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# Mathematical Modelling in Disaster Management: A Study of the Wayanad Landslide

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## Abstract

The increasing occurrence of natural disasters has emphasized the need for effective disaster management strategies, particularly in vulnerable regions. Landslides represent one of the most significant hazards in mountainous terrains, often triggered by a combination of environmental and anthropogenic factors. This study examines the 2024 landslide event in Wayanad district, Kerala, with the objective of analyzing its causes, impacts, and broader implications.

In addition, the paper investigates the role of mathematical modelling as a tool for understanding and assessing landslide risk. A simplified analytical framework based on key variables such as rainfall intensity, slope angle, and soil stability is discussed to explain the mechanism of slope failure.

The study indicates that increased rainfall variability, along with human-induced alterations in land use, has contributed to higher landslide susceptibility in the region. It further highlights that integrating mathematical modelling with disaster management practices can enhance risk assessment and support more informed decision-making for mitigation and preparedness.

## Keywords

*Disaster Management; Landslides; Mathematical Modelling; Wayanad Landslide 2024; Rainfall Threshold; Slope Stability; Factor of Risk; Western Ghats*

## Introduction

Disasters are events that disrupt the normal functioning of societies, often resulting in significant loss of life, property, and environmental resources. Over the past few decades, the frequency and intensity of natural hazards have shown a noticeable rise, influenced by factors such as climate variability, population growth, and unsustainable land-use practices. In this context, disaster management has emerged as an essential field focused on reducing risks and improving resilience through systematic planning and response mechanisms.

Among various types of natural disasters, landslides are particularly prominent in regions characterized by steep terrain and high rainfall. These events involve the downward movement of soil, rock, or debris under gravitational forces and are typically triggered by conditions such as intense precipitation, geological instability, and human interference. Due to their sudden nature and destructive potential, landslides pose serious challenges to both infrastructure and human safety.

The Western Ghats, a biodiversity-rich mountainous region in India, is especially susceptible to landslides. The 2024 landslide event in Wayanad district serves as a critical example, highlighting the combined influence of natural and human factors in disaster occurrence. The severity of this event underscores the need for improved understanding and better predictive approaches.

Mathematical modelling offers a structured way to analyze such complex phenomena by representing relationships between key variables affecting slope stability. By incorporating factors such as rainfall intensity, slope gradient, and soil characteristics, modelling techniques can assist in evaluating landslide probability and identifying high-risk zones.

The present study aims to examine the Wayanad landslide of 2024 and to explore how mathematical modelling can contribute to disaster management by enhancing analysis, prediction, and planning.

Study Area and Event Description

Wayanad district, located in the Western Ghats region of Kerala, India, is characterized by steep slopes, high rainfall, and ecologically sensitive terrain. The region is known for its susceptibility to landslides, particularly during the southwest monsoon season.

In July 2024, Wayanad experienced a series of intense landslide events following prolonged and heavy rainfall. The affected areas included hilly settlements such as Mundakkai and Chooralmala, where slope failures resulted in significant destruction. The landslides were accompanied by debris flow and localized flooding, which further intensified the impact.

## Causes of the Landslide

The 2024 Wayanad landslide was the result of a combination of natural and anthropogenic factors:

### (a) Rainfall Trigger

Continuous and high-intensity rainfall led to increased soil moisture and pore water pressure, reducing the shear strength of slope materials and triggering slope failure.

### (b) Geomorphological Factors

The presence of steep slopes and weathered rock formations contributed to slope instability. The terrain of Wayanad inherently increases susceptibility to gravitational movement.

### (c) Soil and Geological Conditions

The region consists of loose and weathered soil, which becomes highly unstable when saturated with water.

### (d) Human Activities

Deforestation, expansion of settlements, road construction, and changes in land use have disturbed natural slope stability and increased vulnerability to landslides.

## Impact Assessment

The landslide events in Wayanad caused widespread damage across multiple sectors:
**Human Impact:** Loss of lives and displacement of local communities
**Infrastructure Damage:** Destruction of houses, roads, and communication networks
**Economic Loss:** Damage to agricultural land and local livelihoods
**Environmental Impact:** Soil erosion, vegetation loss, and landscape alteration

The blockage of roads and debris accumulation also led to temporary isolation of affected areas, complicating rescue and relief operations.

## Response and Management Measures

Following the landslide events, immediate response actions were undertaken by government and disaster management authorities:
Deployment of rescue teams, including national and state disaster response forces
Establishment of temporary shelters and relief camps
Provision of emergency medical assistance and essential supplies

Initiation of debris removal and restoration of connectivity

In addition, efforts were made to improve early warning systems and conduct landslide hazard assessments for future risk reduction.

## Key Observations

The Wayanad landslide of 2024 highlights several important aspects of disaster management:
Landslides are strongly influenced by the interaction of rainfall, terrain, and human activities
Increasing rainfall intensity, possibly linked to climate variability, plays a critical role in triggering slope failure
Human-induced changes in land use significantly amplify disaster risk
There is a need for integrated approaches combining environmental monitoring and analytical modelling

Methodology and Mathematical Modelling

## Research Approach

The present study adopts a **case study-based and conceptual modelling approach** to analyze landslide occurrence. The 2024 Wayanad landslide is taken as the primary case, supported by comparative analysis of similar landslide events across India.

The modelling framework is based on measurable physical variables such as rainfall intensity, slope angle, and soil strength, allowing a simplified but scientifically supported interpretation of slope instability.

## Model Variables and Observed Ranges

Landslide occurrence is governed by key physical variables, whose typical ranges have been observed in various studies across India:

**Rainfall ($R_1$)**:
Landslides are often triggered when rainfall intensity exceeds approximately **0.45–0.50 mm/hour over 48 hours**, or when cumulative rainfall reaches around **80 mm over a 10–15 day period**.

**Slope Angle (θ)**:
A majority of landslides occur on slopes ranging between **20° and 45°**, with the highest frequency observed in the **30°–45° range**, where gravitational forces significantly influence instability.

**Driving Force (S)**:
Increases with added water load due to rainfall infiltration and is directly proportional to slope angle and mass of saturated soil.

**Resisting Force (R)**:
Depends on soil cohesion and friction, which decrease significantly under saturated conditions, particularly in high rainfall zones receiving **1500–2500 mm annually**.

## Model Formulation

The probability of landslide occurrence can be expressed as:

$$\mathbf{P(L) = f\,(R1, S, R, \theta)}$$

A simplified failure condition is given by:

$$\mathbf{S > R}$$

where slope failure occurs when driving forces exceed resisting forces.

## Model Interpretation with Quantitative Basis

The interaction of variables can be explained quantitatively as follows:
Rainfall exceeding **0.5 mm/hour** over prolonged durations increases soil moisture and pore water pressure
Increased pore pressure reduces soil cohesion, thereby decreasing resisting force (R)
Simultaneously, water accumulation increases the effective mass of the slope, increasing driving force (S)
Slopes within **30°–45°** amplify gravitational stress, making them highly susceptible to failure

Thus, under conditions of high rainfall and steep slopes:
$\mathbf{S \uparrow \text{ and } R \downarrow \quad \Rightarrow \quad S > R}$

## Application to Wayanad Landslide (2024)

The Wayanad region receives annual rainfall in the range of **2000–3000 mm**, placing it within a high-risk zone for landslides. During the 2024 event, continuous and intense rainfall likely exceeded threshold values, resulting in prolonged soil saturation.

The slope angles in the region typically fall within the critical range of **20°–40°**, further contributing to instability. As rainfall infiltrated the soil, pore water pressure increased, reducing the shear strength of slope materials.

Consequently:
Resisting force (R) decreased due to soil weakening
Driving force (S) increased due to added water load and slope stress

This imbalance satisfied the condition S > R, leading to landslide occurrence.

## Comparative Evidence from Other Indian Landslides

Similar numerical patterns can be observed in other landslide-prone regions:
**Kedarnath (2013):**
Extreme rainfall exceeding threshold limits led to rapid slope saturation and failure in steep Himalayan terrain.
**Malin (2014):**
Continuous rainfall combined with altered land use reduced soil stability, triggering landslides in moderate to steep slopes.
**Himachal Pradesh (2023):**
Repeated landslides occurred in areas with steep slopes (>**30°**) and intense monsoon rainfall.
**Sikkim Region:**
High rainfall and steep gradients consistently produce slope failures under similar conditions

## Generalized Interpretation

The integration of observed numerical ranges across different regions indicates that landslides follow a consistent pattern governed by rainfall thresholds, slope angle, and soil stability.

Mathematically, this relationship can be summarized as:
**High rainfall (≥ 0.5 mm/hr) + Steep slope (20°-45°) + Reduced soil strength ⇒ S>R**

Thus, the probability of landslide occurrence increases under conditions where driving forces are enhanced and resisting forces are weakened.

This demonstrates that landslide events, despite geographical differences, can be effectively analyzed using a unified mathematical modelling framework, reinforcing the role of mathematics in disaster management and risk prediction.

## Factor of Risk Formulation

To quantify landslide susceptibility, a **Factor of Risk (FR)** can be defined as the ratio of driving forces to resisting forces acting on a slope:
$FR = F_d/F_r$

where
$F_d$ = Driving force (gravitational + water load)

$F_r$ = Resisting force (soil cohesion + frictional resistance)

Failure Condition
$FR > 1 \Rightarrow$ Landslide Occurrence
$FR \leq 1 \Rightarrow$ Stable Slope

Expanded Mathematical Form

The forces can be expressed as:
$F_d \propto W \sin\theta$
$F_r \propto C_s + (W \cos\theta) \tan\phi$

$$FR = \frac{W \sin\theta}{C_s + (W \cos\theta)\tan\emptyset}$$

where
W = Weight of saturated soil mass
$\theta$ = Slope angle
$C_s$ = Soil cohesion
$\phi$ = Angle of internal friction

The factor of risk provides a quantitative framework to evaluate landslide susceptibility. Using observed ranges of rainfall and slope angle, the model demonstrates that landslide occurrence is primarily controlled by the increase in driving forces and simultaneous reduction in resisting forces. This formulation supports the application of mathematical modelling in predicting landslide-prone conditions.

## Results and Analysis

The application of the proposed mathematical framework to the Wayanad landslide case, along with comparative observations from other regions, provides important insights into the factors controlling slope instability.

The analysis indicates that **rainfall intensity and duration** play a dominant role in influencing landslide occurrence. When rainfall exceeds approximately **0.45–0.50 mm/hour over extended periods**, or accumulates to significant levels over several days, soil saturation increases considerably. This leads to a rise in pore water pressure, which in turn reduces the effective shear strength of the soil.

At the same time, the increase in water content contributes to a higher mass of the slope material, thereby enhancing the **driving force ($F_d$)**. This simultaneous increase in driving force and decrease in resisting force ($F_r$) shifts the stability condition of the slope.

The graphical representation of the **Factor of Risk (FR)** further supports this observation. The results show that for lower rainfall values, the slope remains stable. However, as rainfall increases, the value of FR rises progressively. Once the threshold FR=1 is crossed, the slope enters an unstable condition, making landslide occurrence highly probable.

Slope angle also plays a significant role in determining landslide susceptibility. The analysis confirms that slopes within the range of **20° to 45°** are particularly vulnerable, as they provide optimal conditions for gravitational forces to overcome resisting forces. This observation is consistent across multiple landslide-prone regions in India.

In the case of Wayanad, the combination of **high annual rainfall (2000–3000 mm)** and slopes within the critical range created favorable conditions for instability. Continuous rainfall during the 2024 event likely exceeded threshold levels, resulting in prolonged saturation of soil and reduction in cohesion. Consequently, the condition Fd >Fr was satisfied, leading to slope failure.

Comparative observations from regions such as Uttarakhand, Himachal Pradesh, and Maharashtra reveal similar patterns. In each case, landslides were associated with intense or prolonged rainfall, steep slopes, and weakened soil conditions. This consistency suggests that landslide occurrence follows a common physical mechanism regardless of geographical differences.

Overall, the results demonstrate that landslide susceptibility can be effectively interpreted using a mathematical framework based on rainfall, slope angle, and soil strength. The integration of real-world data with the proposed model provides a logical explanation for the increasing frequency of landslides and highlights the importance of predictive analysis in disaster management.

## Conclusion

The results of this study indicate that landslide occurrence is primarily controlled by the interaction of rainfall, slope angle, and soil strength. In the Wayanad landslide (2024), prolonged and intense rainfall led to soil saturation, reducing resisting forces while increasing driving forces, thereby satisfying the condition Fd>Fr

Similar patterns observed in regions such as Uttarakhand, Himachal Pradesh, and Maharashtra suggest that landslides across India follow a common mechanism. This supports the applicability of a unified mathematical model for analyzing slope instability.

The Factor of Risk model further demonstrates that increasing rainfall leads to a transition from stable to unstable slope conditions. However, the model is simplified and does not account for factors such as vegetation and geological variability.

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