillsides (Wilson, 2005). The warning system was based on a set of rainfall thresholds for triggering significant debris-flow activity developed by Cannon and Ellen (1985), forecasting of severe storms by the NWS, and real-time monitoring of rainfall by both agencies. The first public warnings were issued during a severe storm sequence in February 1986 which triggered debris flows that corresponded well with the time intervals of issued advisories (Keefer et al., 1987). Subsequent public advisories were issued during or just before severe storms in 1991, 1993, and 1995. The rapid distribution of a landslide warning and the proper response by the public were problems beyond the measurement of rainfall related to the thresholds for triggering debris flows. Although relatively few people listened directly to the landslide warnings broadcast on the NWS Weather Radio, the warnings would be picked up and rebroadcast by commercial radio and television stations; consequently, these warnings were widely distributed to the public. In addition, many local fire and law enforcement agencies regularly monitored the NWS Weather Radio broadcasts, so these warnings were heard by those responsible for public safety (Wilson, 2005). Although attempts were made to educate the public to respond wisely to landslide warnings, there was no documentation of how the public responded to the issued warnings and how many lives and property values were saved.

In Hong Kong, risk of debris flows from torrential rainstorms with the passage of typhoons, tropical depressions, and severe thunderstorms (Brand, 1985, 1988) has inspired the development of the most comprehensive landslide warning system in the world (Hanson et al., 1995; Wilson, 2005). In May 1982, over 1,000 landslides occurred during four days of severe rain, followed by another 500 during another intense storm in August of that year. The warning system, operated jointly by the Geotechnical Engineering Office of the Hong Kong Government and the Hong Kong Observatory, began issuing warnings in 1984. The warnings are issued when weather forecasts and rainfall data suggest that numerous (>10) debris flows are expected within the city. The rainfall thresholds for numerous debris flows were 175 mm during a 24-h period or 70 mm within one hour. On 5 November, 1993 Lantau Island, west of Hong Kong, experienced an intense storm with a peak 1-hr intensity of 94 mm, peak 6-hr intensity of 423 mm, and 24-hour intensity of 742 mm, resulting in about 600 natural slope failures (Hansen et al., 1995).

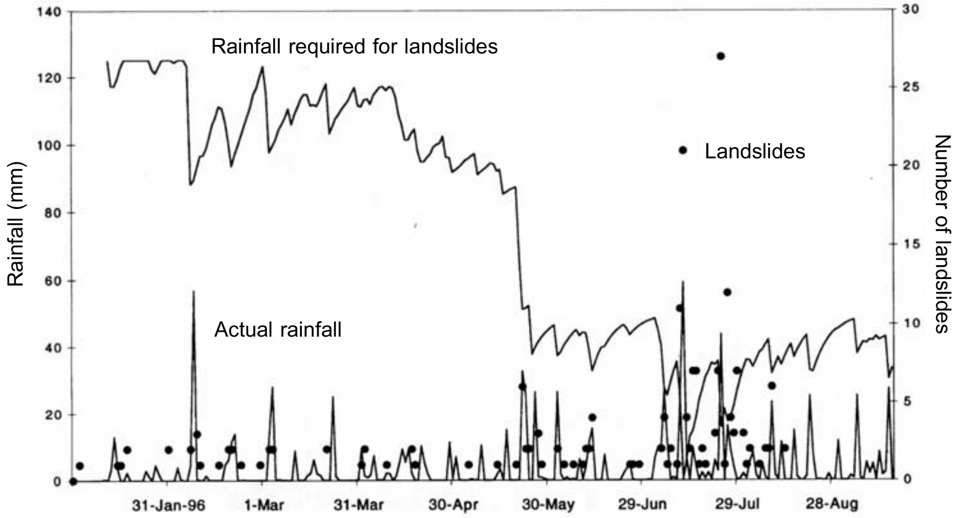

Figure 14.14. Landslide occurrence, daily rainfall, and rainfall required to trigger landslides based on calculations applying the "*Antecedent Soil Water Status*" model (Crozier, 1999). Bold dots refer to the number of landslides, the lower line is the actual rainfall, and the top line indicates the rainfall required to trigger landslides. Note that landslides are also initiated by low-magnitude rainstorm events.

As previously mentioned, Crozier (1999) coupled the previously introduced *Soil Water Status* model with climatic conditions to develop a landslide-triggering threshold for Wellington, New Zealand. Using a water-balance routine with input of daily evaporation and daily rainfall, and constants for soil water storage capacity and a drainage function, daily soil moisture was evaluated using the *Antecedent Soil Water Status model* (Figure 14.14). Based on the evaluation of daily soil moisture a predictive evaluation of the probability of rainfall sufficient for the triggering of landslides was developed (Glade, 1997; Crozier and Glade, 1999; Glade et al., 2000).

Hydrologic models have been developed for forecasting activation of various types of landslides (Reid, 1994; van Asch and Buma, 1997; Bonomi and Cavallin, 1999; see also Chapter 4). A hydrologic model of rainfall infiltration into shallow soils (Iverson, 2000) has been used to represent temporal changes in pore pressure and their effects on regional slope stability for the triggering of debris flows (Baum et al., 2002; Crosta and Frattini, 2003). Continuous remotely-sensed rainfall data from Doppler radar has been utilized with four different hydrologic models to compare predicted slope instability with the timing, number, and distribution of documented debris flows following intense rainstorms (Morrissey et al., 2005; Crosta and Frattini, 2003) (Figure 14.15).

In combination with rainfall thresholds and real-time remotely-sensed rainfall data, regional slope stability models could be used to provide a means of near-real-time prediction and warning of debris-flow hazards. For local sites, detection of debris flows, combined with instrumentation of climatic factors, could be used for

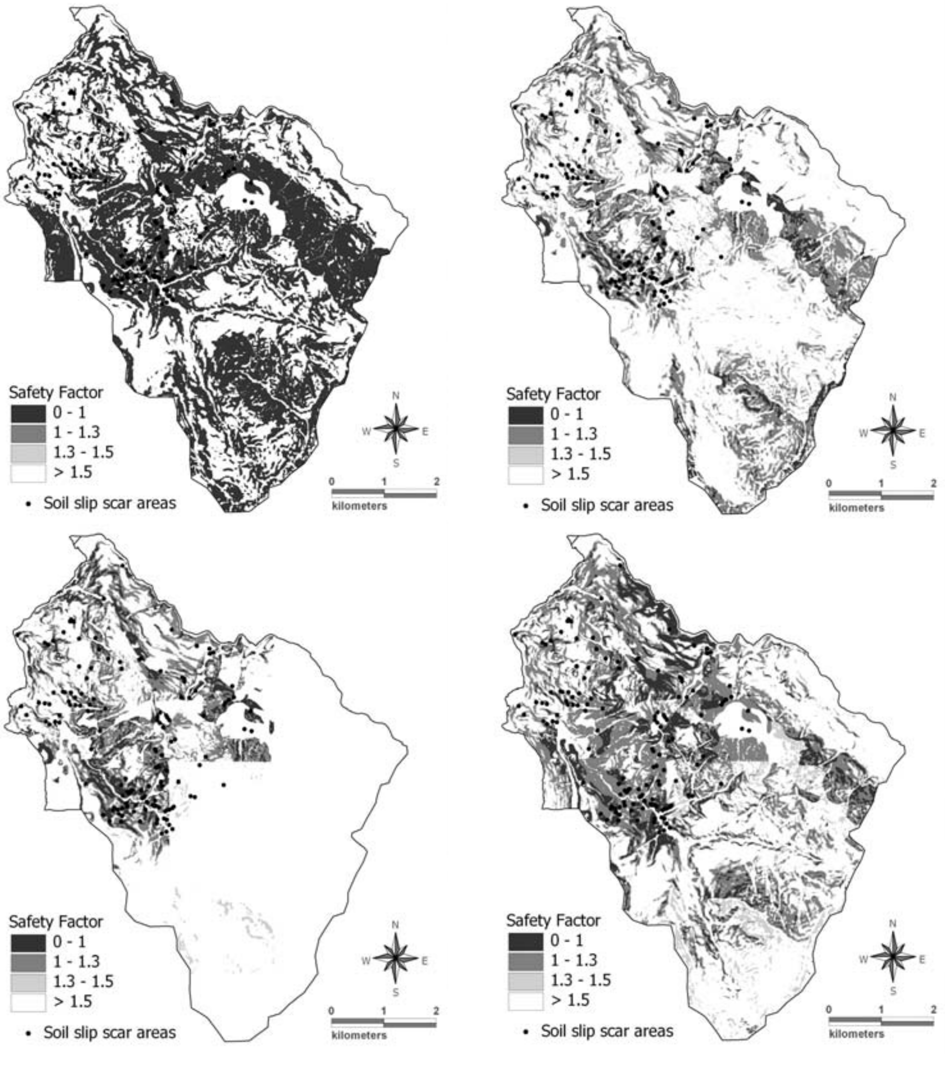

Figure 14.15. Slope stability maps from simulation with different hydrologic models: (a) steady-state model; (b) piston flow model with uniform precipitation; (c) piston flow model with distributed precipitation; and (d) diffusive model with distributed precipitation.

Crosta and Frattini (2003).

hazard warning (Chang, 2003). For example, Arattano et al. (1997) used a monitoring system, including rain gauges, ultrasonic sensors, and a video camera in the upper part of the Moscardo basin, Italy, to detect twelve debris flows between 1989 and 1995. For local hazard warning, monitoring of climatic conditions could serve as a preliminary indicator of potential debris-flow initiation, which could then be further verified by detection of debris-flow movement.

14.5 EFFECTS OF CLIMATE CHANGE ON DEBRIS-FLOW ACTIVITY

The time frame of significant variations in climatic factors relevant to the triggering of debris flows ranges from hourly for rainfall intensity, to daily or weekly for antecedent rainfall, to yearly or multi-yearly for seasonal patterns such as El Niño Southern Oscillation (ENSO), to many thousands of years for fluctuations during the Holocene and Pleistocene. Long-term climatic variations can significantly alter vegetation, topography, and geologic and hydrologic factors, all of which may influence debris-flow susceptibility.

14.5.1 El Niño-Southern Oscillation

The North and South American continents have historically been affected by an irregularity in seasonal patterns of precipitation, known as ENSO. In North America, ENSO generally causes increased rainfall in the southern part of the continent (south of 40° latitude) and dryer conditions in the northern part. The increased storm intensity and seasonal rainfall have resulted in an increase in many types of landslides, including debris flows. Severe El Niño-related storms in 1982–1983 and 1983–1984 triggered thousands of landslides, ranging from debris flows to deep-seated slumps and slides, in Nevada, Utah, and western Colorado (Schuster and Wieczorek, 2002).

In southern coastal Peru, flood and debris-flow deposits have been correlated with previous El Niño events (Keefer et al., 2003). An El Niño seasonal event in this region causing more severe effects than any in recent history has been dated within the period of 1607–1608 AD. Older deposits dominated by flood and debris-flow deposits of similar scale indicate that severe El Niño events occurred throughout the late Pleistocene and Holocene. The period of greatest debris-flow frequency in this part of Peru began about 12,000 years ago and lasted for about 3,600 years during the early Holocene when at least 6 debris-flow events occurred at one site. No severe debris-flow events were detected during the Middle Holocene between about 8,400 and 5,300 years ago, when other evidence indicates that the ENSO pattern was particularly weak (Keefer et al., 2003).

14.5.2 Warmer and dryer climates

Warming trends can be a longer term, secondary climatic influence that causes retreat of glaciers and consequent slope instability. Evans and Clague (1994) demonstrated an increase in slope instability in deglaciated mountainous regions worldwide during climatic warming during the last 100–150 years. Recent retreat of glacial ice has resulted in widespread destabilization of many mountainous areas, resulting in large floods, debris flows, and other types of landslides. In the Swiss Alps, numerous large debris flows were triggered by intense rainfall during the summer of 1987 (Zimmerman and Haeberli, 1992). In this case, glacial melt had uncovered areas of steep, unconsolidated materials which were now prone to mass movement activity. Similarly, the deterioration of alpine permafrost led to the failure of previously frozen talus slopes. In many cases, the source of debris is Little Ice Age glacial deposits left uncovered and oversteepened following recent glacial retreat (Evans and Clague, 1994). Outbursts from moraine-dammed and glacier-dammed lakes also generate floods and debris flows. Recent slope instability due to warming in glacial regions during the past 150 years are probably at least an order of magnitude less than those associated with late Pleistocene deglaciation around 15,000 to 10,000 years ago (Evans and Clague, 1994; Wieczorek and Jäger, 1996).

Examination of prehistoric evidence has shown that in some areas warmer and dryer climate periods affect vegetation, resulting in increased fire frequency and consequently more fire-related debris flows (see Chapter 15). Meyer and Pierce (2003) used ^{14}C-dated geologic records to examine spatial and temporal variations in climate and sedimentation. They found that in Yellowstone National Park, USA episodes of fire-induced debris flows occurred at 300–450-year intervals during the past 3,500 years. Debris-flow deposition decreased during cooler episodes during the Little Ice Age ~1,200–1,900 AD because wetter conditions prevented most fires from spreading. However, the warmer period between 900 and 1,200 AD caused many large fire-related debris flows.

In the Holocene, humans converted large areas from native forest and brush land into agricultural production in various areas throughout Europe. The linkage between climate impact, human impact, and landslide initiation during the Holocene has been shown for Germany (Grunert and Hardenbicker, 1997), Scotland (Innes, 1997), England (Ibsen and Brunsden, 1997), and Italy (Rodolfi, 1997; Wasowski, 1998). Common to these examples is the uncertainty involved in trying to correlate past landslide occurrence with former climate regimes. Dating techniques applicable to mass movements are reviewed by Lang et al. (1999). Examples of applications of these methods are given for the Carpathians in Poland and for Europe by Starkel (1997) and for northern Spain by Gonzalez-Diéz et al. (1999). The complexity of these analyses is increased by human interference with nature and the resulting changes in frequency and magnitude of geomorphic processes, including debris flows.

14.5.3 Forecasting effects of climate change

Speculation regarding global climate change can raise questions regarding the potential for changes in frequency of debris flows in the mid to long-term future. Although forecasts of climate change are uncertain, a tendency for future debris flows can be estimated. Belaya (2003) predicted the likelihood of debris-flow hazards for a scenario of climate change by the year 2050 for a territory within the former USSR. An example from the Caucasus identifying the number of days of the DFDP for the present-day climate, as well as for a scenario of the climate change by the year 2050 is shown in Figure 14.16.

The following examples give applications of General Circulation Models (GCMs) to (1) a complex landslide involving both earth flow and debris flow, and (2) the previously introduced regional landslide-triggering rainfall thresholds based on the *Soil Water Status* model.

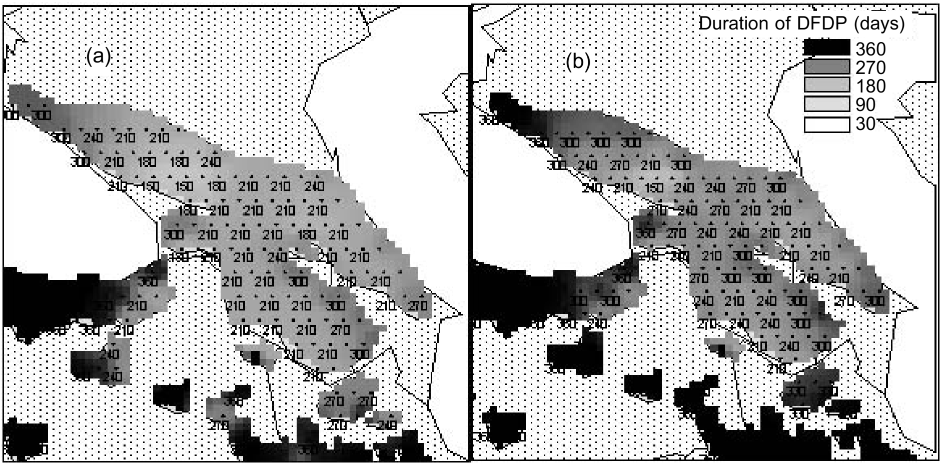

Figure 14.16. Grid points (0.5° latitude by 0.5° longitude spacing) of the CRU Global Climate Dataset and duration of DFDP (in days) in the Caucasus region: (a) for present-day climate and (b) for the year 2050, according to a scenario of the Hadley Center for Climate Prediction and Research (HadCM2).

Belaya (2003).

Dehn and Buma (1999) applied an analogue statistical downscaling technique to predict landslide activity depending on climatic variables in the Barcelonnette basin of the French Alps for the periods of 2020–2049 and 2070–2099. Mean monthly precipitation and temperature were used to calculate potential evapotranspiration for three different GCMs. Climatic data were coupled with a simple hydrological model which simulates groundwater levels in the slope and leads to predictions of landslide movement. The results give no consistent picture of future landslide activity. Some models give decreased activity, some increased. Consequently, improved GCMs and an optimization of the approach are necessary to obtain better information on landslide movement.

Schmidt and Glade (2003) took a similar downscaling approach, and applied GCMs to the regional *Soil Water Status* model for Hawke Bay and Wellington, both located on the North Island of New Zealand. The results show good agreement between observations and the control run for the period 1950–1979 (Figure 14.17(a, b), see color section). In contrast, the predicted values of soil water status for 2070-2099 are shifted towards the y-axis, indicating a decrease in soil water (Figure 14.17(c)). Thus, the probability of landslide events in the period 2070–2099 appears to decrease compared to current conditions (Figure 14.18, see color section).

These examples illustrate the uncertainty associated with such predictions. However, such calculations provide a preliminary approximation of what might happen in the future. Climate change will exert spatially and temporally different responses to the surface and subsurface hydrology of hillslopes. Having established that the interaction of antecedent conditions and rainfall intensity is important to predict debris-flow occurrence, any predictions of the impacts of climate change on debris flows will require knowledge of the climatic effects on each variable. For example, coastal British Columbia has become approximately 10% wetter during the past 100 years (a 10% increase in the total annual precipitation). However, a detailed study of rainfall intensities has not shown any long-term trends, but has identified decadal variations as determined by the Pacific Decadal Oscillation (PDO) (Jakob et al., 2004). This means that any predictions of future debris-flow activity will have to take into account changes in total rainfall, changes in storm frequency, and changes in storm intensity which seem to undergo decadal-scale cycles. It is therefore safe to say that predictions of debris-flow activity, as a consequence of climate change, are in their infancy and much more work has to be done before concrete predictions can be made.

14.6 CONCLUSIONS

Many methods and concepts are available to investigate the relation between climatic factors and debris-flow occurrence. These range in complexity and depend on the scale of investigation. Both site-specific and regional models have demonstrated their validity, and offer a set of choices that can be evaluated for applicability to a given region and civil authority. Further research is necessary to:

- evaluate existing methods;
- transfer them to other regions by calibrating input parameters; and
- develop improved methods by introducing new observational techniques for both monitoring of debris flows and measurement of climatic parameters.

14.7 ACKNOWLEDGEMENTS

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