Impact of Threshold Rainfall on Landslides: A Case study of Kerala

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ABSTRACT

A major natural hazard, landslides can seriously endanger infrastructure, property, and human life, especially in areas like Kerala that have high rainfall and steep terrain. To improve landslide risk assessment and aid in the creation of early warning systems, this research intends to examine the connection between past landslide incidents and rainfall patterns throughout Kerala. The study aims to determine crucial rainfall thresholds that can serve as triggers for slope instability by comparing rainfall data from neighboring rain gauge stations with historical landslide events. The study uses a slope stability model, which simulates the effects of heavy rainfall and determines the Factor of Safety (FS) for slopes in saturated soil conditions, to further evaluate the danger of landslides. This model maps stability throughout the research area by combining topographical, soil, and vegetation data. It is anticipated that the results would provide important information on areas that are vulnerable to landslides and pinpoint certain rainfall trends linked to landslide occurrences. The ultimate goal of this research is to support an efficient early warning system that will help residents in susceptible areas receive timely notifications and lessen the negative effects of landslides.

Keywords: Landslide, Rainfall Threshold, Antecedent Rainfall

1. INTRODUCTION

The steep Western Ghats, intense monsoon rains, and human activities including deforestation, unchecked growth, and agricultural expansion are the main causes of landslides in Kerala. They are now more frequent and severe because of climate change, which poses serious risks to public safety, livelihoods, and infrastructure. The prediction and control of landslide risk have improved with recent studies. Using Deep Neural Networks (DNN) to identify landslide-prone areas, Achu et al. (2024) discovered that 13% of Kerala was particularly vulnerable during periods of heavy rainfall.[1] According to Hao et al. (2022), 76% of the 2018 monsoon landslides happened in vegetated areas, suggesting that even in places with a lot of vegetation, human activity exacerbates slope instability.[3] The length and intensity of rainfall are important landslide triggers. In the Garhwal Himalayas, Saha et al. (2024) determined particular rainfall limits for shallow landslides, whereas Chellamuthu et al. (2024) discovered that 18% of the Nilgiris were extremely vulnerable as a result of extended rainfall[7,2]. Liu et al. (2024) emphasized the necessity of climate-adaptive measures by projecting more frequent extreme rainfall using Global Climate Models (GCMs).[4] For the Jammu-Srinagar National Highway (NH-44) and Kashmir Valley, regions vulnerable to landslides because of their steep topography and intense monsoon rains, Bilquis Shah et al. (2024) established rainfall intensity-duration thresholds.[8] To minimize interruptions along NH-44 and improve regional hazard

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management, their empirical model helps early warning systems by determining when rainfall is most likely to cause landslides.

Early warning systems at the regional level are also based on rainfall thresholds. The SIGMA (Sistema Integrato Gestione Monitoraggio Allerta) model was created by Martelloni et al. (2012) and employs rainfall thresholds determined by precipitation duration and amount to initiate various alert levels.[5] Decision-makers may evaluate landslide hazards across wide regions with this real-time monitoring approach, improving preparedness and mitigation measures. For reducing the risk of landslides, early warning systems (EWS) are essential. Naidu et al. (2018) used slope stability assessments with rainfall data to create an affordable EWS for Amboori, Kerala.[6] By dynamically accounting for fluctuating rainfall events, Sun et al. (2024) highlighted a move to machine learning-based probabilistic models, which improve prediction accuracy.[9] In regions with restricted data availability, Vishnu et al. (2022) showed how combining satellite and ground-based rainfall data improves prediction reliability.[10]

Landslide prediction and mitigation have greatly improved because of developments in machine learning, deep learning, and geospatial analysis. In Kerala and other landslide-prone areas, incorporating rainfall thresholds, land-use monitoring, and sophisticated early warning systems is crucial for efficient catastrophe planning as climate change intensifies rainfall patterns.

2. LANDSLIDES IN KERALA

Landslides are a frequent geological hazard in Kerala, due to the steep terrain and heavy monsoonal rainfall in Kerala. The region's unique topography and climate make it more susceptible to landslides, especially during the monsoon season when heavy rainfall can saturate the soil which destabilizes the slopes and triggers landslides. Factors such as deforestation, urbanization, and mining activities could further increase the risk of landslides.

The Western Ghats, which run parallel to the western coast of Kerala, consist of steep hills and valleys that are prone to slope failures. Hence the parts of Kerala covered by Western Ghats are more susceptible to landslides. Historically, landslides in Kerala have been linked to intense rainfall events, especially during the monsoon season from June to September. When rainfall infiltrates into the soil, it increases the pore water pressure and reduces the friction between soil particles, which may cause failure of the slope. Prolonged periods of heavy rain can erode vegetation, further increasing the risk of landslides.

2.1. Factors affecting Landslides

Numerous natural and man-made elements can cause landslides. Earthquakes destabilize slopes through ground shaking, inducing liquefaction in water-saturated soils, reactivating dormant landslides, and weakening slopes through seismic cracks or ruptures [2]. Rainfall increases soil susceptibility to failure by raising pore water pressure, which causes debris flows, mudslides, or minor landslides, especially in steep terrains, as loose material becomes saturated and flows downward rapidly [2].Slope angle is also important since steeper slopes are more likely to break due to gravity, and instability increases with heavy rains. Geology affects landslides because softer materials like clay and shale dissolve more readily than harder rocks like granite, and slope instability is caused by weak soil layers, fractures, and fissures. Slope foundations are further weakened by infiltration and underground water flow, which degrade soil and increase the risk of landslides. Drainage problems include excessive rainfall water or insufficient drainage. By absorbing water through its roots, vegetation helps stabilize slopes, but soil erosion and deforestation make instability worse. While well-compacted soils lessen the chance of slipping, geotechnical factors such as loose, non-cohesive soils (like sand) and low shear strength raise the chances of slope failure. Land-use changes, urbanization, and water diversion also increase erosion, surface runoff, and total landslide susceptibility, making human activities like excavation, construction, and deforestation a major contributor to slope instability. Because each of these elements can affect the occurrence of landslides either alone or in combination, thorough risk evaluations are crucial for mitigation initiatives.

2.2. Spatial Analysis of Historical Landslide Events

In this study, we analyzed a dataset comprising 150 recorded landslide events. Each entry includes important parameters such as the date of occurrence, the area by landslide, and specific measurements of the landslide's dimensions, including length, width, and depth. This comprehensive dataset could be used for the detailed assessment of landslide patterns and their correlation with rainfall thresholds.

Table 1. Landslide Events Sample Data

S.No	Location	Area affected(m^2)	Length (m)	Depth(m)	Width(m)	Date
1.	Mundakkai-Chooralmala	86000	8000	50	100	30-7-2024
2.	Venniyani	35000	48	2	35	09-06-2001
3.	Kavalappara	40468	320	5	280	08-08-2019
4.	Konibail	2800	30	2	20	06-08-2007
5.	Adukkom	28000	800	2	35	05-06-2001
6.	Ambemoole	3000	100	2	30	29-07-1994

Table 1 shows a sample of data collected from KSDMA, NCESS Reports, and Newspaper articles showing the major landslides in Kerala. Similar information on 150 landslide events was collected for the study.

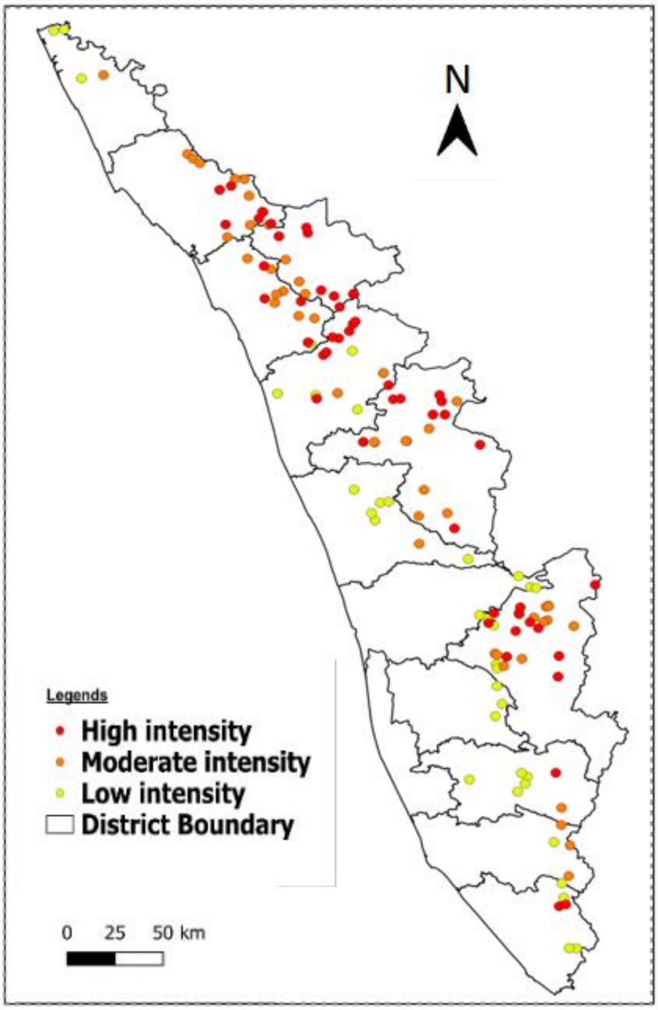

Figure 1: Landslide Events map

Figure 1 shows the map illustrating the locations of 150 recorded landslide events across Kerala, highlighting the spatial distribution and intensity of these landslides. Each point on the map represents a specific landslide event, accompanied by data regarding its date, affected area, and dimensions. The map serves as a visual tool to identify high-risk regions and trends in landslide activity in different locations across Kerala. This geographic representation helps for a better understanding of how the landslides correlate with factors such as rainfall patterns and topography.

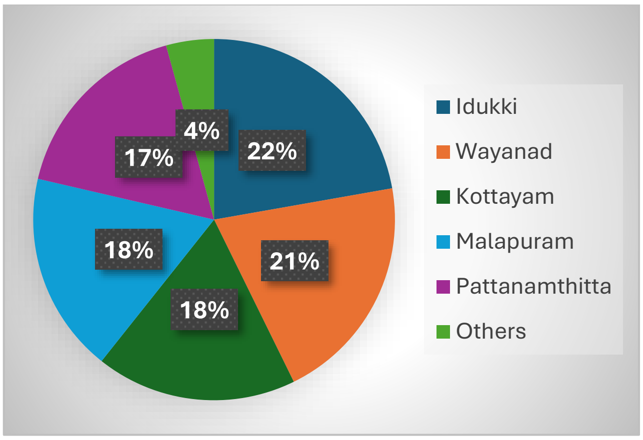

Figure 2: Landslide distribution

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Figure 2 shows the distribution of landslide events across various districts, with each segment representing the percentage of total occurrences in that district. Idukki experiences the highest number of events, making up 21% of the total, highlighting its vulnerability likely due to steep terrain and high rainfall

3. Classification of Landslides Based on Area Affected

Landslides are classified into three categories based on the area affected: High, Moderate, and low intensity. This classification helps in assessing the impact of rainfall-triggered landslides and is crucial for determining threshold values that can trigger landslides.

Table 2. Landslide Classification

High Intensity	>10000m^2
Moderate Intensity	10000m^2-1000m^2
Low Intensity	<1000m^2

3.1 High-Intensity Landslides

These landslides affect large areas, leading to widespread displacement of soil, rocks, and debris. They have significant impacts on infrastructure, vegetation, and human settlements, often resulting in severe disruption and high restoration costs. High-intensity landslides are typically associated with intense, prolonged rainfall events and steep slopes.

3.2 Moderate-Intensity Landslides

Landslides of moderate intensity affect intermediate areas. While they may not be as widespread as high-intensity events, they can still cause considerable damage to property and infrastructure. Such landslides may occur during moderate rainfall events and tend to have a localized impact, potentially disrupting transportation and daily activities in the affected areas.

3.3 Low-Intensity Landslides

Low-intensity landslides affect smaller, more contained areas. These events typically occur during short, intense rainfall or after cumulative minor precipitation over time. The impact is generally limited to small portions of land, and while the damage may be less severe.

4.Meteorological Data

Rainfall data were obtained from the India Meteorological Department (IMD) to analyze precipitation levels at the time of landslide occurrences. This data includes daily rainfall measurements in millimeters (mm) recorded on landslide event dates and during the days preceding these events, known as antecedent rainfall. By studying both the immediate and antecedent rainfall, we can assess the impact of rainfall on soil saturation levels, which is crucial in understanding rainfall thresholds that trigger landslides.

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Table 3. Rainfall Data in millimeters [11]

DATE	LOCATION	Day of incident	2 DAY	5 DAY	10 DAY
24-07-2005	Anthoniyar Colony, Idukki	75.21	108.12	180.25	210.12
24-07-2005	Government College,Munnar	89.16	50.10	100.67	150.81
08-08-2019	Puthumala, Wayanad	254.62	306.81	367.11	412.03
08-08-2019	Kavalappara, Malapuram	267.83	305.19	390.01	319.80

Table 3 shows the precipitation data on the exact date of each landslide in millimeters. It provides insight into the rainfall required to directly trigger landslides. Antecedent rainfall represents cumulative precipitation over a specified number of days before each landslide event. This data is crucial for examining how progressive soil saturation from prior rainfall contributes to slope instability. Higher antecedent rainfall typically indicates an increased risk of landslide occurrence due to reduced shear strength in soil and rock layers.

5. RESULTS AND DISCUSSIONS

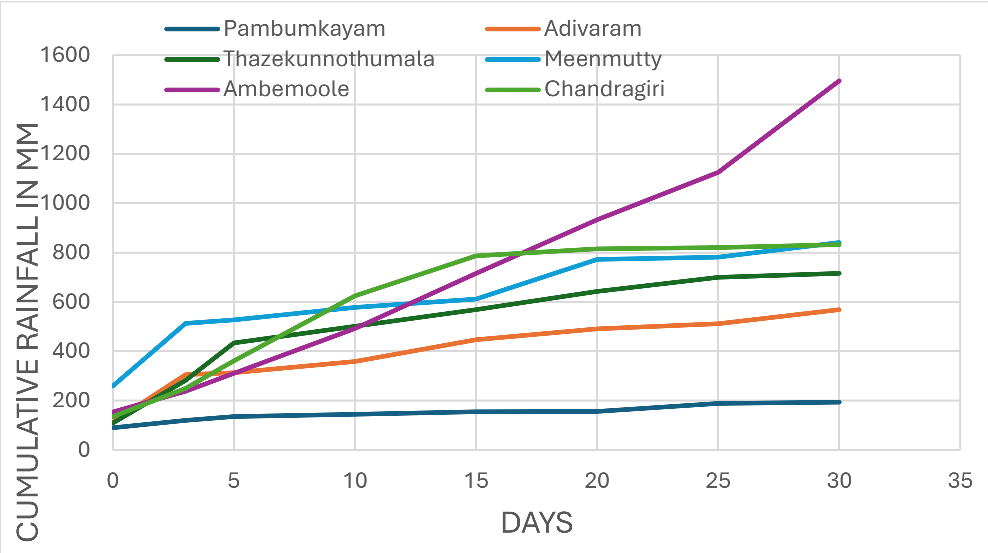

Figure 3: Cumulative rainfall trends prior to Landslide events

The observed trends in cumulative rainfall further highlight variations in rainfall intensity and distribution across different locations, emphasizing the localized nature of landslide triggers. Stations such as Pambumkayam exhibit significantly higher cumulative rainfall compared to other sites, indicating higher vulnerability due to prolonged intense rainfall episodes. Conversely, stations like Adivaram and Meenmutty show relatively steady but moderate rainfall accumulation, suggesting that even sustained moderate rainfall can act as a precursor to landslides, particularly in areas with pre-existing vulnerabilities. The distinct rainfall patterns at each location underscore the critical role of integrating localized rainfall data with geological and topographical analyses to refine hazard prediction models. These variations also point to the need for spatially distributed rainfall monitoring networks to ensure accurate and timely risk assessment in regions prone to landslides. A major cause of landslides in Kerala, prolonged monsoonal rainfall is indicated by the rising trend in cumulative rainfall. All locations show a gradual rise in cumulative rainfall during the initial days, followed by steeper increases in some stations, particularly Pambumkayam suggesting episodes of more intense rainfall later in the period.

These results highlight the spatial variability of rainfall, influenced by local topography and prevailing weather patterns, which leads to significantly different amounts of moisture infiltration at each site. In landslide prone regions, prolonged or heavy rainfall can elevate pore water pressures in the soil, weakening slope stability. High totals at Pambumkayam suggest an increased likelihood of slope failure there, while moderate yet sustained rainfall at locations like Thazhekunnothumala and Ambemoole may also trigger landslides if other vulnerability factors, such as steep slopes or poor vegetation cover, are present. Monitoring site-specific conditions such as soil moisture and groundwater levels, alongside refining short-term rainfall thresholds, would offer more robust early warning for landslide hazards. In order to improve landslide prediction and mitigation, these findings emphasize the necessity of ongoing monitoring of high-rainfall locations and evaluating threshold exceedances.

6. CONCLUSIONS

This research establishes a comprehensive and well-defined relationship between rainfall variability and landslide occurrences in Kerala, with a particular emphasis on high-risk districts such as Idukki, Wayanad, Kottayam, and Malappuram. The findings indicate that prolonged and intense monsoonal precipitation, in conjunction with steep topography, unfavorable geological formations, and human-induced activities, significantly contribute to slope instability, increasing the likelihood of landslides. A thorough analysis of historical rainfall patterns and documented landslide events has led to the identification of critical rainfall thresholds that serve as key indicators for potential slope failures. These thresholds, when integrated with real-time rainfall observations, have the potential to enhance the accuracy and efficiency of predictive models and early warning systems, thereby facilitating proactive disaster preparedness. The ability to anticipate and respond to landslide-prone conditions through timely evacuations and the implementation of effective mitigation measures can substantially reduce the impact of such natural hazards on both human lives and infrastructure. Furthermore, the study underscores the imperative need for continuous monitoring practices, scientifically informed land-use planning strategies, and well-structured policy interventions aimed at strengthening regional resilience against landslides. By refining early warning mechanisms and adopting data-driven risk management approaches, authorities can make informed decisions that contribute to disaster risk reduction and sustainable development in vulnerable regions. Additionally, the methodologies and insights derived from this research are not confined to Kerala alone but can be extended to other regions with similar geological and climatic characteristics, offering a valuable framework for landslide risk assessment on a broader scale. Ultimately, this study highlights the significance of a data-informed approach to landslide mitigation, ensuring the development of safer communities, the protection of critical infrastructure, and the promotion of sustainable land management practices in high-risk areas.

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