National River Conservation Directorate
Ministry of Jal Shakti,
Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Landslide Susceptibility Mapping Periyar River Basin

March 2026

cPeriyar

IIT PALAKKAD

cGanga

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Periyar River Basin

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Acknowledgment

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Preface

Landslides are among the most recurring and destructive natural hazards affecting the Western Ghats of Kerala, causing significant loss of life, damage to infrastructure, and degradation of river basins and ecosystems. The Periyar River Basin, spanning Idukki, Ernakulam, and Thrissur districts, is one of the most landslide-prone and strategically critical river systems in peninsular India, encompassing the Idukki reservoir complex, the Periyar Tiger Reserve, and large highland communities engaged in plantation agriculture. Devastating events such as the 2018 floods, the Pettimudi landslide of 2020, and the Mundakkai-Chooralmala landslide of 2024 have reinforced the urgent need for systematic, science-based landslide risk assessment and early warning infrastructure across the basin.

This Landslide Risk Report presents a comprehensive GIS-based susceptibility mapping, vulnerability assessment, composite risk zonation, monitoring framework, and management recommendations for the Periyar River Basin, using the Frequency Ratio statistical method integrated with multi-source geospatial datasets. The findings are intended to directly support the Idukki District Disaster Management Plan, KSDMA's early warning operations, and land use governance in landslide-prone areas of the basin. We sincerely acknowledge the contributions of the GSI, IDRB, KSEB, IMD, KSDMA, CGWB and NBSS&LUP, whose datasets, platforms, and scientific work have been essential to this report. We hope this report serves as both a technical reference and a practical planning tool for policymakers, disaster managers, researchers, and communities working towards safer and more resilient outcomes in the Periyar River Basin.

Landslide risk in the Periyar River Basin is not a fixed condition, it will continue to evolve under the combined pressures of climate change, shifting land use patterns, and growing infrastructure demands on vulnerable highland terrain. Projections of increasing extreme rainfall intensity under future climate scenarios, alongside the ongoing expansion of settlements and roads into high-susceptibility zones, make it imperative that risk assessment, monitoring, and preparedness efforts are sustained, updated, and institutionally embedded over the long term. It is our hope that this report will not only address the immediate need for evidence-based risk reduction but will also lay the groundwork for a continuously improving, science-driven approach to landslide disaster management and sustainable basin governance in the years ahead.

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1. Introduction

1.1 Introduction

Landslides rank among the most destructive and recurrent geophysical hazards on earth, causing significant loss of life, damage to infrastructure, and long-term degradation of natural ecosystems. Globally, a comprehensive dataset compiled by Petley (2012) recorded 2,620 fatal landslide events between 2004 and 2010 alone, resulting in 32,322 documented fatalities, a figure considered to be an underestimate of actual human costs. A subsequent analysis by Froude and Petley (2018) covering the extended period from 2004 to 2016 confirmed that the global burden of fatal landslides continues to rise, within Asia, particularly monsoon-influenced mountain systems, accounting for the overwhelming majority of both events and casualties. Within the Indian subcontinent, the Himalayan mountain system (0.32 million km^2) and the Western Ghats (0.09 million km^2) together constitute the two principal landslide-prone physiographic regions, with approximately 12 percent (0.42 million km^2) of total land area of India is identified as susceptible to mass movement hazards (Geological Survey of India (GSI); National Disaster Management Authority (NDMA), 2009). The Western Ghats, a mountain chain extending nearly 1,600 km along southwestern coast of India is designated a UNESCO World Heritage Site and a global biodiversity hotspot, yet it is simultaneously one of the most landslide-prone belts (14.7% of the total landslides in India) in peninsular India (Martha et al., 2021).

The state of Kerala, situated almost entirely within the influence of the Western Ghats, occupies a particular position of hazard exposure. Kuriakose et al. (2009) established, through a systematic survey of archival documents and post-event investigation reports, that 13 of 14 districts in Kerala are prone to landslides and that anthropogenic disturbances, including deforestation since the early 18th century, conversion of natural forest to plantations, terracing, and the obstruction of ephemeral streams have progressively accelerated slope instability over the historical period. Landslides in the region manifest predominantly as debris flows and earth slides, referred to locally in Malayalam as 'urul pottal', and are initiated principally on the west-facing scarps of the Western Ghats where thin lateritic and residual soils overlie deeply weathered charnockite and gneissic basement rocks (Sajinkumar et al., 2011). In Ernakulam and Idukki districts, most of the previous landslides occurred in highly weathered zones, especially in areas dominated by hornblende gneiss, lateritic soil, and highly erodible rock outcrops, highlighting the strong influence of weathering on landslide occurrence in the region (Sajinkumar et al., 2011).

The frequency and destructiveness of landslide events in Kerala have intensified in sloping terrains of the state, especially during monsoons. The catastrophic floods and mass movements of August 2018, the worst flooding in Kerala in nearly a century, triggered 4728 landslide events across the state, with Idukki District alone recording 2,219 occurrences (Jones et al., 2021). The Pettimudi landslide (Figure 1) of August 2020 in Idukki caused 66 fatalities of residents (among which four are still missing) in a single event (Achu et al., 2021). The 2019 Kavalappara debris flow in Malappuram District caused 59 fatalities and destroyed an entire settlement. The disaster was primarily triggered by five days of excessively heavy rainfall (400% above normal), acting on structurally disturbed and weakened bedrock, incompetent residual alteration products, reduced cohesive strength, supersaturated earth materials, and nonchalant human interventions (Wadhawan et al., 2020). Most recently, the Mundakkai–Chooralmala landslide of 30th July 2024 in Wayanad District caused over 400 deaths, making it among the deadliest landslide events in Kerala's recorded history. This landslide was likely caused by a combination of geological, geomorphological, climatic factors, and long-term climate change impacts (Das, 2024).

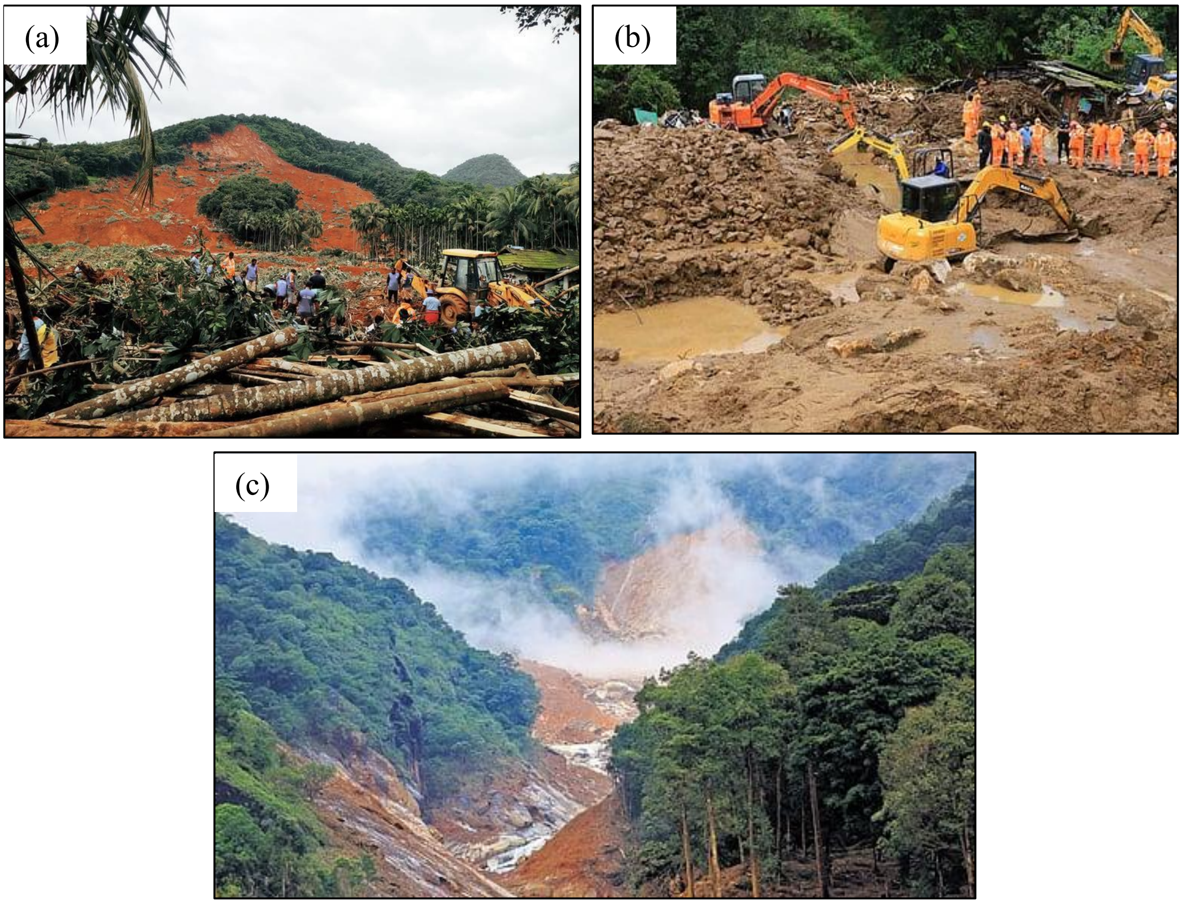


Figure 1: (a) Kavalappara Landslide - 2019 (*Source: The Indian Express)* **(b) Pettimudi landslide – 2020 (***Source: The News Minute***) and (c) Mundakkai-Chooralmala landslide – 2024 (***Source: The New Indian Express)*

These events collectively demonstrate that the Western Ghats of Kerala faces a compound and intensifying hazard driven by the convergence of steep and deeply weathered terrain, extreme monsoonal rainfall, accelerating land use change, and expanding human settlements and infrastructure on vulnerable hillslopes. In this context, a systematic landslide susceptibility mapping, the spatial delineation and classification of terrain units based on their relative susceptibility to future slope failure, constitutes an important scientific foundation for disaster risk reduction, land use planning, and the integrated management of river basins located within this highly sensitive landscape.

The Periyar River Basin (PRB), spanning the highland-to-coastal continuum across Idukki, Ernakulam, and Thrissur districts of Kerala, represents one of the most strategically significant and hydrologically complex river systems in peninsular India. It supports the water supply of the greater Kochi metropolitan area, supports critical hydroelectric generation through the Idukki and Idamalayar reservoir complexes, and encompasses extensive areas of protected forest including the Periyar Tiger Reserve and Eravikulam National Park. The highland terrain of the basin is acutely susceptible to rainfall-induced mass movements, and landslide-derived sediment loads degrade river water quality, accelerate reservoir siltation, disrupt riparian habitats, and compromise the hydrological services upon which millions of downstream residents depend. This study addresses the basin-scale landslide susceptibility assessment and risk evaluation for the PRB through a careful, multi-factor GIS-based approach, generating outputs directly applicable to river basin management, disaster preparedness, and conservation planning.

1.2 Background

1.2.1 Landslide Susceptibility Mapping: Concepts and Evolution

Landslide susceptibility mapping (LSM) refers to the spatial estimation of the likelihood of landslides occurring in a given area and aims to predict ‘where’ they are likely to happen (Reichenbach etal., 2018) rather than ‘when’, based on the local terrain conditions (van Westen et al., 2006; Guzzetti et al., 2005). It is the foundational step in a hierarchical hazard assessment framework that proceeds from susceptibility through hazard, vulnerability, and ultimately risk zonation (Varnes, 1984; NDMA, 2009). Susceptibility maps identify areas where the combination of geological, geomorphological, hydrological, pedological, land use, and anthropogenic conditioning factors causes the terrain vulnerable to future slope failure, enabling planners and disaster managers to prioritize interventions before triggering events occur.

The methodological evolution of LSM spans heuristic (knowledge-driven), statistical (data-driven), and physically based approaches, each with distinct data requirements, assumptions, and spatial scales of application (Kanungo et al., 2012). Among statistical methods, bivariate techniques such as the Frequency Ratio (FR) method and the Weights of Evidence (WofE) model are widely applied for their transparency and computational feasibility (Prasannakumar and Vijith, 2012; Feby et al., 2020). The FR method, adopted in the present study, quantifies the statistical relationship between each class of each conditioning factor and the spatial distribution of known landslide occurrences from the inventory, producing a dimensionless ratio that reflects the relative susceptibility contribution of each factor class. A FR value greater than 1.0 indicates a positive correlation with landslide occurrence, while values below 1.0 suggest lower susceptibility for that class. Multi-criteria decision analysis methods such as the Analytical Hierarchy Process (AHP) permit the structured incorporation of expert knowledge alongside spatial data (Bhagya et al., 2023). In recent years, machine learning algorithms have demonstrated superior predictive accuracy in capturing complex, nonlinear relationships among conditioning factors (Jones et al., 2021; Badapalli et al., 2025).

The NDMA, Government of India, published national guidelines on the management of landslides and snow avalanches in 2009, establishing a standardized framework for Landslide Hazard Zonation (LHZ) at macro (1: 50,000) and meso (1: 25,000) scales, and mandating the progressive coverage of landslide-prone areas with scientifically validated susceptibility maps. These guidelines identified nine strategic areas for systematic landslide hazard management, including inventory preparation, risk zonation, knowledge management, early warning systems, and capacity building (NDMA, 2009). In alignment with these national objectives, the GSI initiated the National Landslide Susceptibility Mapping (NLSM) project in 2014 to undertake multi-scale landslide susceptibility and hazard mapping across landslide-prone regions of India at a 1: 50,000 scale. To further strengthen high-resolution landslide assessment practices, the GSI published the Standard Operating Procedure (SOP) for meso scale (1: 10,000/5,000) Landslide Susceptibility Mapping in 2021, providing a systematic methodology for detailed susceptibility analysis, thematic data integration, field validation, and site-specific landslide risk evaluation.

1.2.2 Landslide Hazard in the Western Ghats: A Kerala Perspective

The Western Ghats of Kerala receive among the highest annual rainfall in peninsular India, with highland areas on the windward western escarpment recording average annual precipitation exceeding 5,000 mm, delivered almost entirely through the southwest and northeast monsoons and pre-monsoon events (Kuriakose et al., 2009). This extreme rainfall regime, acting on steep slopes underlain by thick profiles of chemically weathered laterite and saprolite over impermeable crystalline basement, generates pore water pressure conditions that constitute the principal trigger mechanism for shallow landslides and debris flows in the region (Kuriakose et al., 2008). The Idukki and Wayanad districts represent the most intensely affected areas within Kerala. GSI post disaster assessment of the 2018 events recorded that most of documented landslide sites coincided with zones previously classified as moderate to highly susceptible in the national susceptibility framework, affirming the predictive utility of systematic mapping.

Hao et al. (2022) demonstrated through multi-temporal land use analysis that landslide locations (90% in Kerala and 83% in Idukki), no significant land use and land cover (LULC) changes were observed prior to the event, indicating that LULC changes during 2010 to 2018 had limited influence on the 2018 landslides. Yunus et al. (2021) identified intensified landslide regimes in the Western Ghats, attributing the trend to the combined effects of extreme rainfall events and anthropogenic landscape modification. Within the Idukki District specifically, Jones et al. (2021) applied logistic regression and artificial neural network models to dataset of landslide events, identifying slope gradient, elevation, rainfall intensity, geology, proximity to drainage, land use type, road density, and quarry density as the statistically most significant conditioning factors. Sanker et al. (2023) showed the importance of land use and land cover change in modifying landslide susceptibility over Idukki using remote sensing and geospatial analysis of 8 years from 2015 to 2023. More recently, Chandan et al. (2025) compared AHP and Logistic Regression approaches for landslide susceptibility zonation in parts of the Western Ghats of Kerala and highlighted the amplifying role of increasing extreme rainfall events and anthropogenic modification in driving landslide frequency and spatial extent.

1.3 Objectives of the Study

The objectives of the present study are organized three key themes, which together constitute a comprehensive and operationally oriented framework for landslide disaster risk reduction in the PRB:

- **Identification of High-Risk Landslide Hotspots:** To delineate landslide-prone areas in the PRB using the Frequency Ratio (FR) method by integrating geo-environmental conditioning factors in a GIS environment, and to prepare a landslide susceptibility map representing the spatial distribution of hazard zones.
- **Establishment of a Monitoring Framework:** To develop a continuous landslide monitoring system using field-based instruments and remote sensing techniques for detecting slope instability and supporting early warning in high-susceptibility zones.
- **Landslide Risk Assessment and Management:** To assess landslide risk by integrating hazard and vulnerability parameters in a GIS-based weighted overlay framework, and to propose suitable structural and non-structural mitigation measures for risk reduction in the PRB.

2. Periyar River Basin

2.1 Physiographic Settings

The Periyar River, commonly referred to as the 'Lifeline of Kerala', originates from the Chokkampatti Malai of the Sivagiri Hills in the Western Ghats, Idukki District, at an elevation of approximately 1930 m above mean sea level (MSL). It is the longest river in Kerala, with a mainstream length of approximately 260.7 km, draining a basin area of approximately 5216 km^2 before discharging into the Arabian Sea near Munambam in Ernakulam District. The basin extends between latitude 9°16'20"N and 10°23'23"N and longitude 76°06'04"E and 77°24'45"E, spanning a considerable elevation gradient from the Anamudi massif (the highest peak in peninsular India at 2681 m MSL) in the eastern highland reaches, through the mid-elevation dissected hill country of the Idukki plateau, to the coastal alluvial plains and estuarine backwaters of Ernakulam District in the west.

Physiographically, the basin is divisible into three distinct altitudinal zones. The physiography consists of rocky and undulating highlands with forests, the midland covering hills and valleys sandwiched between highlands and lowlands, and the lowlands characterized by thickly populated coasts (Krishnakumar et al. 2021). The high-altitude zone (above 1,000 m MSL), predominantly within Idukki District, is characterized by rugged terrain, steep slopes, and dense forest cover, with these physical features significantly increasing landslide risk during the monsoon season (Murugaiah & Lancelet, 2025); the upstream tributaries pass through steep slopes and deep gorges, underlain by charnockites, charnockite gneiss, and hornblende gneiss, often overlain by laterite (Sadhwani et al., 2023), making this zone the region of the highest landslide hazard potential in the basin. Relative relief, slope gradient, and drainage density are the most prominent terrain susceptibility contributors, with concave slopes of 20°–30° and relative relief values of 225–300 m/km² showing the strongest positive association with landslide occurrence (Pradeep et al., 2023). The mid-altitude transitional zone (300–1,000 m MSL) comprises undulating hills, inter-montane valleys, and plantation agriculture on deeply weathered gneissic rocks, where conversion of natural vegetation to plantations, step cutting of slopes, and construction on natural drainage channels have collectively contributed to slope instability (Vasudevan et al., 2022). The low-altitude zone (below 300 m MSL) encompasses river floodplains, paddy lands, and the urbanized coastal fringe, where landslide hazard diminishes but flood risk and secondary sediment impacts from upstream mass movements remain significant (Sadhwani et al., 2023).

2.2 Hydrology

The PRB contains one of the most intensively developed reservoir systems in Kerala. The Idukki reservoir, formed by the Idukki arch dam, the Cheruthoni dam, and the Kulamavu dam, has a combined storage capacity of approximately 1.996 BCM (billion cubic metres) and serves as the primary reservoir for the Idukki hydroelectric project. The Idamalayar reservoir, damming over the Edamalayar tributary, has a capacity of approximately 1.1 BCM. The Mullaperiyar dam, constructed across the Mullayar tributary in the upper reaches of the basin, diverts water eastward to the Vaigai basin in Tamil Nadu for irrigation. During the August 2018 extreme event, Kerala received 53% above-normal monsoon rainfall, with 1, 2, and 3-day extreme rainfall registering return periods of 75, 200, and 100 years respectively; critically, six of the seven major reservoirs were already at more than 90% of their full storage capacity on 8th August 2018, prior to the most intense phase of rainfall (Mishra et al., 2018). HEC-HMS modelling established that the PRB received a 145-year return period rainfall during this event, and that reservoir operations could have achieved only 16–21% peak flow attenuation, as the dominant flood contribution originated from the unregulated intermediate catchment (Sudheer et al., 2019). Projections under the CMIP6 SSP5-8.5 scenario indicate that Probable Maximum precipitation across the Periyar basin will increase substantially through 2100, elevating both

Probable Maximum Flood magnitudes and the compounding risk of flood-triggered landslides (Harikumar and Thampi, 2025).

2.3 Climate

The PRB is characterized by a humid tropical monsoon climate, governed by the southwest monsoon (June–September), the northeast monsoon (October–December), and occasional pre-monsoon showers (March–May). Annual average rainfall in the basin ranges from approximately 2,500 mm in the lower Ernakulam plains to over 5,000 mm in the high-altitude Idukki regions, with the western escarpment of the Ghats receiving some of the highest orographic rainfall intensities in peninsular India (Kuriakose et al., 2009). Rainfall intensity and duration are the primary triggers of landslides in the basin. Rising extreme rainfall events, intensified by climate change and human-driven land-use pressures, have emerged as key triggers of landslides across the Western Ghats, as tragically evidenced by the devastating slides of 2018, 2019, and 2024 (Chandan et al., 2025).

2.4 Land Use and Land Cover

The land use and land cover (LULC) of the PRB reflects the progressive modification of a once extensively forested landscape by plantation agriculture, hydroelectric infrastructure development, road construction, settlement expansion, and industrial activity (Krishnakumar et al., 2022). Plantation agriculture comprising tea, coffee, cardamom, rubber, and mixed spices constitutes the dominant land use in the highland and midland portions of the basin, particularly throughout Idukki District (cPeriyar: River at a glance, 2024). Dense natural forest, including shola-grassland mosaics and tropical evergreen forest, is concentrated within the Periyar Tiger Reserve, Eravikulam National Park, and other reserved forests (Kerala Forest Department, 2024). The conversion of natural forest to plantation agriculture and the expansion of built-up areas on hillslopes are widely documented drivers of elevated landslide susceptibility in Kerala (Vasudevan et al., 2022; Sanker et al., 2023).

2.5 Historical Landslide Inventory

The PRB, and Idukki District in particular, has a well-documented history of landslide occurrence. Kuriakose et al. (2009) compiled a baseline inventory of 29 major landslide events in Kerala from 1984 to 2007, identifying Idukki as predominantly affected by shallow landslides and debris flows. The August 2018 floods triggered in excess of 1,000 landslides statewide, with Idukki recording 2,219 separate occurrences (Jones et al., 2021). The Pettimudi landslide of 2020, occurring on a tea plantation slope in Rajamalai range, Idukki, caused catastrophic loss of life (Achu et al., 2021).

The inventory used for FR method comprises landslide point locations extracted from the GSI Bhukosh geospatial portal for the PRB (Figure 2). Landslide types recorded include shallow debris flows, earth slides, and debris avalanches - consistent with the dominant failure modes documented for the Western Ghats lateritic terrain by Sajinkumar et al. (2011) and Kuriakose et al. (2008).

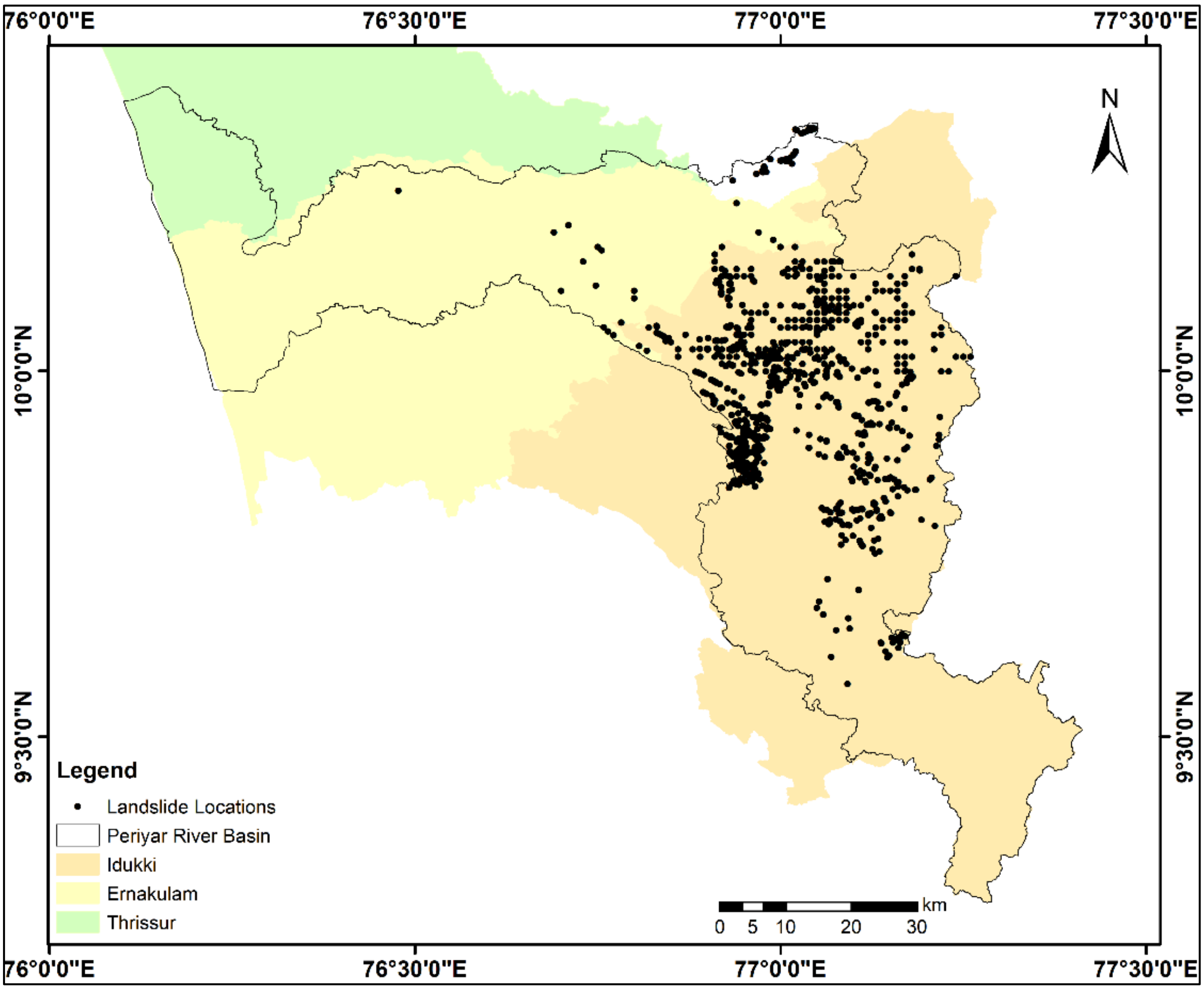


Figure 2: Landslide inventory map of the PRB

3. Methodology

3.1 Overview of Methodological Framework

The methodology adopted in this study comprises two integrated components: (i) LSM using the FR bivariate statistical method, and (ii) Landslide Risk Assessment through the integration of a Hazard Index derived from the susceptibility map with a composite Vulnerability Index computed from spatial demographic, infrastructural, and land cover datasets. The overall workflow was executed within a GIS environment using QGIS and ArcGIS platforms, with spatial data processed at 30 m resolution consistent with the FABDEM baseline. The methodological framework adopted for the present study is schematically illustrated in Figure 3.

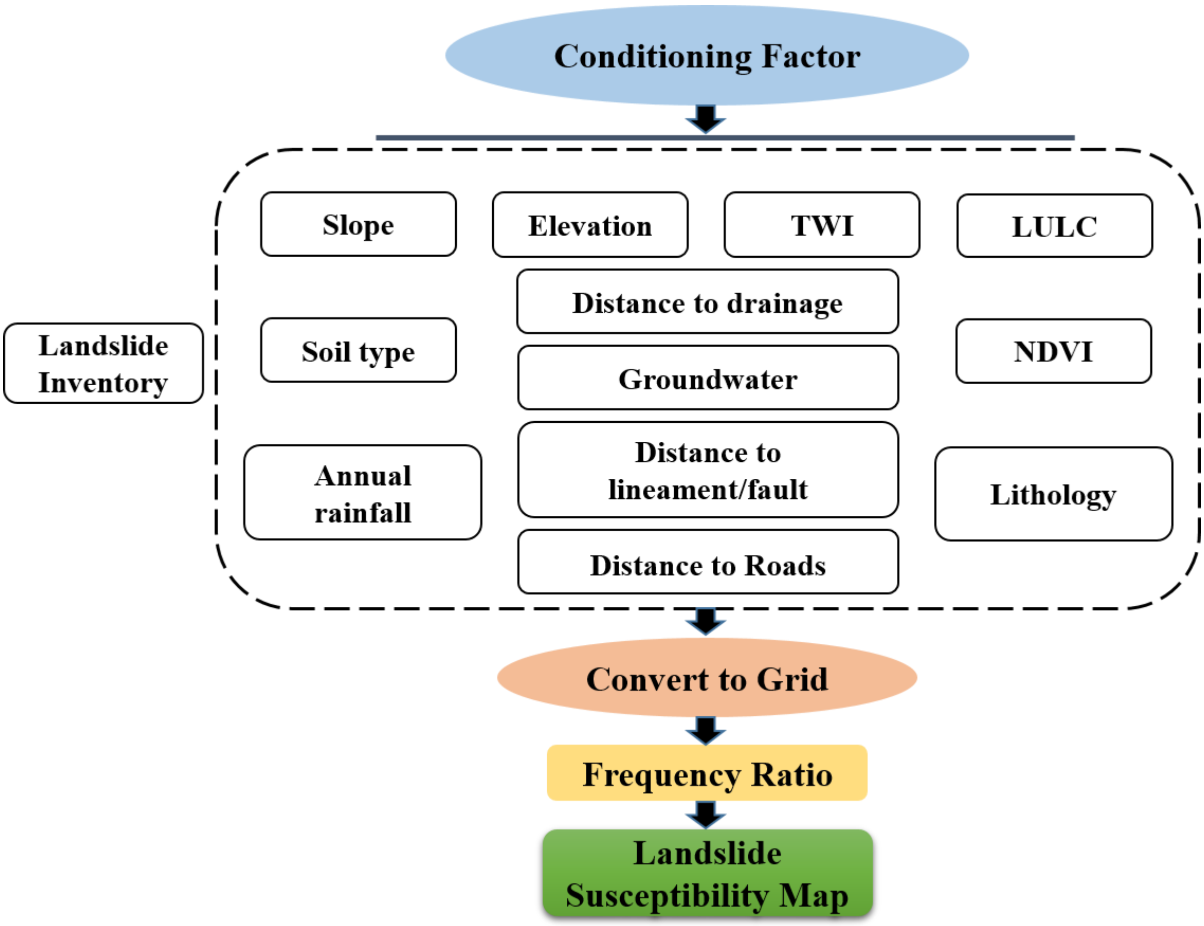


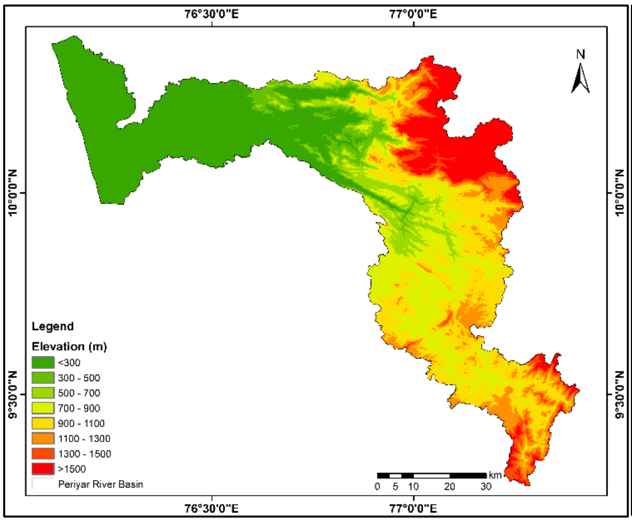
Figure 3: Methodological framework for the study

3.2 Conditioning Factors for Frequency Ratio Analysis

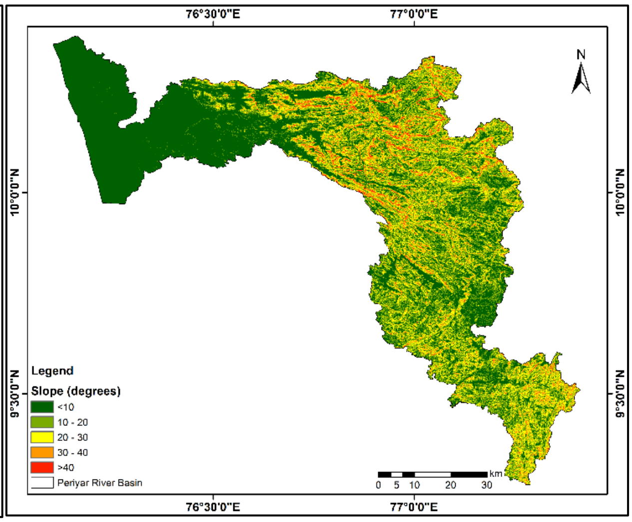
Twelve geo-environmental conditioning factors (Figure 4) were selected for the FR-based susceptibility assessment based on their documented relevance to landslide initiation in the Western Ghats, data availability at the basin scale, and absence of multicollinearity. Prior to FR computation, there were 15 conditioning factors which are assessed for multicollinearity using Pearson correlation coefficient matrix. From that, factors such as aspect, SPI, and plan curvature are removed because of the collinearity test. The selected factors and their sources are summarized in the Table 1.

Table 1: Data used for the study

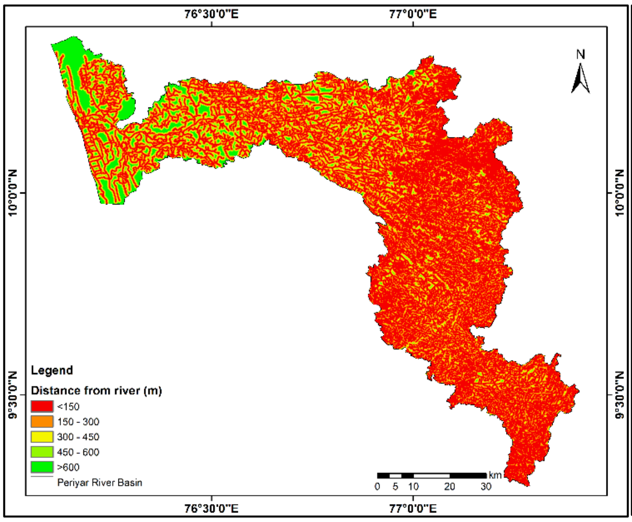
Factor Category	Conditioning Factor	Data Source
Topographic and Terrain data	Slope (degrees)	Derived from FABDEM 30 m
	Elevation	
	Topographic Wetness Index (TWI)	
Hydrological data	Distance to drainage	cPeriyar — River Atlas (Centre for Periyar River Basin Management and Studies, IIT Palakkad and NIT Calicut)
	Annual rainfall	Irrigation Design and Research Board (IDRB) & Kerala State Electricity Board (KSEB)
	Groundwater	Central Ground Water Board (CGWB)
Geological and Structural Data	Lithology	GSI
	Distance to lineament/fault	GSI
Pedological data	Soil type	National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) soil map
Remote Sensing Data	LULC	ESRI Sentinel-2 10 m LULC 2024
	NDVI	Sentinel 2 - 10 m
Infrastructure Data	Distance to Roads	OpenStreetMap road network data accessed via GEOFABRIK data extracts (geofabrik.de)


76°30'0"E
77°0'0"E
10°0'0"N
9°30'0"N
N
Legend
Elevation (m)
<300
300 - 500
500 - 700
700 - 900
900 - 1100
1100 - 1300
1300 - 1500
>1500
Periyar River Basin
0 5 10 20 30 km

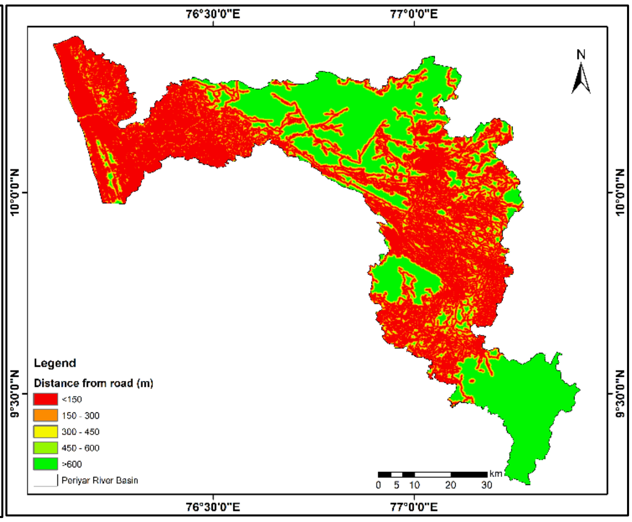
(a)


76°30'0"E
77°0'0"E
10°0'0"N
9°30'0"N
N
Legend
Slope (degrees)
<10
10 - 20
20 - 30
30 - 40
>40
Periyar River Basin
0 5 10 20 30 km

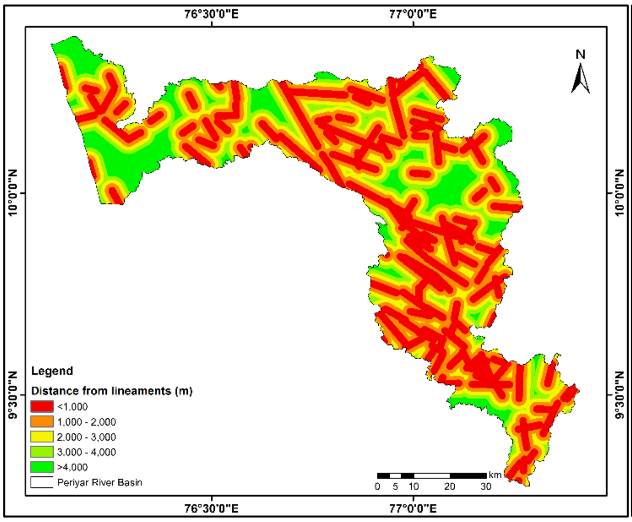
(b)


76°30'0"E
77°0'0"E
10°0'0"N
9°30'0"N
N
Legend
Distance from river (m)
<150
150 - 300
300 - 450
450 - 600
>600
Periyar River Basin
0 5 10 20 30 km

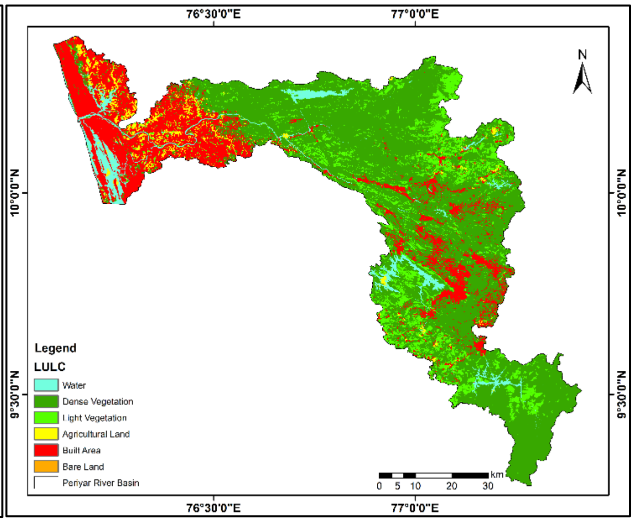
(c)


76°30'0"E
77°0'0"E
10°0'0"N
9°30'0"N
N
Legend
Distance from road (m)
<150
150 - 300
300 - 450
450 - 600
>600
Periyar River Basin
0 5 10 20 30 km

(d)


76°30'0"E
77°0'0"E
10°0'0"N
9°30'0"N
N
Legend
Distance from lineaments (m)
<1,000
1,000 - 2,000
2,000 - 3,000
3,000 - 4,000
>4,000
Periyar River Basin
0 5 10 20 30 km

(e)


76°30'0"E
77°0'0"E
10°0'0"N
9°30'0"N
N
Legend
LULC
Water
Dense Vegetation
Light Vegetation
Agricultural Land
Built Area
Bare Land
Periyar River Basin
0 5 10 20 30 km

(f)

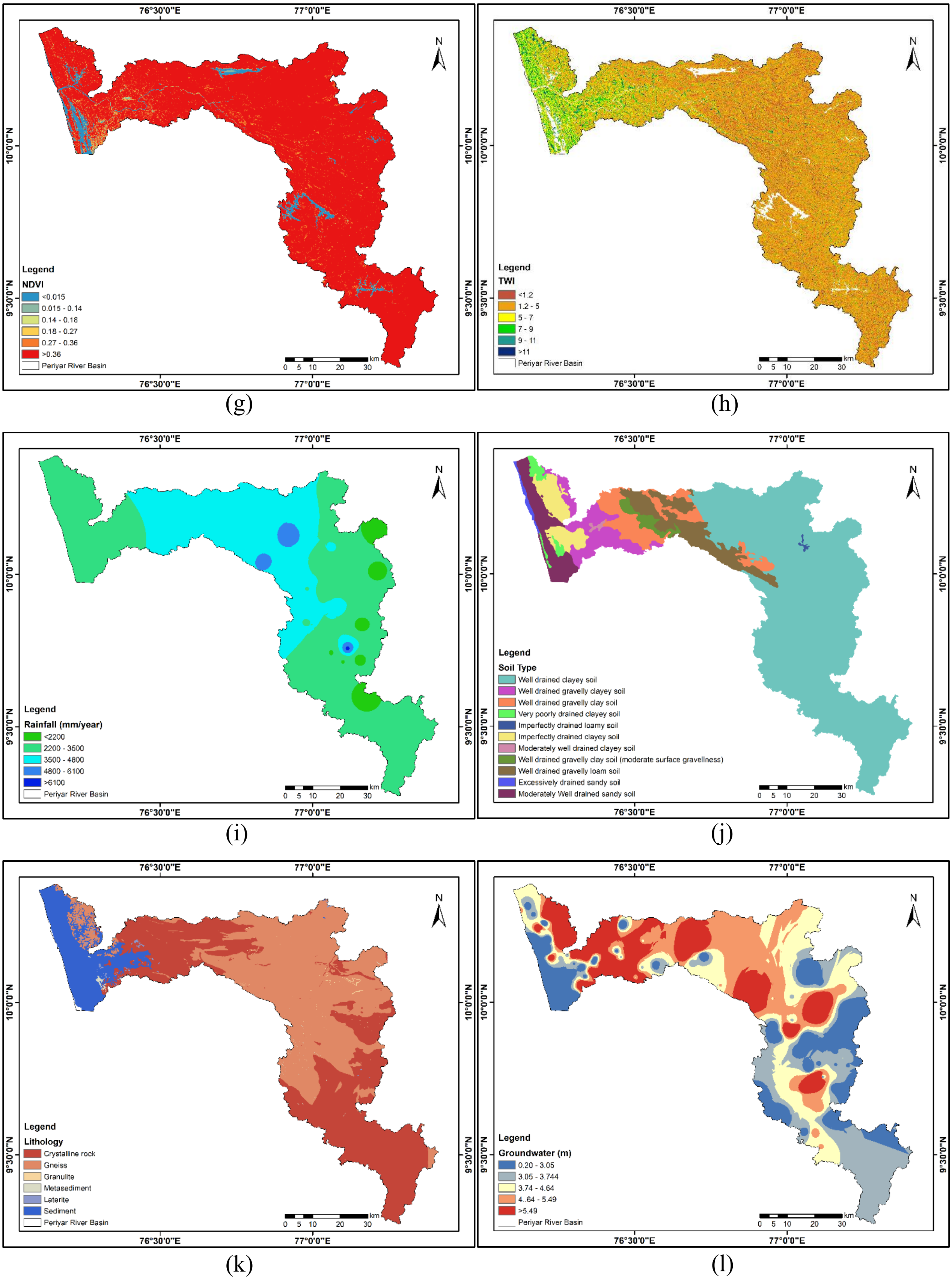


Figure 4: Conditioning factor maps of the PRB for FR method: (a) Elevation, (b) Slope (degrees), (c) Distance from river, (d) Distance from road, (e) Distance from lineaments, (f) LULC, (g) NDVI, (h) TWI, (i) Annual rainfall (mm/year), (j) Soil texture, (k) Lithology, (l) Groundwater.

3.3 Frequency Ratio Method

The Frequency Ratio (FR) is a bivariate statistical method that establishes the empirical correlation between the spatial distribution of landslide occurrence points and each class of each conditioning factor. It suggests the possibility of a future event to occur based on past information (Yilmaz, 2009; Chimidi et al., 2017). FR quantifies the ratio of the percentage of landslide pixels in a factor class to the percentage of total pixels in that class (Nohani et al., 2019; Shano et al., 2020) using the equation below.

$$\mathbf{FR}_{i} = (\boldsymbol{LS}_{i}/\mathbf{LS})/(\mathbf{A}_{i}/\mathbf{A})$$

Where FR_i = FR of i^{th} class, LS_i = number of landslide pixels in the i^{th} class, LS = total number of landslide pixels in the study area, A_i = total number of pixels of i^{th} class and A = total number of pixels in the study area. The weight assigned to each factor are shown in Table 2.

Table 2: Weight assigned to each factor

Sl.No.	Conditioning factors	Weight
1	Elevation	0.66
2	Slope	0.61
3	River	0.77
4	Road	0.90
5	Lineament	0.19
6	LULC	0.67
7	NDVI	0.76
8	TWI	0.58
9	Rain	0.88
10	Soil	1.40
11	Lithology	0.83
12	Groundwater	0.40

FR values exceeding 1.0 indicate a positive association between the factor class and landslide occurrence; values below 1.0 indicate lower-than-average susceptibility. The final landslide susceptibility index is computed by summing the FR values of all conditioning factor classes for each pixel.

The resulting continuous LSI raster is classified into five susceptibility zones as, very low, low, moderate, high, and very high, using the natural breaks (Jenks) classification method, which minimizes intra-class variance and maximizes inter-class variance, thereby producing statistically optimal class boundaries appropriate for the non-normal distribution typical of susceptibility indices (Feby et al., 2020).

3.4 Landslide Risk Assessment Framework

Following the generation of the Landslide Susceptibility Map, a composite Landslide Risk Index (LRI) was computed by integrating a Hazard Index (HI) and a Vulnerability Index (VI) using a weighted overlay approach in GIS. The risk framework adopted follows the widely accepted formulation, Risk = Hazard x Vulnerability, operationalized through a weighted linear combination of spatially distributed hazard and vulnerability indicators, consistent with the methodological approach standardized for India by the National Disaster Management Authority (NDMA, 2009).

- **Hazard Index**

  The Hazard Index (HI) is derived directly from the Landslide Susceptibility Map generated using the FR method. The five susceptibility classes (very low, low, moderate, high, and very high) were reclassified to ordinal hazard scores of 1 to 5 respectively, producing a spatially continuous hazard surface across the PRB. The HI was assigned a weight of 60% in the composite risk index, because of its consideration as the primary determinant of spatial risk distribution.

- **Vulnerability Index**

  The Vulnerability Index (VI) was computed as a weighted composite of four spatial vulnerability indicators representing the exposure and fragility of elements-at-risk to landslide impact. The four indicators and their assigned weights within the Vulnerability Index are presented in Table 3. Each indicator layer was independently classified into five ordinal classes (1-5) and spatially integrated using weighted overlay analysis. The Vulnerability Index was assigned a weight of 40% in the composite Risk Index.

  - **Population density** is derived from the WorldPop 2020 gridded population dataset and disaggregated to a 30 m raster surface. It was assigned a weight of 30% within the VI, reflecting its consideration as the most direct indicator of human life at risk.
  - **Building density** is computed from building footprint data (OpenStreetMap and Google Open Buildings) as the number of building units per unit area. It was assigned a weight of 30% within the VI, equivalent with population density, to capture the physical exposure of structures and property assets to landslide damage (Papathoma-Köhle et al., 2017).

- **Road density** is derived from the data from GEOFABRIK service. It was assigned a weight of 20% within the VI, reflecting the critical role of road infrastructure in connectivity and emergency response.
- **Land Use and Land Cover (LULC)** is derived from the ESRI Sentinel-2 LULC of 2024 dataset and reclassified to an ordinal vulnerability score (1-5) based on the sensitivity and economic value of each land use type to landslide damage with built-up areas and managed plantations assigned the highest vulnerability scores. LULC was assigned a weight of 20% within the VI.

Table 3: Vulnerability indicators, rationale, and weights assigned within the Vulnerability Index

Vulnerability Indicator	Rationale	Weight within Vulnerability Index (%)
Population Density	Direct measure of human exposure to landslide hazard - Higher density increases potential for casualties	30
Building Density	Proxy for physical exposure of built infrastructure and assets - Denser built fabric amplifies potential structural damage and loss	30
Road Density	Infrastructure fragility indicator - Road networks are critical lifelines whose disruption amplifies disaster impacts and impedes emergency response	20
Land Use and Land Cover (LULC)	Indicator of land use sensitivity and economic exposure - certain land use types (e.g., settlements, plantations) represent higher asset values and fragility on susceptible slopes	20

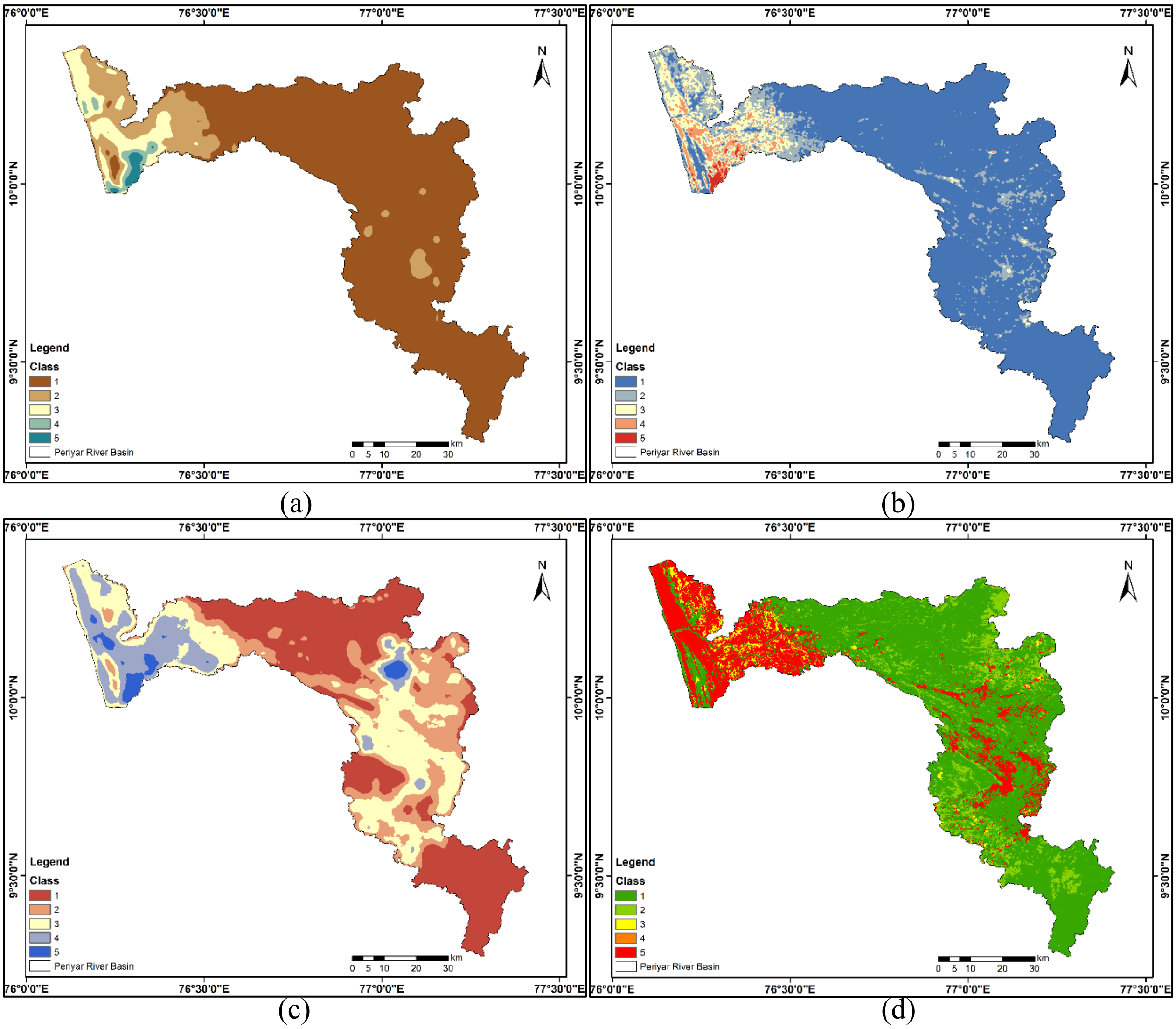


Figure 5: Conditioning factor maps of the PRB for VI: (a) Population density, (b) Building density, (c) Road density and (d) LULC

❖ Composite Risk Index Computation

The composite Landslide Risk Index (LRI) was computed as a weighted linear combination of the Hazard Index and the Vulnerability Index according to the following formula:

$$\boldsymbol{LRI} = (\boldsymbol{HI} \times \mathbf{0.60}) + (\boldsymbol{VI} \times \mathbf{0.4})$$

Where: LRI = Landslide Risk Index; HI = Hazard Index (FR-based susceptibility score, reclassified 1-5); VI = Composite Vulnerability Index (weighted combination of population density, building density, road density, and LULC, each scored 1-5).

The resulting continuous LRI raster was classified into five risk zones - very low, low, moderate, high, and very high - using natural breaks (Jenks) classification, and mapped at the basin scale to identify high-priority risk hotspots for management intervention.

Table 4: Classification scheme for susceptibility, vulnerability, and risk indices

Score Range	Susceptibility / Risk Class	Assigned Ordinal Score	Management Implication
Lowest	Very Low	1	Minimal intervention required
Low	Low	2	Periodic monitoring
Moderate	Moderate	3	Precautionary measures
High	High	4	Priority monitoring and structural mitigation
Highest	Very High	5	Immediate intervention, evacuation planning

4. Results and Discussion

4.1 Landslide Susceptibility Mapping using Frequency Ratio

The FR values computed for each class of the twelve conditioning factors reveal the differential contribution of individual geo-environmental variables to landslide susceptibility across the PRB. Key findings from the FR analysis are summarized below:

Among the topographic parameters, slope gradient in the 20°-30° range exhibited the strongest positive FR values, consistent with the threshold slope angles for shallow debris flow initiation on lateritic soils documented for the Western Ghats by Kuriakose et al. (2008). Slopes exceeding 40° showed slightly reduced FR values, likely reflecting the prevalence of rocky outcrops and thinner soil profiles at extreme gradients. Elevation classes in the 500-700 m range showed the highest FR values, corresponding to the deeply weathered lateritic terrain of the Idukki plateau and the ghat escarpment where landslide density is highest in the inventory.

Hydrological parameters indicated that low-to-moderate TWI classes showed positive FR correlations, suggesting that moderately converging terrain with intermediate soil moisture conditions, rather than fully saturated zones, are more susceptible to slope failure in this basin. Proximity to rivers within 150 m and proximity to roads within 150 m both having high FR values, indicating the destabilizing influence of fluvial undercutting and anthropogenic slope modification respectively on landslide initiation.

Lineament distance classes in the 2000–3000 m range showed elevated FR values, showing that areas at intermediate distances from structural discontinuities, rather than immediately adjacent zones, exhibit higher failure susceptibility, possibly due to the diffuse propagation of tectonic stress and associated weathering. Among land use and land cover classes, built-up areas and dense vegetation have the highest FR values, reflecting the co-occurrence of anthropogenic pressure and deep-rooted canopy cover on steep, moisture-retentive slopes. Higher NDVI values were positively associated with landslide occurrence, validating the known pattern in the Western Ghats where dense plantation and forest cover on steep lateritic hillslopes contributes to elevated root-zone moisture and surcharge loading.

Rainfall exceeding 6100 mm annually showed the highest FR values among climatic classes, affirming the dominant role of intense and prolonged monsoonal precipitation as the primary triggering mechanism for landslides in the basin. Among pedological classes, imperfectly drained loamy soils exhibited the highest FR values, consistent with their low permeability, high moisture retention capacity, and susceptibility to rapid pore pressure build-up during rainfall events.

Lithological units comprising charnockite and hornblende gneiss - the dominant basement rocks in the highland zone - showed elevated FR values were overlain by thick weathering profiles, consistent with the weathering-landslide relationship documented by Sajinkumar et al. (2011). Groundwater depth in the 0.20–3.05 m range showed the highest FR values, reflecting shallow water table conditions that promote near-surface saturation and reduce effective shear strength along potential failure planes.

The final LSI values were classified into five susceptibility zones. The spatial distribution of susceptibility zones across the PRB indicates that very high and high susceptibility zones are predominantly concentrated along the western escarpment of the Ghats in the upper Idukki, the ghat road sections, the first and second order stream headwaters, and the interface zones between forest and plantation land use. In the Idukki District local bodies; Adimali, Idukki Kanjikuzhy, Mankulam, Munnar, Konnathady, Vathikudy, Vazhathope, Mariyapuram, Kattapana, Erattayar, Devikulam, and Nedumkandam, are in very high to high susceptibility zones. Low and very low susceptibility zones predominate in the alluvial plains and coastal zone of Ernakulam District. Figure 6 shows the landslide susceptibility zonation map of the PRB.

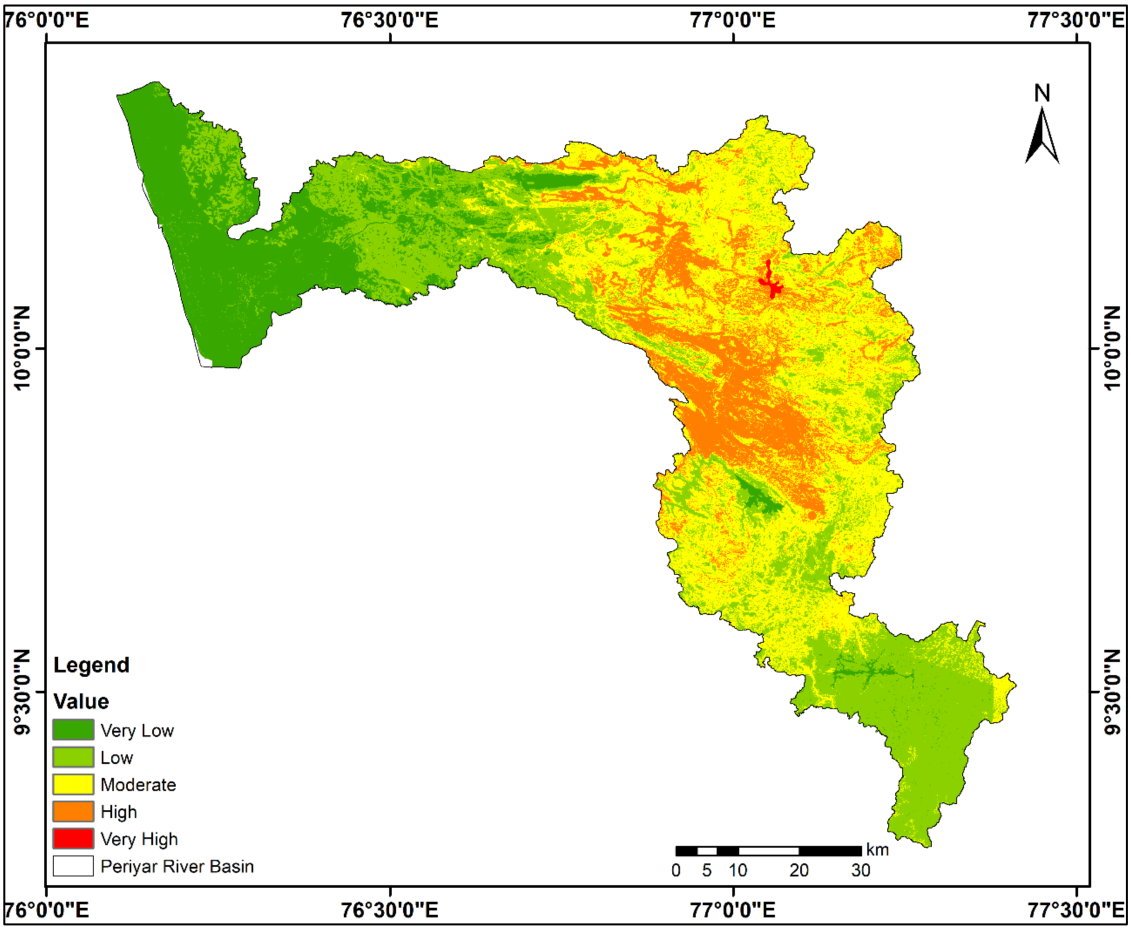


Figure 6: Landslide susceptibility zonation map of the PRB

4.2 Vulnerability Assessment

The four vulnerability indicators - population density, building density, road density, and LULC - were independently classified and integrated using the assigned weights to produce a composite Vulnerability Index surface. High vulnerability zones, reflecting elevated population density and building concentration, are primarily distributed in the mid-altitude market towns and roadside settlements of Idukki District, including areas around Thodupuzha, Kothamangalam, and the Munnar–Adimali corridor. Road density vulnerability is highest along the major ghat road alignments that traverse the western escarpment, where high road density coincides with high and very high landslide susceptibility - a particularly critical overlap for infrastructure risk management. LULC-based vulnerability is highest in built-up and intensively cultivated plantation zones. Figure 7 illustrates the vulnerability map of the PRB.

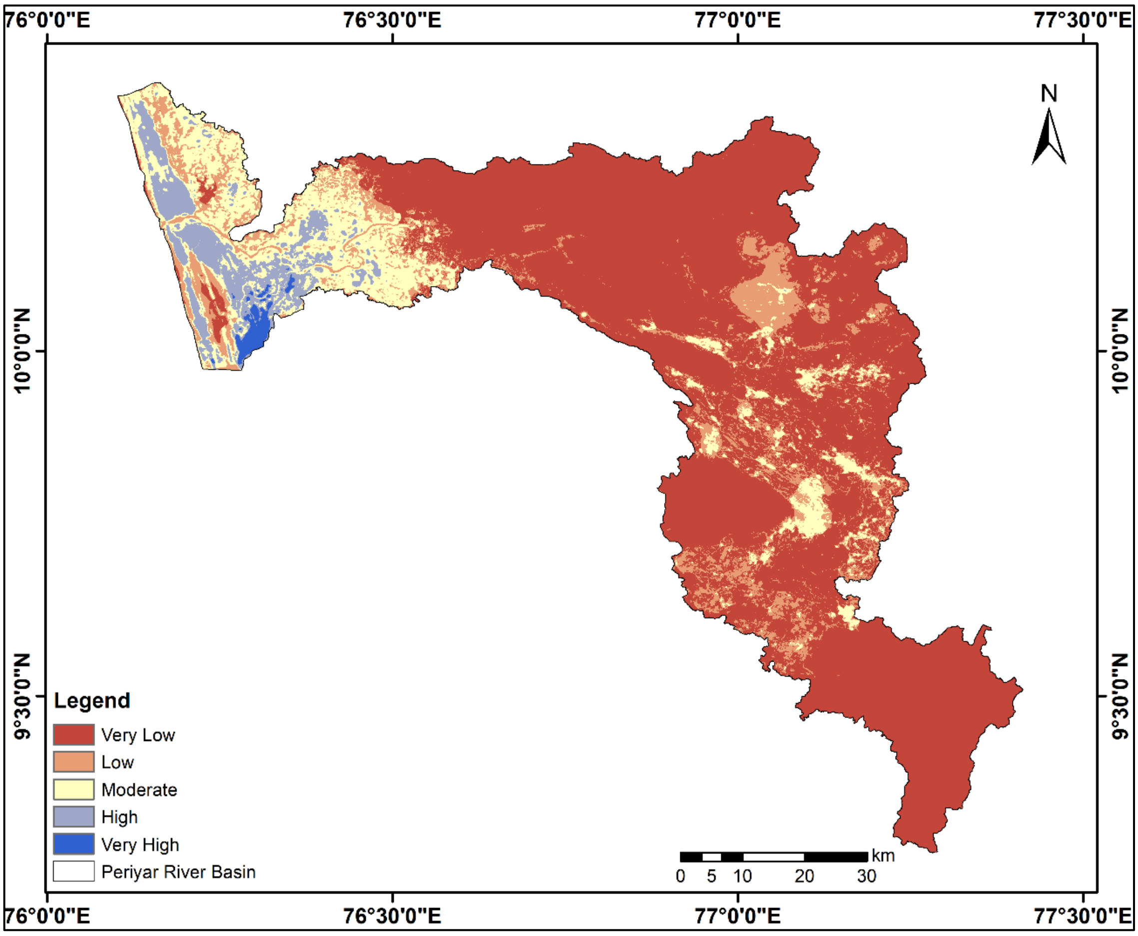


Figure 7: Vulnerability map of the PRB

4.3 Composite Risk Assessment

The composite Landslide Risk Index, integrating the Hazard Index (weight: 60%) and the Vulnerability Index (weight: 40%), reveals a differentiated risk landscape across the PRB. Very high risk zones are identified at the spatial intersection of very high landslide susceptibility and elevated exposure of population, infrastructure, and built environment - particularly along the ghat road corridors and in settlements situated on steep plantation slopes. These areas represent priority targets for structural risk mitigation, enhanced monitoring, and community-level preparedness planning.

High risk zones encompass a wider belt along the Idukki highland margin where moderate-to-high susceptibility overlaps with moderately dense settlement patterns. Moderate risk zones dominate the transitional mid-altitude areas, while low and very low risk characterizes the alluvial plains and coastal zone where susceptibility is negligible despite high population density. This spatial risk disaggregation demonstrates the value of the integrated hazard–vulnerability framework: areas of high population density in the lowlands do not translate to high landslide risk in the absence of susceptibility, while sparsely populated but highly susceptible highland terrain presents a different risk profile requiring early warning rather than evacuation infrastructure. The local bodies in Idukki District, such as Kattapana, Erattayar, Vathikudy, Vazhathope, Idukki Kanjikuzhy, Adimali, Konnathady, Munnar, and Nedumkandam, contains high vulnerability zones. Figure 8 illustrates the landslide risk map of the PRB.

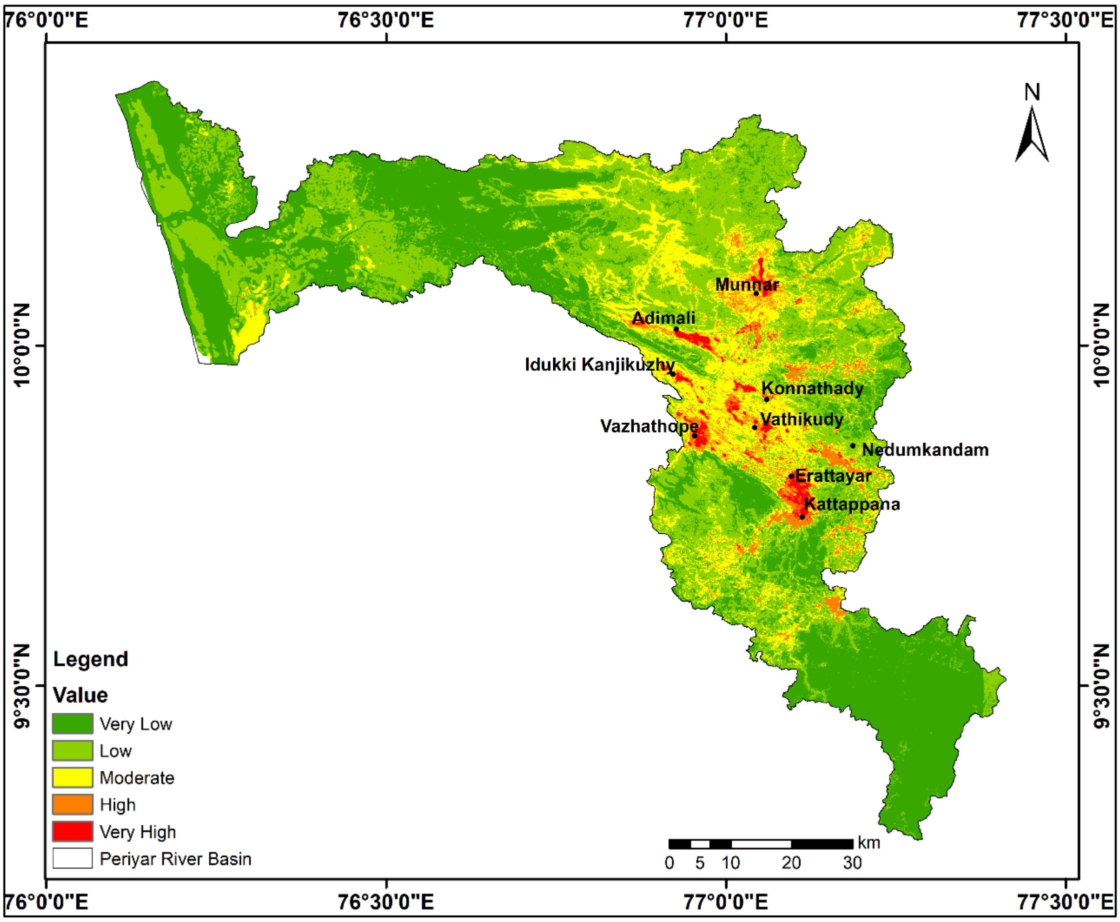


Figure 8: Landslide risk map of the PRB

5. Monitoring Framework for Landslide-Prone Zones

5.1 Rationale for a Monitoring System

The establishment of a systematic monitoring framework for landslide-prone zones identified through susceptibility and risk mapping is a critical operational requirement for translating scientific outputs into actionable disaster risk reduction. Early detection of slope instability through in-situ instrumentation and remote sensing enables the operationalization of rainfall thresholds and displacement-based warning criteria, allowing timely evacuation of at-risk communities and suspension of ghat road traffic before slope failures reach catastrophic scale (Naidu et al., 2018; Ramesh, 2011).

The PRB, particularly the Idukki highlands (Munnar, Devikulam, Adimali, Vathikudy, and Konnathady), represents one of the most challenging landslide monitoring environments in peninsular India. The combination of extreme orographic rainfall (>5,000 mm/year), deeply weathered lateritic and saprolitic profiles over impermeable crystalline basement, extensive ghat road cut slopes, and plantation agriculture on steep terrain allows the transition from pre-failure deformation to catastrophic debris flow within hours of a critical rainfall event, as demonstrated by the Pettimudi (2020) and Mundakkai–Chooralmala (2024) disasters (Achu et al., 2021; Achu et al., 2025).

A multi-layered monitoring framework for the PRB should fulfil four operational objectives:

- **a.** Continuous detection of rainfall approaching or exceeding landslide-triggering thresholds.
- **b.** In-situ measurement of geotechnical precursors such as pore water pressure, soil moisture, and slope displacement.
- **c.** Satellite-based monitoring of slope deformation and post-event landslide inventory updating across the basin.
- **d.** Integration of all monitoring data into a multi-level warning system providing actionable alerts to KSDMA, local governments, plantation workers, and highway authorities.

The existing Amrita Landslide Early Warning System (A-LEWS), already operational at Munnar since 2009 which is recognized by the International Consortium of Landslides as a World Centre of Excellence on Landslide Risk Reduction (Ramesh et al., 2023) and the Slope Instability Predictor–Kerala (SLIP-K) platform, deployed for Idukki District (Mohan et al., 2025), provide a strong institutional and technical foundation for the proposed framework.

5.2 Proposed In-Situ Instrumentation Network

The proposed monitoring framework for the PRB consists of a hierarchical, IoT-enabled sensor network comprising basin-scale hydro meteorological monitoring, site-specific geotechnical instrumentation, and real-time deformation monitoring systems. The network is organized into three tiers:

a. ***A basin-level hydro meteorological layer - Automated rain gauges and weather stations.***

Automated rain gauges (ARGs) and automated weather stations (AWSs) constitute the hydro meteorological layer that are intended to provide continuous measurements of rainfall intensity, cumulative rainfall, temperature, humidity, and other meteorological variables required for landslide forecasting models. A minimum density of one ARG per 10 km² is recommended within very high susceptibility zones, particularly in Munnar, Devikulam, Adimali, Mankulam, and Vathikudy, to facilitate rainfall threshold exceedance detection and provide inputs to operational warning systems such as SIGMA and SLIP-K.

b. ***A site-specific geotechnical instrumentation layer - Piezometers, inclinometers, soil moisture sensors, tiltmeters.***

The geotechnical monitoring component includes vibrating-wire piezometers, soil moisture sensors, inclinometers, extensometers, and MEMS (Micro-Electro-Mechanical Systems)-based tiltmeters. Piezometers installed within representative lateritic and saprolitic slopes would monitor pore water pressure, which has been identified as the primary trigger of shallow landslides in the Western Ghats (Kuriakose et al., 2008; Kesavaram et al., 2025). Soil moisture sensors would provide information on saturation conditions preceding failure, while inclinometers and extensometers would detect progressive subsurface and surface slope movement. Along critical ghat road corridors, tiltmeters and MEMS accelerometers can be deployed to monitor rapid slope deformation and provide inputs for traffic management and emergency response protocols.

c. ***A real-time deformation monitoring layer - Ground-based InSAR at critical sites.***

Ground-based InSAR systems are proposed for selected high-risk locations such as Munnar and Rajamala, where continuous millimetre-scale displacement monitoring can provide near real-time information on slope instability. Priority deployment of the monitoring network is recommended in Munnar, Devikulam, Adimali, Rajamala–Pettimudi, Vathikudy, Konnathady, and Mankulam, where high susceptibility coincides with population centres, transportation corridors, and previous landslide occurrences.

❖ **Rainfall Threshold Monitoring and Warning Protocol**

Rainfall threshold monitoring constitutes the primary mechanism for landslide warning generation within the basin. Abraham et al. (2021) applied the SIGMA (Sistema Integrato Gestione Monitoraggion Allerta) model to Idukki District using historical landslide data from 2018 and 2019, defining cumulative rainfall thresholds at 1–30 days. Unlike conventional empirical approaches, SIGMA issues multiple escalating warning levels based on accumulated rainfall expressed as multiples of the standard deviation of historical cumulative rainfall. Abraham et al. (2019) earlier derived empirical rainfall thresholds specifically for Idukki using a 9-year historical event record, providing the calibration baseline.

The SLIP-K system (Mohan et al., 2025), integrates the GIS-TISSA physics-based slope stability model with empirical rainfall thresholds derived from eight automated weather stations across Idukki District, delivering dynamic, colour-coded landslide hazard updates at 15-minute intervals through a web and mobile application hosted on the Google Earth Engine platform, with multilingual and community participatory reporting capability.

The University of Kerala and KSDMA supported LEWS project, hosting a 21-station rain gauge network and GEE-based nowcasting system for Idukki (SEG, 2023), represents a complementary operational platform that should be harmonised with A-LEWS alert levels and the GSI National Landslide Forecasting Centre (launched July 2024) to create a unified, non-redundant PRB warning system.

To maximize operational effectiveness, the existing A-LEWS, SLIP-K, University of Kerala LEWS, and GSI National Landslide Forecasting Centre systems should be integrated into a unified basin-wide warning framework. Based on the very high and high susceptibility zones delineated in this study, additional AWS stations may be installed to ensure complete coverage of the high-susceptibility regions of the PRB.

- **Remote Sensing-Based Monitoring**

Remote sensing techniques should complement the in-situ monitoring network by providing basin-scale observations of slope deformation and landscape change. Sentinel-1 SAR interferometry offers a cost-effective means of monitoring pre-failure deformation across large areas, with advanced techniques such as Small Baseline Subset (SBAS) and Persistent Scatterer Interferometry (PSI) capable of detecting millimetre-scale ground movement. PSI analysis of the Irshalwadi landslide (Maharashtra, 2023) by Jain et al. (2024) demonstrated that subsurface creep at ~12 mm/year was detectable by InSAR years before the catastrophic event, underlining the value of in-situ inclinometry and satellite monitoring as complementary pre-failure detection tools. Systematic monitoring of high and very high susceptibility zones using both ascending and descending Sentinel-1 tracks is recommended (Devaraj et al., 2022).

Multi-temporal optical imagery from Sentinel-2 (10 m, 5-day revisit), Resourcesat-2A LISS-IV (5.8 m, 5-day revisit), PlanetScope (3 m, near-daily), and Cartosat-3 (0.25 m, 5-day revisit) can support rapid post-event landslide mapping, inventory updating, and detection of vegetation loss and terrain disturbance. These images can be used for routine pre- and post-monsoon monitoring of ghat road corridors to identify tension cracks, scarps, debris accumulation, and other indicators of slope instability.

5.3 Community-Level Participatory Monitoring

Community participation can significantly extend the spatial coverage of formal monitoring systems, particularly in remote highland areas where instrument deployment is constrained by terrain, accessibility, and cost (Hakkim and Deb, 2023). A structured participatory monitoring programme is therefore recommended for very high and high susceptibility panchayats within the basin.

- **Rainfall Crowdsourcing:** Training of 50-100 community volunteers (Kudumbashree members, Aapda Mitra volunteers, Apathbandhu Volunteers, tribal community leaders etc.) in the very high and high susceptibility panchayats to manually record daily rainfall totals in rain gauges co-located with settlement rain shelters, with daily reporting via crowdsourcing platforms such as mobile apps and WhatsApp to the KSDMA district monitoring dashboard.
- **Participatory Hazard Reporting (SLIP-K App):** Community members in Munnar, Devikulam, Adimali, and Vathikudy panchayats should be trained to use the SLIP-K mobile application's current citizen science module to report landslides (visual signs of slope distress - tension cracks, seepages, tilting trees, unusual spring discharge) which should be geo-tagged and transmitted to the KSDMA monitoring dashboard for expert assessment and site inspection.
- **Involvement of Tribal Community:** Tribal communities (Mannans, Paliyans, Mala Arayans & Uralis etc.) within the Periyar Tiger Reserve and adjacent buffer zones should be engaged through the Kerala Tribal Welfare Department, to identify and report visual pre-failure indicators using a simplified illustrated field guide developed in Malayalam and tribal dialects. Thereby areas where formal instrumentation is constrained by protected area regulations can be monitored.

6. Landslide Risk Management Strategies for the PRB

6.1 Structural Mitigation Measures

❖ Ghat Road Cut Slope Stabilization

The national and state highway traversing through the high and very high susceptibility terrain in the PRB represents the highest-priority structural intervention needed in the basin. The following recommended engineering measures can be implemented for ghat road cut slopes.

- Soil nailing and rock bolting: Grouted soil nails and pre-tensioned rock anchors at exposed weathered charnockite and gneissic cut faces.
- Shotcrete and wire mesh facing: Fibre-reinforced shotcrete with galvanized wire mesh on steep cut faces to prevent loosening and detachment of rock fragments and shallow failure of jointed rock; drain holes at 2 m spacing to relieve hydrostatic pressure.
- Catch ditches and rock catch fences: Flexible rockfall protection systems at locations with documented rockfall or debris-flow runout onto road pavement.
- Drainage correction: Interceptor drains, chute drains, and sub-horizontal perforated drainage pipes at cut slopes with high TWI values and seepage evidence, addressing the primary pore pressure trigger documented for PRB saprolitic profiles (Kuriakose et al., 2008; Kesavaram et al., 2025).
- Road realignment / tunnel bypass: Feasibility assessment and, where viable, realignment or tunnel bypass of particularly vulnerable sections.

❖ Bioengineering and Vegetative Slope Stabilization

Nature-based solutions are appropriate for the PRB's highland terrain given the ecological sensitivity of shola grassland and tropical evergreen forest interfaces and limitations on hard engineering within ESZ boundaries. A variety of species can also be selected instead of a single species depending on the slopes in which such interventions are required (Sujatha et al., 2023). Key interventions include:

- Plantation escarpment reforestation: Replacement of tea and cardamom monoculture on the upper scarp margins of very high susceptibility estates in Munnar, Devikulam, and Vathikudy with native grass–shrub–tree buffer strips.
- Shola grassland restoration: Natural regeneration and active replanting of degraded shola patches in the Eravikulam National Park buffer and Periyar Tiger Reserve interface zones.

- ➢ Debris flow channel vegetation: Coir geotextile matting and seeding with native grasses on walls of active debris flow channels to reduce erosion and channel incision.

❖ **Check Dams in Headwater Streams**

Gabion and concrete check dams in first- and second-order headwater streams of the Muthirapuzha, Perinjankutty, and Mullayar sub-basins reduce downstream sediment and debris delivery to the Idukki reservoir and moderate peak flow velocities in debris-flow-prone channels.

❖ **Retaining Structures for Settlement Protection**

Where settlement relocation is not feasible, particularly in established plantation worker colonies in Munnar and Devikulam, structural protection measures such as reinforced cement concrete retaining walls (RCC gravity walls or geogrid-reinforced earth walls) and gabion mattresses can be implemented at the toe of vulnerable slopes. The design of these measures should be based on slope geometry and pore water pressure data from the monitoring network to ensure adequate drainage performance during extreme rainfall events.

6.2 Non-Structural Risk Reduction Measures

❖ **Early Warning System**

The multi-level EWS is the primary non-structural risk reduction instrument. Its effectiveness depends on the completeness of the institutional chain from real-time sensor data through KSDMA control rooms to community-level alert receipt and response. The command chain and inter-agency coordination protocols between KSDMA, the District Disaster Management Authority (DDMA) Idukki, the Irrigation Department, and plantation estate management must be formalized in writing and tested through annual pre-monsoon simulation exercises. This study recommends explicit incorporation of A-LEWS, SLIP-K, and University of Kerala LEWS alert outputs as formal trigger inputs to the district alert escalation decision.

❖ **Land Use Regulation in Very High Susceptibility Zones**

Regulatory management is the most cost-effective long-term non-structural measure, preventing the creation of new exposure before it occurs. Recommended instruments:

- ➢ ESZ notification enforcement: Ministry of Environment, Forest and Climate Change (MoEFCC) Eco-Sensitive Zone notifications around Periyar Tiger Reserve and

Eravikulam National Park strictly enforced, with very high susceptibility zone boundaries from this study used as an additional spatial criterion for project screening by State Environment Impact Assessment Authority (SEIAA) Kerala.

- Building regulation: Idukki District Collectorate to prohibit building permits within very high susceptibility zones under Disaster Management Act (2005); High susceptibility zones to require mandatory geotechnical assessment as a permit condition.
- Plantation slope management: Necessary actions should be taken to prohibit slope-cutting, terracing, and road construction in very high susceptibility plantation estates without geotechnical clearance.

❖ Community Awareness and Disaster Preparedness

Community-scale preparedness is critical; its effectiveness in Kerala was demonstrated in the 2018-2019 disaster responses, where grassroots mobilization through Kudumbashree, Aapda Mitra Volunteers, Apathbandhu volunteers, and Gram Panchayat committees significantly reduced mortality (Hakkim and Deb, 2023). Recommended measures for very high- and high-risk panchayats:

- Hazard awareness materials: Panchayat-level landslide hazard posters in Malayalam displaying ward-level susceptibility zones, evacuation routes, and assembly points for distribution in public buildings, schools, and plantation offices in Munnar, Devikulam, Adimali, and Vathikudy.
- Annual pre-monsoon mock evacuation drills: Simulated landslide evacuation exercises in very high susceptibility settlements (Anthoniar Colony Munnar, Rajamala plantation workers, Adimali hill settlements) before the southwest monsoon onset, coordinated by KSDMA with Gram Panchayat disaster management committees.
- WhatsApp EWS network: Establishment and quarterly testing of WhatsApp-based alert chains linking KSDMA district control room to Panchayat Secretary, Ward Councillors, Apathbandhu and Aapda Mitra team leaders, and plantation supervisors in all very high and high susceptibility LSGDs.
- SLIP-K app promotion: Distribution of SLIP-K app installation guidance through the Gram Panchayat network and plantation employee welfare offices in Idukki, enabling community participatory hazard reporting.

7. Summary

This study presents a comprehensive basin-scale LSM and integrated risk assessment for the Periyar River Basin, Kerala, using the Frequency Ratio bivariate statistical method and a weighted hazard–vulnerability overlay framework. Twelve geo-environmental conditioning factors were selected from an initial set of fifteen, following removal of three factors (aspect, Stream Power Index, and plan curvature) due to multicollinearity, and analyzed to generate a spatially distributed Landslide Susceptibility Index, classified into five susceptibility zones, which serve as the Hazard Index (weight: 60%) in the composite risk model. Four vulnerability indicators such as population density (weight: 30% within VI), building density (weight: 30%), road density (weight: 20%), and land use/land cover (weight: 20%), were integrated to produce a Vulnerability Index (weight: 40% in composite risk). The resulting Landslide Risk Index spatially identifies very high- and high-risk hotspots concentrated along the ghat escarpment, plantation hillslopes, and ghat road corridors of Idukki District.

The findings directly inform a proposed monitoring framework integrating automated rain gauges, piezometers, inclinometers, and satellite-based InSAR and optical change detection for the identified high-risk zones. Management recommendations spanning structural measures (bioengineering, drainage, retaining structures) and non-structural measures (early warning systems, land use regulation, community preparedness) provide an operationally actionable risk reduction pathway for the Periyar River Basin. The susceptibility and risk maps produced by this study are intended for direct integration into district disaster management plans, river basin management frameworks, and eco-sensitive zone governance structures in Kerala.

8. Recommendations and Role of Stakeholders

The landslide susceptibility assessment of the Periyar River Basin (PRB) identified several zones with varying degrees of susceptibility, highlighting areas that require priority attention for disaster risk reduction and sustainable land management. The results indicate that factors such as slope, geology, land use/land cover, drainage characteristics, rainfall, and anthropogenic activities play significant roles in controlling landslide occurrence within the basin. Therefore, a comprehensive and basin-specific landslide risk management strategy is essential.

It is recommended that the generated landslide susceptibility map be integrated into regional and local planning frameworks to support informed decision-making. High and very high susceptibility zones should be prioritized for detailed field investigations, continuous monitoring, and implementation of mitigation measures. Development activities, infrastructure expansion, and settlement growth in highly susceptible areas should be regulated through appropriate land-use planning policies. Furthermore, slope stabilization measures, afforestation programs, proper drainage management, and the adoption of soil and water conservation practices should be encouraged to reduce slope instability.

The establishment of real-time rainfall monitoring networks and landslide early warning systems is also recommended, particularly in highly susceptible regions. Integration of susceptibility maps with rainfall thresholds and weather forecasts can significantly improve preparedness and facilitate timely evacuation during extreme rainfall events. Periodic updating of the susceptibility assessment using recent landslide inventories, high-resolution terrain data, and changing land-use conditions is necessary to ensure the continued reliability of the results.

The effective implementation of these recommendations requires the active involvement of multiple stakeholders. Government agencies responsible for disaster management, land-use planning, and environmental protection should utilize the susceptibility maps for hazard zonation, infrastructure planning, and risk reduction initiatives. Geological and scientific institutions should continue research on landslide processes, susceptibility assessment techniques, and climate-induced changes in slope stability. Local governments and district administrations should incorporate susceptibility information into development planning, emergency preparedness, and public awareness programs. At the community level, awareness regarding landslide hazards, safe construction practices, and adherence to early warning advisories should be promoted. Community participation in slope conservation, vegetation restoration, and reporting of early signs of slope failure can significantly enhance local resilience. Through coordinated efforts among government agencies, researchers, planners, and local communities, the impacts of landslides in the PRB can be effectively minimized, contributing to sustainable watershed management and disaster-resilient development.

9. References

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