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Assessment of Rainfall-Induced Shallow Landslides in Kavre District, Nepal

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ABSTRACT

Steep slopes and fragile geology make Nepal a landslide-prone country. Kavre district experiences a large number of shallow landslides in the monsoon season. This research aims to establish rainfall intensity relation with rainfall duration along with rainfall threshold for the initiation of shallow landslides in the Kavre district, Nepal. The six rain gauge stations' rainfall data in the Kavre district from 1987-2016 and landslide data from 1987-2013 were used for establishing rainfall thresholds. The rainfall that risks the landslide event was sorted and the regression analysis of the rainfall and landslide yielded a relationship $I = 86.738 * D^{-1.066}$ having a coefficient of determination $R^2 = 0.1257$. The analysis also incorporates the drawing of the lower boundary which is the 48-h rainfall depth that indicates the rainfall threshold for the initiation of landslide in the Kavre district. The 48-hour rainfall intensity and rainfall depth at which the risk of landslide initiation is high in the Kavre district is 1.4 mm/h. and 67.18mm. Analysis of the antecedent rainfall and the landslide occurrence event indicated that the daily rainfall at failure conditions is better correlated with 3 days of cumulative rainfall at failure than with 5, 7, 10, 15, and 30 days. The study is significant for rainfall-induced landslide disaster management.

Keywords: Antecedent rainfall; Rainfall duration; Rainfall intensity; Rainfall thresholds; Shallow landslides

INTRODUCTION

Steep slopes and fragile geology make Nepal a landslide-prone country. There were 7295 disasters from 14 April 2022 to 12 September 2023 in Nepal, 657 people lost their lives with an estimated loss of NRs. 4,120,887,197. MoHA (2023) reported that 66 landslides from 15 April 2022 to 8 September 2023 in Kavre District resulted in the death of 9 persons and an estimated loss of NRs. 50,216,000 (MoHA, 2023). There were 302 landslide disasters in total from 14 April to 11 August 2019 in Nepal in which 57 people lost their lives and an estimated loss of NRs. 53,953,000 (MoHA, 2019). Kavre District experiences a large number of shallow landslides in the monsoon season. Six people lost their lives in a landslide on 23 July 2002 in Kavre District (DPA, 2002); about 2000 households in places like Pokharichaur, Devitar, Bhimkhori, Maadan Kundari, Kattike Deurali, Kaidabhanjyang, and Chunche Danda in this district are at high risk of landslides (Adhikari, 2015). The hydrologic characteristics of an area play an important role in landslide occurrences. Landslides affect human life and economic activities and also lead to sedimentation in rivers affecting the hydropower structure and degradation of water quality. It affects the biotic life leading to environmental degradation (Sanstha, 2016). Most of the landslide studies carried out in Nepal are on landslide susceptibility mapping and hazard mapping, and limited studies are found on rainfall thresholds. (Gautam et al., 2021)

conducted landslide susceptibility mapping of the Indrawati Watershed, a high mountain area of central Nepal employing four approaches: frequency ratio, logistic regression, artificial neural network (ANN), and support vector machines, and found that Eutric cambisols soil type has a strong association with landslide occurrence; he further added that the ANN approach possessed the best predictive capability and yielded more reliable results. (Devkota et al., 2013) assessed landslide susceptibility mapping utilizing three models - index entropy, logistic regression, and certainty factor, in GIS applying to the Mugling-Narayanghat road section, Nepal, and found all three models showed reasonably good accuracy in predicting landslide susceptibility. (Kayastha et al., 2013) applied the analytical hierarchy process in the Tinau watershed, Nepal to prepare a landslide susceptibility map, and found that landslide susceptibility levels agree with past landslide occurrences.

Mandal & Sarkar (2021) estimated the rainfall thresholds of shallow landslides along National Highway-10 in the Darjeeling Himalayas. It identified 288 rainfall events that caused 681 landslides. The rainfall thresholds were calculated using a power law. The threshold rainfall intensity and duration threshold were calculated according to lithostratigraphy. Koley et al. (2019) assessed rainfall thresholds for landslide events in the Sikkim Himalaya, India. Using data from daily rainfall, they attempted to define the local facet of thresholds for landslides. The study examined 210 landslides, which were grouped into 155 landslides connected to rainfall information. The threshold relationship for landslide onset was determined by fitting the lower boundary limit. The short-term (24-hour) rainfall events that increased the risk of landslides along the road corridor in Sikkim and 10-day and 20-day antecedent rainfall needed for the onset of landslides were found. Dikshit et al. (2019) estimated the rainfall thresholds for the manifestation of landslides in the Bhutan Himalayas. The relationship was established for Chukha Dzongkhag using a power law fitted to the lower limit of rainfall conditions plotted in logarithmic scales. Moreover, the study includes antecedent rainfall of 3 to 30 days focusing on 10 days and 20 days. Dikshit & Satyam (2018) estimated rainfall thresholds for landslide occurrences in the Kalimpong area situated in the Darjeeling Himalayas, India. The rainfall data and landslide data were analyzed and rainfall thresholds were calculated using power law. The study analyzed daily rainfall before failure and rainfall over periods of 3, 7, 10, 15, 20, and 30 days. Lee (2016) conducted a correlation analysis between rainfall and landslides and made predictions based on climate change. The climate change scenarios were examined by applying the GCM model and geo-statistics method Co-kriging for interpolation. Larsen & Simon (1993) studied rainfall intensity-duration thresholds for landslides located in humid tropical environments, in Puerto Rico; analyzing 256 storms, 41 storms were extracted that resulted in landslides, and a lower boundary line was fitted to define rainfall thresholds. In the Indian Garhwal Himalayas, near the Rishikesh-Badrinath National Highway, Kanungo & Sharma (2014) studied rainfall thresholds for the prediction of shallow landslides in road segments in and near the Karnaprayag-Chamoli-Joshimath region; an empirical intensity duration thresholds were developed. They further studied the 10-day and 20-day antecedent rainfall before failure. Dahal & Hasegawa (2008) conducted research on rainfall thresholds establishing rainfall intensity-duration threshold and normalized rainfall threshold followed by a study of antecedent rainfall of 3,5,10,20 and 30 days. Shrestha et al. (2008) researched creeping landslide for effective use in planning and execution of slope stability enhancement measures in Otoyo Town, Shikoku, Western Japan, utilizing a three-dimensional model. Giannecchini (2006) developed the threshold for soil slip initiation in terms of mean intensity, duration, and mean annual precipitation (MAP) for the southern Apuan Alps, Italy.

Studies on rainfall-induced landslides and determining their threshold haven't been carried out in the Kavre District. Rainfall is critical in contributing to landslides, and the study of rainfall-induced landslides is significant in disaster management. In today's climate change setting, it has become critical to investigate climate change impact on rainfall-induced landslides. This study aims to determine the rainfall threshold for the initiation of shallow landslides in the Kavre District, Nepal.

MATERIALS AND METHODS

Study Area

Kavre District lies in the Bagmati Province, South-East of Kathmandu at a distance of 25 km. It is bounded on the East and East-South by Sindhuli, on the North by Sindhupalchowk, Kathmandu on the West, Lalitpur on the West-South, and Makwanpur in the South covering an area of 1396 km^2. Its elevation ranges from 280m to 3018m, climate ranges from sub-tropical to temperate but most regions have sub-tropical climates. The mean annual rainfall is 1121mm. Sunkoshi and Roshi are major rivers of the Kavre District. The Kavre District map with landslide area and no landslide areas are shown in Figure 1.

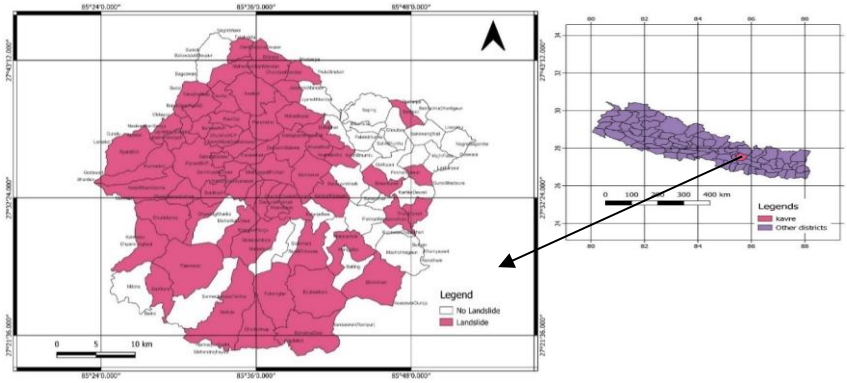

Figure 1 Kavre District Map with location of landslide areas

Methods

The shape file of the Kavre District was downloaded (www.diva-gis.org/gdata). The landslide locations were obtained from Desinventar, the disaster inventory management system. The landslide locations are depicted in color on the map using QGIS showing landslide and no landslide area.

The six rain gauge stations' rainfall data of the Kavre District from 1987-2016 was collected. Landslide data from 1987-2013 of the Kavre district were downloaded from Desinventar and used for establishing rainfall thresholds. The daily rainfall and antecedent rainfall corresponding to landslide occurrence events were analyzed taking Khopasi rain gauge station as the base station. The rainfall intensity (I) is calculated by dividing the accumulative rainfall by the total duration (D). A non-linear regression analysis was carried out and its line was drawn on a logarithmic scale. The relationship was developed concerning rainfall intensity I and duration D employing the power law (equation 1).

$$I = \alpha * D^{\beta} \quad (1)$$

The analysis incorporates the drawing of the lower boundary that is the 48-h rainfall depth that indicates the rainfall threshold above which the initiation of landslide is high. The rain from the beginning to the day of the landslide event was taken as antecedent rainfall. The linear regression analysis was carried out for the antecedent rainfall study and plotted on an arithmetic scale.

RESULTS AND DISCUSSIONS

Rainfall Threshold

The non-linear regression analysis of the rainfall and landslide yielded rainfall thresholds with the creation of the best-suited regression line having a coefficient of determination $R^2 = 0.1257$. Equation 2 illustrates the relationship between rainfall duration (D) in hours and intensity (I) in mm/h. The rainfall threshold regression line graph is shown in Figure 2.

$$I = 86.738 * D^{-1.066} \quad (2)$$

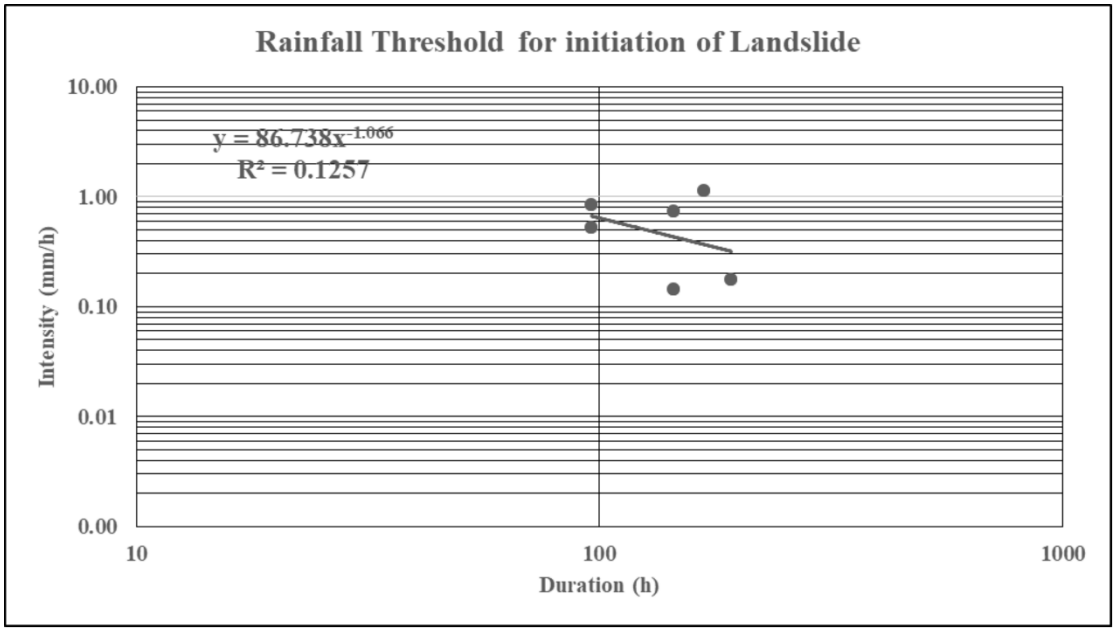

Figure 2 Rainfall intensity-Duration threshold for initiation of a landslide

On substitution of the duration value in the above-developed equation it was found that at 48-h all the data at which the landslide had occurred was observed to be above the 48-h boundary line which is said to be the threshold. The 48-h threshold boundary line is shown in Figure 3. Utilizing the developed relationship (equation 2) the rainfall intensity corresponding to the 48-h duration is 1.4 mm/h (67.18 mm in 48 hours). Thus the rainfall intensity at which the possibility of landslide initiation is high in the Kavre District is 1.4 mm/h.

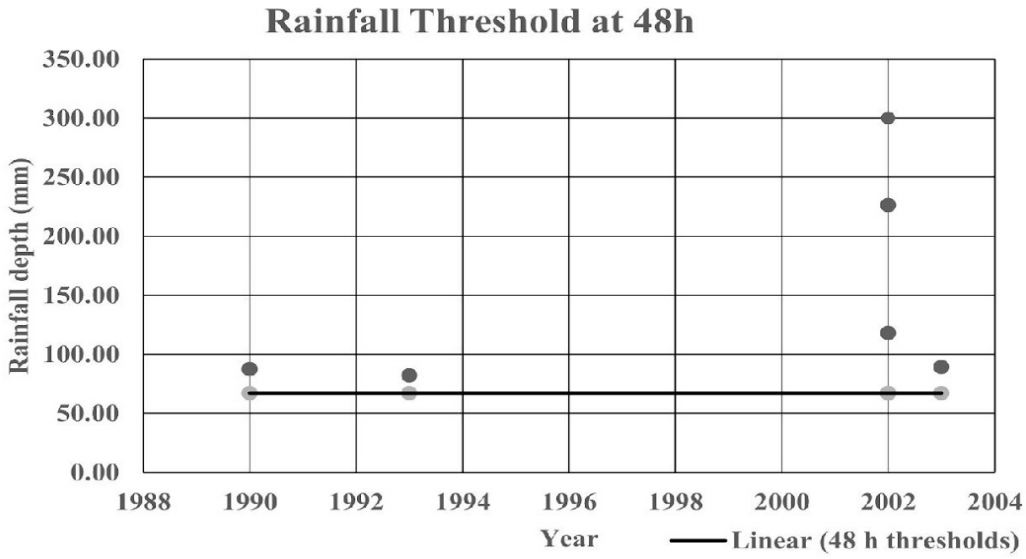

Figure 3 Rainfall threshold (mm)

Various researchers have studied rainfall thresholds at the global, regional, and local levels. The rainfall thresholds can be broadly classified into physically based and empirically based rainfall thresholds. The empirical-based rainfall threshold studies have been carried out in the Lesser Himalayan region. The 24-hour rainfall of 0.95 mm/h in the Darjeeling Himalayas has a high risk of landslide initiation (Dikshit & Satyam, 2018). The short-term rainfall of 24 hours of 1.82mm/h increases the risk of landslides along the Sikkim road corridor (Koley et al., 2019). The 48-hour rainfall of 36.7mm can lead to landslides in the Kalimpong region,

Darjeeling Himalayas (Teja et al., 2019). The possibility of landslides by 24 hours of rain with a cumulative rainfall of 53 mm is high in Chukha Dzongkhag of Bhutan (Dikshit et al., 2019). The empirical intensity duration thresholds of 0.87 mm/h have a high likelihood of triggering landslides on the Rishikesh-Badrinath national highway (Kanungo & Sharma, 2014). The rainfall threshold exceeding 144mm of daily rainfall increases the risk of landslides in the Himalayan Mountains (Dahal & Hasegawa, 2008).

Antecedent Rainfall

The rainfall and cumulative rainfall on the day of failure were analyzed by linear regression. The coefficient of determination of a relationship between daily rainfall at failure and cumulative rainfall at failure R^2 is 0.3747. The relationship was identified for 5 days, 7 days, 10 days, 15 days, and 30 days but their coefficient of determination is lower than that of 3 days. This indicates that rainfall on the day of failure is better correlated with 3 days of antecedent rainfall. The daily rainfall at failure against cumulative rainfall at 3, 5, 7, 10, 15, and 30 days is shown in Figure 4.

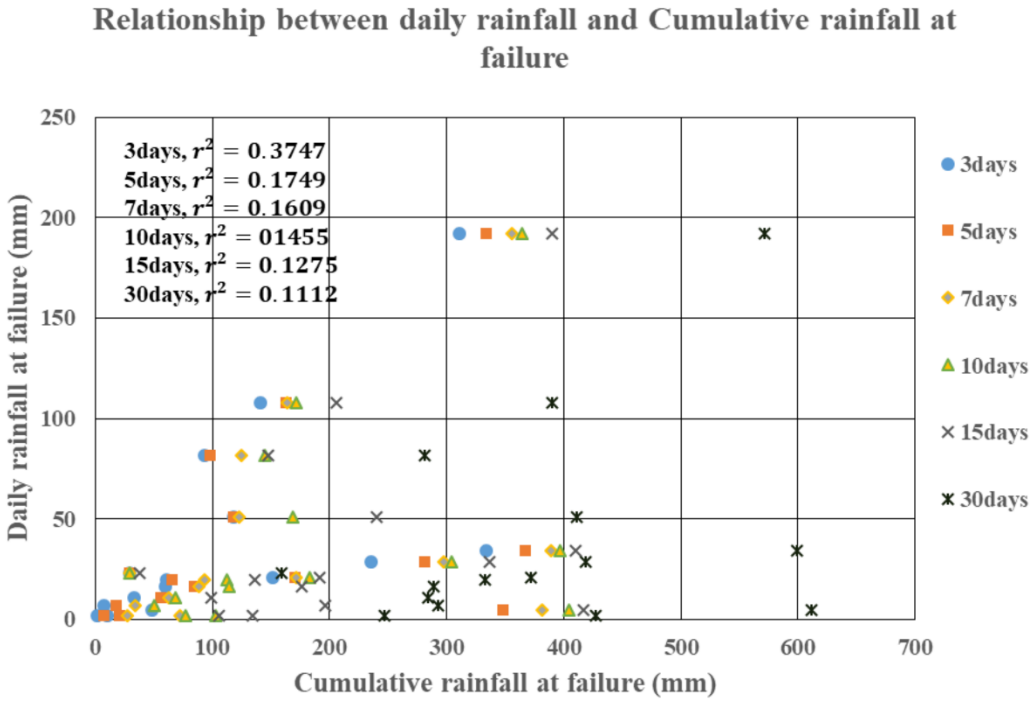

Figure 4 Daily rainfall versus Cumulative rainfall at failure

The antecedent rainfall effect and its contribution to triggering landslides have been studied in various regions of Lesser Himalaya and has been mentioned that its relationship is significant. The previous rainfall of three to five days is effective in causing landslides (Mandal & Sarkar, 2021). The 10-day and 20-day antecedent rainfall needed for the onset of landslides is 58mm and 139mm respectively (Koley et al., 2019). The antecedent rainfall study of 3 to 30 days was carried out in Bhutan and 10 days and 20 days rainfall initiating landslide was found to be 88mm and 142mm (Dikshit et al., 2019). (Dikshit & Satyam, 2018) mentioned the requisite of 88.37 and 133.5mm antecedent rainfall at 10-day and 20-day for landslide in Kalimpong region, India. (Kanungo & Sharma, 2014) discovered that 185 mm rainfall of in 20 days is necessary for the onset of landslides in the Garhwal Himalayas in India.

CONCLUSION

The 48-h rain intensity and rainfall depth at which the risk of landslide initiation is high in the Kavre District are 1.4mm/h and 67.18 mm respectively. The study found that the daily rainfall at failure and 3 days of antecedent rainfall at failure have a better correlation. The effect of cumulative rainfall is found to be lesser in 5, 7, 10, 15, and 30 days. The study of rainfall threshold helps in installing a landslide warning system. The study is significant for rainfall-induced landslide disaster management. Further research on landslides, using additional factors, is required in the Kavre District.

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