Determination of rainfall thresholds for shallow landslides using limited data

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Abstract

Landslides have become the most recurring phenomenon causing immense and irreparable damage to people and properties all over the world. In the context of Indian Himalayas, landslides have been an increasing menace disrupting human lives, agricultural land. Recently, attempts have been made to determine rainfall thresholds for various Himalayan regions. The primary limitation to define such limits the availability of historical precipitation and landslide occurrence data which is the majorly the case especially in Kalimpong, Darjeeling Himalayas. This paper presents a technique which would determine precipitation threshold values with limited data involving daily rainfall and rainfall event parameters. This approach was applied to Kalimpong region of Darjeeling Himalayas. After that, early warning levels have been chosen, and probabilistic limits have determined the respective thresholds. The results determined shows that an effective warning system can be established and could even be applied to regions which have been lacking threshold calculation due to limited data.

1. Introduction:

The Indian Himalayan region has long been affected by rainfall-induced shallow landslides and is widespread in the entire area. Globally, the study of rainfall triggered landslides has been studied using an empirical approach utilising historical precipitation and landslide data. Such methods utilise various parameters of rainfall and accordingly determine the minimum rainfall conditions for landslide incident in an area. The parameters mostly used are rainfall intensity, rainfall duration and antecedent rainfall, of which rainfall intensity and duration (I-D) thresholds have been mostly determined (Segoni et al. 2018). Similar studies have been also conducted across Himalayan belt (Froehlich and Starkel 1993; Sengupta et al. 2010; Kanungo and Sharma, 2014; Dikshit and Satyam, 2018). Depending on various scales of the study area, such study can also be categorised as global, local or regional studies (Guzzetti et al. 2007). For local studies, models need to be developed to comprehend the precariousness component of an individual landslide. The model results need to be further validated using a monitoring system for precipitation and slope movements and an in-depth analysis needs to be conducted. Similar analysis has been carried out worldwide (Thiebes 2012; Carey and Petley, 2014; Dikshit et al. 2018).

The techniques used to set up an early warning system (EWS) for larger section involves statistical or empirical models which depend on specific rainfall parameters. The determination of such thresholds depends heavily on the availability of rainfall and landslide event data. The Indian Himalayan region especially Kalimpong has limited available data which makes it difficult to determine the intensity-duration thresholds accurately. The technique used in this paper would help to eliminate the limitations mentioned above and determine the thresholds with limited available data. The study describes the method to determine thresholds for shallow landslides using limited available data. The thresholds are calculated using rainfall intensity and cumulative rainfall parameters. Such study could go a long way in determining thresholds in various Indian Himalayan regions where there is a scarcity of rainfall and landslide data.

2. Study Area:

The study area belongs to the steep and rugged Himalayan mountainous terrain in the Darjeeling region of West Bengal. Kalimpong is situated on a curved ridge and is hemmed between the Teesta River flowing in the west and Relli River running in the east (Fig. 1). The eastern slopes of Kalimpong are gentler and stable whereas the western face is mostly steep and rugged. The annual temperature in this region ranges from a maximum of 17°C to a minimum of 5°C (Chatterjee, 2010). The soil in Kalimpong is typically reddish in colour and at some places they are found with abundant phyllite and schists (Dikshit and Satyam, 2017). According to the Geological Survey of India (GSI) report, 2016 around 76% of all the landslides between 2016-2013 have been triggered by rainfall. This makes the study of rainfall triggered landslides significant in case of Kalimpong.

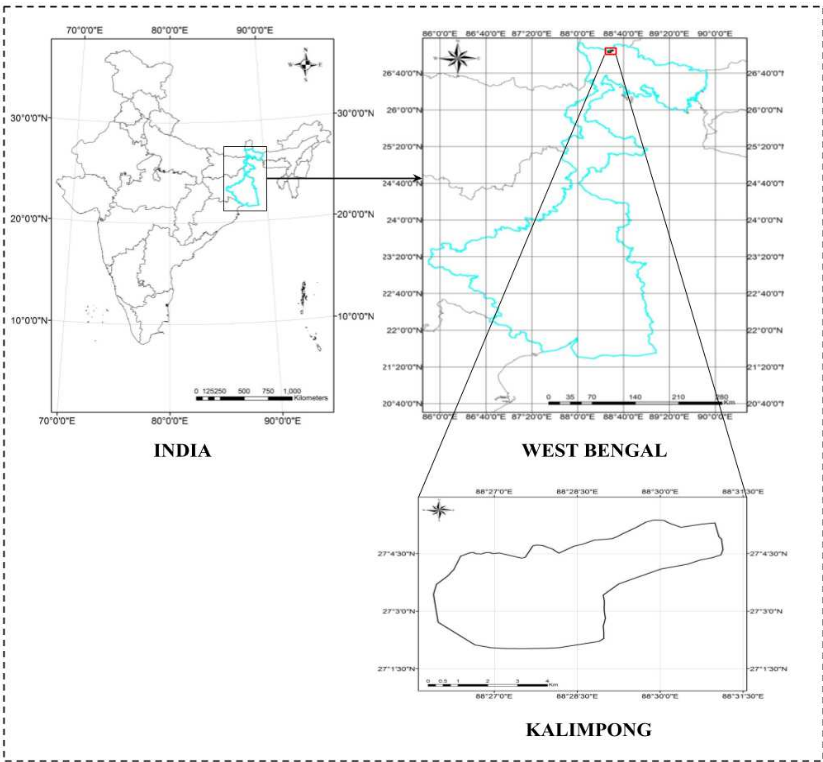

Figure 1 Study Area

The landslides in the region are primarily caused by heavy monsoonal rainfall along with a network of untrained mountain water streams. The triggering of landslides is further intensified due to the perennial streams which immensely drain the area (Dikshit and Satyam, 2018). Apart from the rainfall and streams, the constant increase in construction activities for infrastructure development has further aggravated the problem with an increase in surface runoff.

3. Rainfall and Landslide Data:

The key to the analysis is the collection of rainfall and landslide data that caused slides. The landslide inventory used for the analysis has been collected from both the Geological Survey of India (GSI) and extensive field survey carried out in the region. Additional sources like newspaper reports, published literature also added to the landslide inventory of Kalimpong between 2010-2016. The monsoonal rainfall contributes more than 80% of the annual rainfall in the region. The average daily rainfall for the study region is depicted in Figure 2.

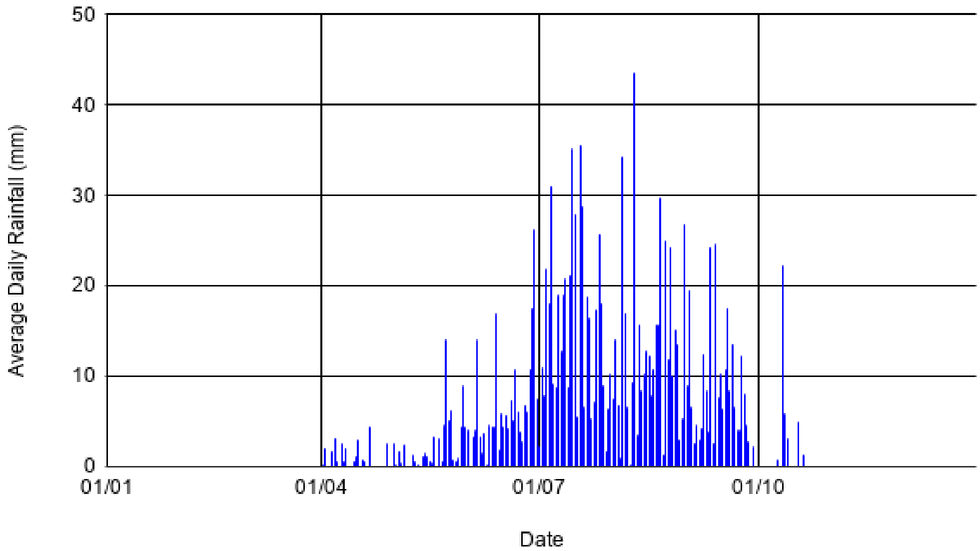

Figure 2 Average Daily Rainfall during 2010-2016

Landslides were considered only if rainfall was triggering parameter for slope failure. Most of the landslides occurred in the monsoon season (June-September) and were triggered solely due to rainfall. In this period, more than 100 landslides occurred but some of them were discarded either due to earthquakes or human activities. Several landslide events did not mention the exact date or location of the occurrence which had to be discarded. This resulted in 36 landslides with exact dates of occurrence and rainfall data and has been presented in Figure 3.

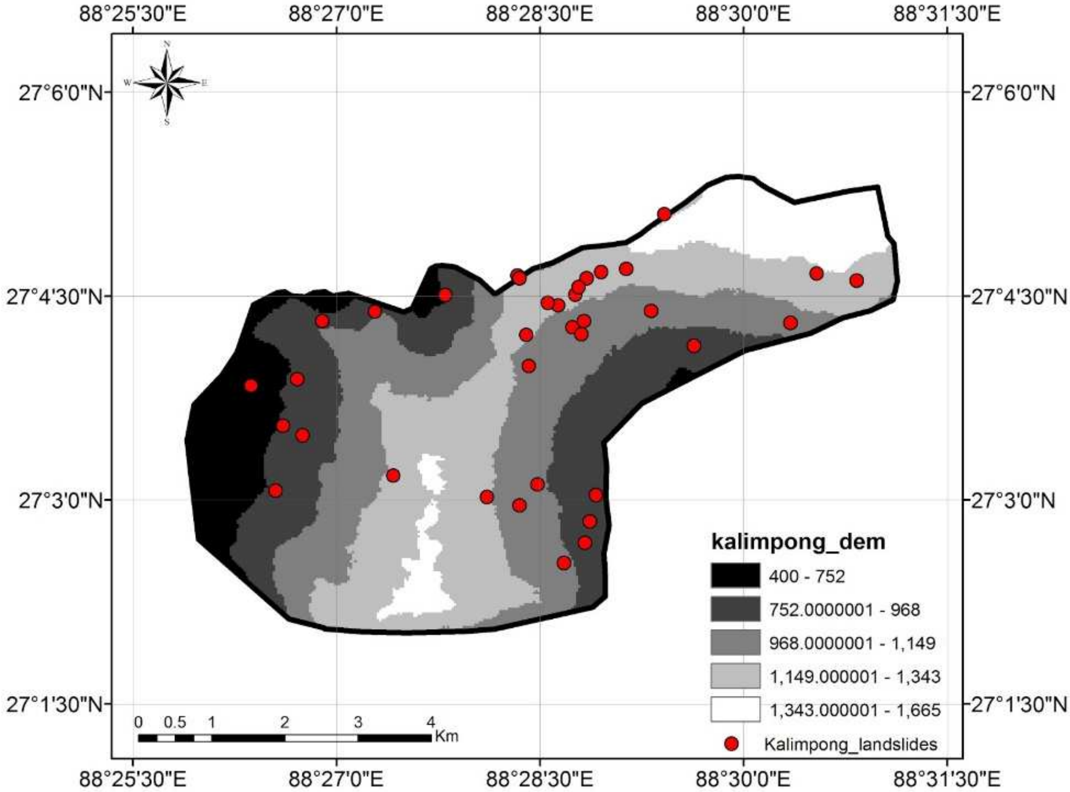

Figure 3 Location of landslides in Kalimpong region (2010-2016)

4. Methodology Adopted:

The approach utilised for this study mainly consists of two components: (i) the collection of landslide and precipitation data (ii) evaluating the relationship between precipitation and landslide events using probabilistic and empirical methods. The determination of regional thresholds in the Himalayan region has been vastly affected due to the non-availability of sufficient rainfall and landslide data. This insufficiency has led to very few works for the determination of thresholds using empirical relationships (Caine, 1980). The limitation of data is such that only a few regions have hourly rainfall data and large areas have been covered by a single manual rain gauge. The proposed method involves a technique that would help in determining thresholds even if the data is limited. The method is based on a hit and trial method. The two most significant rainfall parameters are obtained, i.e., rainfall intensity and cumulative (event) rainfall. In this case, since hourly rainfall was not available, rainfall intensity was determined by dividing the total event rainfall with the total number of event days. Rainfall event has been defined as the number of consecutive days of rainfall and the total rainfall is termed as cumulative or event rainfall. This approach has been successfully applied to certain sections in China (Jan et al. 2002; Huang et al. 2015). However, such study had the benefit of hourly rainfall data which lacks in the present study and for various sections in the Himalayan region.

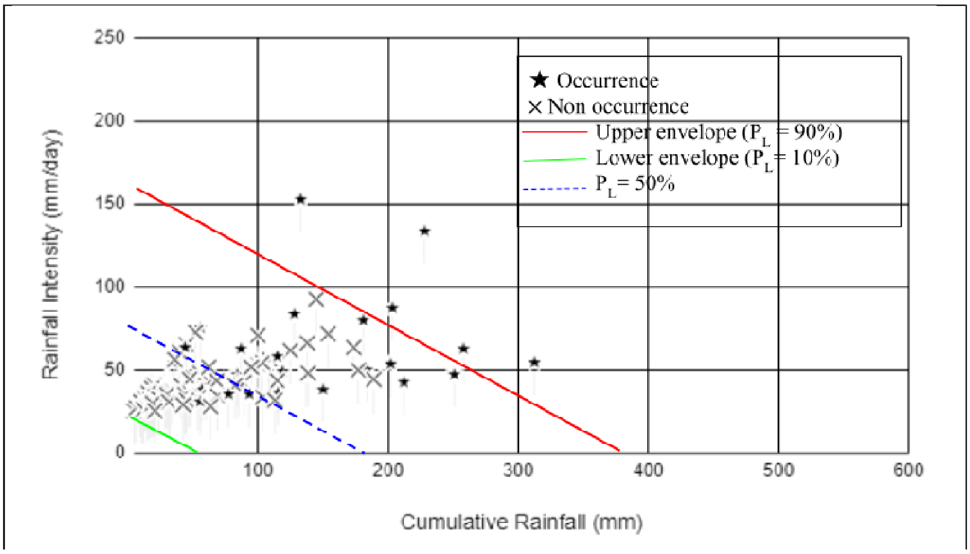

Figure 4 Graph between cumulative rainfall and rainfall intensity for occurrence (star) and non-occurrence (cross) of landslide events in Kalimpong.

5. Envelopes for Landslide Occurrences:

The lowermost points with a slope (-m) are drawn which illustrates the landslide event under rainfall conditions as depicted in green in Fig. 4. The area of the wedge between the green line, abscissa and ordinate define combinations of event rainfall and rainfall intensity represents a zero probability of landslide occurrence. Typically, a coefficient of 10% is treated for conservative consideration which makes the probability of landslide occurrence equal to 10% (Huang et al. 2015).

Similarly, a line with similar slope is drawn above the highest points, representing combinations of event rainfall and rainfall intensity without the landslide occurrence depicted by a red line. The area of the wedge between the green line, abscissa and ordinate define combinations of event rainfall and rainfall intensity represents the maximum probability of landslide occurrence. Considering the similar coefficient for the highest points, the probability turns out to be 90%.

The algorithm for each probability line

The area between the lower and upper envelope the probability lines can be identified using the same approach. The probability line can be described as:

$$C_r + mI_d = X \qquad (1)$$

Where, C_r is the cumulative rainfall (mm), I_d is the daily rainfall intensity (mm/day), and X is a constant. The two constants according to the lower and upper envelope can be termed as X_{min} and X_{max} respectively. The relation between the constant X and the probability of landslide occurrence is determined by the following equation:

$$\frac{X-X_{min}}{X_{max}-X_{min}} = P^2 \qquad (2)$$

The graph in Figure 4 depicts the probability of landslide occurrences and the maximum and minimum probability is represented by red and green respectively. The blue line depicts the probability of landslide occurrence to be 50%. For probability between 10-50%, the number of points is 11 whereas the number of points between 10-90% is 31. The ratio of the two points comes out to be 35.4% which can be considered to have a medium probability of landslides in the region. The availability of more data would help the method to be more accurate for early warning system.

6. Conclusions:

Landslides triggered by precipitation causes immense harm in terms of human lives as well as economic loss especially in the Indian Himalayan region. One of the most affected region is Kalimpong located in the Darjeeling Himalayas in West Bengal. Therefore, there is an urgent need to develop methods to determine the minimum rainfall required for landslide incidents. Most of the regions in Himalayan region like Kalimpong suffer from very limited rainfall data and the locations of landslides are not accurate which is very important to determine thresholds using the traditional empirical approach. To overcome this limitation, the paper uses a method to calculate the rainfall thresholds. The rainfall parameters used in the study are daily rainfall intensity and cumulative rainfall. It is achieved by plotting a scatter plot of the occurrences and non-occurrences of landslides for various rainfall parameters and thereby determining the lowest and highest points of landslide occurrence. The lowest and highest points are given a probability of 10% and 90% of landslide occurrence (Huang et al. 2015). The results indicate that there is a probability of over 35% of landslide incident in the region which makes the region moderately susceptible for landslide occurrence.

However, one should understand that it represents a simplified version of the complex relationship between rainfall and landslide occurrence. The cause of landslide is a combination of several factors and the use of this method for setting up an early warning system would require several iterations of the approach. Despite such shortcomings, the method can be used as a first line of action for regions where thresholds are yet to be generated with an objective to reduce the losses caused by landslides.

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