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A Review of Rainfall Thresholds for Landslide Occurrence in the Hindu Kush Himalaya (HKH)

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Abstract: The Hindu Kush Himalaya (HKH) region is one of the world's most landslide-prone areas because of its rugged topography, complex geology, and intense monsoonal rainfall. Rainfall thresholds are widely used to forecast rainfall-induced landslides and form a key component of landslide early warning systems. This study presents a comprehensive review of rainfall-threshold research across HKH countries, including Nepal, India, China, Bangladesh, Bhutan, Afghanistan, Pakistan, and Myanmar. A bibliometric analysis using the Scopus database was complemented by a systematic review of peer-reviewed literature from Scopus, Web of Science, and Google Scholar. A total of 54 studies defining 61 rainfall thresholds were identified and evaluated based on publication trends, dataset characteristics, threshold formulations, derivation methods, validation procedures, and operational applications. The results show a substantial increase in rainfall-threshold research during the past three years, with most studies conducted in India and China. Empirical and statistical approaches dominate, whereas physically based models remain limited because of their high data requirements. Most thresholds are derived from 5–25 years of daily rainfall records, with Intensity–Duration (I–D) and Event–Duration (E–D) relationships being the most common formulations. The review identifies major gaps in data reporting, threshold derivation, and validation, while only a few studies demonstrate operational implementation in early warning systems. No region-wide rainfall threshold currently exists for the HKH, highlighting the need for standardized methodologies, robust validation, long-term monitoring datasets, and stronger integration into operational landslide early warning systems.

Keywords: ***Landslide, Rainfall threshold, Early Warning System, Hindu Kush Himalaya, Intensity-duration relationship***

Introduction

Rainfall is the primary trigger of landslides across the Hindu Kush Himalaya (HKH), a region characterized by steep slopes, active tectonics, and highly variable monsoonal precipitation (Dahal and Hasegawa, 2008). Rainfall thresholds represent critical rainfall conditions beyond which landslides are likely to occur and are widely used for hazard forecasting and early warning systems. Thresholds may be defined using empirical, probabilistic, or physically-based approaches and can be developed at global, regional, or local scales.

Despite increasing research activity, a comprehensive synthesis of rainfall-threshold studies in the HKH region remains limited. This study reviews published rainfall threshold research across HKH countries to identify research trends, methodological approaches, data characteristics, and future needs for landslide early warning applications.

Methodology

A bibliometric analysis was conducted using the Scopus database with combinations of the keywords “landslide”, “rainfall”, and “threshold” together with HKH country names. Subsequently, peer-reviewed studies were collected from Scopus, Web of Science, and Google Scholar. Only English-language studies proposing rainfall thresholds for landslides within HKH countries were included.

A total of 54 publications defining 61 rainfall thresholds were selected. Information was compiled on publication characteristics, study area, rainfall and landslide datasets, threshold types, derivation methods, validation approaches, and implementation in early warning systems.

Results and discussion

The review revealed rapid growth in rainfall-threshold research, particularly after 2023. Approximately 41% of studies were conducted in India and 33% in China, while no threshold studies were identified for Afghanistan and Pakistan.

Most thresholds were developed at local and regional scales. Rainfall and landslide datasets commonly covered periods of 5–25 years. Daily rainfall data were used in nearly two-thirds of studies, whereas high-temporal-resolution rainfall records were relatively uncommon.

Empirical and statistical approaches dominate threshold development, while physically-based models account for only about 7% of reviewed studies. Intensity–Duration and Event–Duration relationships are the most widely adopted threshold forms. Although methodological advances have improved threshold estimation, many studies fail to provide adequate

validation or clear descriptions of data quality and sources.

A major finding is that operational implementation remains limited. While most studies emphasize early warning applications, few have progressed to functioning warning systems. Furthermore, no unified rainfall threshold has yet been proposed for the HKH region.

Conclusions

This review demonstrates increasing scientific interest in rainfall thresholds for landslide prediction within the HKH region. Current research is dominated by empirical approaches and concentrated mainly in India and China. Several shortcomings remain, including inadequate validation, inconsistent reporting of datasets, and limited operational implementation.

Future studies should focus on standardized threshold-development procedures, longer-term datasets, rigorous validation frameworks, and integration with operational landslide early warning systems. Development of a regional-scale HKH rainfall threshold represents an important future research direction.

References

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