Representative Rainfall thresholds for landslides in the Nepal Himalaya

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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 $I = 73.90\ D^{-0.79}$ (I = rainfall intensity in mm hr^{-1} and D = duration in hours), revealed 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 $N_I = 1.10\ D^{-0.59}$ (N_I = normalized intensity (h^{-1}) and D = duration in hours). 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.

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 percent 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 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 (1983), 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 5,500 mm in some isolated areas of central Nepal. However, mean annual rainfall of 1,500–2,500 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 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; Canon 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 Hohensim 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), Piedmont region of Italy (Polloni et al., 1996; Aleotti, 2004), Korea (Kim et al., 1991), southren 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 catchments in central Nepal, the rainfall threshold was 100 mm in 24 hours, and the landslide frequency increased later in the monsoon, presumably as a result of increased groundwater 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 region. Having emerged as a result of tectonic uplift of sedimentary deposits, the rock-mass in the Himalaya has 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.

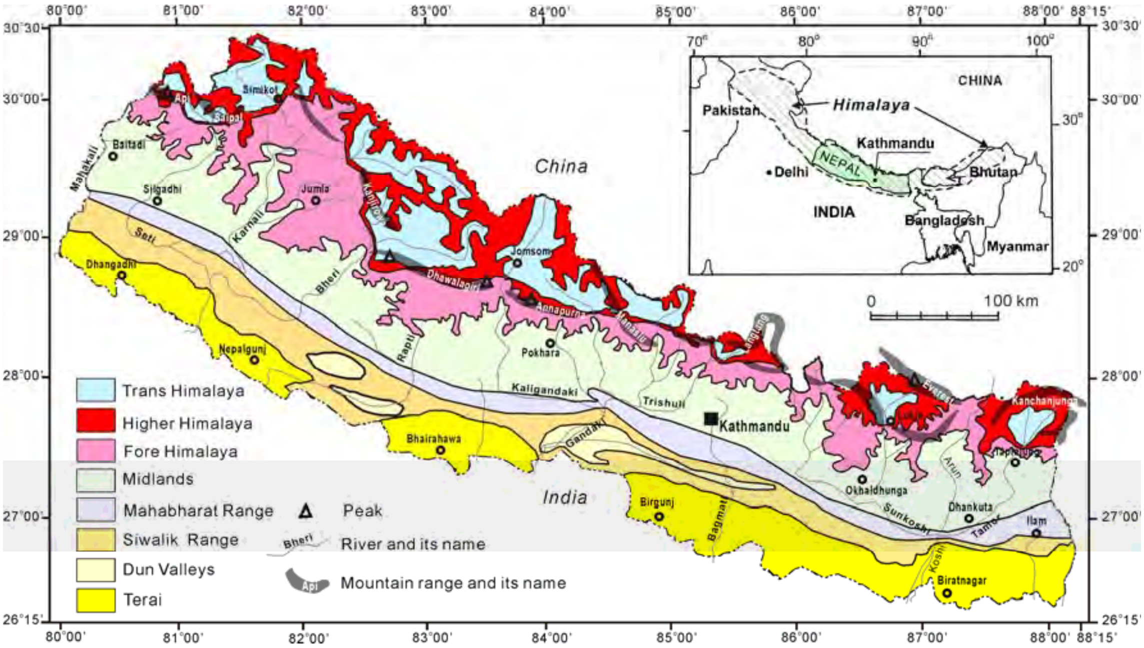

Fig. 1. Regional geomorphic map of Nepal (modified after Hagen, 1969 and Upreti, 1999). Inset shows location of Nepal in the Himalaya.

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).

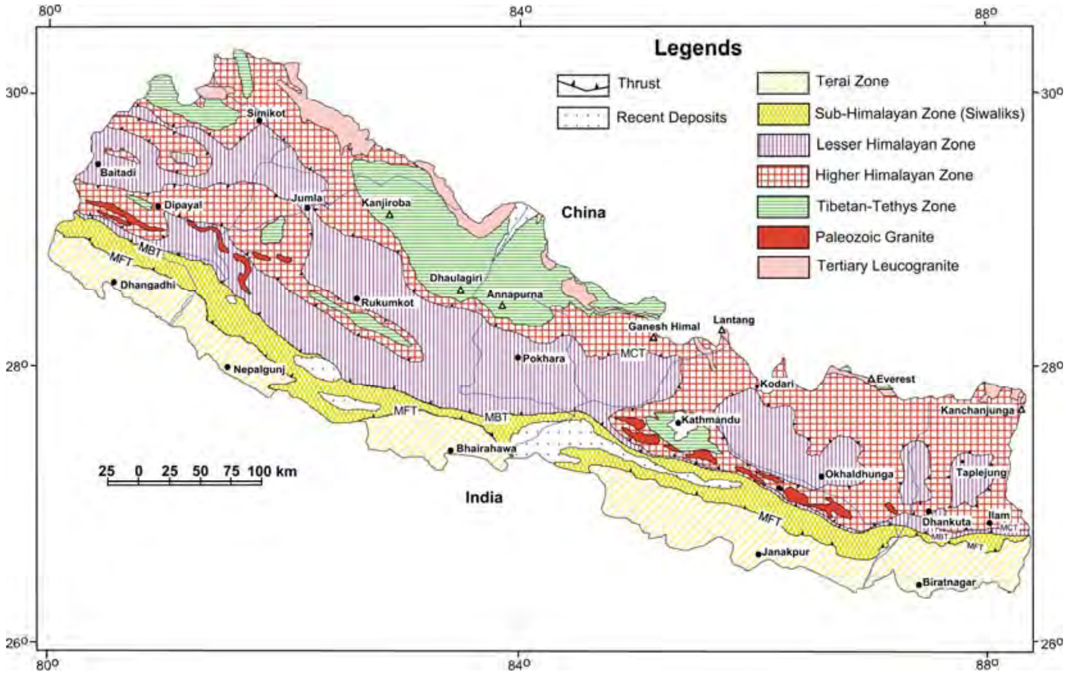

Fig. 2. Geological map of Nepal (modified after Amatya and Jnawali, 1994; Dahal, 2006c)

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).

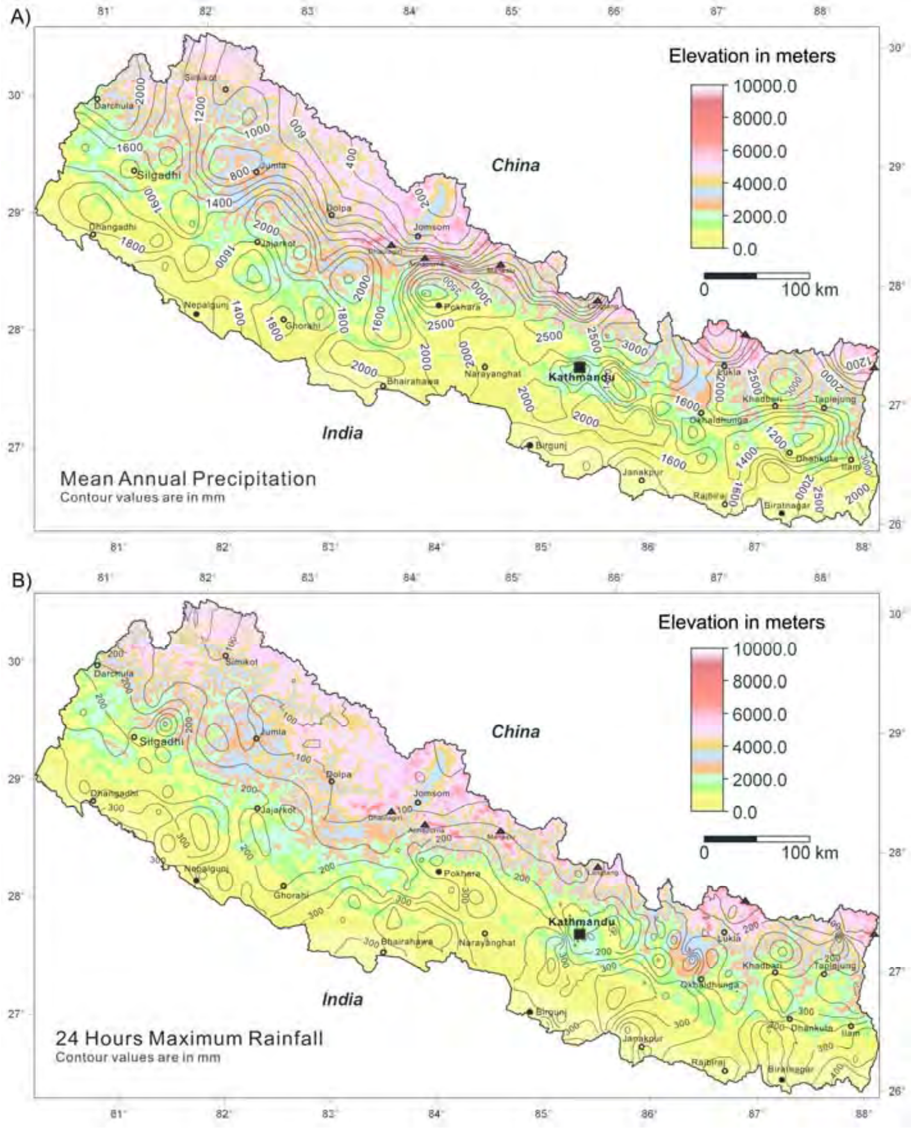

Fig. 3. Rainfall distribution in Nepal. A) Mean annual precipitation; B) Maximum rainfall of 24 hours. In both figures peak values are around central Nepal (modified after DHM, 2000, 2003).

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 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 Cozier (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 (Gorkhapatra, 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; Poudel 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.

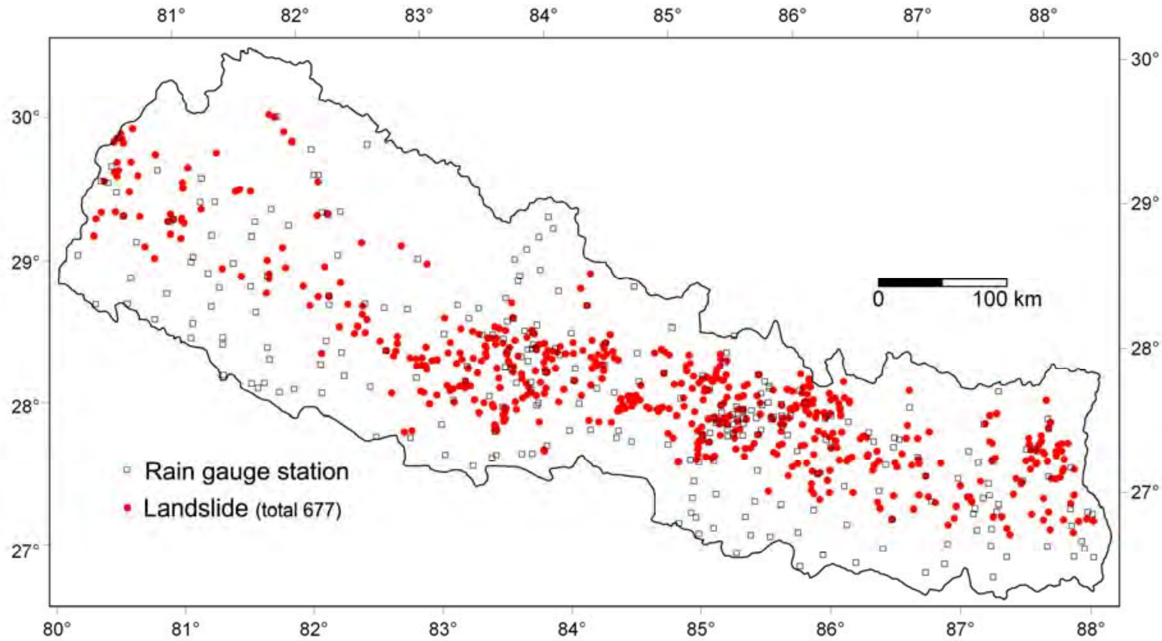

Fig. 4. Landslides in Nepal (data collected from 1951 to 2006) and location of rain gauge stations. The landslides are mainly concentrated in the region of high mean annual rainfall and high 24-hour extreme rainfall. Majority of landslides are concentrated in the Midlands and the Fore Himalaya.

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 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):

$$\frac{P_t}{P_{24}} = Sin\left(\frac{\pi \cdot t}{48}\right)^{0.4727} \qquad \text{………………..} \; (1)$$

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 hours.

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 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 hours (total rainfall of 8:45 AM of 22 July to 8:45 AM of 23 July and the time between 8:45 AM to 8:00 PM of July 23, i.e. ~11 hours) 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). The threshold, as defined by the lower boundary of the points representing landslide-triggering rainfall events, is expressed as:

$$I = 73.90 D^{-0.79} \qquad \text{……………………………………..} \; (2)$$

where I is hourly rainfall intensity in millimeters (mm hr^{-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 hours and 30 days.

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

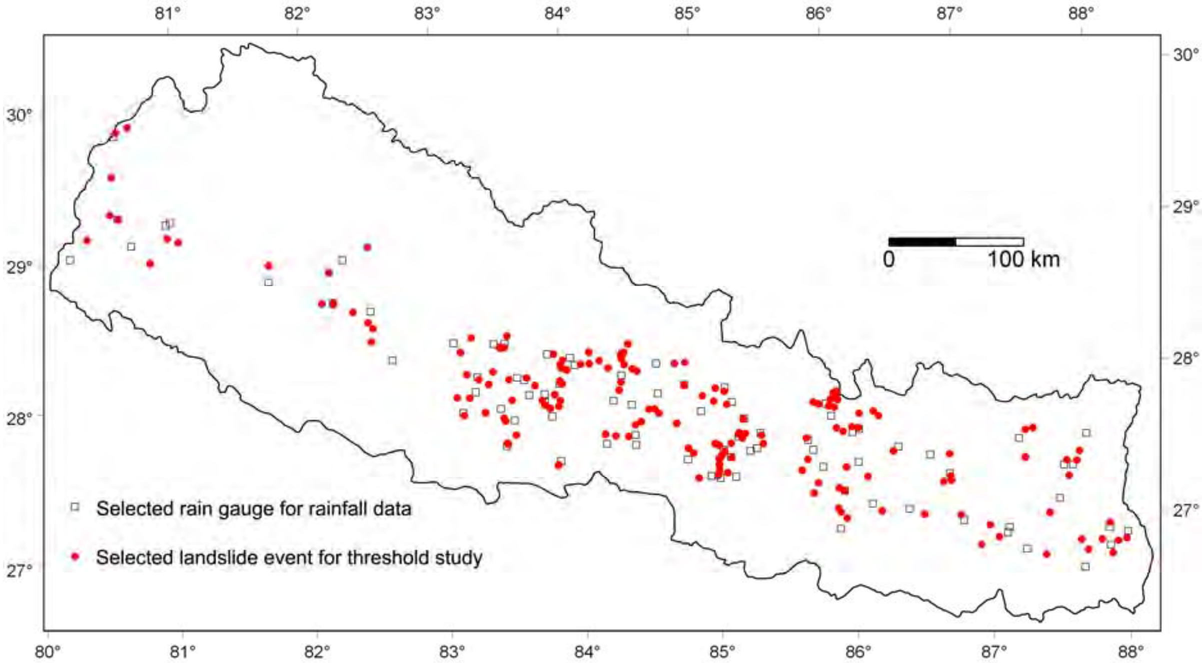

Fig. 5. Selected rainfall events and rain gauge stations for threshold analysis

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 landslides that occurred in the Kulekhani watershed (Dhital et al., 1993, DPTC and TU 1996a; Dhakal et al., 1999; Thapa, 2001) and the surrounding area (Poudel, 1995; Thapa, 1995; Woli, 1996) of central Nepal.

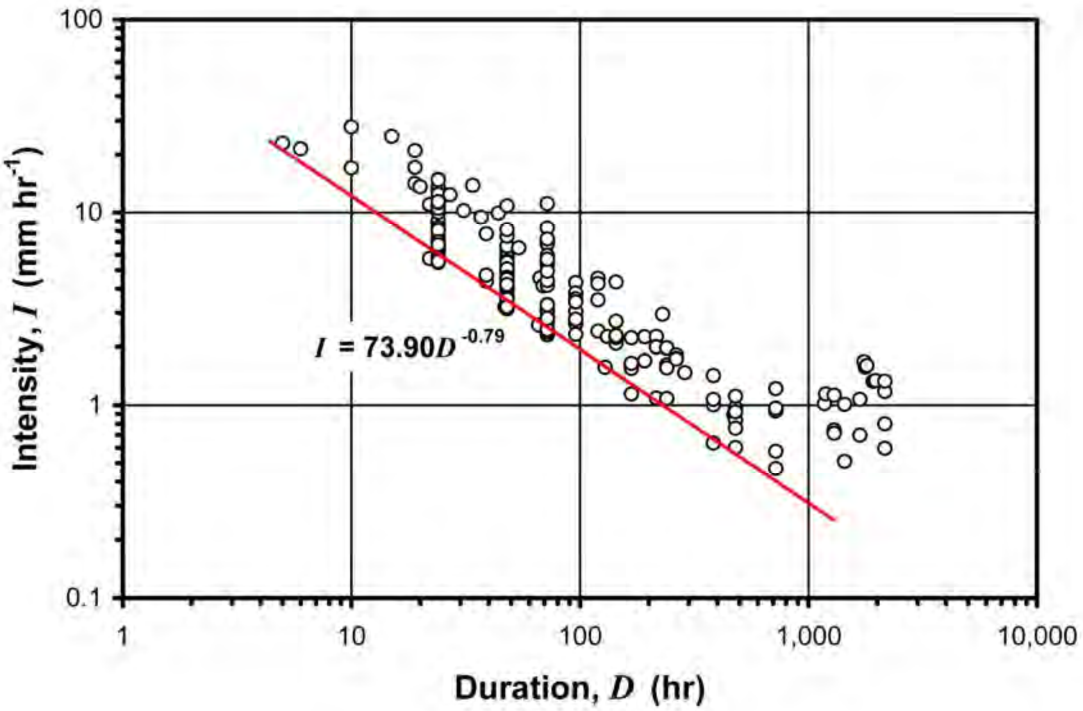

Fig. 6. Rainfall intensity–duration threshold curve for landsliding in the Nepal Himalaya

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 (2003). 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 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).

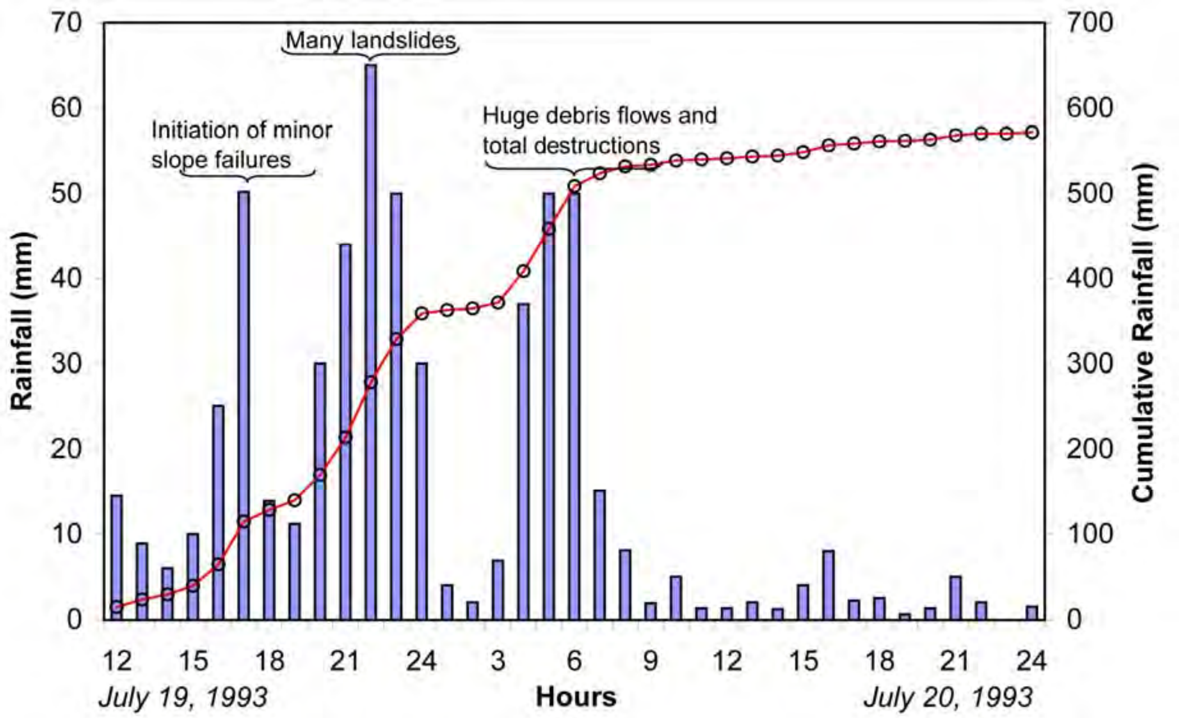

Fig. 7. Rainfall at Tistung, central Nepal on July 19 and 20, 1993, and the landslides disaster associated with this extreme rainfall, the highest one day precipitation (541.4 mm) ever recorded in Nepal (source: Department of Soil Conservation and Watershed Management)

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

$N_{\mathrm{I}} = 1.10D^{-0.59}$ …………………………………….. (3)

where N_{I} is normalized rainfall intensity (hr^{-1}) and D is duration in hours. 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 hours, a normalized rainfall intensity of 0.28 hr^{-1} (i.e. 28% of *MAP*) is required to trigger landslides, while a normalized rainfall intensity of less than 0.07 hr^{-1} (7% of *MAP*) appears sufficient to cause landslides if continued for more than 100 hours.

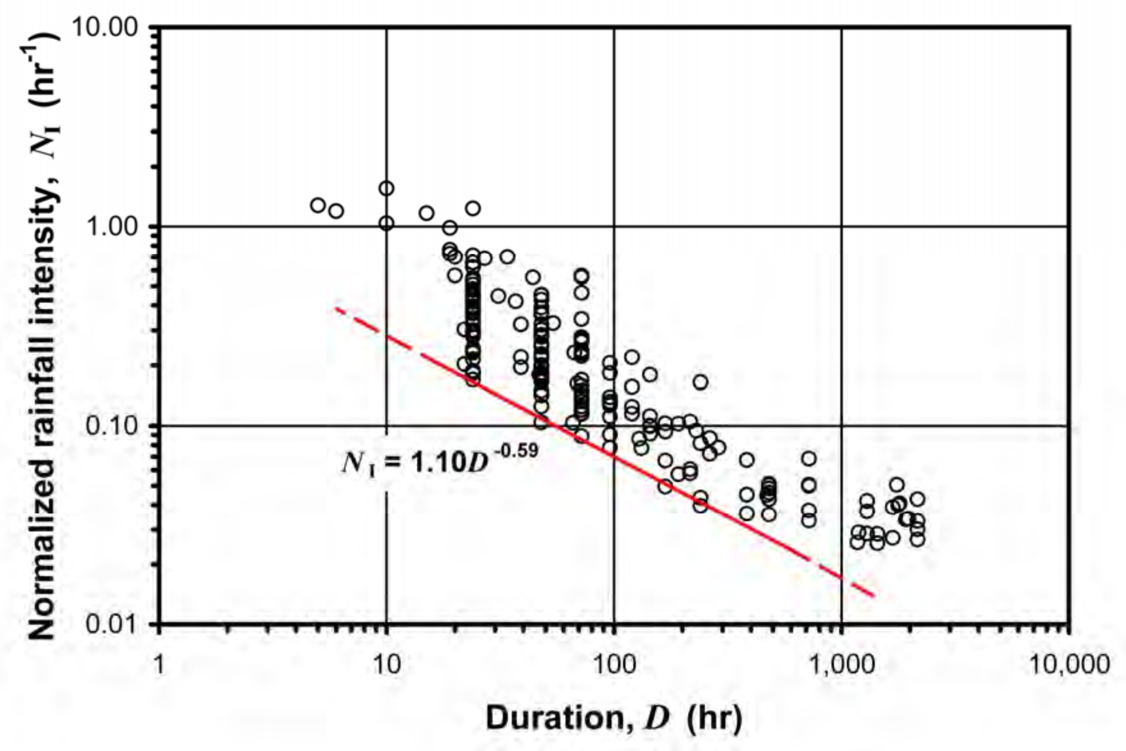

Fig. 8. Normalized rainfall intensity–duration thresholds for the initiation of landslides in the Nepal Himalaya.

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 Guzzeti 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.

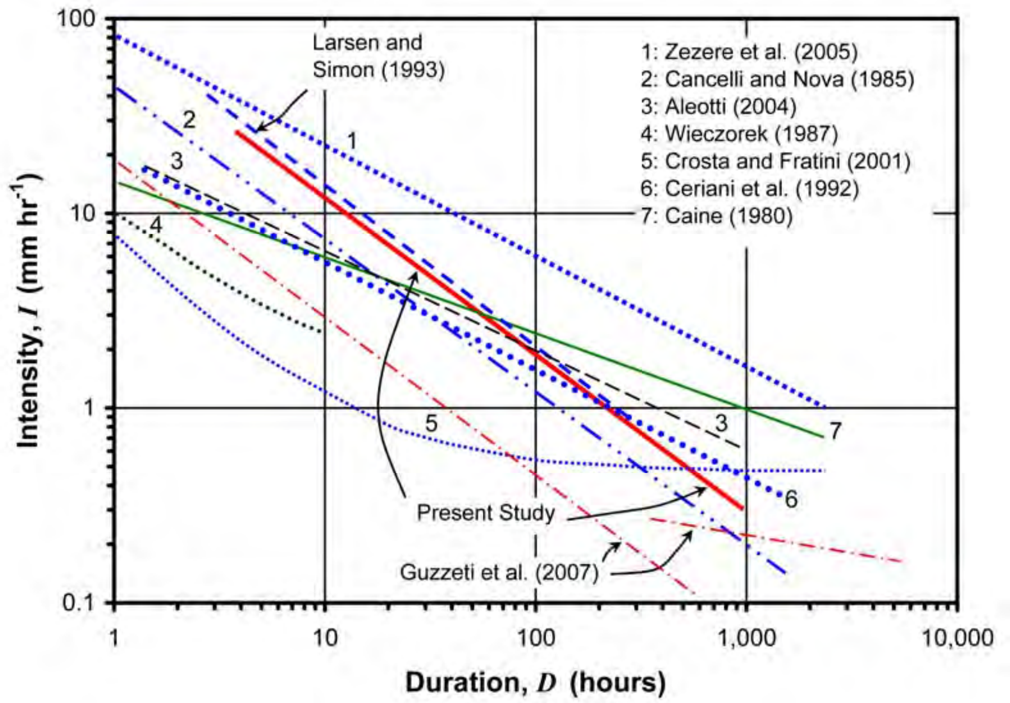

Fig. 9. Comparison of the landslide triggering rainfall intensity–duration thresholds from various studies.

Guzzeti et al. (2007) reveal that inclination of the threshold lines generally depends on the climatic environment of the region. 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.

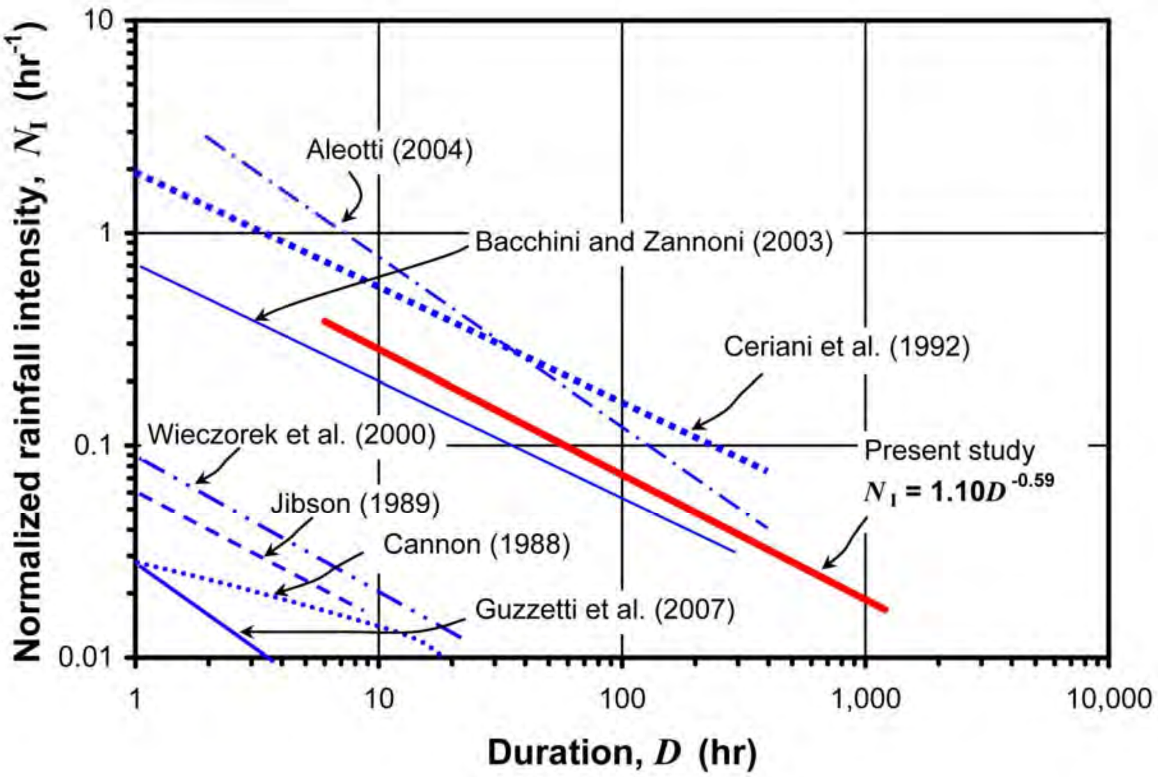

Fig. 10. Comparison of the normalized rainfall intensity–duration thresholds from various studies.

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 hours, 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 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 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 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 $r^2 = 0.592$, $r^2 = 0.598$, $r^2 = 0.744$, $r^2 = 0.332$, for 3-, 5-, 10- and 30-day intervals, respectively. It suggests that 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.

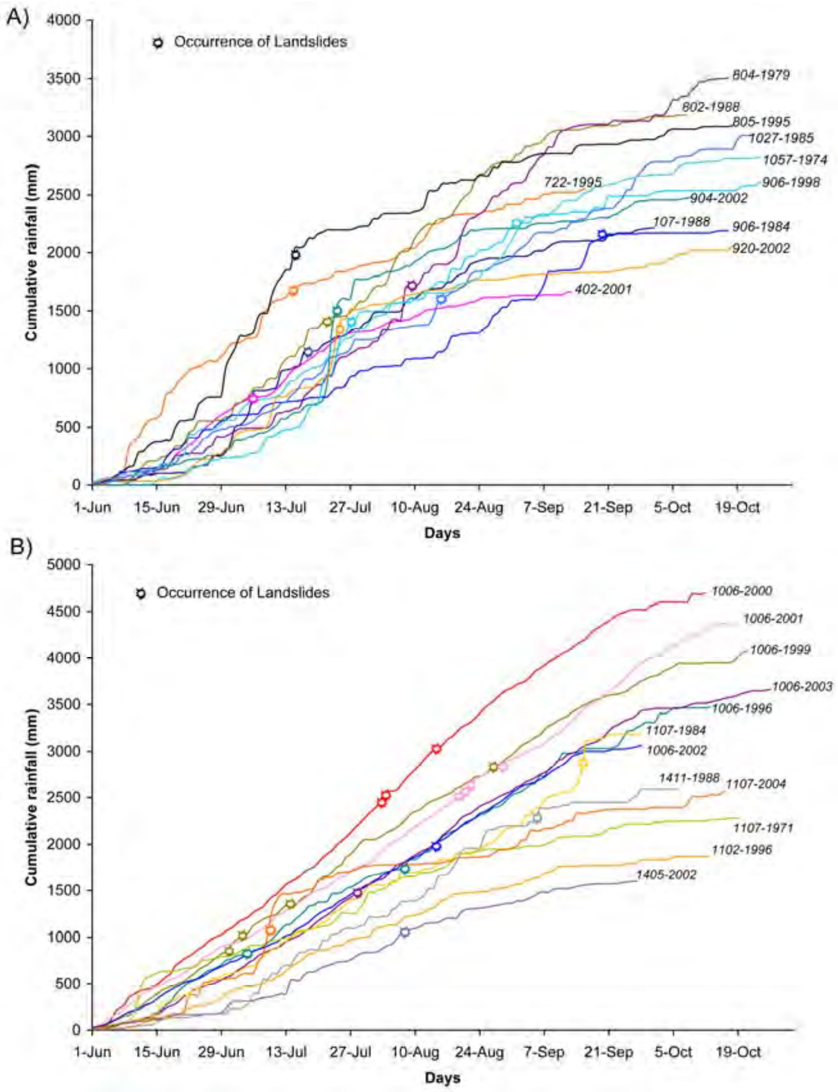

Fig. 11. Illustration of cumulative rainfall and occurrence of landslides. Each curve is labeled with the station index number and year. Rainfalls of June to October were plotted here. A) rainfall of western part of Nepal; B) eastern part. Cumulative rainfall of station 1006, situated at about 60 km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

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 hours to 90 days). On an average, a rainfall of 10 hours or less requires a rainfall intensity in excess of 12 mm $hr^{-1}$to trigger failure, but a rainfall duration of 100 hours or longer with an average intensity of 2 mm hr^{-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 hours is considered.

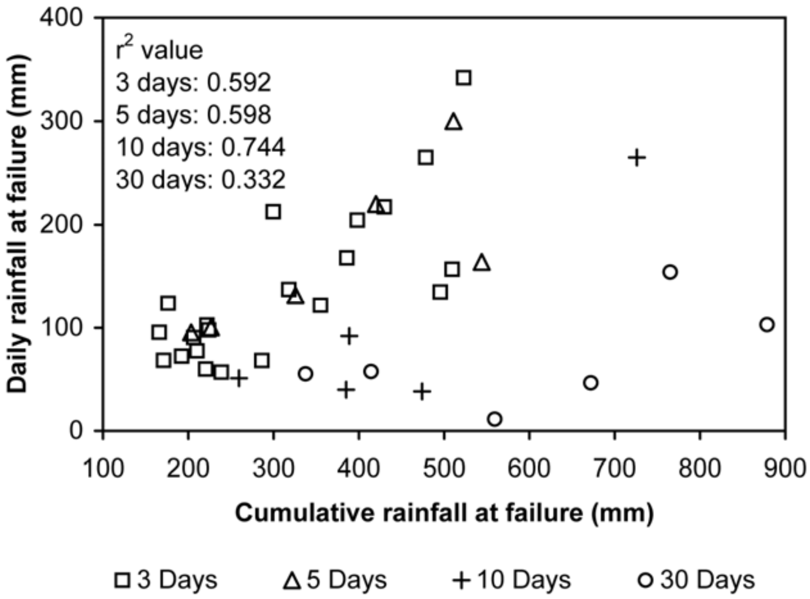

Fig. 12. Relationships between daily rainfall at failure and total rainfall of monsoon at failure, with correlation coefficient values.

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 hours. The threshold relation indicates that for rainfall events of short duration, such as less than 10 hours, 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 hours. 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.

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