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ORIGINAL PAPER

Rainfall thresholds for the initiation of landslide at Lanta Khola in north Sikkim, India

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Abstract In the Indian Himalaya, a 15 km stretch of the North Sikkim Highway that is exceptionally susceptible to landsliding is characterized by fine-grained, low permeability debris material. Lanta Khola is one of the major debris slides in this stretch and is active every year during the monsoons. Although the relationship between rainfall and landsliding in the area is obvious, there is no previous study of precipitation thresholds for landslide initiation. Review of available rainfall and landslide activity data for the area between 1998 and 2006 suggests that sliding cannot be modeled by typical exponential relationships between cumulative rainfall (E) and rainfall duration (D). An alternative rainfall threshold has been proposed that predicts sliding if normalized cumulative rainfall for more than 15 days exceeds 250 mm. It is suggested that when this cumulative rainfall threshold is exceeded, the debris zone in the affected stretch becomes saturated and fails, causing landsliding.

Keywords Rainfall · Rainfall threshold · Landslide · Lanta Khola · Sikkim

1 Introduction

Rainfall is recognized as one of the factors responsible for the triggering of landslides, particularly in regions characterized by heavy seasonal precipitation. Earlier workers have long attempted to correlate rainfall precipitation and triggering of the slope failure (Wieczorek 1996; Glade et al. 2000), a problem of great importance for devising strategies for proper disaster management. Landslides triggered by rainfall are primarily caused by

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the build-up of pore water pressures in the ground (Campbell 1975; Wilson 1989). Groundwater conditions responsible for slope failures are related to rainfall through infiltration, soil characteristics, antecedent degree of saturation, and rainfall history (Wieczorek 1996). These phenomena are poorly understood; in addition, prediction of rainfall-induced landslides in many areas has been problematic due to lack of monitoring and availability of reliable data.

In the Indian state of Sikkim, the Lanta Khola landslide is one of the major landslides on the North Sikkim Highway (NSH) that connects the state capital, Gangtok, to the Chinese (Tibet) border. The correlation between rainfall and landsliding in Sikkim is well known to all people in the area, but no attempt has yet been made to assess the precise amount and duration of rainfall that triggers mass movement. This can be attributed to the extremely inhospitable and remote nature of the terrain, parts of which are not yet electrified. In the monsoon season, sliding at several points, but particularly at Lanta Khola, frequently leads to the complete isolation of the northernmost sector of the state. A 15 km stretch of the NSH around the Lanta Khola landslide is known to be particularly susceptible to landsliding, including both rock and debris slides. Sudden closure of the only road in this area is a major headache for the tourists and the military establishment, as people may be stranded on the road some times for days at a stretch. Further, periods of slide activity have also caused loss of life for people in transit, and entire villages have been devastated by mudslides in the area, such as at Manul in 1983. Thus, an early warning mechanism is necessary for this stretch of the road, to caution civilian and military personnel of impending danger and possible shutdown of the highway. Although the role of rainfall is indisputable, it has been observed that sliding at Lanta Khola is not directly correlatable with every cloud burst event, or with every prolonged period of continuous precipitation. As a part of a study to understand the mechanism of sliding and identifying the factors responsible for slope instability at the Lanta Khola landslide, a preliminary analysis of the *only* available historical data on rainfall at the site is reviewed, and an attempt is made to correlate it with the triggering of the landslide. This paper presents the findings of this study in terms of suggested rainfall threshold values that have triggered the Lanta Khola landslide in the past.

2 The Lanta Khola landslide

The Lanta Khola slide is located 71.4 km from Gangtok on the NSH in Sikkim, India (Fig. 1). The NSH is not only the lifeline to the district of North Sikkim, but is also of strategic importance for the military. The NSH preserves a number of landslides of varying dimension. Of these, the Lanta Khola presently poses the most severe threat to the communication network in North Sikkim. The slide has been active since 1975 (Verma 1984). It is a predominantly debris slide that remains susceptible to mass movement. In 1975, the area initially developed into a sinking zone. It is believed that this instability was caused by erosion as a consequence of heavy discharge in the monsoon period (Verma 1984). Thereafter, following further heavy showers, heterogeneous, non-cohesive soil, and boulders were carried down along the valley bed with such momentum that the road bench along with the culvert was washed away. Since then, the old and small subsidence areas along the Lanta Khola road bench have developed into one of the largest destabilized zones on the NSH. In 1983, a 200 m long stretch of the road bench was washed away by the high velocity surface runoff caused by persistent heavy precipitation on the 10th and 11th September (Verma 1984). Following the rainfall, the road remained closed for over 6

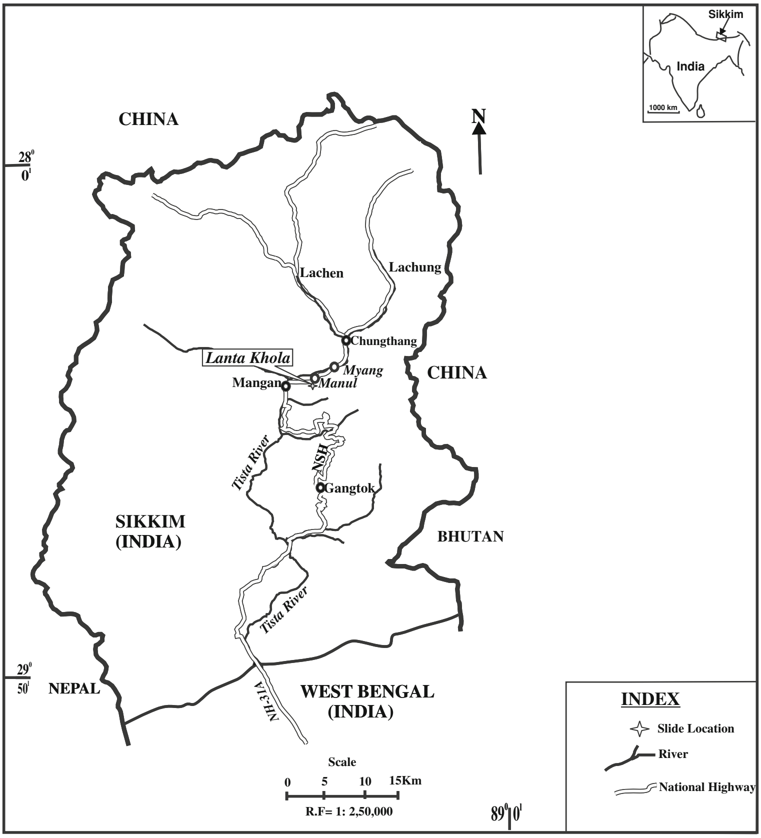


Fig. 1 Location of the Lanta Khola landslide on the North Sikkim Highway (NSH). The 15 km stretch from Mangan to Manul is exceptionally susceptible to landslides

months, as a 10 m deep, 150 m wide scar was formed at Lanta Khola that extended down to the banks of the Tista River. Initially, the crown of the scar was located at a height of about 196 m above the road level. Thereafter, the slide remained relatively dormant up to 3rd to 4th June 1998, when the area got denuded of all vegetation and trees, and a large mass disintegrated from the crown into the bed of the river, again following heavy rainfall. The slide became severely active once again in 1999, after modifying its shape and dimension and caused long periods of roadblocks in July 1999. Again, in 2001, following monsoonal rain, the NSH was blocked in phases for 54 days due to sliding at Lanta Khola. Apart from these periods of catastrophic failure, debris movement on the Lanta Khola occurs periodically almost every year, generally in the aftermath of the monsoons.

The Lanta Khola slide (Fig. 2) width is around 50–70 m, but has a longitudinal extent of over 900 m with an average surface slope (of the debris material) of only around 24°. At present, the crown is located at a height of 1,650 m, while the toe occurs close to the Tista River. The sides of the slide are sharp and marked by prominent scarps; the height of these side scarps decreases upslope and becomes minimal near the crown. The road bench is located at a height of 1,375 m; natural benches are also located at heights around 1,440 and 1,600 m. An outcrop of biotite schist (i.e. sheared Lingtse gneiss) is exposed within the

Fig. 2 **a** A view of the Lanta Khola Landslide at and above the Road (NSH) Level. Note the preponderance of boulders and debris material. **b** View of the Lanta Khola slide below the Road Bench. Note the remains of the gabion walls used for the slope protections during earlier remedial measures

debris material near the head of the slide. In the top portion of the slide, the slope surface is very wet but no surface run-off is visible. However, the lower part of the slide is characterized by a number of anastomosing streams.

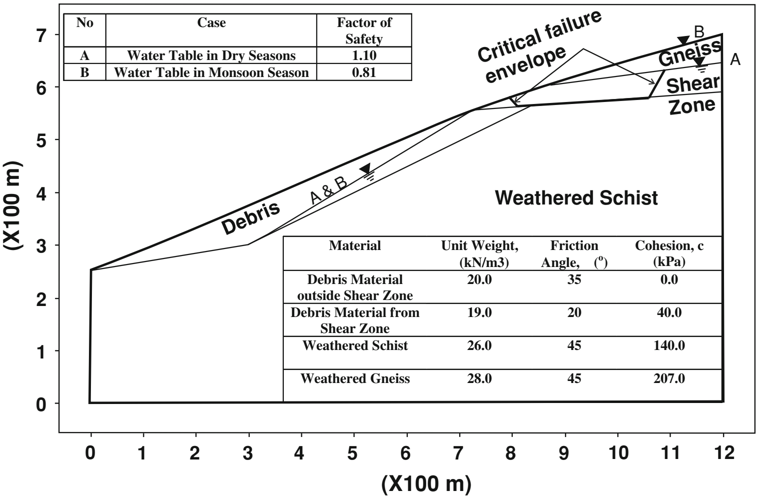
The bedrock in the near vicinity of the Lanta Khola landslide consists of quartzofeldspathic gneiss and mica schist. Within the slide itself, bedrock is not visible except near the crown of the slide. The slide materials at the Lanta Khola occur in a variety of grain sizes including boulders, cobbles, pebbles, and granules, along with slurry/fine masses. The upper part of the slide has a higher proportion of boulders, while pebbles and fines show an increase toward the road bench and the toe. This can be attributed to the removal of fines from the upper part of the slide and from their accumulation in the vicinity of the road bench (Anbarasu et al. in press). Within the most mobile part of the slide boulders, cobbles, pebbles, and granules are embedded within the slurry and fine mass. Most of the boulders are gneissic in nature. The smaller size ranges include fragments of garnet-staurolite-kyanite schist, quartzofeldspathic gneiss, and mafics (amphibolites). The fine materials have a consistency of sand and silt. With an average permeability of 10^{-4} cm/sec, the fine materials present in the slide have a tendency to retain water and a ‘quick condition’ exists at places within the slide body in the monsoon period. Several remedial measures, including chute drains along the slope to drain the surface runoff, concrete retaining walls along the highway to protect the road cut and gabion walls along the slope, were constructed in order to mitigate the problem, but none of these measures were effective and lasted more than two monsoon seasons. Figure 2 shows the remains of some earlier attempted remedial measures at the Lanta Khola slide.

2.1 Mechanism of sliding at Lanta Khola

Along the NSH, the stretch extending from Mangan to Myang (Fig. 1) is particularly vulnerable, with a number of rock slides, debris slides, and sinking zones occurring along the entire 15 km distance where the hill slope strikes roughly east–west and dips north. Geologically, this region comprises a ductile shear zone (the Main Central Thrust) where a penetrative foliation consistently trends NW-SE and dips 45° toward north-east. This foliation ‘daylights’ (Hoek and Bray 1981) along vertical road cuts, and thereby leading to the frequent rock sliding in the region. Interestingly, the debris slides are also controlled by the same general mechanism of ‘daylighting’. Geological studies indicate that the shear zone rock is characterized by a decrease in grain-size and an increase in the proportion of mica within the rocks. Weathering of these shear zone rocks leads to the formation of a debris layer with finer grain-size that also parallels the penetrative geological foliation, and therefore also ‘daylights’ along road cuts like the bounding rocks. Geotechnical studies (Anbarasu et al. in press) of this debris material indicate a lower permeability (10^{-4} cm/s) compared to debris derived from other parts of the sequence. This zone, therefore, tends to retain water, thereby lowering its shear strength and leading to failure following saturation. At Lanta Khola, debris sliding clearly originates from within this zone, while the slope above the slide remains stable.

A slope stability analysis of the representative cross-section through the Lanta Khola slide was performed using the computer program UTEXAS2 (Edris Earl and Wright 1992). The Bishop’s method of limit analysis was adopted for the study. Two cases—one, with a water table that is restricted to within the shear zone (Case A), representing the ‘dry’ condition that prevails through most of the year; and second, with an elevated ground water table that reaches the slope surface at the shear zone and above (Case B)—were analyzed. The latter case (Case B) represents the scenario during the monsoon season. The strength of the slide materials and the results of the stability analyses are shown graphically in Fig. 3. The figure depicts a typical cross-section through the slide. The depth of debris shown in the figure is based on the results of borehole drilling and vertical electrical sounding. The depth is highest at road level (100 m), and decreases upslope; the average bedrock depth is estimated at 30 m. The results of the limit equilibrium stability analyses show clearly that the sliding is shallow, and initiates in the debris at the shear zone located along the gneiss-schist contact within the slide, when the ground water table rises to the top of the slope during the monsoon season. More reliable ground water hydrology modeling of the slide could not be conducted during this study, since a perennial stream with an unidentified source passes through the slide; in addition, the land above the crown of the slide is densely vegetated and consequently extremely difficult to access.

The critical control on the initiation of debris sliding is therefore the extent of precipitation required to saturate the debris zone, leading to its failure. Till the present study, slide movement could not be directly correlated either with the total duration or with the intensity of rainfall, although the sliding was clearly dependent on both. A rapid predictive



No	Case	Factor of Safety
A	Water Table in Dry Seasons	1.10
B	Water Table in Monsoon Season	0.81

Material	Unit Weight, (kN/m3)	Friction Angle, (°)	Cohesion, c (kPa)
Debris Material outside Shear Zone	20.0	35	0.0
Debris Material from Shear Zone	19.0	20	40.0
Weathered Schist	26.0	45	140.0
Weathered Gneiss	28.0	45	207.0

Fig. 3 Results of slope stability analyses for the Lanta Khola Slide. The analyses consider two cases—'A' represents the water table during the dry season, while 'B' shows the water table during the monsoon, when it coincides with the slide surface. The material strength parameters utilized in the analyses are given in the lower table, while the upper table shows the calculated factor of safety for the two cases. For the adopted parameters, the slope is found to be unstable in the monsoon season

threshold for this region is urgently required so that remedial measures can be effectively devised.

3 Types of rainfall thresholds

A threshold is the minimum or maximum level of some quantity needed for a process to take place or a state to change (White et al. 1996). A minimum threshold defines the lowest level below which a process does not occur. A maximum threshold represents the level above which a process always occurs. For rainfall-induced landslides, a threshold may define the amount of rainfall that, when reached or exceeded, is likely to trigger landslides. Rainfall thresholds are usually defined on an empirical basis (Corominas 2000; Crosta and Frattini 2001; Aleotti 2004; Wieczorek and Glade 2005). These thresholds are usually obtained by drawing lower-bound lines to the rainfall conditions that resulted in landslides. Rainfall intensity (I) and duration (D) thresholds are the most common type of thresholds proposed in the literature. Rainfall intensity (I) is the amount of precipitation accumulated in a period of time or the rate of precipitation in a period, most commonly measured in millimeters per hour. The following global I–D threshold for debris slides has been proposed by Caine (1980):

$$I = 14.82D^{-0.39} \quad \text{with} \quad 0.167 < D < 500. \tag{1}$$

Besides (I–D) threshold, thresholds based on the total event rainfall (R) (Campbell 1975), rainfall event (E)—duration (D) thresholds (Cannon and Ellen 1985), and rainfall event (E)—intensity (I) thresholds (Jibson 1989) have also been utilized to predict rainfall-induced landslides. Caine (1980) also suggested the following global E–I threshold for shallow debris slides:

$$E = 14.82D^{0.61} \quad \text{with} \;\; 0.167 < D < 500. \tag{2}$$

Antecedent precipitation influences groundwater levels and soil moisture, and has been also used to determine when landslides are likely to occur (Glade et al. 2000). A simple way of using antecedent precipitation measurements consists of establishing a threshold based on the amount of the antecedent rainfall. Govi et al. (1985), Cardinali et al. (2005), Terlien (1998), Pasuto and Silvano (1998), Kim et al. (1991), De Vita (2000), Chleborad (2003), Heyerdahl et al. (2003), Aleotti (2004), and Gabet et al. (2004) have correlated antecedent rainfall with the triggering of landslides. When using antecedent rainfall measurements to predict landslide occurrence, a key difficulty is the definition of the period over which to accumulate the precipitation. Review of the literature reveals a significant scatter in the considered periods. This large variability may be attributed to different factors including: (i) diverse lithological, morphological, vegetation, and soil conditions, (ii) different climatic regimes and meteorological circumstances leading to slope instability, (iii) and heterogeneity and incompleteness in the rainfall and landslide data used to determine the thresholds.

The only comparable studies in the Himalayan region have been done by Bhandari et al. (1991) and Gabet et al. (2004). Bhandari et al. (1991) have proposed the following thresholds for the eastern Himalayas:

$$\begin{array}{cl} E_{\mathrm{MAP}} < 0.05 & \text{for low probability of landslides,} \\ 0.05 < E_{\mathrm{MAP}} < 0.10 & \text{for intermediate probability of landslides,} \\ 0.10 < E_{\mathrm{MAP}} < 0.20 & \text{for high probability of landslides,} \\ E_{\mathrm{MAP}} > 0.20 & \text{when landslides will always occur.} \end{array} \tag{3}$$

In the above equation, E_{MAP} is the normalized cumulative event rainfall (a unit less parameter), that is, cumulative event rainfall (E) divided by MAP ($E_{\mathrm{MAP}} = E/\mathrm{MAP}$). MAP is the mean annual precipitation of the area. It is a long-term yearly average precipitation obtained from historical rainfall records. Gabet et al. (2004), working in the Himalayas, determined an empirical threshold for the triggering of landslides based on the daily rainfall and the accumulated monsoon rain. These authors further determined that a minimum seasonal antecedent rainfall of 528 mm must accumulate and a minimum daily rainfall of 9 mm must be exceeded before landslides are triggered in the Himalayas.

4 Landslide and rainfall data at Lanta Khola

The Lanta Khola slide has been active since 1975, but landslide record for the slide is only available from 1983. The local rainfall data for the area is only available since 1998. This data confirms that the North Sikkim district receives very high rainfall. The mean annual precipitation (MAP) for the area is 2,500 mm. Of this, the area receives 2,000 mm rainfall during the monsoon season alone, that is, between the months of June and September. During the pre-monsoon season (March to May), the area receives about 400 mm, while 100 mm of rainfall is received during the post-monsoon (October–December) season. The rainfall is recorded at 24 h interval. Figure 4 shows the rainfall data at the Lanta Khola between the years 1998 and 2006, with the timing of the major landslide events also indicated (with asterisk). Rainfall data for the years 2001 and 2003 are not available, while the data for the year 2002 are incomplete. Nevertheless, the record shows that there are at least 14 events during which the peak rainfall exceeded 50 mm, with five major landslide events. Interestingly, none of the landslide events correspond to the periods of peak rainfall. In all these cases, however, the landslide event followed periods of prolonged precipitation, during which heavy (more than 10 mm per day) rainfall persisted for several days. This suggests that a certain minimum amount of rainfall (i.e. cumulative rainfall) is needed to saturate the ground surface at the slide location. The debris material at the Lanta Khola slide is mostly silty in nature with low permeability (Anbarasu et al. in press), and therefore tends to retain water. The debris material is only saturated after a certain minimum quantum of rainfall has occurred, and is therefore influenced more by the total amount of rain that occurs during an event, rather than the intensity of the rain. Once the ground is saturated and ground water rises up to the sloping surface in the shear zone, the debris loses cohesion and starts to flow along with the boulders and loose rocks, thereby triggering the landslide, as suggested by the numerical analyses presented in Fig. 3. Thus, a good correlation is observed between the cumulative event rainfall, number of days of continuous rainfall and triggering of the landslide. On the other hand, there is no such obvious relationship between the intensity of rainfall and triggering of the landslide at Lanta Khola; this data is therefore not presented here.

5 Rainfall thresholds for the Lanta Khola landslide

Based on the data of the local rainfall and landslide presented in Fig. 4, the cumulative rainfall event (*E*, in mm) versus duration (*D* in hours) are plotted for all the peak rainfall events and shown in Fig. 5. The events which led to landsliding are shown by curves with

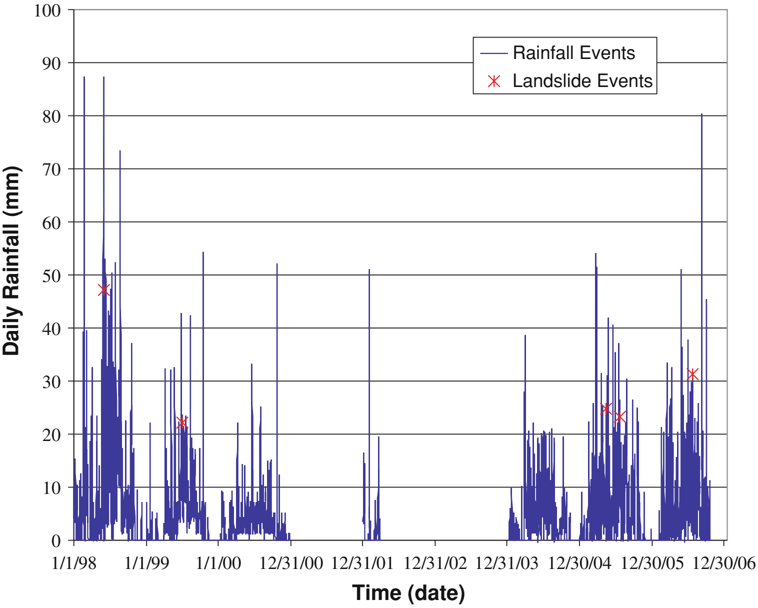


Fig. 4 Rainfall and landslide data for the Lanta Khola slide, shown from January 1998 to the end of December 2006. The *red* asterisk marks depict the timing of major landsliding at the Lanta Khola that led to road blockage for several days. Note that each major rainfall event is not invariably associated with landslide activity

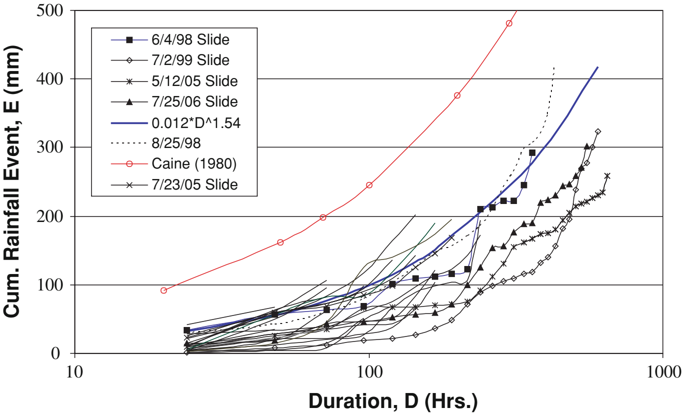


Fig. 5 Cumulative rainfall versus duration (*E–D*) thresholds for the Lanta Khola landslide. Lines with symbols indicate those events associated with landsliding. The line in *red* is the threshold curve suggested by Caine (1980), and is clearly not suitable for the present case. An alternative, best-fit exponential curve can be derived from the present study (in *blue*). Note, however, that several events not associated with landsliding (i.e. lines without symbols) also occur below (i.e. to the right of) the *blue* line

symbols. The events that are not associated with landslides are shown by lines without symbols. For the sake of comparison, the global (*E–D*) threshold for debris slides proposed by Caine (1980) is also shown in Fig. 5. As can be seen from the figure, the threshold proposed by Caine cannot be applied to the Lanta Khola slide. Based on the rainfall events that led to landslides at Lanta Khola, a (*E–D*) threshold line has been drawn. The equation of the line is given by:

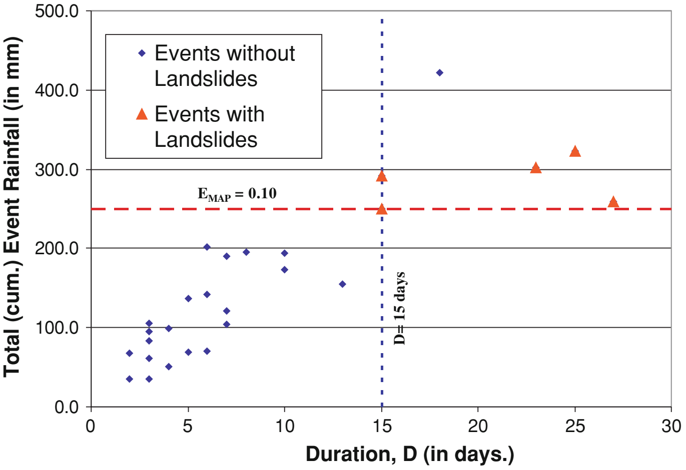


Fig. 6 Proposed Rainfall Thresholds for the Lanta Khola Landslide, based on plots of total cumulative rainfall (*E*) against event duration (*D*). All events not associated with sliding (in *blue*) occur below an *E* value of 250 mm (or E_{MAP} of 0.1), and *D* of 15 days, while slide-associated events (in *red*) occur at higher values. The only observed exception is discussed in the text

$$E = 0.012D^{1.54} \quad \text{with } 20 < D < 600. \tag{4}$$

It can be seen that several events (shown by plain lines without symbols) that did not trigger landslides are also found to fall below the new (*E*–*D*) threshold line. Thus, a rainfall threshold based on a simple exponential relationship between *E* and *D* cannot explain triggering of the Lanta Khola slide. In Fig. 6, total (cumulative) rainfall at the end of an event is plotted against the duration of the event. The figure shows that all the rainfall events which triggered landslides at Lanta Khola involved more than 15 days of continuous rainfall, with a total (cumulative) rainfall (*E*) of more than 250 mm. If this threshold value of *E* is normalized by dividing it by the MAP (= 2,500 mm) of the area, we get E_{MAP} of 0.10. So, if E_{MAP} is equal to or greater than 0.10 for any event that has duration of 15 days

Table 1 Data for each peak rainfall event

Date	Maxm Intensity of Rainfall, I_{max} (in mm/h)	Duration of event, *D* (in hours)	Duration of event, *D* (in days)	Cumulative rainfall event, *E* (in mm)	E_{MAP}
Events with no landslide:					
2/21/1998	3.6	240.0	10	193.8	0.08
3/5/1998	1.6	168.0	7	103.6	0.04
6/11/1998	2.2	72.0	3	105.9	0.04
6/22/1998	1.3	48.0	2	67.7	0.03
6/29/1998	1.8	120.0	5	136.7	0.05
7/6/1998	2.0	144.0	6	202.3	0.08
7/23/1998	1.4	144.0	6	142.2	0.06
10/19/1999	2.3	72.0	3	82.7	0.03
3/31/2004	1.6	168.0	7	121.7	0.05
3/21/2005	2.3	96.0	4	98.8	0.04
4/28/2005	1.3	312.0	13	155.4	0.06
5/24/2005	1.7	72.0	3	61.7	0.02
6/18/2005	1.7	120.0	5	68.8	0.03
6/30/2005	1.5	96.0	4	50.6	0.02
8/25/2005	1.3	240.0	10	172.6	0.07
9/23/2005	0.5	72.0	3	35.2	0.01
10/20/2005	1.0	48.0	2	34.7	0.01
3/16/2006	1.4	144.0	6	70.6	0.03
6/1/2006	2.1	168.0	7	190.4	0.08
9/15/2006	3.3	192.0	8	194.8	0.08
10/4/2006	1.9	72.0	3	95.2	0.04
Events with landslide:					
6/4/1998	3.6	360.0	15	292.2	0.12
7/2/1999	1.8	600.0	25	322.9	0.13
5/12/2005	1.0	648.0	27	259.1	0.10
7/23/2005	1.5	360.0	15	250.0	0.10
7/25/2006	1.3	552.0	23	302.5	0.12
Anomalous event:					
8/25/1998	3.1	432.0	18	421.6	0.17

or more, a landslide might be triggered at Lanta Khola (Fig. 6). Interestingly, this threshold value is close to the one proposed by Bhandari et al. (1991) (shown as Eq. 3) for the eastern Himalayas, but it shows much lower amount of total rainfall required to trigger a landslide than that suggested by Gabet et al. (2004). The rainfall event of 08/25/98 (shown by dashed line in the Fig. 5) is the only one showing an anomaly. This event has an E value of 421.6 mm and it lasted for 18 days; however, this event did not trigger a landslide. The anomaly can be explained by a closer look at Fig. 4. About 3 months before this particular event, a landslide was triggered (on 6/4/98) at Lanta Khola. Following this event, the slope probably reached a stable configuration thereby preventing further failure, even though the required rainfall condition for sliding was satisfied. Table 1 shows the relevant data in terms of maximum intensity of rainfall during an event, duration of an event in hours and days, cumulative rainfall during an event and normalized (E_{MAP}) cumulative rainfall for all the peak rainfall events that are considered here.

Thus, this study suggests that in Himalayan terrains characterized by unusually high precipitation, usual empirical threshold values for rainfall may not be appropriate. In the present study area of the Sikkim Himalaya, a total of 250 mm cumulative rainfall over a period of at least 15 days is necessary to trigger debris sliding. In physical terms, this can be speculated to represent the amount of precipitation required to saturate the shear zone debris material at the slide site, thereby triggering slope failure. Further monitoring of slide activity and of the fluctuation of the water table in the debris zone can confirm this model.

6 Conclusions

Analyses of the rainfall and landslide data for the Lanta Khola slide in North Sikkim show that the typical intensity (I)–duration (D) and cumulative rainfall (E)–duration (D) thresholds are not suitable for predicting landslides in the area. An alternative local threshold based on the E (or E_{MAP}) value has been proposed. The landslide is found to have been triggered when E exceeds 250 mm (or, the E_{MAP} value is equal to or greater than 0.10) over a 15-day period of continuous rainfall. This threshold value is close to the one proposed by Bhandari et al. (1991) for the eastern Himalayas. The present threshold values are based on limited data, but we emphasize that this is the *only* available data on the area, and can serve as a preliminary warning of possible slope failure. Continuous monitoring of the Lanta Khola landslide and other slides in the vicinity is required for validation of the proposed threshold values.

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