

Rainfall Threshold for Landslide Initiation in Gorkha District, Central Nepal

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Abstract: Rainfall-induced landslides pose significant hazards in Gorkha District, central Nepal, where steep terrain, fragile geology, and conditions following the 2015 earthquake increase slope instability. This study develops an empirical rainfall intensity–duration threshold for landslide initiation and examines its potential application to landslide early warning systems. A historical landslide inventory was compiled using satellite imagery, field verification, and available records, while rainfall observations from the Department of Hydrology and Meteorology were spatially interpolated using ordinary kriging. Rainfall intensity and duration were analyzed through ordinary least squares regression and the CTRL-T approach. Bootstrap resampling established prediction bands to assess uncertainty, and a Random Forest model evaluated the relative importance of rainfall, land use, and terrain variables. The analysis identified rainfall intensity and duration as dominant factors influencing landslide initiation. Approximately 80% of recorded landslides occurred during July and August, reflecting strong monsoon influence. Threshold validation reported a probability of detection of 0.889, indicating that most recorded triggering events were captured. Comparisons with published regional and global thresholds highlighted the need for locally adapted models. The findings support continued rainfall monitoring and development of practical, community-based early warning systems to effectively strengthen landslide preparedness and risk management in Gorkha and surrounding mountainous communities.

Keywords: *Rainfall-Induced landslides, Rainfall intensity-duration threshold, Gorkha district, CTRL-T algorithm, Ordinary least squares, Bootstrapping, Landslide early warning system*

Introduction

Landslides are among the most destructive natural hazards affecting the mountainous regions of Nepal, particularly during the monsoon season when intense and prolonged rainfall contributes to slope instability. The country's steep terrain, complex geological formations, and varying climatic conditions make many areas highly susceptible to rainfall-induced landslides. Rainfall infiltration increases pore-water pressure within slope materials, reducing effective stress and soil shear strength, which may eventually result in slope failure. The occurrence of landslides is influenced by several factors, including rainfall intensity, duration, antecedent rainfall, geological conditions, and land

use. Understanding these relationships is essential for identifying potentially hazardous rainfall conditions and improving landslide risk management.

Gorkha District, located in central Nepal, is particularly vulnerable to landslides due to its rugged topography, steep slopes, fragile geological formations, and geological conditions affected by the 2015 Gorkha Earthquake. The district experiences considerable variations in elevation, climate, and geomorphological characteristics, contributing to differences in slope stability across the region. During the monsoon season, rainfall-induced landslides frequently threaten settlements, agricultural land, roads, and other infrastructure. These events can disrupt transportation, communication networks, and essential services, creating significant challenges for affected communities.

Rainfall threshold analysis provides an important approach for understanding the relationship between precipitation and landslide initiation. By examining historical landslide occurrences alongside rainfall intensity and duration, critical rainfall conditions associated with slope failure can be identified. Empirical rainfall thresholds offer a relatively cost-effective method for assessing landslide hazards, particularly in mountainous regions where extensive slope monitoring systems may be difficult to establish and maintain.

This study focuses on determining an empirical rainfall intensity–duration threshold for landslide initiation in Gorkha District. The research combines historical landslide inventories, rainfall observations, spatial interpolation, statistical regression, bootstrapping, and machine learning techniques to examine rainfall conditions associated with slope failures. The findings aim to support the development of localized Landslide Early Warning Systems (LEWS), improve hazard preparedness, and contribute to more effective landslide risk management in the region.

Rainfall threshold analysis and landslide early warning systems

Rainfall threshold analysis is an important method for identifying the critical rainfall conditions associated with landslide initiation. In Gorkha District, where

monsoon rainfall is a major factor influencing slope instability, understanding the relationship between rainfall intensity and duration provides a basis for assessing potential landslide hazards. The study developed an empirical intensity–duration relationship using historical rainfall records and verified landslide occurrences. Rainfall data obtained from the Department of Hydrology and Meteorology were processed through ordinary kriging interpolation to estimate precipitation conditions at individual landslide locations. Ordinary Least Squares regression and the CTRL-T algorithm were then applied to develop a rainfall threshold, while bootstrap resampling was used to quantify uncertainty through prediction bands.

The study also examined the influence of rainfall and terrain characteristics on landslide occurrence using a Random Forest classification model. The analysis identified rainfall intensity and duration as the most influential predictors, while land use and topographic conditions played additional roles in modifying slope instability. The seasonal distribution further demonstrated the importance of monsoon rainfall, with approximately 80% of recorded landslides occurring during July and August. These findings indicate that both intense rainfall over shorter periods and prolonged rainfall events can contribute to landslide initiation, depending on the prevailing slope conditions.

The developed rainfall threshold provides a basis for improving landslide early warning systems in Gorkha District. By combining the threshold with continuous rainfall observations, local authorities can identify rainfall conditions associated with increased landslide risk and issue timely warnings to vulnerable communities. The study emphasizes the importance of installing rain gauges, maintaining reliable monitoring networks, improving communication systems, and involving local communities in preparedness activities. Continued monitoring and the incorporation of additional landslide records can further refine the threshold and improve its practical application. Such an approach supports the development of cost-effective, community-based early warning systems in landslide-prone mountainous areas.

Influence of rainfall and geological conditions on landslide initiation

Landslide initiation in Gorkha District is strongly influenced by rainfall characteristics, geological formations, and surrounding terrain conditions. The study identified rainfall intensity and duration as the most significant factors contributing to slope instability, particularly during the monsoon season. Approximately 80% of recorded landslides occurred during July and August, with July alone accounting for around 40% of the total events. This seasonal concentration highlights the strong relationship between monsoon rainfall and landslide occurrence. Intense rainfall over shorter durations can trigger shallow landslides, while

prolonged rainfall of moderate intensity can contribute to deeper slope failures through increasing saturation and pore-water pressure.

Geological conditions also influence the distribution and occurrence of landslides throughout the district. The Ranimatta Formation, consisting of shales, phyllites, slates, quartzites, and carbonate beds, exhibits a high density of landslides. Similarly, the Galyang, Sangram, and Ghan Pokhara formations show considerable landslide concentrations. Areas near geological fault zones also experience high landslide densities, particularly in the Higher Himalayan region. These observations demonstrate how geological characteristics contribute to variations in slope instability across the study area.

Furthermore, the Random Forest analysis showed that land use and vegetation cover influence landslide occurrence alongside rainfall conditions. Sparsely vegetated and cultivated areas demonstrated moderate importance, while slope aspect and other topographic variables showed comparatively lower importance. The findings emphasize that rainfall acts as the dominant triggering factor, whereas geological formations, land use, and terrain characteristics influence the susceptibility and spatial distribution of landslides in Gorkha District.

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