Landscape Dynamics and Its Impact on Landslide Susceptibility: A Case Study of Idukki District, Kerala

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Abstract

Hazard is an event which may cause danger by natural, and human made activities. The hazard will become a disaster when it leads to life property and environment. Among the Natural hazard the Landslide are particularly devastating, especially in steep region, intense rainfall and uncontrolled or unregulated land use practices. The study Area Idukki district is reportedly the most prominent landslide susceptibility zone in Kerala. For this study the Multi Influencing Factor (MIF) method integrated with Geographic Information System (GIS) to assess the Landslide vulnerability zones of Idukki. The eleven parameters were selected for the analysis, which is Rainfall, Slope, Geology, Geomorphology, Land use land cover, Drainage density, Road density, soil, Normalized Difference Vegetation Index (NDVI), Topographic Wetness Index (TWI), Curvature and Elevation. These parameters are taken and converted into individual spatial layers then overlay these layers and find final output for the study. From this output the study provides detailed landslide susceptibility maps and categorises the study area into various susceptibility zones such as very low (0.33), low (5.42), moderate (31.10), high (63.12) and very high (3.59) susceptibility regions. The findings reveal that the area with steep slope, High rainfall, LULC especially unplanned human activities like deforestation, unregulated construction this will also exacerbate the risk of landslide. Understanding the dynamics of landscape and its impact in landslide susceptibility clearly indicates why the study area is demarcated as the intense zone of landslide vulnerability in Kerala and it will help to showcase through maps and can generate future developmental activities according to this fact.

Keywords: *Landslide, Western Ghats, MIF, GIS, Idukki*

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1. Introduction

Landslides are one of the most destructive natural hazards, endangering lives, property, and disrupting infrastructure in vulnerable regions across the globe. These events involve the rapid down slope movement of earth, rock, or debris, often initiated by a mix of geological, environmental, and climatic triggers. Natural catastrophic agents such as heavy rainfall, earthquake, and anthropogenic activities such as deforestation and construction are frequently cited as catalysts (Guzzetti et al., 1999). In India, the Western Ghats recognised by UNESCO as biodiversity hotspot and spreading mountain range, are particularly more susceptible to landslides. This mass wasting process accelerating especially in the topographic steepness and intensive monsoon rainfall areas (Kuriakose et al., 2010). These are all the main factor in the Idukki District of Western Ghats range in Kerala emerges as a focal point for landslide risk. Many studies indicate that Idukki is the most severely impacted region in Kerala when it comes to disaster distribution (Kumar, 2020). Even though the region faces the wrath of most of the hazards, Landslides are identified as the major one. Thus, the key objective of this research is to undertake a comprehensive and detailed investigation specifically centered on Idukki District. The increased vulnerability of Idukki district to landslides can be understand from its different geographical features. Due to the influence of Western Ghats, Idukki is categorised by rugged terrain, steep slopes, and dense forest cover (Sajinkumar et al., 2014). These physical features significantly increase the Idukki's landslide risk, especially during the monsoon season when torrential rains are very common. Globally, these mass wasting landslides in the mountain areas have caused devastating losses for both human lives and assets. From the historical data, it reveals that the most catastrophic landslides have resulted in as many as 100,000 fatalities (Li and Wang, 1992).

The studies related to landslides in the mountainous terrain of Idukki district point out that the interactions of steep slopes and heavy precipitation create a risky environment (Thennavan & Pattukandan, 2021). From this understanding, this research tries to investigate the causes, consequences, and possible mitigation strategies to reduce landslide risks in the district. This research also aims to provide application-oriented strategies by thoroughly examining 11 parameters related to the physiographic and climatic characteristics of the area. These parameters include slope, soil, elevation, curvature, drainage pattern, rainfall, NDVI, TWI, geology, land use and land cover, and road density. The goal of the study is to strengthen preparedness and resilience against future landslide events in Idukki. This study will help us to estimate the loss of landslides including loss of agriculture and damage in infrastructure in similar contexts (Petley, 2012).

It is evident from an understanding of landscape dynamics and how they affect landslide susceptibility why the study area has been designated as Kerala's high-risk landslide zone. This knowledge can be used to illustrate the area on maps and to inform future development initiatives.Understanding these impacts in Idukki can inform policy decisions and resource allocation.

The land based development is always been a question in our country. How can a region which is prone to multiple hazards can intervene in developmental activities and is it even possible for the region and its people to engage themselves in a quality of life as enjoyed by the other people. The answer remains, only if the development is done based on a proper planning and management that is suitable for the vulnerable location, then only the successful implementation of future building through infrastructure can happen and as to happen the same it is very much evident to understand the landscape dynamics. Especially in Idukki district of Kerala, comparatively, the varied topography with hilly and mountain terrain always falls behind such development.

Moreover, the study builds on prior research that shows the role of anthropogenic factors, such as land-use changes, in exacerbating landslide risks (Wasowski et al., 2011). By synthesizing these findings, this investigation aims to contribute to a broader framework for disaster risk reduction. Ultimately, the focus on Idukki District highlights the need for tailored strategies to address this pressing challenge. Through a detailed assessment of local conditions, this study aspires to pave the way for enhanced safety and sustainability in one of India’s most landslide-prone regions.

2. Geographical Profile of the Study Area

In the state of Kerala Idukki was the worst hit district of landslide. Idukki District lies in the Western Ghats of Kerala, India, between 9°15’ and 10°21’ North latitude and 76°37’ to 77°25’ East longitude. Covering 4,612 square kilometers, it is Kerala’s largest district, making up 12.9% of the state’s area (Figure 1). It borders Kottayam, Pathanamthitta, Thrissur, Ernakulam, and Tamil Nadu’s Dindigul, Coimbatore, and Theni districts. Its elevation spans from 130 meters above sea level to 2,695 meters at Anamudi, South India’s highest peak. The average elevation is about 900 meters, supporting diverse flora and fauna. This range shapes the district’s climate, agriculture, and ecological richness. Research shows an average annual rainfall of 377 centimeters (3,770 millimeters), key for plantation crops. Rainfall varies from 250 to 425 centimeters, with some areas like Peermedu reaching 500 centimeters. Lower rainfall, around 150 centimeters, occurs in rain shadow zones like Marayur. Temperatures fluctuate between 16°C and 32°C, influenced by elevation and the Western Ghats. The hot season (March to May) peaks above 87°F, while the cool season (June to September) dips below 80°F. High elevations like Munnar can near freezing, with mist above 1,300 meters. The 2011 census records a population of 1,108,974, with a density of 217 per square kilometer. This low density reflects a landscape over 50% forested and mountainous. The sex ratio is 1,006 females per 1,000 males, showing gender balance. The literacy rate is 92.18%, surpassing the national average, driven by urban centers. Kattappana and Thodupuzha are denser, while rural villages remain sparse. The district has 8 blocks and 52 grama panchayats for administration. Idukki generates 66% of Kerala’s hydroelectric power, notably via the Idukki Dam. It’s a tourist draw with Munnar hill station and Periyar National Park. Agriculture, including tea, coffee, and spices, thrives due to elevation and rainfall. Tribal communities and regional influences enrich their cultural heritage. Sustainable development is vital for its ecological and economic future. This analysis highlights Idukki’s role as an agricultural and ecological hub.

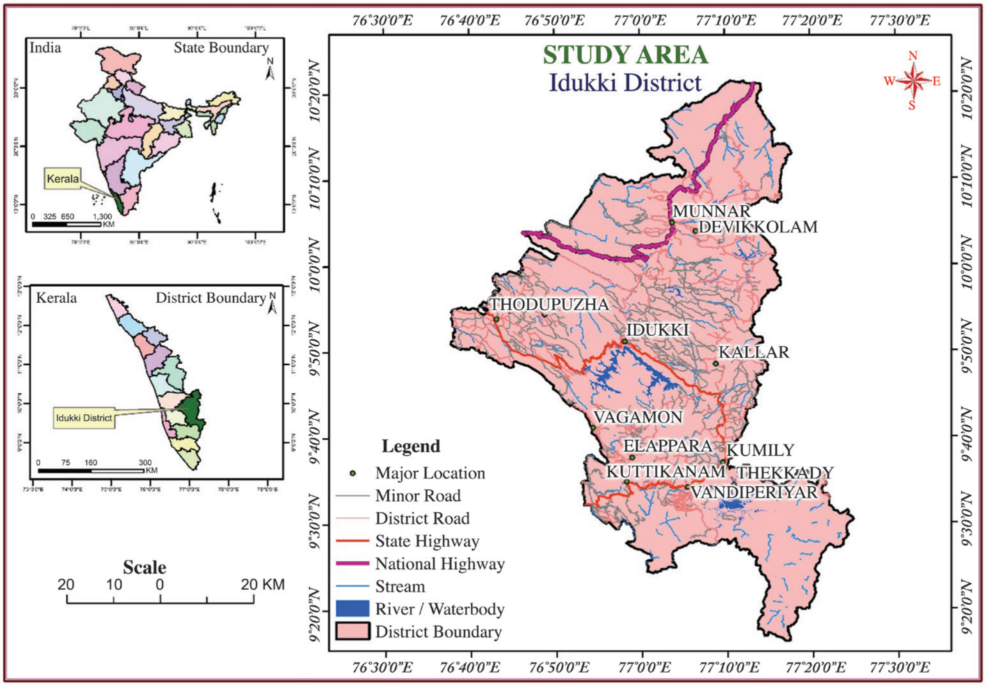

Figure 1 : Study Area

3. History of Landslides in Idukki District

Idukki district has a long history of landslides, with numerous significant events recorded over the years. News reports and historical data highlight major landslides along with their fatalities, revealing the severity of these incidents. The area's vulnerability to landslides is largely undulating steep slope and hilly terrain. Periyar river floods are recorded as the massive ones caused due to slope failure in history dates to 1341 AD (Sekhar L. Kuriakose et al., 2008). In recent decades, landslides become a more frequent and destructive agent. One of the earliest major tragedies was the Kumpanpara debris flow on 26 June 1985, which claimed 9 lives in Thodupuzha taluk. This was followed by the Bison Valley landslide on 14 July 1994, killing 7 people in Udumbanchola taluk. Deadly series of landslides struck Devikulam taluk between 21-25 July 1997, resulting in 13 deaths in Pazhampallichal, Ozhuvathadam, Cheeyappara, and Valara regions. The Kattapana-Thodupuzha corridor experienced around 70 landslides between 20-25 August 2000. Some of the other notable landslides are Chinikuzhi slide (9 July 2001, 3 deaths) and the Venniyani Mala landslide (9 July 2002), which killed a photojournalist. In July 2005 multiple disasters affecting Idukki district including the Anthoniar Colony slide (25 July, 4 deaths) and collapses at Kozhippalli, Velliyani Mala, and Methotti Mala (31 July). The 2007 monsoon triggered several landslides, including those at Edamuttam, Churuli, Dyemuttam-Vandiperiyar, and Chelachuvadu (22 June), as well as Periyar Valley, Kudikayathil, Rajapuram, Konnathadi, and Muthanmudi (1 July). The Mankulam rotational slump was also linked to replantation activities. In 2018, multiple landslides in Adimali, Korangatti, and other areas caused at least 11 deaths. The 2020 Pettimudi disaster was especially devastating, with 66 fatalities, highlighting the persistent landslide threat. The 2021 Koottickal and Kokkayar landslides along the Meenachil River killed 13 people, while the 2022 Kudayathoor landslide near Thodupuzha resulted in 5 deaths. While these major events are well-documented, many smaller landslides without casualties likely go unreported, suggesting the actual number of incidents is much higher.

4. Data Source

The present study employed a range of thematic layers from credible data sources to asses landslide susceptibility. The rainfall data was collected from NASA's earth data portal, while the topographic parameters such as slope, curvature and TWI were extracted from the advanced land observing satellite ALOS and Dem with a spatial resolution of 12.5 meters. Vegetation cover was represented using the Normalized Difference Vegetation Index (NDVI), derived from Landsat 8 OLI/TIRS Level 1 imagery (Path 144, Row 053) dated 2 March 2021, accessed via the USGS Earth Explorer platform. Geological data were obtained from the Idukki District Mineral Resource Map at a scale of 1:250,000. Drainage density was calculated using both ALOS DEM and Survey of India (SOI) topographical maps at a 1:50,000 scale. Land use and land cover information was sourced from the Kerala State Land Use Board (2015), and road density was mapped using data from OpenStreet Map. Soil characteristics were incorporated from the Idukki Soil Map provided by the Kerala State Soil Survey Department. Data sources and their detailed metadata are given in Table 1.

Table 1 : Data Sources

Sl No	Parameter	Data source	Year	Band/Toposheet Number
1	Rainfall	https://dsp.imdpune.gov.in/	1951-2023	-
2	Elevation, Slope, TWI, Relief	ALOS DEM (12.5 Meter Resolution)	2024	-
3	Land use land cover	https://earthexplorer.usgs.gov/r-Landsat 8 OLI/TIRS C1 Level-1, Path 144, Row: 052	2023	Band 2, Band 3, Band 4, Band 5, Band 10, Band 11
4	NDVI	Landsat-8 from Google Earth Engine.		Band 4, Band 5
5	Road Density	www.openstreetmap.com	2023	
6	Drainage Density	Survey of India (1: 50,000) toposheet)	1970	58A08, 58A12, 58A16, 58 B09
7	Geomorphology	Kerala State Land Use Board	2005	-
8	Geology	Idukki District Geology and Mineral Resource Map (1: 2,50,000) prepared by Geological Survey of India	-	-
9	Soil Texture	https://www.keralasoils.gov.in	2020	

5. Materials and Methods

The multi-criteria analysis approach is assessing more than one criterion together, which have different measurement units and are incoherent among each other and which are weighed to determine and group more than one alternative and to determine priority choices (Yoon, K., Hwang, C. 1995). There are different methods that are used to conduct multi-criteria analysis within the environment of GIS. These methods are mainly based on Boolean operator principles of AND and OR. When degree of significance is considered among the criteria in addition to that, the weighting process among criteria has been made (Malczewski, J. 1999).

Delineating landslide vulnerable area is done through the Multi-Influencing Factor (MIF) technique. MIF methods have been widely accepted by academics

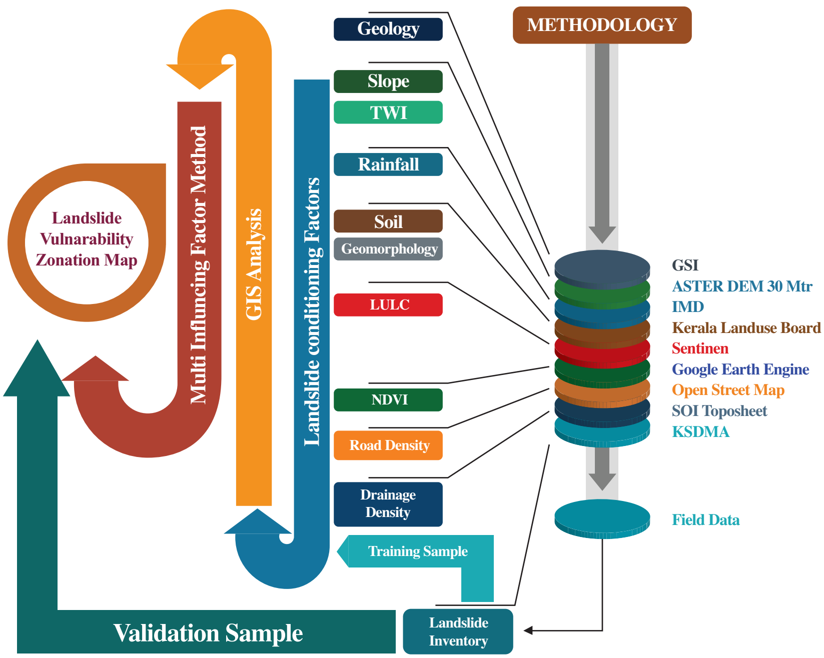

Figure 2 : Methodology Chart

since the 1990s for the spatial decision-making process (Roy, S. et al., 2023); in addition, with the integration of GIS and remotely sensed data it is possible to solve critical problems regarding spatial distribution and choosing desirable locations (Alkaradaghi et al., 2019; and Hussein et al., 2018). Therefore, several researchers have found that geographic information systems (GIS) and remotely sensed data in combination with the MIF method have a great potential for enhancing land related applications (Pramanik, 2016; Orhan et al. 2021; Everest et al., 2021; Mendas et al., 2021). FAO (1976) provided a logical method to evaluate land suitability ranges from highly suitable to unsuitable based on climatic data, topographical features, and factors related to soil parameters. Additionally, a weighted aggregation method based on equations was proposed by Bandyopadhyay et al. (2009) for assessing agricultural land suitability potentials using remote sensing and GIS. However, when it comes to spatial mapping, the interplay between different thematic layers is critical (Thomas & Duraisamy, 2018). Therefore, despite several methods, it is always appropriate to integrate remote sensing and GIS with MIF technique for critical evaluation of landslide and land degradation assessment, as it benefits planners and managers, as well as helps to determine the most appropriate spatial pattern for sustainable management (Kumar et al., 2021).

Rainfall, Slope, Soil, Drainage Density, Land Use Land Cover, TWI, Road Density, Geology, Vegetation Cover, and Curvature are the major parameters considered for the delineation of landslide assessment (Figure 3). Each parameter is interdependent on other parameters viz. Each parameter has a major effect (A) and minor effect (B) upon other parameters. For each major and minor inter-related factor, a weightage of 1 and 0.5 is assigned respectively. A relative rate is calculated for each factor by cumulating all the weights of major and minor interrelated factors (A+B). A factor with a higher relative rate shows a larger impact on the landslide and vice versa. This relative rate is further used to calculate the score by each influencing factor by using the following formula (equation 1).

$$= \left\{ \frac{(A+B)}{(\sum A+B)} \right\} X100 \text{.........Equation 1}$$

Where A is the major inter-relationship between two factors B is the minor inter-relationship between two factors A+B is the relative weight of each factor (Table 2 & 3).

Table 2 : Influencing Factors with major and minor effect

Influencing Factors	Major Effect A	Minor Effect B
Rainfall	Soil, Drainage Density, TWI, Vegetation Cover, Land Use Land Cover	Slope, Road Density, Geology, Curvature
Slope	Soil, drainage density, land use land cover, TWI, Road Density, Vegetation Cover, Curvature	Rainfall, Geology
Soil	Rainfall, Slope, LULC, Geology, Vegetation Cover	TWI, Road Density, Drainage Density, curvature
Drainage Density	Slope, Rainfall, TWI, Vegetation Cover	Soil, LULC, Road Density, Geology, Curvature
Land Use Land Cover	Rainfall, Soil, Road Density, Vegetation Cover, Slope	TWI, Geology, Curvature, drainage density
TWI	Geology, Rainfall, curvature, Vegetation Cover, slope, Drainage Density	Soil, LULC, Road Density,
Road Density	Slope, LULC	Rainfall, Soil, Drainage Density, TWI, Geology, curvature
Geology	Soil, Curvature, TWI	Rainfall, Slope, Drainage Density, Road Density, Vegetation Cover, LULC
Vegetation Cover	Rainfall, Soil, Slope, TWI, Drainage Density	Curvature, Road Density, LULC, Geology
Geomorphology	Slope, TWI, Geology, Drainage Density	Vegetation Cover, Rainfall, Soil, LULC, Road Density

Here, the Table 2 indicates that the influencing factors taken for the study is directly or indirectly related with other potential factors. Through this table, it is more relevant in understanding how each parameter is influencing the other potential factors in causing both major and minor effects.

Table 3 : Influencing Factors: Their Impact, Relative Rates and Scores

Influencing Factors	Major Effect A	Minor Effect B	Proposed Relative Rates (A+B)	Proposed Score for Each Influencing Factors
Rainfall	1+1+1+1+1	0.5+0.5+0.5+0.5	7	10
Slope	1+1+1+1+1+1+1	0.5+0.5	8	12
Soil	1+1+1+1+1	0.5+0.5+0.5+0.5	7	10
Drainage Density	1+1+1+1	0.5+0.5+0.5+0.5+0.5	6.5	9
Land Use Land Cover	1+1+1+1+1	0.5+0.5+0.5+0.5	8	12
TWI	1+1+1+1+1+1	0.5+0.5+0.5	7.5	11
Road Density	1+1	0.5+0.5+0.5+0.5+0.5+0.5+0.5	5.5	8
Geology	1+1+1	0.5+0.5+0.5+0.5+0.5+0.5	6.5	9
Vegetation Cover	1+1+1+1+1	0.5+0.5+0.5+0.5	7	10
Geomorphology	1+1+1+1	0.5+0.5+0.5+0.5+0.5	6.5	9
SUM			**68.05**	**100**

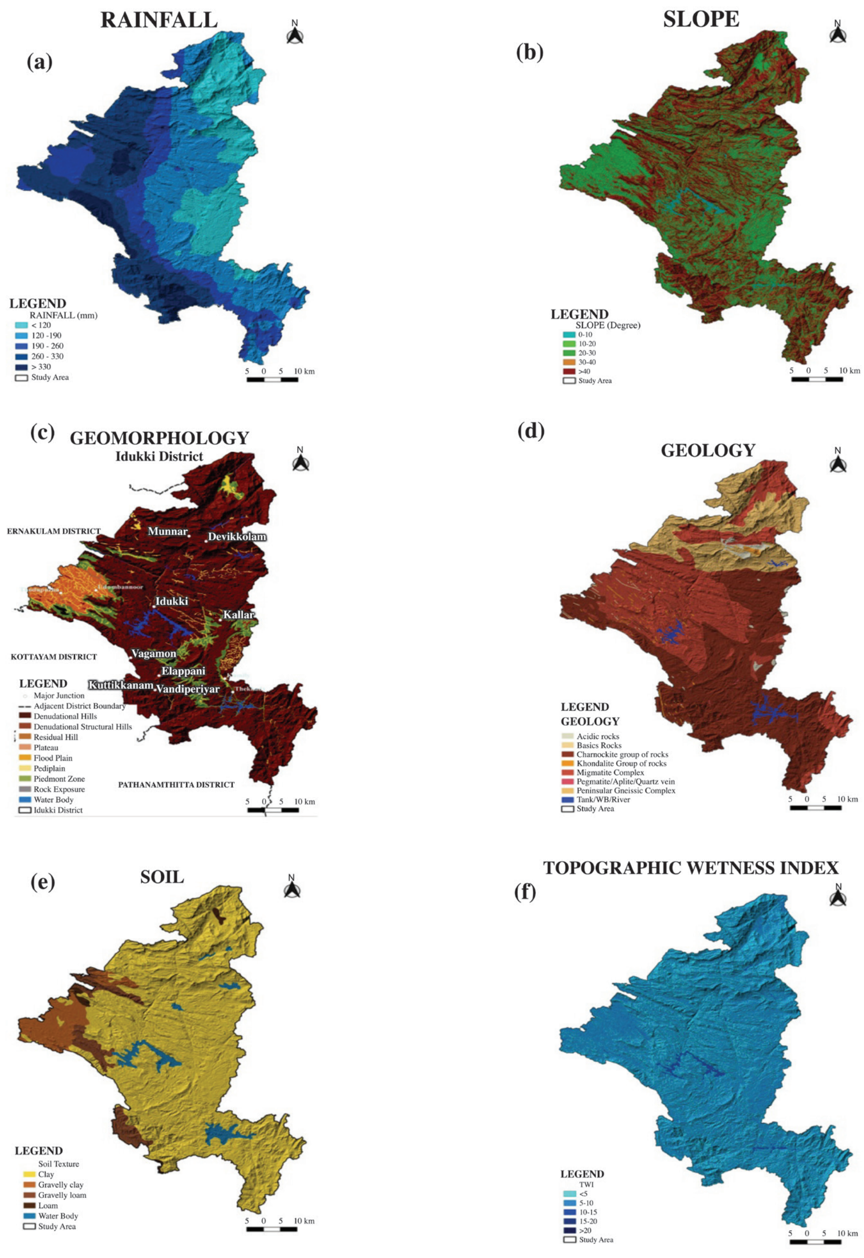

Figure 3 : Landslide Influencing Factors

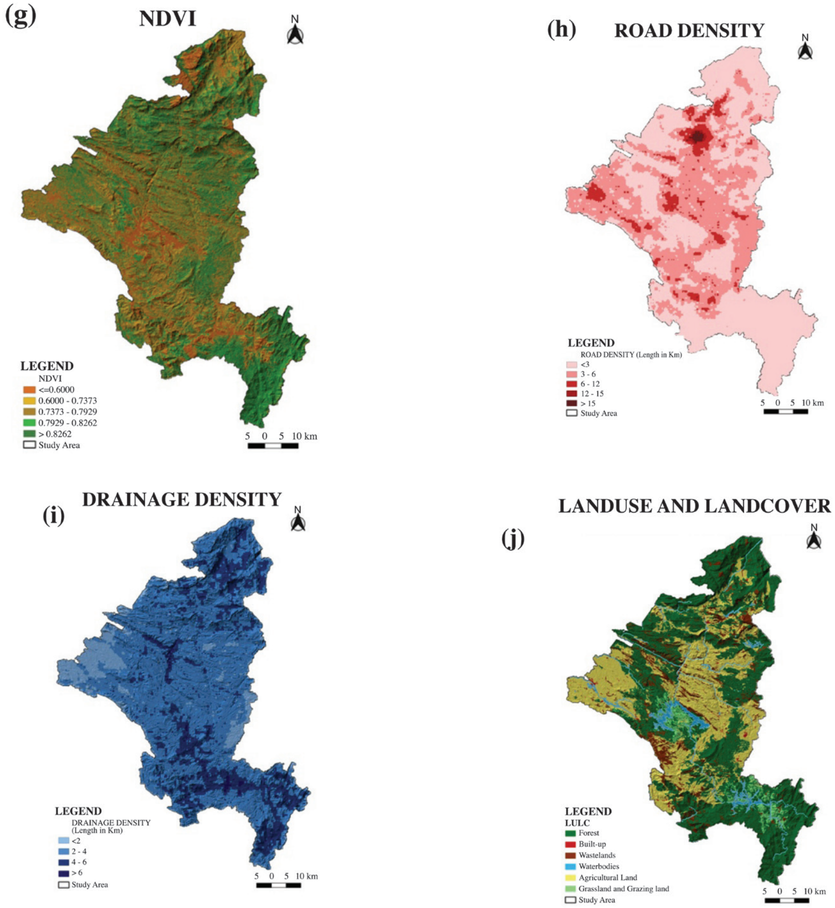

Figure 3 : Landslide Influencing Factors

5.1 Rainfall

The relationship between rainfall and landslides in the Idukki district is a critical area of study due to the region's susceptibility to landslides, particularly during the monsoon season. Heavy rainfall acts as a primary trigger for landslides, triggered by the district's unique topography and soil conditions. Factors such as slope, elevation, and rainfall, along with anthropogenic factors like land use, significantly influence landslide susceptibility (Jones et al., 2021). The scarp of the Western Ghats receives an annual rainfall high as 5000mm as a southwest monsoon, northeast monsoon and the pre-monsoon (Kuriakose, S.L et al., 2009). The high intensity of rainfall leads to pore water pressure within the soil mass, which eventually decreases the shear strength of the soil (Figure 3a). This will be considered as the primary triggering factor of landslides in the Western Ghats (Jaiswal, P and van Westen, C.J., 2009). For the purpose of infrastructure like road developmental activity and tourism related constructions this will lead to large scale hill toe modification which leads to hill slope becoming steeper without any lateral support. The terraced slopes, modified for monoculture plantations with no sufficient drainage provisions, aggravated the scenario (Abraham et al., 2019). Due to the drainage blockage the water from the intense rainfall accumulates in the top soil layer leads to landslide activity. The landslide types vary from creep and subsidence to debris flows, along the district's road corridors the earth or debris slide will commonly become monsoon period (Sajeev, R et al., 2014). Continuing rainfall and the subsequent pore pressure increase adversely affect the steep slopes and leads to landslides. Here the impact caused by Rainfall in the study area is major. The regions that receive a higher rate of rainfall is more susceptible to landslide risk zones.

5.2 Geology

Geologically the study area consists of charnokite, khandolite and migmatite group of rocks contribute the formation of a part of a part of south Indian Precambrian metamorphic shield (Sulal, N et al., 2019). The geology of Idukki District, characterized by Precambrian crystalline rocks of the Southern Granulite Terrain, significantly influences its landslide susceptibility patterns, with major lithologies including charnockites, khondalites, migmatites, gneisses, lateritic cappings, and alluvial deposits (Figure 3d). Charnockites, while generally resistant, represent jointed and fractured structures that facilitate water infiltration, particularly along shear zones, whereas khondalites, rich in garnet and sillimanite, weather into clay-rich soils that reduce slope stability. Migmatites and gneisses, with their foliated structures, are prone to differential erosion, creating tension cracks and overhang that lead to rock fall and debris slides, while lateritic deposits, though porous, are vulnerable to piping erosion during heavy rainfall. Structural weaknesses such as the NNE-SSW trending Periyar Shear Zone act as groundwater conduits, elevating pore pressure, and deep weathering profiles in khondalites further diminish shear strength, correlating with moderate to high landslide risk zones.

5.3 Geomorphology

Idukki District in Kerala is characterized by a diverse geomorphology, dominated by the rugged Western Ghats, deep river valleys, and rolling hills. The Periyar and Thodupuzha rivers shape its terrain, while the Idukki Arch Dam sits amidst steep slopes. Anamudi (2,695 m), India's highest peak, lies here, along with dense forests, plateaus, and waterfalls.Geomorphic classification of the terrain divided the district into four. They are rugged hills, ridges and valleys, fringe slopes and plateau (Sulal, N et al., 2019). Scarps of the Idukki district consist of frictional soil with less cohesion, thus being stable in dry conditions and losing their strength when the moisture contentincreases (Figure 3c). Plateau regions have a thick layer of topsoil which is rich in clay content, due to their morphology and tropical climate (Sajeev, R.; Sajinkumar, K.S. (2013).

5.4 NDVI

The relationship between vegetation condition and landslides in Idukki district is critical, as changes in land use and vegetation cover significantly influence landslide susceptibility (Figure 3g). The decline in dense vegetation, coupled with increased built-up areas, has heightened the region's vulnerability to landslides over the past eight years (Sankar et al., 2023).This is boost up by heavy rainfall, which is a primary trigger for landslides in the area, as evidenced by the establishment of rainfall thresholds for future predictions (Abraham et al., 2019). When vegetation cover decreases landslide risk will increases and more areas become highly prone to landslides (Sankar et al., 2023). Vegetation plays an important role in keeping soil cohesion, as plant roots hold the soil in place and help to prevent soil erosion, which reduces the intensity of landslide occurrences. (Lalitha et al., 2021).

5.5 Drainage Density

Drainage density and landslides in Idukki district are correlated as drainage density impact slope stability and hydrological conditions. As a result, in the recurring events landslides are more frequent in the more drainage density regions. When drainage density increases, the runoff and soil saturation also increase, which are the crucial factors in landslide occurrence. The undulating terrain and steep slopes of Idukki leads to high drainage density (Figure 3i), which increase landslide risks (Raveendran et al., 2015). The increasing drainage density leads to rapid runoff, increasing soil moisture and initiating pour water pressure, which are critical in triggering landslides (Kuriakose, 2024). The landslide hazard zoning analysis in Idukki reveals that the highly vulnerable zones can be linked to areas of high drainage density (Raveendran et al., 2015). Deforestation and other human activities like urban expansion, unplanned infrastructure activities etc. that lead to the drainage density further destabilizing the slope and thereby ramp up the landslide frequency (Aparna et al., 2023).

5.6 Topographic Wetness Index (TWI)

Landslide susceptibility studies required Topographic Wetness Index (TWI) data, especially the hilly terrain of Idukki district. Because TWI directly helps to landslide vulnerability due to its mountainous topography and abundant rainfall. TWI is a metric that evaluates possible soil saturation, a major landslip trigger, by combining slope and upstream contributing area. Because regions with high TWI values are more likely to have soil saturation and subsequent slope failures, there is a considerable correlation between TWI and landslides in Idukki. Soil saturation levels can be predicted using TWI valueas and it is important for determining the risk of landslides. The high TWI values indicate places where water collection is expected more, increasing the risk of landslides (Montgomery & Dietrich, 1994). The integration of TWI with other factors such as slope angle and soil properties enhances the landslide susceptibility models using GIS based methods (Thomas et al., 2021). In Idukki, rainfall is the primary means of landslides, and empirical models reveal that antecedent rainfall conditions have a substantial effect on landslide occurrences (Abraham et al., 2019). The correlation between the high TWI area and the actual positions of landslides has now been confirmed with SAR interferometry and other remote sensing methods in studies performed to determine the suitability of TWI in landslide prediction (Kalaranjini& Ramakrishnan, 2020). Topographically based models that consider TWI and other topographic and hydrological factors have been found to be consistent with observed patterns of landslides and so could be used in regional landslide risk analysis (Montgomery & Dietrich, 1994). The huge number of water bodies like streams, rivers and the reservoirs are the main factors that contribute to the water accumulation of the whole district.

5.7 Road Density

The relationship between road density and mass wasting in the Idukki hilly region is combined by both natural and human induced factors. Roads can aggravate landslide risks by altering natural drainage patterns and destabilizing slopes, while also providing access for mitigation efforts. In Idukki, the interaction between road networks and landslide occurrences is significant, as evidenced by various studies focusing on the region's geospatial and geotechnical characteristics (Figure 3h). Geospatial techniques have been employed to map landslide-prone areas along the Thodupuzha-Idukki-Munnar road, identifying highly fragile zones that require immediate attention (Abraham & Shaji, 2013).To make it possible to classify areas depending to their fragility—a critical component of road design and maintenance GIS platforms incorporate topography data as slope, land use, and drainage density (Abraham & Shaji, 2013). Roads can increase landslide susceptibility by disturbing the natural stability of slopes, as seen in the Adimali-Munnar road study, which identified unstable slope profiles due to both natural and man-made factors (Ishack & Abraham, 2011). A spatial statistical analysis across various regions indicates that landslide density is often higher near roads, suggesting a potential mapping bias or a genuine increase in susceptibility due to road proximity.

5.8 Land Use and Land Cover (LULC)

Land Use and Land Cover (LULC) changes and landslides in Idukki district is significant. Over the past years, urbanization has increased while dense vegetation has decreased, and this situation leads to increased landslide susceptibility. Studies indicate that both natural and man-made factors contribute to this phenomenon. Increased built up areas have been observed in the district, which disrupts natural drainage and increases runoff (Sankar et al., 2023). The decline in dense vegetation of the district reduced soil stability, making the slope more susceptible to landslides occurance(Sankar et al., 2023). The expansion of agriculture in the early period, land and deforestation have made worse to the situation, that contribute to increased landslide frequency and while the focus on LULC changes highlight the increasing risk of landslides, it is also essential to consider the role of climate change and extreme weather events, which further complicate the landscape and increase vulnerability in Idukki district (Aparna et al., 2023). Due to the plantation activities and restructure in the agricultural activities became one of the important reason among Wasteland, Built up area, Forest, etc.

5.9 Soil

The soil characteristics of the district, particularly the Atterberg limits play a crucial role in landslide occurrences. The stability of the soil in various moisture conditions is controlled by these limits, which are altered by elements including weathering and soil composition. The Atterberg limits, which include the soil convert to plastic stage to liquid stage and flow like thick liquid (liquid limit), the soil changing to semi solid to the (plastic stage), lowest moisture content at which the moisture content of the soil rolled into thin threads without crumbling (plastic limit) and the range of moisture content in the soil stay in moldable and help to assess its stability and potential for swelling (plasticity index) are critical in assessing soil stability. Idukki is vulnerable to deep landslides and possesses regolith thicknesses that vary from 0.25 to 5 m (Kuriakose, S.L et al., 2009) (Government of Kerala, 2018).In Idukki, the highly weathered lateritic soils exhibit low cation exchange capacity and variable charge minerals, making them prone to landslides during heavy rainfall and the soil profile morphometry, with specific plastic limit values, is associated with landslide occurrences, particularly in steep sloping areas(Lalitha et al., 2021). The natural factors such as slope, elevation and rainfall significantly influence landslide occurrences and the topography and high rainfall during monsoons exacerbate the risk (Jones et al., 2021). Human activities, including land use changes, road density, increased quarry density and deforestation lead to an increase in landslide susceptibility. The increase in built up areas and decrease in dense vegetation over recent years have heightened the risk of making landslide scenario (Sankar et al., 2023). The increasing frequency and intensity of landslides is mainly due to climate change and human activities.

5.10 Slope

The Western Ghats' peculiar geography renders the region more vulnerable; several landslides have been reported there, especially during the monsoon seasons when the area suffers steep slopes with substantial rainfall.The geography of the region consists of a slope as steep as 80° and elevation ranges up to 2695m. About 97% of the major roads in the district cut through this rugged mountain and hills which are often blocked due to landslide in the monsoons (Sajeev, R et al., 2014). Idukki district has a high incidence of landslides, with 2,219 occurrences reported, making it the most affected area in Kerala during the 2018 disaster (Jones et al., 2021). Landslides are predominantly found on steep slopes, with studies indicating that 22 out of 27 observed slides occurred in steep terrain (Kalaranjini and Ramakrishnan, 2020). The heavy rainfall (61.6 cm) and steep slope in Pettimudi during august 2020 give a way to worse landslide in the district (Achu et al., 2021). The combination of natural factors like slope, geology and anthropogenic influences land use, road density significantly increases landslide susceptibility (Jones et al., 2021). So here we can understand that the slope, especially deep slope region will very vulgarly be converted into more risk region during monsoon.

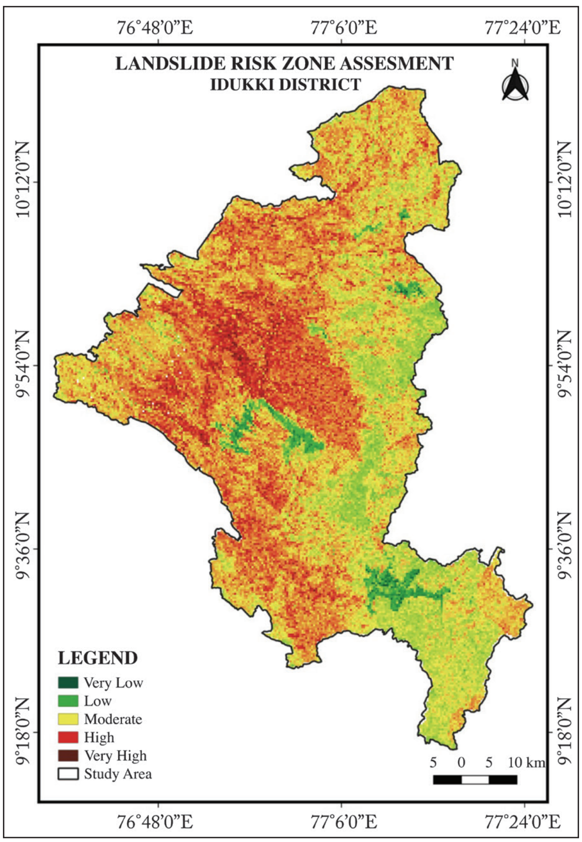

Figure 4 : Landslide risk zone assessment

Table 3 : Landslide risk area

Sl.No	Land Slide Risk Area	Area in Km^2	Area in %
1	Very Low	14.44	0.33
2	Low	47.01	1.86
3	Moderate	1349.62	31.10
4	High	2739.56	63.12
5	Very High	155.72	3.59
	Total	**4361.40**	**100**

6. Results and Discussion

The landslide susceptibility zonation for Idukki District, generated using the Multi-Influencing Factor (MIF) technique, reveals a spatially revealed risk distribution influenced by geomorphological, hydrological, and anthropogenic factors. The analysis classified the region into five risk categories: Very Low (0.33%), Low (1.86%), Moderate (31.10%), High (63.12%), and Very High (3.59%), covering a total area of about 4,361 km².

The Very Low and Low risk zones, encompassing only about 2.19%, moderate covers and high risk zones covers 94.22% of the district, correlate with stable geological formations, gentle slopes (<10°), and dense vegetation cover, which mitigate slope instability (Figure 3b). These areas are predominantly underlain by less weathered rocks and show low drainage density, reducing water-induced shear stress. In contrast, the Moderate risk zones (25.28%) coincide with intermediate slope angles (10°– 20°), mixed land use (e.g., agriculture), and moderate rainfall (2,600–3,300 mm/year). Here, the interplay between soil saturation (TWI >5) and periodic anthropogenic disturbances (e.g., road cuts) elevates susceptibility.

The High and Very High risk zones (66.71% combined) are localized in steep slopes (>30°), fractured lithologies (e.g., migmatites), and areas with high drainage density

(>4 km/km²). These regions are further aggravated by intense monsoon rainfall (>3300 mm/year), which amplifies pore pressure, and deforestation, which reduces root cohesion. Notably, the Very High risk pockets (0.03%) align with concave slope profiles and proximity to road networks, where cut-and-fill activities destabilize slopes.

The MIF-based susceptibility map demonstrates strong agreement with observed landslide occurrences, particularly in the High and Very High risk zones of Devikulam and Udumbanchola taluks. The slope gradient emerged as the dominant vulnerable factor, with steeper slopes revealing higher displacement potential due to gravitational stress. Rainfall acts as a primary triggering mechanism, with prolonged precipitation increasing hydraulic pressure in permeable soils (e.g., laterites), leading to reduced shear strength.

Soil type and geology further modulate susceptibility; for instance, clay-rich soils in the Western Ghats exhibit low permeability, promoting rapid runoff and surface erosion, while weathered granulites are prone to deep-seated failures (Fig. 3e). Drainage density exacerbates risk in high-order streams, where concentrated flow undercuts slopes. Land use changes, such as tea plantations replacing natural forests, diminishing evapotranspiration and increasing infiltration, elevating groundwater-induced instability.

Topographic Wetness Index (TWI) highlights convergence zones where water accumulation lowers soil cohesion, particularly in hollows and valleys (Fig. 3f). Road density introduces anthropogenic triggers by altering natural drainage and creating artificial fill slopes. The study also highlights the interaction of contributing factors, where slope characteristics and rainfall patterns form the primary physical basis for landslides, while human interventions such as road construction significantly increase the inherent instability of these slopes.

From table no. we can identify that the very low landslide risk zone addressed only seven landslides, then in the low landslide occurrence zone have about 120 landslide incidents it records 5.42 percentage of the total landslide in the district. Moderate landslide risk zone reports 457 landslides that record 20.63 percent of the total landslide occurrence. The high landslide risk zone has 857 landslides and that was

38.69 percent of the total landslide and in very high 774 incidents occurred that was about 34.94 percent of the total landslide occurrence. From the table we can understand that most of the landslides occurred in high and very high landslide risk zone of the study area that was 73.63 percent.

7. Conclusion

This study assessed landslide susceptibility in Idukki District, Kerala, using the Multi-Influencing Factor (MIF) method integrated with GIS. The analysis incorporated 10 parameters—Rainfall, Slope, Geology, Geomorphology, LULC, Drainage Density, Road Density, Soil, NDVI and TWI to classify the region into five risk zones. Results revealed that 73% of the area falls under very low to low risk, characterized by stable slopes and dense vegetation, while 1.72% (high to very high risk) comprised steep slopes (>30°), fractured lithologies, and intense rainfall zones. The majority (85%) of fatal landslide events occurred between June-August during the monsoon season, with Devikulam followed by Thodupuzha taluks being the most active landslide-prone areas. The MIF technique effectively highlighted the interplay of natural and anthropogenic factors, with slope and rainfall emerging as dominant triggers, while road construction and deforestation exacerbated instability. The susceptibility map aligned with historical landslide occurrences, particularly in these high-risk taluks. This study reveals the need for monsoon-specific early warning systems and sustainable land-use planning, especially in Devikulam and Thodupuzha, to enhance resilience against future landslides. The findings provide a scientific basis for policymakers to implement targeted mitigation measures in this ecologically sensitive Western Ghats region. Landslide vulnerability is addressed as a notable risk on a global scale, especially in India's varied topography with mountains and hilly terrains. By giving an empirical approachin understanding variables like slope, rainfall, and geology, the study may create more accuracy in susceptibility maps using quantitative models like FR and MIF. These resultsempowerhazard preparedness throughout susceptible zones by covering large areas with high precision. The significance of these data-driven evaluations will only increase on a regional and global scale as landslides become more frequent.

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