Representative rainfall thresholds for landslides in the Nepal Himalaya

Ranjan Kumar Dahal [a,b,*,1], Shuichi Hasegawa [a]

[a] Department of Safety Systems Construction Engineering, Faculty of Engineering, Kagawa University, 2217-20, Hayashi-cho, Takamatsu City, 761-0396, Japan
[b] Department of Geology, Tri-Chandra Multiple Campus, Tribhuvan University, Ghantaghar, Kathmandu, Nepal

Abstract

Measuring some 2400 km in length, the Himalaya accommodate millions of people in northern India and Pakistan, Nepal, Bhutan, and parts of other Asian nations. Every year, especially during monsoon rains, landslides and related natural events in these mountains cause tremendous damage to lives, property, infrastructure, and environment. In the context of the Himalaya, however, the rainfall thresholds for landslide initiation are not well understood. This paper describes regional aspects of rainfall thresholds for landslides in the Himalaya. Some 677 landslides occurring from 1951 to 2006 were studied to analyze rainfall thresholds. Out of the 677 landslides, however, only 193 associated with rainfall data were analyzed to yield a threshold relationship between rainfall intensity, rainfall duration, and landslide initiation. The threshold relationship fitted to the lower boundary of the field defined by landslide-triggering rainfall events is $I=73.90D^{-0.79}$ ($I=$rainfall intensity in mm h^{-1} and $D=$duration in hours), revealing that when the daily precipitation exceeds 144 mm, the risk of landslides on Himalayan mountain slopes is high. Normalized rainfall intensity–duration relationships and landslide initiation thresholds were established from the data after normalizing rainfall-intensity data with respect to mean annual precipitation (MAP) as an index in which $N_I=1.10D^{-0.59}$ ($N_I=$normalized intensity in h^{-1}). Finally, the role of antecedent rainfall in causing landslides was also investigated by considering daily rainfall during failure and the cumulative rainfall to discover at what point antecedent rainfall plays an important role in Himalayan landslide processes. Rainfall thresholds presented in this paper are generalized so they can be used in landslide warning systems in the Nepal Himalaya.
© 2008 Elsevier B.V. All rights reserved.

Keywords: Himalaya; Rainfall thresholds; Landslides; Antecedent rainfall

1. Introduction

The Himalayan mountain chain measures 2400 km in length and is one of the tectonically most active mountain ranges on the earth. These mountainous terrains of the Himalaya are home to millions of people living in northern India, northern Pakistan, Nepal, Bhutan, and parts of other Asian nations. Rugged topography, unstable geological structures, soft and fragile rocks, common earthquakes, along with heavy and concentrated rainfalls during monsoon periods cause severe landslides and related phenomena in the Himalayan region. Landslides in the Himalaya are scale-dependent, from massive extent of whole mountain ranges (gravity tectonics) through failure of single peaks to very minor slope failures (Shroder and Bishop, 1998).

The annual economic loss due to landslide damages alone in this region is estimated to exceed one billion US dollars, including hundreds of human fatalities. Studies indicate that the loss due to landslides and related problems in the Himalayan region alone constitutes about 30% of the world's total landslide-related damage value (Li, 1990). In Nepal, for example, in only the half monsoon period of 2007 (i.e., from June 10 to August 15), 70 people were killed by landslides (NRCS, 2007). In 1988, a huge landslide at Darbang, about 200 km west of Kathmandu in Nepal, killed 109 people and temporarily blocked the Myagdi River (Yagi et al., 1990). Another unforgettable landslide tragedy in the region took place at Malpa, Uttarakhand of India on 11 and 17 August 1998, causing the death of 380 people when massive landslides washed away the entire village. Apart from such disastrous

* Corresponding author. Department of Safety Systems Construction Engineering, Faculty of Engineering, Kagawa University, 2217-20, Hayashi-cho, Takamatsu City, 761-0396, Japan. Tel.: +81 87 864 2140; fax: +81 87 864 2031.
E-mail address: ranjan@ranjan.net.np (R.K. Dahal).
URL: http://www.ranjan.net.np (R.K. Dahal).
[1] Tel.: +977 1 411 2090.

landslides, many small-scale landslides go unreported, especially when they occur in remote areas of the Himalaya.

Situated entirely in the Himalaya, Nepal suffers from tremendous landslide disaster problems every year, and a great number of people are affected by large- and small-scale landslides throughout the country, especially during monsoon periods. The small-scale rainfall-triggered landslides in Nepal are generally shallow (about 0.5 to 2.5 m thick) and are triggered by changes in physical properties of slope materials during rainfall (Upreti and Dhital, 1996; Thapa and Dhital, 2000; Khanal and Watanabe, 2005). Relatively large-scale and deep-seated landslides, on the other hand, are affected by long-term variation in rainfall. Although the relation between landslides and precipitation is important, analysis of its controlling factors has remained limited. Many research papers and reports dealing with Himalayan landslides mainly focus on loss of life and wealth, physical properties of landslides and debris flows, effects of regional and local geological settings, and recommendations for environmental-friendly preventive measures (e.g., Brunsden et al., 1981; Wagner, 1983; Manandhar and Khanal, 1988; Dhital et al., 1993; JICA, 1993; Upreti and Dhital, 1996; Gerrard and Gardner, 2000; Dhital, 2003; MoHA 2004; Dahal et al., 2006a), while other works, such as Caine and Mool (1982), Dhakal et al. (1999), DFID and Scott Wilson (2003) focused mainly on landslide risk assessment in Himalayan terrains.

Annual monsoon rainfall in Nepal ranges from as low as 160 mm in the northwestern region to as high as 5500 mm in some isolated areas of central Nepal. However, mean annual rainfall of 1500–2500 mm predominates over most of the country (Chalise and Khanal, 2001). More than 80% of the total annual precipitation occurs during the summer four months (June–September). Likewise, the distribution of daily precipitation during the rainy season is also uneven. Sometimes, 10% of the total annual precipitation can occur in a single day (Alford, 1992), and 50% of the total annual precipitation is often recorded within 10 days of the monsoon period. Such an uneven rainfall pattern is thought to play an important role in triggering landslides in Nepal.

Although rainfall is one of the main factors triggering landslides in Nepal and throughout the Himalaya, the relationship between landslide occurrence and rainfall characteristics, either in empirical equations, or in known physical interactions of slope materials, is still unclear. In the Himalaya, the empirical relationship of rainfall with landslide occurrence, such as the minimum or maximum amount of rainfall necessary for triggering landslides, is yet to be established. There are a few reports towards this effort, but they only address small areas or catchments. Realizing the importance of rainfall threshold for landslides, this paper therefore attempts to portray the regional aspect of rainfall threshold for landslides in the Himalaya, mostly taking into account the cases of landslides in the Nepal Himalaya. For the purpose of establishing an empirical relation for rainfall intensity–duration threshold in the Himalaya, 193 landslide events through 55 years (1951–2006) have been considered for analysis in this paper. The main objectives of this paper are: 1) determining empirical rainfall intensity–duration

thresholds for landslides in the Himalaya; 2) establishing empirical normalized intensity–duration threshold for landslides in the Himalaya; and 3) discovering effectiveness of diurnal intensity and antecedent rainfall for landsliding. The method employed in establishing the rainfall thresholds is similar to that by other researchers (e.g., Caine, 1980; Cancelli and Nova, 1985; Larsen and Simon, 1993; Aleotti, 2004) for such estimations in different parts of the world.

2. Rainfall thresholds for landsliding

The minimum or maximum level of some quantity needed for a process to take place or a state to change is generally defined as a threshold (White et al., 1996; Reichenbach et al., 1998). A maximum threshold refers to a level above which a process always occurs, or there is 100% chance of occurrence of the process at any time when the threshold value is exceeded (Crozier, 1997). In the case of landslides and rainfall, however, the minimum intensity or duration of rainfall necessary to cause a landslide of shallow soil slips, debris flows, debris slides or slumps (Varnes, 1978) is known as the rainfall threshold for landsliding. Wieczorek (1996) defined rainfall threshold as rainfall intensity that facilitates slope instability for a given region.

Characterization of landslide-triggering rainfall has been used to establish the relation between rainfall and landslides in various parts of the world. The most commonly investigated rainfall parameters in relation with landslide initiation include cumulative rainfall, antecedent rainfall, rainfall intensity, and rainfall duration. Attempts have been made to define thresholds employing various combinations of these parameters. Since the majority of slope failures are triggered by extreme rainfall, a number of researchers (e.g., Campbell, 1975; Cotecchia, 1978; Caine, 1980; Innes, 1983; Pomeroy, 1984; Cannon and Ellen, 1985; Neary and Swift, 1987; Keefer et al., 1987; Kim et al., 1991; Li and Wang, 1992; Wilson et al., 1992; Larsen and Simon, 1993; Wilson and Wieczorek, 1995; Wieczorek, 1996; Terlien, 1997, 1998; Crosta, 1998; Crozier, 1999; Glade et al., 2000; Wieczorek et al., 2000; Aleotti, 2004; Guzzetti et al., 2004, 2007; Hong et al., 2005; Zezere et al., 2005; Giannecchini, 2006) have attempted to establish rainfall-intensity thresholds so that slope failure predictions could be made accurately. These various works define rainfall threshold in terms of rainfall intensity, duration vs. intensity ratio, cumulative rainfall in a given time, antecedent rainfall vs. daily rainfall ratio, event rainfall vs. yearly average rainfall ratio, and daily rainfall vs. antecedent excess rainfall ratio.

Caine (1980) first established worldwide rainfall threshold values for landslides. Similar threshold values have been proposed for California (e.g., Cannon and Ellen 1985; Wieczorek, 1987; Wieczorek et al., 2000), Carinthia of Austria (Moser and Hohensinn, 1983), the Southern European Alps (Cancelli and Nova, 1985; Ceriani et al., 1992; Polloni et al., 1992), pre-Alpine regions of northern Italy (Deganutti et al., 2000; Guzzetti et al., 2004), the Piedmont region of Italy (Polloni et al., 1996; Aleotti, 2004), Korea (Kim et al., 1991), southern China (Li and Wang, 1992), Japan (Cotecchia, 1978;

Yatabe et al., 1986; Yano, 1990; Hiura et al., 2005) and Puerto Rico (Larsen and Simon, 1993). Recently Guzzetti et al. (2007) reviewed rainfall thresholds for the initiation of landslides worldwide and proposed new empirical rainfall thresholds for an area of central and southern Europe.

It is understood that, in general, two types of rainfall thresholds can be established; empirical thresholds and physical thresholds (Aleotti, 2004). The empirical thresholds refer to relational values based on statistical analysis of the relationship between rainfall and landslide occurrences (Campbell, 1975; Caine, 1980; Larsen and Simon, 1993; Crozier, 1999; Guzzetti et al., 2004), whereas physical thresholds are usually described with the help of hydrologic and stability models that take into account the parameters such as relationships between rainfall and pore-water pressure, suction, infiltration, slope morphology, and bedrock structures (Montgomery and Dietrich, 1994; Wilson and Wieczorek, 1995; Crosta, 1998; Terlien, 1998; Crosta and Frattini, 2001; Jakob and Weatherly, 2003). Antecedent rainfall (Wilson, 1997; Crozier, 1999; Rahardjo et al., 2001) also plays an important role in the determination of rainfall thresholds.

For the Himalaya no generalized studies exist for landslide and debris-flow initiating precipitation thresholds although these mountains have tremendous landslide problems compared to other parts of the world. A few studies report the relationship between rainfall amount or intensity and size of landslides and debris flows. For example, Starkel (1972), for the first time, observed geomorphic effects of an extreme rainfall event in the eastern Himalaya near Darjeeling, India. In the same area, Froehlich et al. (1990) found that shallow slides and slumps on steep slope segments occur when 24-hour rainfall reaches 130–

150 mm or continuous three-day rainfall totals 180–200 mm. Slumps, landslides, and debris flows at larger scales, however, were observed only after 24-hour rainfall exceeded 250 mm or continuous three-day rainfall reached 350 mm (Froehlich and Starkel, 1987). On the other hand, extensive and simultaneous debris flows occurred after >300 mm in a 24 hour rainfall or >600 mm of continuous three-day rainfall (Froehlich et al., 1990; Froehlich and Starkel, 1993). In a study involving the Kolpu Khola catchment in central Nepal, the rainfall threshold was 100 mm in 24 h, and the landslide frequency increased later in the monsoon, presumably as a result of increased ground-water levels and soil saturation (Caine and Mool, 1982). In the southern hills of Kathmandu, Dahal et al. (2006b) observed that debris slides and flows occurred when 24-hour cumulative rainfall exceeded 260 mm, but for shallow debris slides, this value was 230–250 mm. Similarly, after having studied several slides and debris flows in different parts of the Syangja district of western Nepal occurring in 1979, 1984 and 1995, Khanal and Watanabe (2005) concluded that daily rainfall of 230 mm was responsible for landsliding there. Gabet et al. (2004) described the rainfall threshold in the Khudi catchment of central Nepal by a process-based approach using 3-year daily sediment load and daily rainfall data. They concluded that a minimum monsoon antecedent rainfall of 528 mm must accumulate and a minimum daily rainfall of 9 mm must be exceeded before any landslides are triggered in the Marshyagdi River catchment.

3. Regional geomorphology, geology and climate

Geomorphology, geology, and climate play the most important role in preparatory process of landslide initiation in any
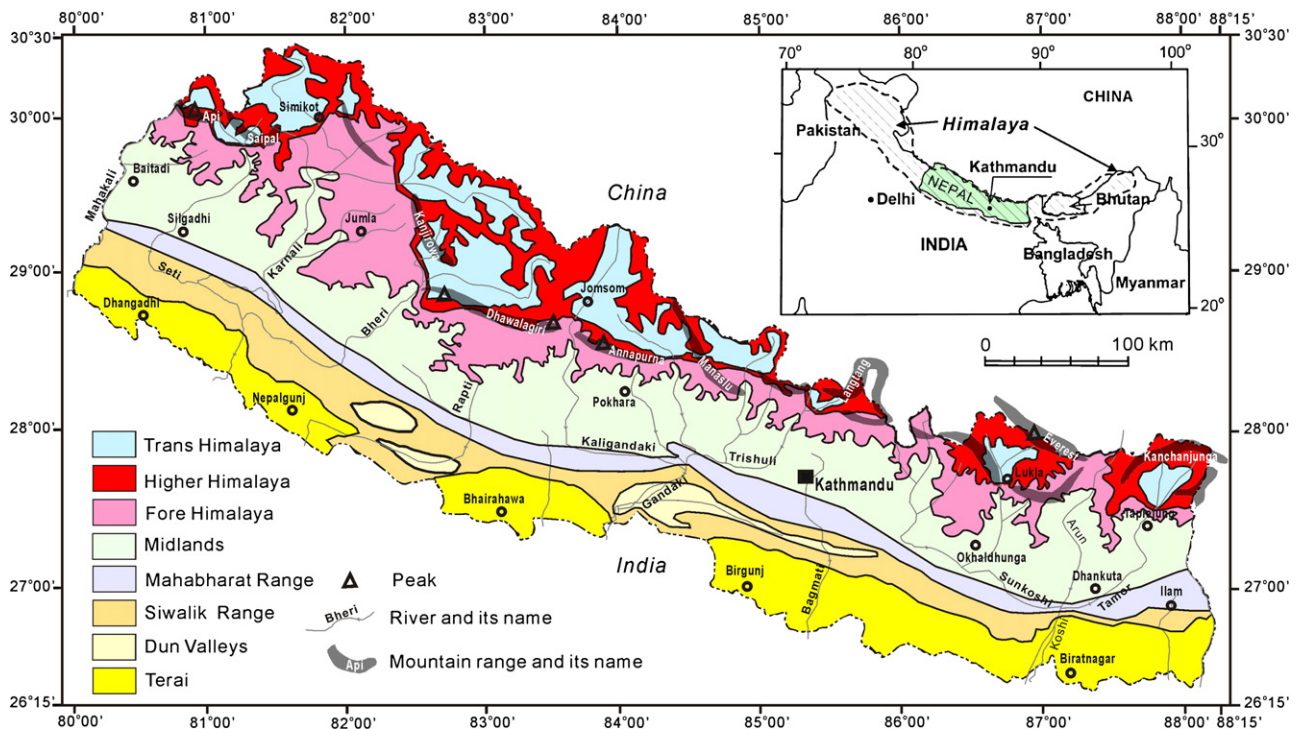

Fig. 1. Regional geomorphic map of Nepal (modified after Hagen, 1969 and Upreti, 1999). Inset shows location of Nepal in the Himalaya.

region. Having emerged as a result of tectonic uplift of sedimentary deposits, the rock-mass in the Himalaya has a high degree of fragility and a greater tendency to undergo accelerated decomposition under the influence of climatic factors. With 83% low to high mountainous area, Nepal covers approximately one third of the Himalayan mountain ranges in the central Himalaya. The Nepal Himalaya has eight well-defined regional geomorphologic zones in a north–south direction: 1) Terai (the northern edge of the Indo-Gangetic plain); 2) Siwalik (Churia) Range; 3) Dun Valleys; 4) Mahabharat Range, 5) Midlands; 6) Fore Himalaya; 7) Higher Himalaya; and 8) Inner and Trans Himalayan Valleys (Hagen, 1969; Upreti, 1999). Each of these zones has unique altitudinal variation, slope and relief characteristics, and climatic pattern. The digital elevation model (DEM) based regional geomorphologic map of Nepal is shown in Fig. 1.

The structural framework of the Himalaya is characterized by three northerly inclined major breaks in the upper crust of the Indian Plate, namely, the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT). These thrust faults distinctly separate the tectonic zones in the Nepal Himalaya, which include the Higher Himalayan Zone, Lesser Himalayan Zone, Siwalik Zone, and Terai Zone (Fig. 2). The MFT on the south separates the sedimentary sequence of the Sub-Himalayan (Siwalik) Zone and the alluvial deposits of Gangetic Plains. The MBT separates the low grade metamorphic rocks of the Lesser Himalayan Zone and the Siwalik Zone. Likewise, the MCT is a boundary between the high grade metamorphic rocks of the Higher Himalayan Zone and the Lesser Himalayan Zone (Schelling, 1992; Upreti, 1999).

Moreover, the South Tibetan Detachment System (STDS) marks the boundary between the Higher Himalayan Zone and the overlying sedimentary sequence of the Tibetan–Tethys Himalayan Zone (Fig. 2).

Controlled by the monsoonal winds and regional geomorphology, the climate of Nepal is extremely varied. It ranges from seasonably humid subtropics to semiarid alpine, but in a more global sense, the climate of Nepal is tropical monsoon, except for parts of the northern area, which lie in the rain shadow of the Himalaya and have a cold semi-desert climate. It is often said that wet monsoon over the Himalaya is responsible for almost 90% of South Asian water resources (Yoshino, 1971; Das, 1995; Upreti and Dhital, 1996; Chalise and Khanal, 2001).

Orographic effects are the main cause of monsoonal rainfall in Nepal, which usually begins in June and ends in September. This effect is largely dependant on the topography. For example, the southern part of central Nepal is gentler than the other parts but rises abruptly in the north to form steep Himalayan peaks like the ranges of Dhaulagiri, Annapurna and Manaslu. As a result of the orography of these ranges, the Pokhara area on the south generally gets much higher rainfall than the other parts of Nepal. For this reason, central Nepal has high values of mean annual rainfall and extreme 24-hour rainfall (Fig. 3).

4. Limitations of the research

Establishing the rainfall threshold for landslides in a particular area requires well-recorded landslide and corresponding rainfall-duration data. In Nepal, however, systematically recorded landslide data are rarely available. This is mainly
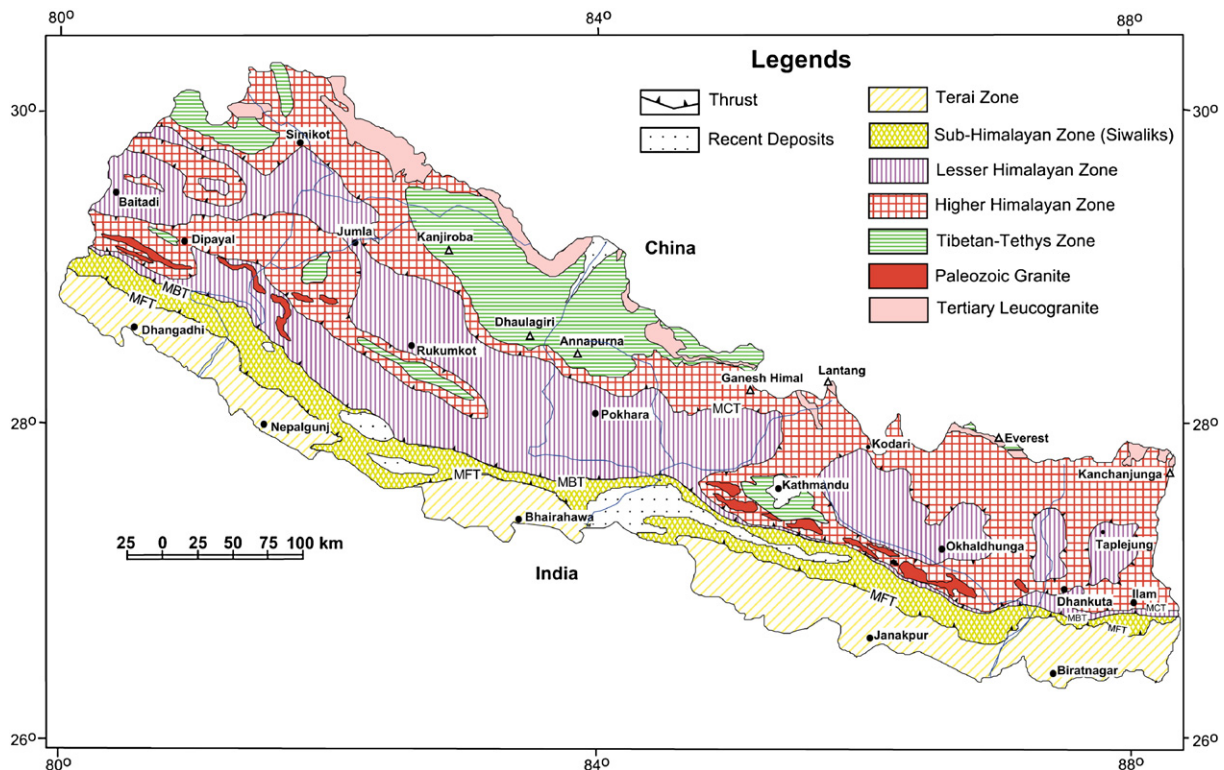

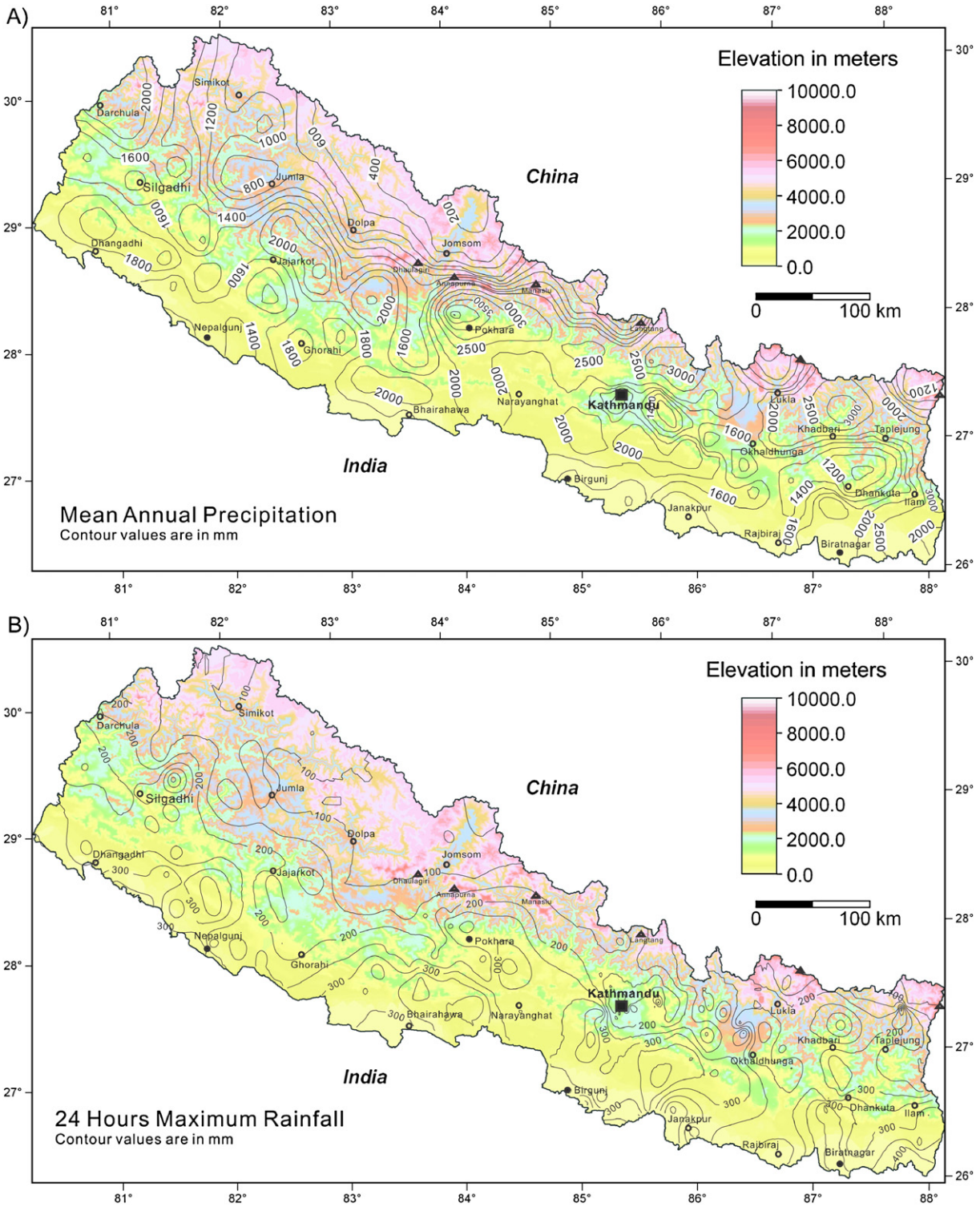Fig. 2. Geological map of Nepal (modified after Amatya and Jnawali, 1994; Dahal, 2006).

Fig. 3. Rainfall distribution in Nepal. A) Mean annual precipitation; B) Maximum rainfall of 24 h. In both figures peak values are around central Nepal (modified after DHM, 2000, 2003).

because no specific authority in Nepal is responsible for recording landslide events in the country. Although the Ministry of Home Affairs (MoHA) collects and publishes natural disaster data in Nepal, landslide and flood disasters have been recorded as the same event. In this paper, therefore, the MoHA disaster data have been used only for cross checking. Other agencies

involved in landslide study and mitigation projects in Nepal include the Department of Water Induced Disasters Prevention (DWIDP) and the Department of Mines and Geology (DMG). Various reports on landslides are published by these organizations, but they lack adequate information on landslide occurrence date and time and corresponding rainfall. The

DWIDP publishes its annual bulletin with annual landslide disaster information (DWIDP Bulletin, 1984–2005). Recently, the Nepal Red Cross Society (NRCS) also prepared an annual disaster database in Nepal.

The method used in calculating rainfall thresholds in this paper is similar to that described by Caine (1980). Crozier (1997), however, pointed out that Caine's dataset did not include climatic events that did not trigger landslides, which is equally important (Larsen and Simon, 1993; Deganutti et al., 2000). In Nepal too, there is no documentation of rainfall events that did not trigger landslides. Likewise, any extreme rainfall events that did not have any correlation with the landslide database of this study do not refer to non-landslide-triggering events. This is because the actual number of landslide events might be different from the information available from newspapers, documentation of MoHA (MoHA, 2004), DWIDP, NRCS and other sources. For this reason, although Crozier (1997) pointed out the issue of non-landslide events, this paper has not been able to trace out such events, which is the main limitation of this research. Some limitations in rainfall data also occurred. Most rainfall stations in Nepal are of non-self recording type, so only 24-hour data, and no hourly data are available. The Department of Hydrology and Meteorology (DHM) measures rainfall data at 8:45 AM each day and records it as the rainfall of that day. A few automated rainfall recording stations also exist, but the data are of limited access. In this research, for each landslide, the corresponding effective, or event-rainfall data on the day of failure were obtained from the nearest rainfall station.

5. Data collection

5.1. Landslide data

For this study, the landslide database was prepared from data in all available sources such as MoHA, DWIDP, NRCS and DMG. The national daily newspapers of Nepal published since 1951 (Gorakhapatra, 1951–2006; Kantipur, 1993–2006) were also considered a source of past landslide information. The personal notes of the first author for the last ten years were also useful. Likewise, some data were collected from the Masters-level dissertations at Tribhuvan University (Karmacharya, 1989; Khanal, 1991; Thanju, 1994; Paudel, 1995; Thapa, 1995; Woli, 1996; Dahal, 1997; Manandhar, 2000; Paudel, 2001). Various published papers were also used in the preparation of the database (Laban, 1979; DPTC and TU, 1994a,b; Amao and Sunuwar, 1993; Dangol et al., 1993a,b, 1996; Dhital et al., 1993; Yagi and Nakamura, 1995; Upreti and Dhital, 1996). To make the data homogeneous, a template was prepared. Landslide locations in terms of village names, ward numbers, and so forth were also recorded, and approximate longitude and latitude of each landslide were also identified from available maps (district maps, topographic maps, and trekking maps). Finally, a database of 677 landslides of different types, scales, and damage levels for the period 1951–2006 was prepared from different secondary- and field-survey data (Fig. 4). Although this database does not include all landslide events since 1951 in Nepal, most landslides caused slight to severe damage. Some debris-flow events were so devastating that they killed more than 50 people, while some events resulted in blockade of highways for only a few hours. In time of failure, out of 677 landslides, nearly 50% were identified as having accurate to middling accuracy of failure time, but the rest had information in terms of day or night only.

5.2. Rainfall data and treatment

A moderate network of rainfall stations in Nepal is maintained by the DHM. Some additionally installed stations belong to the Department of Soil Conservation and Watershed Management, the Department of Irrigation, Nepal Electricity
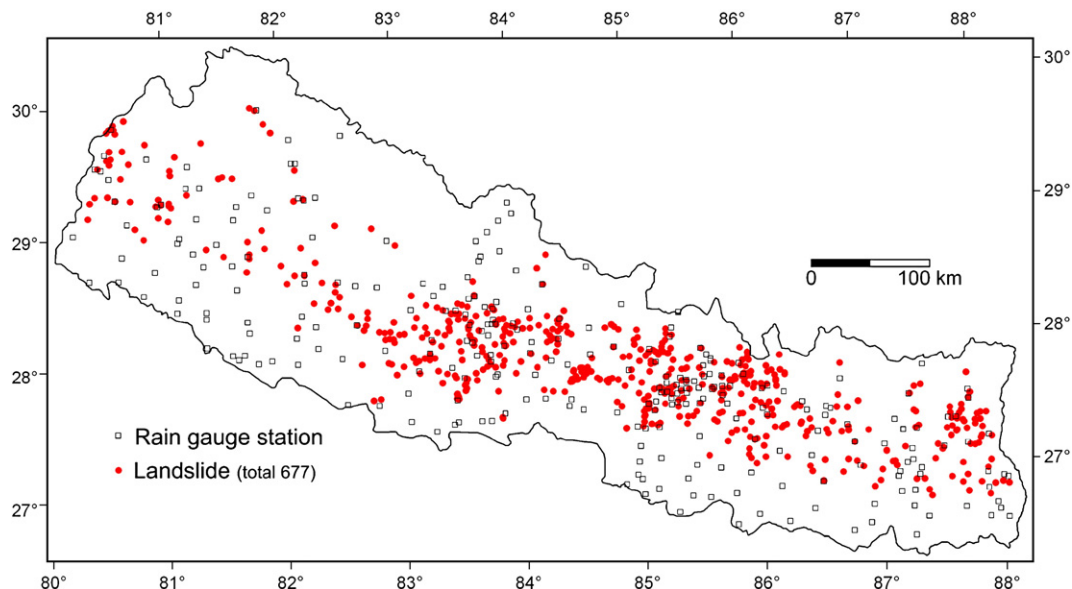

Fig. 4. Landslides in Nepal (data collected from 1951 to 2006) and location of rain gauge stations. The landslides are mainly concentrated in the region of high mean annual rainfall and high 24-hour extreme rainfall. Majority of landslides are concentrated in the Midlands and the Fore Himalaya.
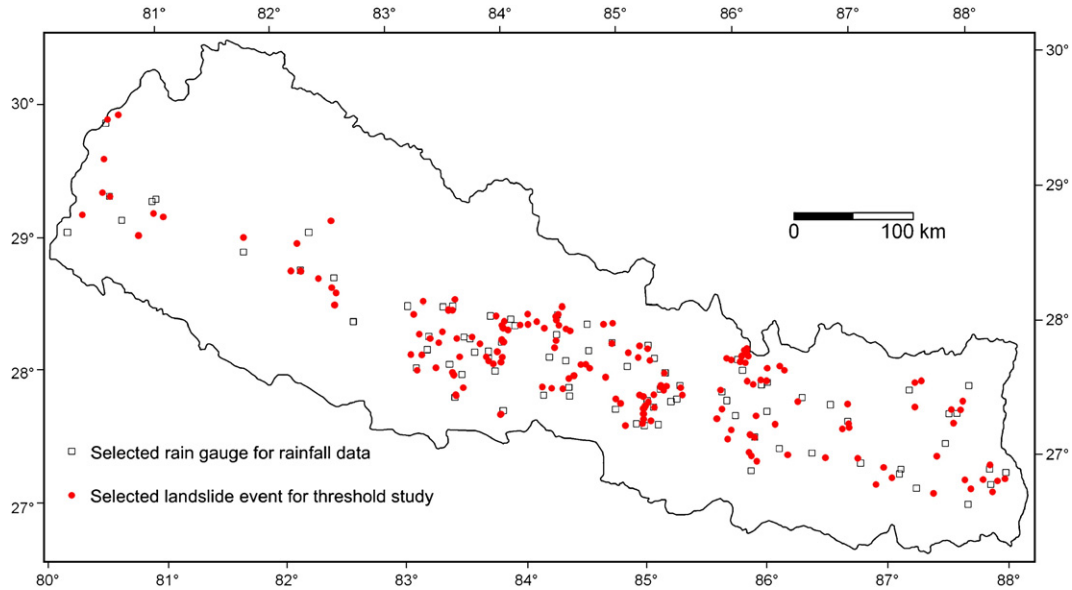
Fig. 5. Selected rainfall events and rain gauge stations for threshold analysis.

Authority, and some non-governmental organizations. The DHM maintains nation-wide networks of 337 precipitation stations, 154 hydrometric stations, 20 sediment stations, 68 climatic stations, 22 agrometeorological stations, nine synoptic stations, and six aero-synoptic stations (Fig. 4). For this study, most of the required rainfall data were purchased from the DHM and some data were also collected from the Department of Soil Conservation and Watershed Management.

To select the rainfall station corresponding to a particular landslide, spatial distributions of landslide locations and precipitation stations were analyzed in a geographic information system (GIS), and the nearest stations were selected. Mainly, the peak precipitation of one day, or continued precipitation of many days at a station, was considered the event rainfall for the corresponding landslide event. During manual tallying of the rainfall data and landslide events, it was noticed that the antecedent rainfalls of 5–90 days were also responsible for triggering some landslide events. The event rainfalls of certain duration other than diurnal, which could not be estimated from the available daily rainfall data, were estimated by the relationship developed by Shakya (2002), who related hourly rainfall and 24-hour total rainfall for the same events, taking into account the data from few automatic stations of Nepal. The relation between 24-hour and lower duration rainfall depths of some specified storm periods can be estimated by the following equation (Shakya, 2002):

$$\frac{P_t}{P_{24}} = \sin\left(\frac{\pi \cdot t}{48}\right)^{0.4727} \tag{1}$$

where t is specified time (in hours) for which rainfall amount needs to be estimated, P_t is rainfall in t hours and P_{24} is total rainfall in 24 h.

Eq. (1) is useful for estimating event rainfall at the time of failure. For example, if the failure time of one landslide is 8:00 PM on 23 July and the continued precipitation record of 23 and 24 July (daily precipitation of 123 mm and 110 mm respectively) is available, the event rainfall duration for this landslide will be 35 h (total rainfall of 8:45 AM of 22 July to 8:45 AM of 23 July and the time between 8:45 AM and 8:00 PM of July 23, i.e. ~11 h) and the total estimated event rainfall will be 206 mm.

6. Threshold analysis

6.1. General intensity–duration relationship

As already stated, out of 677 landslide events, only 193 landslides were identified with respect to rainfall duration. Using the rainfall data corresponding to these 193 landslide events (Fig. 5), a threshold relationship between rainfall intensity and duration for landsliding was established (Fig. 6).
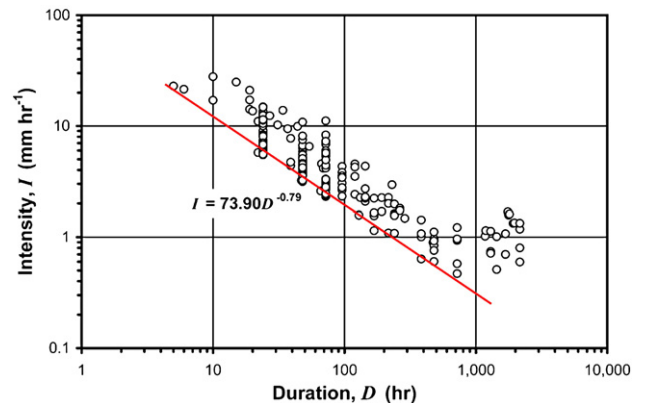

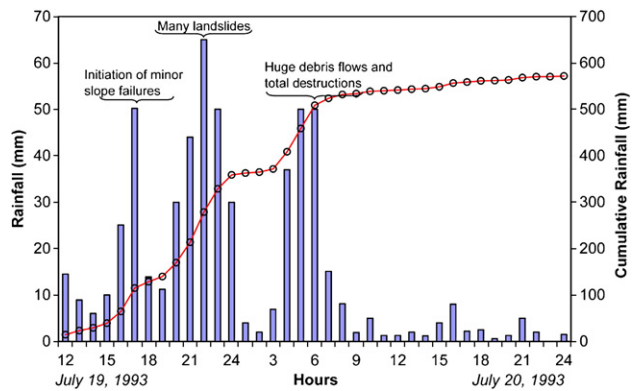Fig. 6. Rainfall intensity–duration threshold curve for landsliding in the Nepal Himalaya.

Fig. 7. Rainfall at Tistung, central Nepal on July 19 and 20, 1993, and the landslides disaster associated with this extreme rainfall, the highest one day (12:00 PM July 19 to 12:00 PM July 20, 1993) precipitation (541.4 mm) ever recorded in Nepal (source: Department of Soil Conservation and Watershed Management).

The threshold, as defined by the lower boundary of the points representing landslide-triggering rainfall events, is expressed as:

$$I = 73.90D^{-0.79} \tag{2}$$

where I is hourly rainfall intensity in millimeters (mm h^{-1}) and D is duration in hours. Eq. (2) has a coefficient of determination of 0.993. Among the 193 landslide data, the proposed curve optimally defines the rainfall events with durations between 5 h and 30 days.

According to this threshold relation for rainfall events of shorter duration such as < 10 h, a rainfall intensity of 12.0 mm h^{-1} is necessary to trigger landslides, while an average precipitation of less than 2 mm h^{-1} appears sufficient to cause landsliding if continued for more than 100 h. Moreover, for continuous rainfall of more than one month, landslides may be triggered even by an average rainfall of less than 1 mm h^{-1} and this is quite possible during monsoon periods.

The short duration rainfalls over the threshold line in Fig. 6 have a strong relation with the landslide characteristics. For example, the rainfall events near the short duration and high intensity side of the threshold line in the figure are responsible for the occurrence of shallow landslides, probably due to abrupt pore pressure development in the soil layer. The landslides of Kulekhani area in central Nepal (Dhital et al., 1993; Thapa, 2001) during the 1993 disasters were typical of that type. The rainfall pattern and the corresponding landslides during the worst monsoon cloud bursts of 1993 in central Nepal are shown in Fig. 7. The hourly rainfall data obtained at the Tistung station, one of the stations installed by the Department of Soil Conservation and Watershed Management, strongly correspond to the land-slides that occurred in the Kulekhani watershed (Dhital et al., 1993, DPTC and TU 1994a; Dhakal et al., 1999; Thapa, 2001) and the surrounding area (Paudel, 1995; Thapa, 1995; Woli, 1996) of central Nepal.

The rainfall events near the long-duration and low-intensity side in Fig. 6, however, have a different description. The long-duration rainfall data belong to Arniko Highway and the surrounding area of Tatopani village, near the Nepal–China

border in central Nepal. This rainfall triggered many large-scale landslides in the area during the monsoons of 1985, 1996, 1999, 2000, 2001, 2002 and 2003. Continuous monsoonal rainfalls of 30 to 90 days were believed responsible for the occurrence of these landslides. One such event of debris slide and debris-flow along Arniko Highway (at Larcha, Bhotekoshi), which killed 54 people in 1996, has been well documented by Adhikari and Koshimizu (2005). They estimated that approximately 120,000 m^3 of soil was displaced on the left bank of the upper reaches of Bhairab Kunda creek.

6.2. Normalized rainfall intensity and thresholds

During data analysis, some landslides were found to have occurred during very low amounts of rainfall corresponding to the nearest stations, which contradicts the threshold relation. The reason for such contradictory data may be a greater rainfall amount at the specific failure location than the amount at the nearest rainfall station, or the influence of human intervention in the form of road construction, which might have reduced the stability of slopes. To ascertain this, the landslides and the corresponding rainfalls were analyzed with respect to the mean annual precipitation (MAP), which is another approach to rainfall threshold analysis (Jibson, 1989; Polloni et al., 1992; Aleotti, 2004; Guzzetti et al., 2007). Some landslide events were found to have occurred during daily accumulation of 4.1% of MAP. This kind of MAP-related landslide-threshold phenomenon was also demonstrated by some researchers for different geographical locations (e.g., Larsen and Simon, 1993; Sandersen et al., 1996; Aleotti, 2004).

The ratio between the critical rainfall of the event and the mean annual precipitation of the site is defined as normalized critical rainfall (NCR), and it is expressed in percentage (Guidicini and Iwasa, 1977; Aleotti, 2004). Remarkable variations in NCR were noted at the time of landsliding in the Himalaya. By normalizing rainfall intensity (Jibson, 1989; Polloni et al., 1992; Aleotti, 2004; Guzzetti et al., 2007) with NCR, it is possible to represent rainfall intensity, duration, and MAP simultaneously. The normalized intensity (i.e., the ratio of rainfall intensity to MAP) can be plotted against duration as
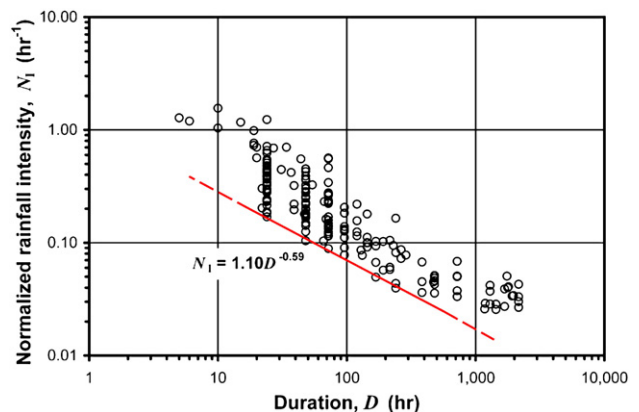

Fig. 8. Normalized rainfall intensity–duration thresholds for the initiation of landslides in the Nepal Himalaya.

indicated in Fig. 8, where the lower bound of the plotted points can be expressed as:

$$N_I = 1.10D^{-0.59} \qquad (3)$$

where N_I is normalized rainfall intensity (h^{-1}). This equation has a coefficient of determination of 0.984. It is useful in estimating rainfall intensity for a landslide event in the form of a percentage of MAP. The threshold relation indicates that for rainfall events of short duration, such as less than 10 h, a normalized rainfall intensity of 0.28 h^{-1} (i.e. 28% of MAP) is required to trigger landslides, while a normalized rainfall intensity of less than 0.07 h^{-1} (7% of MAP) appears sufficient to cause landslides if continued for more than 100 h.

6.3. The threshold comparison

Different climatic regions have different threshold values for rainfall intensities. Guzzetti et al. (2007) have listed 52 previous works of intensity–duration thresholds and 19 previous works of normalized intensity–duration thresholds for the initiation of landslides in global, regional and local contexts. When the Himalayan threshold is compared with some of these relations available in the literature (Fig. 9), it resembles that proposed by Larsen and Simon (1993) for humid tropical Puerto Rico but with a slightly lower threshold value. The threshold obtained by Cancelli and Nova (1985) for the San Francisco Bay Region of high MAP is a little less than the Himalayan threshold, but the curve inclination is the same. The global thresholds proposed by Caine (1980) and Guzzetti et al. (2007), however, are quite different from the Himalayan threshold. Compared to the global threshold, the Himalaya needs high intensity rainfall for landsliding, but when the rainfall duration exceeds 4 days, the rainfall intensity is less than that in the global threshold. This indicates that geomorphological and climatological differences between tropical monsoon and temperate environments may not be significant where hillslopes undergo large amounts of rainfall over a prolonged period. The comparisons with some other threshold equations are also provided in Table 1.

Guzzetti et al. (2007) reveal that inclination of the threshold lines generally depends on the climatic environment of the region.
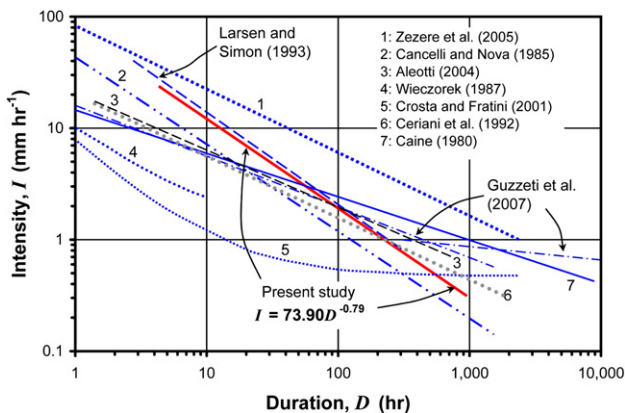
Table 1
Some of rainfall intensity–duration threshold equations for global, regional and local scales

Researchers	Area	Equation
Caine (1980)	World	$I=14.82D^{-0.39}$
Cancelli and Nova (1985)	Valtellina, northern Italy	$I=44.67D^{-0.78}$
Ceriani et al. (1992)	North Italy	$I=20.1D^{-0.55}$
Larsen and Simon (1993)	Porte Rico, Caribbean Sea	$I=91.46D^{-82}$
Deganutti et al. (2000)	Italian Alps, a torrent	$I=15D^{-0.70}$
Wieczorek (1987)	California	$I=1.7+9D^{-1}$
Crosta and Frattini (2001)	World	$I=0.48+7.2D^{-1}$
Aleotti (2004)	Piedmont region, Italy	$I=19D^{-0.50}$
Giannecchini (2006)	Tuscany, Italy	$I=76.199D^{-0.692}$
Guzzetti et al. (2007)	CADSES mid-latitude climate for $D<300$ h	$I=18.6D^{-0.81}$
Guzzetti et al. (2007)	CADSES mid-latitude climate for $D>300$ h	$I=0.82D^{-0.79}$
Present study	Himalaya, Nepal	$I=73.90D^{-0.79}$

They point out that the thresholds defined by various researchers for mid-latitude climates are steeper (power value of D in between −0.70 and −0.81) than the thresholds obtained for the mountains and cold climates (power value of D in between −0.48 and −0.64). This observation also holds true for the threshold in the Himalaya, which lies in the middle latitudinal area.

The normalized rainfall intensity–duration thresholds were also compared with similar thresholds obtained for different parts of the world by various researchers, as presented in Fig. 10. As seen in the figure, for rainfall durations exceeding 100 h, the normalized rainfall intensity–duration threshold for landsliding in the Himalaya is similar to the local threshold proposed by Bacchini and Zannoni (2003) for Cancia, northeastern Italy. Compared to other places, such as Virginia (Wieczorek et al., 2000), Puerto Rico (Jibson, 1989) and California (Cannon, 1988), the Himalayan threshold value is high, whereas it is less than the thresholds obtained for the central European Alps (Ceriani et al., 1992) and Piedmond, Italy (Aleotti, 2004).

7. Effect of antecedent rainfall

Antecedent moisture plays a significant role in the slow saturation of soils, and it influences groundwater level and soil

Fig. 9. Comparison of the landslide-triggering rainfall intensity–duration thresholds from various studies.
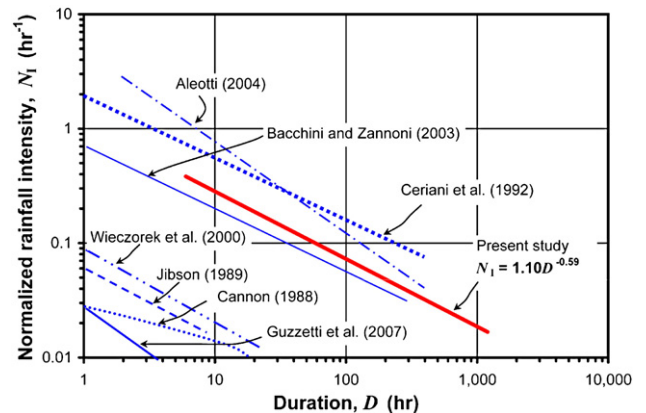

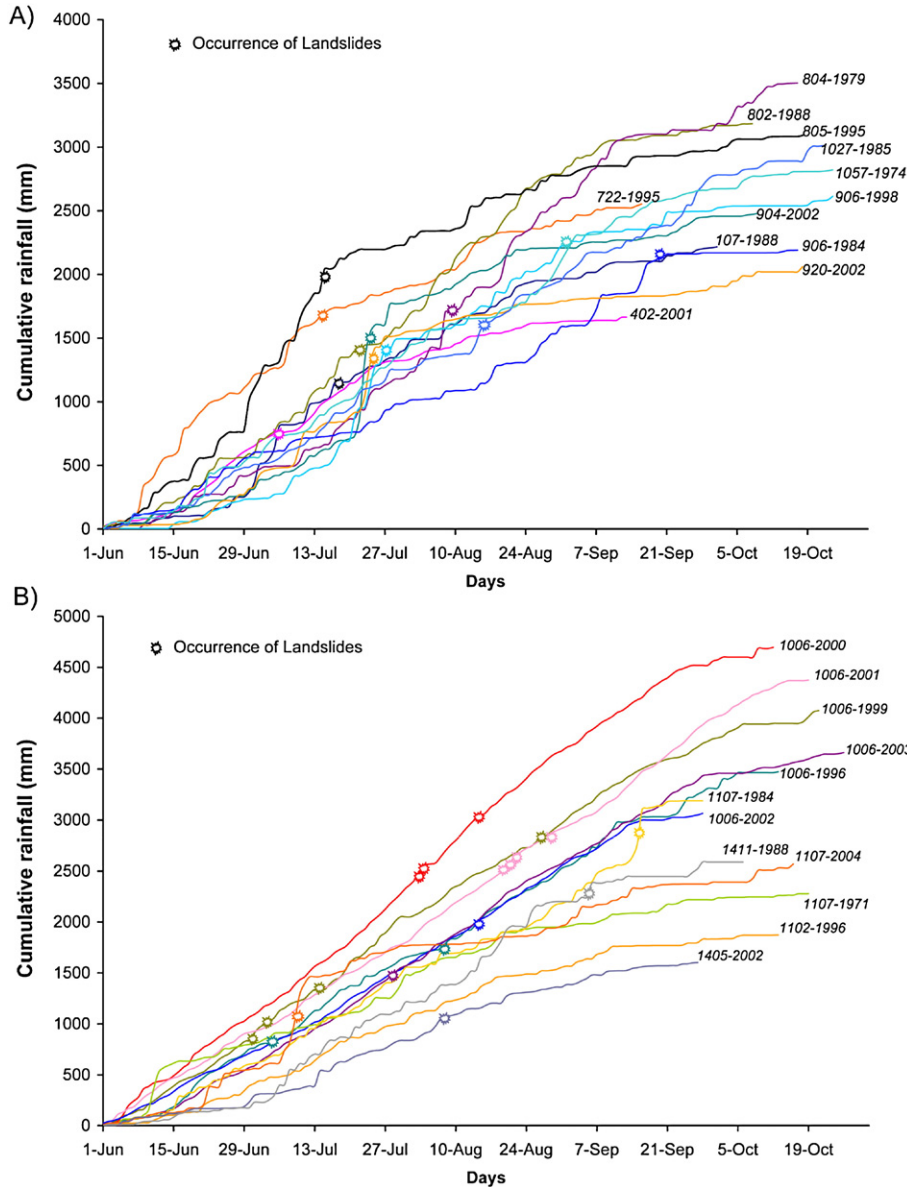Fig. 10. Comparison of the normalized rainfall intensity–duration thresholds from various studies.

Fig. 11. Illustration of cumulative rainfall and occurrence of landslides. Each curve is labeled with the station index number and year. Rainfalls of June to October were plotted here. A) rainfall of western part of Nepal; B) eastern part. Cumulative rainfall of station 1006, situated at about 60 km north east of Kathmandu, has a linear relationship with monsoon days.

moisture. A considerable number of landslides were triggered in the Himalaya by continuous rainfall of 3 to 90 days. The media news in Nepal on the Himalayan landslides often stated "…. continuous rainfall of 5 days (or 7 days or 10 days) blocked the highway and buried …people…". The first author has also noticed such landslide events in the Nepal Himalaya for the last 10 years. Fig. 11 shows examples of rainfall and landslide occurrence time during monsoon period in Nepal. It clearly demonstrates the relationship of progressive monsoon rainfall and frequency of landsliding in the Himalaya.

Much debate ensues on whether or not the rainfall intensity of some period, or the antecedent rainfall, governs slope failure. Some remarkable works on landslide occurrence and antecedent rainfall reveal that antecedent rainfall of 3 days, to as much as 4 months could be significant for explaining landslide
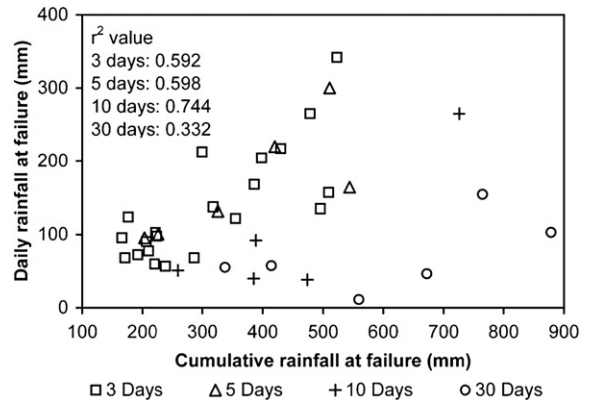

Fig. 12. Relationships between daily rainfall at failure and total rainfall of monsoon at failure, with correlation coefficient values.

occurrences (Kim et al., 1991; Pasuto and Silvano, 1998; Terlien, 1998; Crozier, 1999; Chleborad, 2000; Gabet et al., 2004; Cardinali et al., 2006). Monsoon rains usually fall with interruptions of 2–3 days and are generally characterized by low intensity and long duration. The role of antecedent rainfall in triggering landslides in the Himalaya thus seems obvious. The time durations of the antecedent rainfall taken into consideration

for the landslide events analyzed in this study were 3, 5, 10 and 30 days. From the data of the 193 landslide events considered in this study, when the daily rainfall at failure is correlated with the total cumulative rainfall of 3, 5, 10 and 30 days, the scattered population sample data (Fig. 12) show the values of relevant correlation coefficients as $r^2 = 0.592$, 0.598, 0.744, and 0.332, for 3-, 5-, 10- and 30-day intervals, respectively. It suggests that
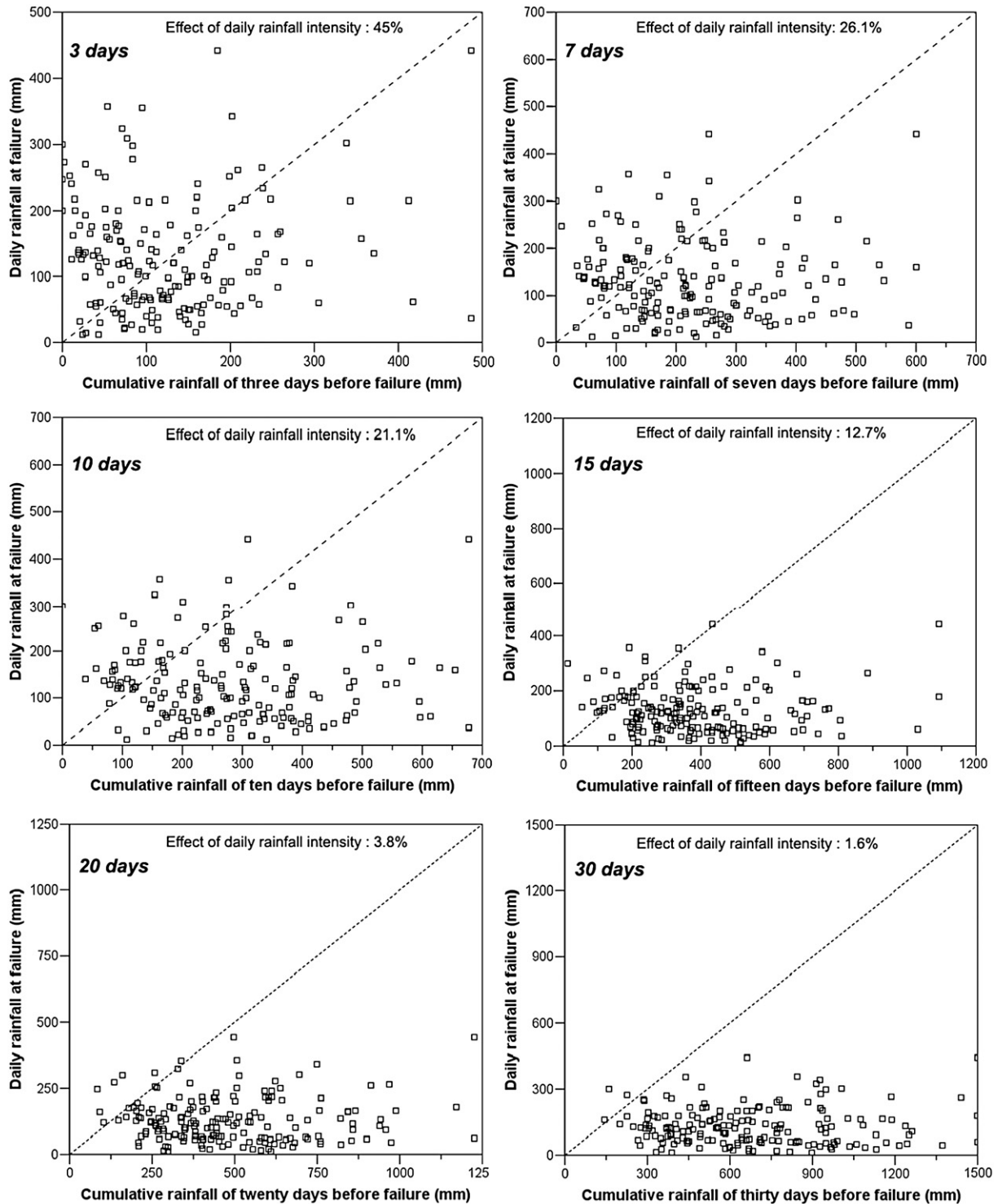

Fig. 13. Relationship between cumulative rainfall (3, 7, 10, 15, 20 and 30 days) and daily rainfall at failure. Broken line (guide line) represents daily and cumulative rainfalls are the same at failure. The effect of daily rainfall intensity for landsliding is found to be decreasing with increment of days of antecedent rainfall.

a moderate correlation exists between the antecedent rainfalls of 3 to 10 days and the daily rainfall at failure.

To understand the effect of antecedent rainfall, another analysis of scattered population of daily rainfall at failure and cumulative rainfall of various days before the rainfall was also carried out. A total of 180 landslide events were selected for analysis of the antecedent rainfall effect. The relationship between daily rainfall at failure and cumulative rainfall of various days (3, 7, 10, 15, 20 and 30 days) before the failure were plotted on arithmetic graphs (Fig. 13). The area of each graph was divided into two halves by a diagonal line in order to distinguish *x*-axis and *y*-axis biased scattering. The divider line in each graph indicates that daily and cumulative rainfalls are the same at the time of failure. This line acts as a guideline to whether daily or cumulative rainfall regulates the landslides (Kim et al., 1991). As shown in Fig. 13, when 3-day cumulative rainfall before failure is plotted against daily rainfall at failure, nearly 45% of the population samples is biased towards the *y*-axis (i.e., daily rainfall at failure), which means out of 180 landslide events, 45% of the events occurred under the influence of daily rainfall intensity. This effect decreases to 26.1%, 21.1%, 12.7%, 3.8% and 1.6% for 7, 10, 15, 20 and 30 days of cumulative rainfall, respectively. This clearly indicates the critical role of antecedent rainfall in the landsliding process in the Himalaya.

8. Concluding remarks

An analysis of the 55-year record of landslides and rainfall events in the Himalaya has suggested that many landslides occurred under the influence of a wide range of rainfall durations (5 h to 90 days). On an average, a rainfall of 10 h or less requires a rainfall intensity in excess of 12 mm h^{-1} to trigger failure, but a rainfall duration of 100 h or longer with an average intensity of 2 mm h^{-1} can also trigger landslides in the Himalaya. Moreover, in the daily rainfall scenario, this study concludes that when daily rainfall amount exceeds 144 mm, there is always risk of landslides in Himalayan slopes. The landslide threshold relation also indicates that as much as three times more rainfall is required to trigger landslides in short duration in the Himalaya than the rainfall amount required to trigger landslides world-wide. Likewise, the difference of rainfall threshold in tropical monsoon and other climates is less significant when rainfall intensity of 100 h is considered.

The comparison between the intensity–duration thresholds and the normalized thresholds of Himalaya shows small variation. The general trend of the threshold lines remains the same, and the pattern of the thresholds is also preserved. However, the normalized intensity–duration threshold could not well represent durations longer than 400 h. The threshold relation indicates that for rainfall events of short duration, such as less than 10 h, a normalized rainfall intensity of 0.28 per hour (i.e. 28% of *MAP*) is required to trigger slope failure, whereas a normalized rainfall intensity of less than 0.07 per hour (7% of *MAP*) may sufficiently cause landsliding when continuous rainfall duration exceeds 100 h. Similarly, for the period of one day, a rainfall amount equaling 17% of *MAP* is required for the initiation of landsliding.

It is also understood that the antecedent rainfall plays an important role in landslide-triggering effect in the Himalaya. Further study may be necessary to understand the effect of antecedent rainfall on the rainfall thresholds for landslides established in this study.

The use of rainfall-landslide thresholds may be most appropriately used in landslide warning systems. The thresholds obtained can be used as a predictive tool, but considerable care must be taken when they are actually used. The empirical threshold usually represents a simplified relationship between rainfall and landslide occurrence. Various factors are involved in causing landslides during rainfall. They include hydraulic, physical and mechanical properties of the terrain and other geomorphological factors such as slope, vegetation cover, micro-climatic characteristics of the area, and perhaps other factors. In this study, no differentiation was made among geological and topographical settings or landuse patterns. A more extensive dataset providing a detailed inventory of failure locations and mechanisms would increase the accuracy of this relation for different parts of the Himalaya. This is just the beginning of this sort of study in the Himalaya and the thresholds proposed in this paper seem a reasonable first approximation for the Nepal Himalaya. Further study is necessary to prepare precise early warning systems from low-resolution hydrometeorological data and the thresholds established in this study that are reliably suitable for the Nepal Himalaya.

References

Adhikari, D.P., Koshimizu, S., 2005. Debris flow disaster at Larcha, upper Bhotekoshi Valley, central Nepal. Island Arc 14, 410–423.

Aleotti, P., 2004. A warning system of rainfall-induced shallow failure. Engineering Geology 73, 247–265.

Alford, D., 1992. Hydrological aspects of the Himalayan region. Occasional Paper No. 18. ICIMOD, Kathmandu. 68 pp.

Amao, K., Sunuwar, L., 1993. Preliminary results of the study on two landslide model sites along the Kathmandu–Trishuli road, central Nepal. Bulletin of the Central Department of Geology, Tribhuvan University 3 (1), 71–76 Special Issue.

Amatya, K.M., Jnawali, B.M., 1994. Geological map of Nepal. Scale: 1:1,000,000. Department of Mines and Geology, Kathmandu, Nepal.

Bacchini, M., Zannoni, A., 2003. Relations between rainfall and triggering of debris-flow: a case study of Cancia (Dolomites, Northeastern Italy). Natural Hazards of Earth System Science 3, 71–79.

Brunsden, D., Jones, D.K.C., Martin, R.P., Doornkamp, J.C., 1981. The geomorphological character of part of the Low Himalaya of Eastern Nepal. Zeitschrift fuÉr Geomorphologie. N.F. Supplementband 37, 25–72.

Caine, N., 1980. The rainfall intensity–duration control of shallow landslides and debris flows. Geografiska Annaler 62A, 23–27.

Caine, N., Mool, P.K., 1982. Landslides in the Kolpu Khola Drainage, Middle Mountain, Nepal. Mountain Research and Development 2, 157–173.

Campbell, R.H., 1975. Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, Southern California. U.S. Geological Survey Professional Paper 851, 1–20.

Cancelli, A., Nova, R., 1985. Landslides in soil debris cover triggered by rainstorms in Valtellina (Central Alps —Italy). Proc. IV international conference and field workshop on landslides, Tokyo, August 1985, pp. 267–272.

Cannon, S.H., 1988. Regional rainfall-threshold conditions for abundant debris-flow activity. In: Ellen, S.D., Wieczorek, G.F. (Eds.), Landslides, floods, and marine effects of the storm of January 3–5, 1982, in the San Francisco Bay Region, California. U.S. Geological Survey Professional Paper, vol. 1434, pp. 27–34.

Cannon, S.H., Ellen, S.D., 1985. Rainfall conditions for abundant debris avalanches, San Francisco Bay region, California. Geology 38, 267–272.

Cardinali, M., Galli, M., Guzzetti, F., Ardizzone, F., Reichenbach, P., Bartoccini, P., 2006. Rainfall induced landslides in December 2004 in Southwestern Umbria, Central Italy. Natural Hazards of Earth System Science 6, 237–260.

Ceriani, M., Lauzi, S., Padovan, N., 1992. Rainfall and landslides in the Alpine area of Lombardia Region, central Alps, Italy. Proceedings, Interpraevent Int. Symp, Bern, vol. 2, pp. 9–20.

Chalise, S.R., Khanal, N.R., 2001. Rainfall and related natural disasters in Nepal. In: Tianchi, Li., Chalise, S.R., Upreti, B.N. (Eds.), Landslide hazards, mitigation to the Hindukush–Himalayas. ICIMOD, Kathmandu, pp. 63–70.

Chleborad, A.F., 2000. Preliminary method for anticipating the occurrence of precipitation-induced landslides in Seattle, Washington. USGS Open-File 00-469 40 pp.

Cotecchia, V., 1978. Systematic reconnaissance mapping and registration of slope movements. Bulletin of the International Association of Engineering Geology 17, 5–37.

Crosta, G., 1998. Regionalization of rainfall threshold: an aid to landslide hazard evaluation. Environmental Geology 35, 131–145.

Crosta, G., Frattini, P., 2001. Rainfall thresholds for triggering soil slips and debris flow. Proc. of EGS 2nd Plinius Conference 2000, Mediterranean Storms. Siena, pp. 463–488.

Crozier, M.J., 1997. The climate–landslide couple: a southern hemisphere perspective. In: Matthews, J.A., Brunsden, D., Frenzel, B., Glaeser, B., Weiss, M.M. (Eds.), Rapid mass movement as a source of climatic evidence for the Holocene. Gustav Fischer Verlag, Stuttgart, pp. 333–354.

Crozier, M.J., 1999. Prediction of rainfall-triggered landslides: a test of the antecedent water status model. Earth Surface Processes and Landforms 24, 825–833.

Dahal, R.K., 1997. Engineering and environmental geological study of Kharidhunga–Tokarpa–Balephi area in the Lesser Himalaya, Central Nepal, M.Sc. Dissertation, Central Department of Geology, Tribhuvan University, Nepal, unpublished, 120 pp.

Dahal, R.K., 2006. Geology for Technical Students — A textbook for Bachelor Level Students. Bhrikuti Academic Publication, Exhibition Road, Kathmandu, Nepal. 756 pp.

Dahal, R.K., Hasegawa, S., Masuda, T., Yamanaka, M., 2006a. In: Marui, H., Marutani, T., Watanabe, N., Kawabe, H., Gonda, Y., Kimura, M., Ochiai, H., Ogawa, K., Fiebiger, G., Heumader, J., Rudolf-Miklau, F., Kienholz, H., Mikos, M. (Eds.), Roadside slope failures in Nepal during torrential rainfall and their mitigation. Proc. Interpraevent Int. Symp, Niigata 2006, Disaster

mitigation of debris flow, slope failures and landslides, vol. 2. Universal Academy Press, Tokyo, pp. 503–514.

Dahal, R.K., Hasegawa, S., Yamanaka, M., Nishino, K., 2006b. Rainfall triggered flow-like landslides: understanding from southern hills of Kathmandu, Nepal and northern Shikoku, Japan. Proc 10th Int Congr of IAEG, The Geological Society of London, IAEG2006 Paper number 819, pp. 1–14 (CD-ROM).

Dangol, V., Shakya, U., Wagner, A., Bhandari, A.N., 1993a. A landslide inventory study (after the disaster of July, 1993) along the Tribhuvan Highway, central Nepal. Bulletin of the Central Department of Geology, Tribhuvan University 3 (1), 59–69 Special Issue.

Dangol, V., Upreti, B.N., Dhital, M.R., Wagner, A., Bhattarai, T.N., Bhandari, A.N., Pant, S.R., Sharma, M.P., 1993b. Engineering geological study of a proposed road corridor in eastern Nepal. Bulletin of the Central Department of Geology, Tribhuvan University 3 (1), 91–107 Special Issue.

Dangol, V., Tamrakar, K.L., Nepali, D.B., Rai, S.M., Joshi, B.M., 1996. Landslide and debris flows of July 1993 in the upper East Rapti River Basin. Bulletin of Central Department of Geology, Tribhuvan University 5, 61–75.

Das, P.K., 1995. The Monsoons, 3rd Ed. National Book Thrust, India. 252 pp.

Deganutti, A.M., Marchi, M., Arattano, M., 2000. Rainfall and debris flow occurrence in the Moscardo basin (Italian Alps). In: Wieczorek, G.F., Naeser, N.D. (Eds.), Proceedings 2nd International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. American Society of Civil Engineers, Taipei, Taiwan, pp. 67–72.

DFID, Scott Wilson, 2003. Landslide risk assessment in the rural access sector, Report on project activities undertaken in Nepal (Nov 2000–March 2003), Landslide Risk Assessment in the Rural Access Sector DoLIDAR/Scott Wilson/DFID, R7815, unpublished, 170 pp.

Dhakal, A.S., Amada, T.K., Aniya, M., 1999. Landslide hazard mapping and application of GIS in the Kulekhani Watershed, Nepal. Mountain Research and Development 19, 3–16.

Dhital, M.R., 2003. Causes and consequences of the 1993 debris flows and landslides in the Kulekhani watershed, central Nepal. In: Rickenmann, D., Chen, C.-L. (Eds.), Proc. 3rd Intl. conf. debris-flow hazardsmitigation: mechanics, prediction and assessment, vol. 2. Millpress, Rotterdam, Netherlands, pp. 931–942.

Dhital, M.R., Khanal, N., Thapa, K.B., 1993. The role of extreme weather events, mass movements, and land use changes in increasing natural hazards. A Report of the preliminary field assessment and workshop on causes of recent damage incurred in south-central Nepal, July 19–20 1993. ICIMOD, Kathmandu. 123 pp.

DHM, 2000. 24 hours extreme rainfall map of Nepal. Department of Hydrology and Meteorology, Kathmandu, Nepal.

DHM, 2003. Mean annual precipitation map of Nepal. Department of Hydrology and Meteorology, Kathmandu, Nepal.

DPTC, TU, 1994a. Preliminary survey of debris flows and landslides in the Palung Khola and the Manohari Khola (Makwanpur district, Central Nepal), Disaster Prevention Technical Centre and Tribhuvan University, Nepal, unpublished, 132 pp.

DPTC, TU, 1994b. Preliminary survey of debris flows and landslides in the Agra Khola, Belkhu Khola, and Malekhu Khola, Disaster Prevention Technical Centre and Tribhuvan University, Nepal, unpublished, 85 pp.

DWIDP Bulletin, 1984–2005. Bulletin of Department of Water Induced Disaster Prevention, Kathmandu, Nepal (total 22 volumes).

Froehlich, W., Starkel, L., 1987. Normal and extreme monsoon rains—their role in the shaping of the Darjeeling Himalaya. Studia Geomerphologica Carpatho–Balcanica, vol. 21, pp. 129–156 (Kakow).

Froehlich, W., Starkel, L., 1993. The effects of deforestation on slope and channel evolution in the tectonically active Darjeeling Himalaya. Earth Surface Processes and Landforms 18, 285–290.

Froehlich, W., Gil, E., Kasza, I., Starkel, L., 1990. Thresholds in the transformation of slopes and river channels in the Darjeeling Himalaya, India. Mountain Research and Development 10, 301–312.

Gabet, E.J., Burbank, D.W., Putkonen, J.K., Pratt-Sitaula, B.A., Oiha, T., 2004. Rainfall thresholds for landsliding in the Himalayas of Nepal. Geomorphology 63, 131–143.

Gerrard, J., Gardner, R.A.M., 2000. Relationships between rainfall and landsliding in the Middle Hills, Nepal. Norsk Geografisk Tidsskrift 54, 74–81.

Giannecchini, R., 2006. Relationship between rainfall and shallow landslides in the southern Apuan Alps (Italy). Natural Hazards of Earth System Science 6, 357–364.

Glade, T., Crozier, M., Smith, P., 2000. Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical Antecedent Daily Rainfall Model. Pure and Applied Geophysics 157, 1059–1079.

Gorakhapatra, 1951–2006. "Gorakhapatra", national daily newspaper of Nepal. Gorakhapatra Sansthan. Kathmandu, Nepal.

Guidicini, G., Iwasa, O.Y., 1977. Tentative correlation between rainfall and landslides in a humid tropical environment. Bulletin of the International Association of Engineering Geology 16, 13–20.

Guzzetti, F., Cardinali, M., Reichenbach, P., Cipolla, F., Sebastiani, C., Galli, M., Salvati, P., 2004. Landslides triggered by the 23 November 2000 rainfall event in the Imperia Province, Western Liguria, Italy. Engineering Geology 73, 229–245.

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2007. Rainfall thresholds for the initiation of landslides in central and southern Europe. Meterology and Atmospheric Physics online first version. DOI 10.1007/s00703-007-0262-7 (accessed on 2007-08-07).

Hagen, T., 1969. Report on the geological survey of Nepal preliminary reconnaissance. Zürich Mémoires de la Soc. Helvétique des Sci. Naturelles. 185 pp.

Hiura, H., Kaibori, M., Suemine, A., Yokoyama, S., Murai, M., 2005. Sediment related disasters generated by typhoons in 2004. In: Senneset, K., Flaate, K., Larsen, J.O. (Eds.), Landslides and Avalanches ICFL2005 Norway, pp. 157–163.

Hong, Y., Hiura, H., Shino, K., Sassa, K., Suemine, A., Fukuoka, H., Wang, G., 2005. The influence of intense rainfall on the activity of large-scale crystalline schist landslides in Shikoku Island, Japan. Landslides 2, 97–105.

Innes, J.L., 1983. Debris flows. Progress in Physical Geography 7, 469–501.

Jakob, M., Weatherly, H., 2003. A hydroclimatic threshold for landslide initiation on the North Shore Mountains of Vancouver, British Columbia. Geomorphology 54, 137–156.

Jibson, R.W., 1989. Debris flow in southern Porto Rico. In: Schultz, A.P., Jibson, R.W. (Eds.), Landslide Processes of the Eastern United States and Puerto Rico. Geological Society of America Special Paper, vol. 236, pp. 29–55.

JICA, 1993. Report of Japan Disaster Relief Team (Expert Team) on heavy rainfall and floods in Nepal. Japan International Cooperation Agency (JICA), JR1JDC/93-03, unpublished, 125 pp.

Kantipur, 1993–2006. "Kantipur", national daily newspaper of Nepal. Kantipur Publication Pvt. (Ltd.), Kathmandu, Nepal.

Karmacharya, M., 1989. Landslide in Nepal in the period 1970–1980. M.Sc. Dissertation, Central Department of Geology, Tribhuvan University, Nepal, unpublished, 55 pp.

Keefer, D.K., Wilson, R.C., Mark, R.K., Brabb, E.E., Brown, W.M., Ellen, S.D., Harp, E.L., Wieczorek, G.F., Alger, C.S., Zatkin, R.S., 1987. Real-time warning during heavy rainfall. Science 238, 921–925.

Khanal, R.K., 1991. Historic landslides of Nepal during 1902–1990 A.D., extent and economic significance. M.Sc. Dissertation, Central Department of Geology, Tribhuvan University, Nepal, unpublished, 94 pp.

Khanal, N.R., Watanabe, T., 2005. Landslide and debris flow hazards induced by heavy precipitation in Nepal. Proc. Intl. symposium on landslide hazard in orogenic zone from the Himalaya to Island Arc in Asia, pp. 111–118.

Kim, S.K., Hong, W.P., Kim, Y.M., 1991. Prediction of rainfall triggered landslides in Korea. In: Bell, D.H. (Ed.), Landslides, vol. 2. A.A. Balkema, Rotterdam, pp. 989–994.

Laban, P., 1979. Landslide Occurrence in Nepal. HMG/FAO and UNDP, Ministry of Forest, Department of Soil Conservation, Integrated Watershed Management, Kathmandu. 27 pp.

Larsen, M.C., Simon, A., 1993. A rainfall intensity–duration threshold for landslides in a humid-tropical environment, Puerto Rico. Geografiska Annaler 75, 13–23.

Li, T., 1990. Landslide management in the mountain area of China. ICIMOD, Kathmandu. Occasion Paper No. 15, 50 pp.

Li, T., Wang, S., 1992. Landslide Hazards and Their Mitigation in China. Science Press, Beijing. 84 pp.

Manandhar, S., 2000. Engineering geological studies of the landslides in the Kulekhani catchment. central Nepal, Lesser Himalaya, M.Sc. Dissertation, Central Department of Geology, Tribhuvan University, Nepal, unpublished, 130 pp.

Manandhar, I.N., Khanal, N.R., 1988. Study on Landscape Process with Special Reference to Landslides in Lele Watershed, Central Nepal. Report submitted to Research Division, Tribhuvan University, unpublished, 53 pp.

MoHA, 2004. Disaster Scenario of Nepal (2000–2003). Ministry of Home Affair. Government of Nepal, 157 pp.

Montgomery, D.R., Dietrich, W.E., 1994. A physically based model for the topographic control on shallow landsliding. Water Resources Research 30, 1153–1171.

Moser, M., Hohensinn, F., 1983. Geotechnical aspects of soil slips in Alpine regions. Engineering Geology 185–211.

Neary, D.G., Swift Jr., L.W., 1987. Rainfall thresholds for triggering a debris avalanching event in the southern Appalachian Mountains. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris flows/avalanches: process, recognition and mitigation. Reviews in Engineering Geology, 7. Geological Society of America, pp. 81–92.

NRCS, 2007. Map of Disaster situation of floods and landslides 2007 (covering 10 July to 15 August, 2007). Nepal Red Cross Society, Kathmandu, Nepal.

Pasuto, A., Silvano, S., 1998. Rainfall as a triggering factor of shallow mass movements, a case study in the Dolomites, Italy. Environmental Geology 35, 184–189.

Paudel, T.R., 1995. Engineering geological and geophysical investigation in the Agra Khola basin. central Nepal, A case study of the landslide disaster of Julv 19–21. 1993. M.Sc. Dissertation, Central Department of Geology, Tribhuvan University, Nepal, unpublished, 89 pp.

Paudel, K.P., 2001. Landslide and its consequences in Nepal (1971–2000). M.A. Dissertation, Central Department of Geography, Tribhuvan University, Nepal, unpublished, 75 pp.

Polloni, G., Ceriani, M., Lauzi, S., Padovan, N., Crosta, G., 1992. Rainfall and soil slipping events in Valtellina. Proc. of the VI International Symposium on Landslides, Christchurch, vol. 1, pp. 183–188.

Polloni, G., Aleotti, P., Baldelli, P., Nosetto, A., Casavecchia, K., 1996. Heavy rain triggered landslides in the Alba area during November 1994 flooding event in the Piemonte Region (Italy). Proc. VII International Symposium on Landslides, Trondheim, vol. 3, pp. 1955–1960.

Pomeroy, J.S., 1984. Storm-induced slope movements at East Brady, north-western Pennsylvania. U.S. Geological Survey Bulletin 1618 16 pp.

Rahardjo, H., Li, X.W., Toll, D.G., Leong, E.C., 2001. The effect of antecedent rainfall on slope stability. Geotechnical and Geological Engineering 19, 371–399.

Reichenbach, P., Cardinali, M., De Vita, P., Guzzetti, F., 1998. Regional hydrological thresholds for landslides and floods in the Tiber River Basin (central Italy). Environmental Geology 35, 146–159.

Sandersen, F., Bakkeoi, S., Hestnes, E., Lied, K., 1996. The influence of meteorological factors on the initiation of debris flows, rockfalls, rockslides and rockmass stability. . Proc. of the VII International Symposium on Landslides, Trondheim, vol. 1. Balkema, Rotterdam, pp. 97–114.

Schelling, D., 1992. The tectonostratigraphy and structure of the eastern Nepal Himalaya. Tectonics 11, 925–943.

Shakya, B., 2002. A new approach within hydrometeorological technique for the estimation of average depth of probable maximum precipitation (PMP) over Nepal. In: Wu, et al. (Ed.), Flood Defence 2002. Science Press, New York Ltd., pp. 599–606.

Shroder, J.F., Bishop, M.P., 1998. Mass movement in the Himalaya: new insights and research directions. Geomorphology 26, 13–35.

Starkel, L., 1972. The role of catastrophic rainfall in the shaping of the relief of the Lower Himalaya (Darjeeling Hills). Geographia Polonica 21, 103–147.

Terlien, M.T.J., 1997. Hydrological landslide triggering in ash covered slopes of Manizales (Columbia). Geomorphology 20, 165–175.

Terlien, M.T.J., 1998. The determination of statistical and deterministic hydrological landslide-triggering thresholds. Environmental Geology 35, 124–130.

Thanju, R., 1994. Engineering geological studies of the Butwal landside (1978) and its adjacent area, west central Nepal, Sub-Himalaya. M.Sc. Dissertation, Central Department of Geology, Tribhuvan University, Nepal, unpublished, 67 pp.

Thapa, K.B., 2001. Water-induced disaster in the Himalaya: case study of an extreme weather event in central Nepal. In: Tianchi, Li, Chalise, S.R.,

Upreti, B.N. (Eds.), Landslide problem mitigation to the Hindukush–Himalayas. ICIMOD, pp. 71–78.

Thapa, P.B., 1995. Engineering geological studies of landslides induced by disaster of July 19–21, 1993, the Agra Khola basin, central Nepal, Lesser Himalaya. M.Sc. Dissertation, Central Department of Geology, Tribhuvan University, Nepal, unpublished, 135 pp.

Thapa, P.B., Dhital, M.R., 2000. Landslides and debris flows of 19–21 July 1993 in the Agra Khola watershed of Central Nepal. Journal of Nepal Geological Society 21, 5–20.

Upreti, B.N., 1999. An overview of the stratigraphy and tectonics of the Nepal Himalaya. Journal of Asian Earth Sciences 17, 577–606.

Upreti, B.N., Dhital, M.R., 1996. Landslide Studies and Management in Nepal. ICIMOD, Nepal. 87 pp.

Varnes, D.J., 1978. Slope movement types and process. In Schuster, R.L., Krizek, R.J. (Eds.), Landslides Analysis and Control. Special Report 176, Transportation Research Board, National Academy of Sciences, Washington D.C., pp. 12–33.

Wagner, A., 1983. The Principal Geological Factors Leading to Landslides in the Foothills of Nepal: A Statistical Study of 100 Landslides — Steps for Mapping the Risk of Landslides. HELVETAS–Swiss Technical Cooperation and ITECO–Company for International Cooperation and Development, unpublished, 58 pp.

White, I.D., Mottershead, D.N., Harrison, J.J., 1996. Environmental Systems, 2nd Ed. Chapman and Hall, London. 616 pp.

Wieczorek, G.F., 1987. Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California. In: Crosta, G., Wieczorek, G.F. (Eds.), Debris Flows/Avalanches: Processes, Recognition and Mitigation. Reviews in Engineering Geology, vol. 7. Geological Society of America, pp. 23–104.

Wieczorek, G.F., 1996. Landslide triggering mechanisms. In: Turner, A.K., Schuster, R.L. (Eds.), Landslides: Investigation and Mitigation, Transportation Research Board, Special Report 247. National Research Council, Washington, pp. 76–79.

Wieczorek, G.F., Morgan, B.A., Campbell, R.H., 2000. Debris flow hazards in the Blue Ridge of Central Virginia. Environmental and Engineering Geoscience 6, 3–23.

Wilson, R.C., 1997. Normalizing rainfall/debris-flow thresholds along the U.S. Pacific coast for long-term variations in precipitation climate. In: Chen, C.L. (Ed.), Proc. 1st Int. Conf. on Debris-Flow Hazard Mitigation. American Society of Civil Engineers, San Francisco, pp. 32–43.

Wilson, R.C., Wieczorek, G.F., 1995. Rainfall threshold for the initiation of debris flow at La Honda, California. Environmental and Engineering Geoscience 1, 11–27.

Wilson, R.C., Torikai, J.D., Ellen, S.D., 1992. Development of rainfall warning thresholds for debris flows in the Honolulu District, Oahu. USGS Open-File 92–521, 45 pp.

Woli, C.B., 1996. Geological and engineering geological studies of the Agra Khola basin with a special reference to landslides induced by disaster of July 19–21, 1993 (central Nepal, Lesser Himalaya). M.Sc. Dissertation, Central Department of Geology, Tribhuvan University, Nepal, unpublished, 139 pp.

Yagi, H., Nakamura, B., 1995. Landslide mapping on large scale and slide in lower Nepal Himalayas. Proceeding of International Seminar on Water Induced Disaster Organized by DPTC, Kathmandu, pp. 160–172.

Yagi, H., Maruo, Y., Saijo, K., Nakamura, S., 1990. The September 1988 large landslide in the vicinity of MCT, Darbang, Nepal. Journal of the Japan Geological Society 26, 45–49.

Yano, K., 1990. Studies on deciding rainfall threshold from warning and evacuating from debris flow disaster by improving the decision method of preceding rainfall. Journal of Japan Erosion Control Society 43 (4), 3–13 (in Japanese with English abstract).

Yatabe, R., Yagi, N., Enoki, M., 1986. Prediction of slope failure based on the amount of rainfall. Japanese Society of Civil Engineers 376, 297–305 (in Japanese).

Yoshino, M.M., 1971. Some aspects of the intertropical convergence zones and the polar frontal zones over monsoon Asia. In: Yoshino, M.M. (Ed.), Water Balance of Monsoon Asia. University of Tokyo Press, pp. 87–108.

Zezere, J.L., Trigo, R.M., Trigo, I.F., 2005. Shallow and deep landslides induced by rainfall in the Lisbon region (Portugal): assessment of relationships with the North Atlantic Oscillation. Natural Hazards of Earth System Science 5, 331–344.