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Presenting the Results of Algorithm-Based Rainfall Thresholds for Landslide Initiation Across Different Regions of Nepal

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Abstract: Landslides are a major hazard in Nepal, driven by steep terrain, fragile geology, and intense monsoon rainfall. This study establishes region-specific rainfall thresholds for landslide initiation using satellite-based GPM IMERG data and ground-based DHM rain gauge observations, applying the CTRL-T algorithm for reproducibility. Hourly and daily rainfall-landslide datasets were analyzed for Bagmati and Karnali Provinces, while thresholds for highly affected districts in Koshi, Gandaki, and Lumbini Province were derived from gauge data. Results reveal significant spatial variability, with lower thresholds in Bagmati and Karnali Provinces and higher thresholds in Taplejung District. Rain gauge-based thresholds were slightly higher than satellite-derived ones, while satellite products showed lower uncertainty but tended to underestimate extreme rainfall. Findings highlight the need for consistent data sources and localized thresholds to improve Landslide Early Warning Systems (LEWS) in Nepal.

Keywords: ***Landslides, Landslide early warning system, Rainfall thresholds, Disaster risk reduction.***

Introduction

Landslides are a frequent natural hazard in Nepal's hilly regions, triggered by steep terrain, fragile geology, intense monsoon rainfall, deforestation, and unplanned settlements. Nepal's susceptibility is heightened by tectonic activity and climate change, particularly rising peak rainfall intensities. Accurate rainfall thresholds are vital for effective landslide risk reduction in such vulnerable, rain-prone mountainous areas.

Landslides in Nepal have led to considerable human and economic losses, with 4,125 incidents and 3,837 fatalities reported between 1970 and 2021—an average of 71 deaths annually (Pradhan, 2020). Establishing Landslide Early Warning Systems (LEWS) using rainfall thresholds offers a promising approach to reduce such impacts. These thresholds represent the minimum rainfall required to trigger landslides and are essential tools for enhancing disaster preparedness and risk management (Guzzetti et al., 2008; Dahal and Hasegawa, 2008).

While rainfall-induced landslides have been studied globally since the 1970s, Nepal has seen limited research. Dahal and Hasegawa (2008) analyzed 193 landslides (1951–2006) and proposed the threshold;

$$I = 73.90\ D^{-0.79},$$

identifying 144 mm/day as the critical trigger. Malakar (2014) suggested community-based thresholds of 50 mm/hour or 200 mm/day, but validation showed these levels were rarely reached, highlighting the need for localized monitoring. These studies underscore the importance of developing and validating region-specific rainfall thresholds to improve LEWS in Nepal.

Methodology

Rainfall thresholds for landslide prediction are often based on intensity–duration (ID) models, but these are limited by interdependent variables. Event–duration (ED) thresholds, using cumulative rainfall (E) and duration (D), are more robust and practical since the variables are independent and easier to measure. However, empirical derivation is often inconsistent due to subjective event definitions, gauge selection, and manual analysis.

The CTRL-T algorithm (Melillo et al., 2018) overcomes these issues by automating rainfall event reconstruction, gauge selection, and threshold fitting. It applies statistical bootstrapping to derive probabilistic ED thresholds of the form:

$$E = (\alpha \pm \Delta\alpha) \times D^{(\gamma \pm \Delta\gamma)},$$

thereby improving reliability and reproducibility. Landslide data were compiled from government and media sources (NDRRP), and rainfall data from the GPM IMERG dataset (NASA–JAXA) and DHM rain gauges. Hourly GPM IMERG data were used for Bagmati Province (Bhattarai et al., 2024), daily GPM IMERG data for Karnali Province, and daily DHM gauge data for one landslide-prone district each in Koshi, Gandaki, and Lumbini Provinces.

Results

The results obtained from the study are shown in Table 1.

Table 1 Key attributes of rainfall thresholds with various non-exceedance probabilities across different regions of Nepal

NEP	Bagmati Province	Karnali Province	Taplejung District (Koshi Province)	Myagdi District (Gandaki Province)	Palpa District (Lumbini Province)
1%, T_1	$(2.6 \pm 0.4)\ D^{0.56 \pm 0.03}$	$(2.3 \pm 0.1)\ D^{0.73 \pm 0.03}$	$(7.6 \pm 2.0)\ D^{0.46 \pm 0.05}$	$(5.7 \pm 1.3)\ D^{0.56 \pm 0.04}$	$(3.0 \pm 1.2)\ D^{0.59 \pm 0.09}$
5%, T_5	$(3.8 \pm 0.5)\ D^{0.56 \pm 0.03}$	$(3.3 \pm 0.2)\ D^{0.73 \pm 0.03}$	$(10.3 \pm 2.6)\ D^{0.46 \pm 0.05}$	$(7.6 \pm 1.7)\ D^{0.56 \pm 0.04}$	$(4.7 \pm 1.8)\ D^{0.59 \pm 0.09}$
10%, T_{10}	$(4.6 \pm 0.6)\ D^{0.56 \pm 0.03}$	$(4.1 \pm 0.2)\ D^{0.73 \pm 0.03}$	$(12.0 \pm 3.1)\ D^{0.46 \pm 0.05}$	$(8.9 \pm 1.9)\ D^{0.56 \pm 0.04}$	$(5.9 \pm 2.3)\ D^{0.59 \pm 0.09}$
20%, T_{20}	$(6.0 \pm 0.8)\ D^{0.56 \pm 0.03}$	$(5.2 \pm 0.3)\ D^{0.73 \pm 0.03}$	$(14.5 \pm 3.7)\ D^{0.46 \pm 0.05}$	$(10.7 \pm 2.2)\ D^{0.56 \pm 0.04}$	$(7.8 \pm 3.0)\ D^{0.59 \pm 0.09}$
35%, T_{35}	$(7.7 \pm 1.0)\ D^{0.56 \pm 0.03}$	$(6.7 \pm 0.4)\ D^{0.73 \pm 0.03}$	$(17.7 \pm 4.6)\ D^{0.46 \pm 0.05}$	$(13.0 \pm 2.7)\ D^{0.56 \pm 0.04}$	$(10.5 \pm 3.9)\ D^{0.59 \pm 0.09}$
50%, T_{50}	$(9.6 \pm 1.2)\ D^{0.56 \pm 0.03}$	$(8.3 \pm 0.5)\ D^{0.73 \pm 0.03}$	$(20.9 \pm 5.4)\ D^{0.46 \pm 0.05}$	$(15.3 \pm 3.1)\ D^{0.56 \pm 0.04}$	$(13.4 \pm 5.0)\ D^{0.59 \pm 0.09}$

Discussion and conclusions

The analysis reveals significant spatial variability in rainfall threshold parameters across Nepal. Bagmati and Karnali Provinces exhibit lower scaling factors (α), indicating that landslides in these regions can occur under relatively moderate rainfall conditions. In contrast, Taplejung district shows substantially higher α values, suggesting that prolonged or intense rainfall is required to trigger landslides. These variations likely stem from differences in topography, geological structure, soil properties, and land-use patterns. Another key finding is that thresholds derived from terrestrial rain gauge data are slightly higher than those obtained from satellite-based rainfall products. This suggests that greater rainfall amounts are needed for landslide initiation when using ground-based measurements. A plausible explanation is that satellite products, such as GPM IMERG, may underestimate extreme rainfall events in complex mountainous terrain, leading to lower threshold estimates. This discrepancy highlights the need for consistency in data sources: thresholds derived from satellite products should guide warnings based on the same dataset. Mixing satellite and rain gauge data can create confusion and reduce reliability. Uncertainty ratios are lower for satellite-derived thresholds than for rain gauge-based ones, likely due to uniform coverage and automated processing. Higher uncertainty in gauge-based thresholds may stem from sparse stations and localized variability but could also reflect the limited number of landslide events available at the district level.

Region-specific rainfall thresholds show significant spatial variability across Nepal, emphasizing the need for localized LEWS. Satellite-based thresholds offer lower uncertainty but may underestimate extreme rainfall, while rain gauge data provide higher thresholds with greater variability. Future work should integrate both datasets with soil, geology, and terrain factors for more accurate forecasting.

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