Rainfall thresholds for the prediction of landslides using empirical methods in Kalimpong, Darjeeling, India

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Rainfall is the primary cause of majority of landslides in India. There have been many attempts to establish rainfall thresholds on global, regional and local scales in terms of intensity-duration which is related to antecedent rainfall. This paper is an attempt towards deriving local rainfall thresholds for landslides in Kalimpong region of Darjeeling district in West Bengal state. The relationship between landslide incidences and rainfall characteristics in Kalimpong still remains unattended in terms of empirical relations. It derives local rainfall thresholds for landslide occurrences based on daily rainfall data of the region, using two statistical methods, including a Bayesian inference method and a new Frequentist approach.

Keywords: Landslides, Rainfall ID threshold, Antecedent rainfall, Kalimpong, Early warning system

Introduction: Darjeeling and Sikkim Himalayas cover more than 40% of landslide prone areas in India. Slide activity have caused loss of life for people, property and sometimes people lose their entire agricultural land eventually losing their only source of income. Sudden closure of roads in this area due to landslides is a major problem for the locals, tourists and the military establishment, as people get stranded on the road, sometime even for days. Estimation of rainfall threshold for landslide occurrence becomes very important for this region. This paper is an attempt to derive local rainfall threshold for landslides in Kalimpong region. Two statistical methods for the definition of objective rainfall intensity-duration (ID) thresholds. The first method is based on Bayesian inference, and the second method adopts a Frequentist approach. Both methods assume a threshold curve of the form: \( I = aD^\beta \) i.e., a simple power law, where \( I \) is the rainfall mean intensity (in mm hr\(^{-1}\)), \( D \) is the duration of the rainfall event (in hr), \( a \) is a scaling constant (the intercept), and \( \beta \) is the shape parameter that defines the slope of the power law curve. The two methods differ in the way the scale \( a \) and the shape \( \beta \) for the threshold curve are determined.

Methodology adopted
The methodology used in this study mainly consisted of two components: (i) collection of landslide and rainfall records and (ii) analysis of the relationship between rainfall and landslide occurrence using empirical methods. Data was collected from various government
agencies and other sources for the analysis of rainfall thresholds. The parameters and analysis model are referred from previous researchers.

Rainfall data
The daily data recorded at the rain gauge in location Teesta, Kalimpong was obtained from 2010 to 2016 from Geological Survey of India (GSI). Measurement of rainfall in landslide investigations should be site specific to each slope failure but as this does not exist for the entire study area and the area is largely ungauged, the rain gauge at Teesta was taken as reference. The cumulative rainfall in the region from 2010 to 2016 were 2283, 1777.3, 1364, 1021.5, 1028, 1031, 1986.5 mm respectively. The monsoon rainfall in this region contributed 75.1, 92.3, 91.1, 68.9, 89.2, 91.8, 85.5% of annual rainfall.

Landslide data
Historical data on landslide incidences in the study area from 1968-2016 was mainly obtained from records maintained by GSI. It was observed that only those damaging events had been reported, which caused casualties or property loss including loss of cattle and agricultural land. Moreover, these reports often contained a vague description of the landslide location and usually the name of the nearby village was only mentioned. However, the information on the time of advent was not available for all landslide incidences and the study was carried out assuming the landslide event to have occurred on the day it was reported.

Analysis of rainfall thresholds
Relationship between rainfall pattern and landslide occurrence in Kalimpong town is studied in detail in this paper. A threshold is defined as the level or the value that must be exceeded to produce a given effect or result. When a threshold is crossed, a radical change of state within a system will occur. Total of 99 landslide events out of which 61 landslides due to rainfall were considered to find out the ID threshold. 61 rainfall events during the monsoon during the monsoon period over the period 2010 to 2016 were identified.

Bayesian Inference Method
Guzzetti et al. (2007) were first to propose the Bayesian inference method, and used it to determine minimum-ID and normalized-ID thresholds for the initiation of landslides in central and southern Europe. In this method, a probability approach is used to obtain estimates for the scale $\alpha$ (the intercept) and the shape $\beta$ (the slope) of the power law curve representing the threshold, based on a set of rainfall intensity (I) and duration (D) conditions that have resulted in landslides. This was achieved by defining a Bernoulli probability of a landslide data point occurring at a given value of I and D. Inference was performed using a package called WinBUGS.

Frequentist Method
The method is based on a frequency analysis of the empirical rainfall conditions that have resulted in known landslides. To account for problems associated with the fitting of data
spanning multiple orders of magnitude (e.g., the least square minimization criteria may not work), the empirical data are first log transformed. The empirical rainfall data are plotted in a single graph, and the distribution of the rainfall conditions, log(I) vs. log(D), that have resulted in landslides is fitted (least square method) with a linear equation of the type log(I)=log(α)-βlog(D) which is entirely equivalent to the power law in linear coordinates.

Next, for each rainfall event, the difference δ(D) between the logarithm of the event intensity log[I(D)] and the corresponding intensity value of the fit log[Î(D)] is calculated. Then, the probability density function pdf of the distribution of δ(D) is determined through Kernel Density Estimation, and the result fitted (least square method) with a Gaussian function, f(x)= a exp−(x−b)2/2c2 where a>0,c>0, and a, b, c∈R (Fig.1b). Lastly, thresholds corresponding to different exceedance probabilities are defined, based on the modeled distribution of δ(D). Calculation of the rainfall thresholds using the Frequentist method was performed using the R open-source software.

![Image 1(a)](https://via.placeholder.com/150)
![Image 1(b)](https://via.placeholder.com/150)

**Fig 1** (a) Rainfall intensity-duration (ID) threshold based on estimation from daily rainfall data for initiation of landslides (b) Kernel Density Estimation of the differences δ(D) fitted with a Gaussian function for the distribution of empirical data points

**Result**

The rainfall threshold relationship according to the power law is found to be I= 3.52 D^{-0.41} using frequentist method, I= 3.72 D^{-0.48} using Bayesian(Fig.2a) and I= 8.40 D^{-0.41} for normalization (Fig.2b). Results depict that the rainfall events of short duration up to 24 hours with a rainfall intensity of 0.95 mm h^{-1} can trigger landslides. For rainfall event of about 5 days which generally occurs in this region during monsoon, an average precipitation of 0.46 mm h^{-1} is sufficient to trigger landslides. Analysis of antecedent rainfall relating to daily rainfall reveals that 20 day antecedent rainfall has the best correlation with respect to landslide occurrences with rainfall of 133.5 mm over 20 day period.
Fig 2 (a) Comparison of rainfall thresholds obtained using the Bayesian, the Frequentist method and normalization (b) Logarithmic data plotted on normal scale along with best fit line.

Conclusions
The problems and damage due to landslides have become complex accounting to huge damage to life and property. Therefore, it becomes imperative for landslide prediction and eventually early warning system. The use of rainfall ID threshold and antecedent rainfall thresholds to derive triggering of shallow landslides has been applied at global, regional as well as local scales. In this paper, rainfall thresholds in terms of intensity duration and antecedent rainfall for landslide occurrences are based from available daily rainfall data for local scale is found out. The region for study is Kalimpong in Darjeeling district. The results can be improved further on availability of detailed rainfall data of shorter period like hourly data.

REFERENCES