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Landslide Hazard Zonation Mapping using AHP and GIS Techniques for the Valapattanam River Basin, North Kerala, India

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ABSTRACT

Landslides are recurrent natural hazards in the Western Ghats of Kerala, frequently intensified by monsoon rainfall and human-induced land modifications. This study develops a detailed Landslide Hazard Zonation (LHZ) map for the Valapattanam River Basin, a region with limited site-specific assessments, using an integrated Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) approach. Nine conditioning factors-geology, geomorphology, slope, land use/land cover (LULC), soil, drainage density, lineament density, road density, and rainfall-were weighted through pairwise comparison and consistency checks. Weighted overlay analysis generated five susceptibility zones ranging from very low to very high hazard. Results reveal that approximately 50% of the basin falls under moderate hazard, 32% under high hazard, and 1% under very high hazard. Validation using a Receiver Operating Characteristic (ROC) curve achieved an accuracy of 91.3%, confirming the robustness of the model. The findings highlight that steep slopes, fragile lithology (charnockite and peninsular gneiss), high lineament and road density, and altered land cover are the key drivers of slope instability. The study provides crucial insights for regional planning, disaster risk reduction, and sustainable land management in a landslide-prone tropical river basin.

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Supplemental data for this article can be accessed online at our website

1. Introduction

Landslides are among the most destructive geo-environmental hazards globally, particularly in tropical mountainous regions with intense rainfall (Wang et al., 2025). In India, about 12.6% of the land area (excluding snow-covered zones) is susceptible to landslides, with the Himalayas and Western Ghats identified as the most vulnerable regions. Numerous landslide hazard map has been made to analyse the relationship between rainfall and landslides. The economic and societal consequences of landslides will continue to climb as regional populations, urbanization, and storm intensities rise as a result of shifting development and climatic patterns, driving up need for better landslide prevention (He & Beighley, 2008).

The National Disaster Management Authority of India identified the Himalayas, the Western Ghats, and the Eastern Ghats as the area's most vulnerable to landslides. ISRO provides an atlas which offers information about landslides that occur in India's landslide regions, along with an evaluation of the damage caused at particular landslide sites. India is one of the top four nations with the highest risk of landslides, with an estimated death toll per 100 km^2 annually exceeding one (Martha et al., 2021). The majority of landslides in India happen during the monsoon season, which runs from June to September. India is responsible for 16% of landslide incidents caused by rains worldwide (Landslide atlas of India, ISRO). In India, about 12.6% of the land area, excluding snow-covered regions, is susceptible to landslides, with major vulnerable zones spread across the Himalayas, Western Ghats, and Eastern Ghats. The Himalayan region, particularly in the northeast and northwest, is not only landslide-prone but also lies in high seismic zones (IV and V), making it vulnerable to earthquake induced landslides (Paudyal & Panthi, 2011).

A notable example is the landslides triggered by the 2011 Sikkim earthquake in the Sikkim-Darjeeling region. In India, landslide risk is heightened by the growing hill population and rapid expansion of hydropower and infrastructure projects. The country is witnessing a surge in development efforts aimed at connecting remote and geologically challenging areas through roads, bridges, tunnels, and railways, especially in both peninsular and fragile mountainous regions. While such progress is essential, it often leads to ecological disturbances like landslides and debris flows, which, if not properly managed, can result in serious geo-environmental hazards, including loss of life and property (GSI).

In India, the Western Ghats-classified as a global biodiversity hotspot are highly susceptible to landslides due to their steep terrain, heavy seasonal rainfall, and anthropogenic disturbances. The state of Kerala, located along the southwestern fringe of the Western Ghats, frequently experiences rainfall induced landslides, especially during the monsoon season, leading to significant loss of life, damage to infrastructure, and disruption of livelihoods. The most recent landslide in Kerala was in Wayanad on 30 July 2024, in places like Mundakkai, Chooralmala, Punjirimattom, Vellarimala. Kerala, located on the western flank of the Western Ghats, is highly prone to rainfall-induced landslides due to steep terrain, heavy seasonal precipitation, and increasing anthropogenic pressures such as quarrying and unplanned road construction. The devastating Wayanad landslide of July 2024, which caused over 120 fatalities, underscores the urgent need for systematic hazard assessment. While several landslide susceptibility and hazard studies have been conducted in southern Kerala districts such as Idukki and Wayanad, northern districts like Kannur remain underexplored. The Valapattanam river basin, with its rugged hills, escarpments, and geomorphic complexity, has witnessed an increasing frequency of landslides in recent decades. However, a comprehensive hazard zonation map integrating expert-based multi-criteria analysis with geospatial tools has not yet been developed for this basin.

This study addresses this gap by applying the Analytical Hierarchy Process (AHP) integrated with Geographic Information Systems (GIS) to produce a high-resolution Landslide Hazard Zonation (LHZ) map. The approach combines expert judgment, thematic spatial data, and weighted overlay analysis to delineate susceptibility zones and identify key contributing factors (Appukuttan et al., 2025). The findings aim to support disaster preparedness, land use planning, and sustainable development in the Western Ghats (Achu et al., 2020; Panchal & Shrivastava, 2022; Ajayakumar, 2024; Ajayakumar & Reghunath, 2025).

2. Study Area

The Valapattanam river basin, covering 1867 km² across and Karnataka, lies on the western slopes of the western ghats between 11°49'30" N–12°13'50" N and 75°58'55" E–75°17'22" E. Approximately 1321 km² of the basin lies within Kerala's Kannur district. The river originates in the Brahmagiri Hills at ~900 m elevation and drains into the Arabian Sea near Azhikkal. The basin exhibits varied physiography, including coastal plains, dissected midlands, and rugged eastern highlands, with elevations ranging from 5 m to nearly 700 m (Fig. 1). The region experiences a tropical monsoon climate with an average annual rainfall of ~2470 mm, of which 80% falls during June–September. Geologically, the basin is dominated by Precambrian formations, including charnockite, khondalite, peninsular gneiss, and laterite. Land use is a mix of agriculture (paddy, coconut, rubber, cashew) and forest cover, with increasing plantation expansion and quarrying in recent decades. The area has a documented history of rainfall-induced landslides, particularly in Ulikkal, Peravoor, and Kottiyoor panchayats.

The Valapattanam basin has experienced numerous minor and major landslides, primarily triggered by floods. Landslides were reported in 27 locations across the rugged terrain of the upstate districts. Several panchayats in Valapattanam, including Kanichar, Peravoor, Kottiyoor, Ulikkal, Ayyankunnu, Aralam, Chappamala, and Iritty, were significantly affected. According to a Times of India article, during the devastating flood of August 2018, a landslide occurred at Ambayathode near Kottiyoor panchayat in Kannur district due to intense rainfall. Further, preliminary reports from experts at Cochin University, who assessed the areas impacted by the landslides on August 1, 2022, noted that two panchayats Kanichar and Kolayad experienced 27 major and minor landslides in a single day. The report highlights that these panchayats lie in hilly regions, making them vulnerable to landslides due to their rugged topography. Additionally, the nearly 25 consecutive days of rainfall in July significantly loosened the soil, which likely triggered the landslides. According to local residents, the landslides in Ulikkal are attributed to the increasing number of stone crushers and quarry operations in the area (Kerala State Biodiversity Board, 2018). The Kerala State Biodiversity Board (2018) also reported that landslides in Ulikkal caused soil to wash off from nearby streams. In July 2023, another landslide occurred in Ulikkal panchayat, specifically in the forest area bordering Karnataka, following heavy rainfall, according to newspaper reports. While the majority of landslides in the basin are believed to be caused by intense and prolonged rainfall, many local people suspect that quarrying activities also play a significant role in triggering these events.

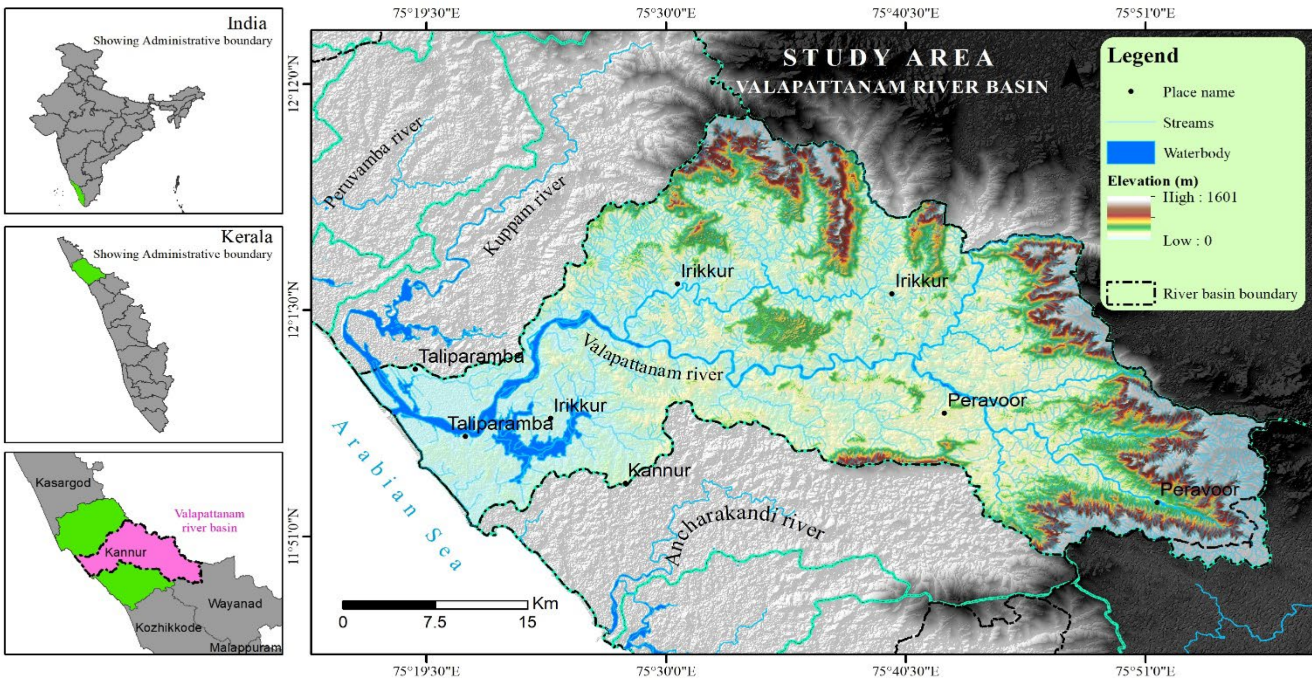

Fig .1 Study area map

3. Materials and Methods

3.1 Data Sources

The study utilized multiple datasets derived from both conventional and satellite-based sources. Topographic information was obtained from Survey of India toposheets at a 1:50,000 scale, while remote sensing inputs were provided by Landsat 8-9 OLI imagery with a spatial resolution of 30 m. Elevation details were extracted from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at 30 m resolution. Geological and geomorphological data were compiled from the Geological Survey of India (Bhukosh portal), and soil characteristics were incorporated from the Soil Survey of Kerala. Rainfall data for the year 2024, in NetCDF format, were sourced from the India Meteorological Department (IMD). In addition, a detailed landslide inventory was integrated from the Geological Survey of India (Bhukosh), providing crucial information on terrain instability. Flow chart shows methodology adopted for the study (Fig.2).

3.2 Conditioning Factors

The selection of conditioning factors is a critical step in landslide hazard zonation, as these variables directly control slope stability and govern the initiation of slope failures. In this study, nine factors were considered based on their proven relevance in previous research, availability of reliable spatial datasets, and applicability to the geomorphic and climatic setting of the Western Ghats. These include geology, geomorphology, slope, land use/land cover (LULC), soil, drainage density, lineament density, road density, and rainfall. Geology plays a fundamental role as lithological units differ in terms of strength, weathering characteristics, permeability, and resistance to erosion. Geomorphology reflects landform processes and terrain evolution. Slope angle exerts a direct influence on gravitational forces acting on slope materials, with steeper gradients being highly prone to mass movement.

LULC represents both natural vegetation cover and human-induced modifications. Deforestation, conversion to agriculture, and expansion of plantations reduce root reinforcement and alter infiltration rates, thereby increasing susceptibility. Soil type and texture govern infiltration capacity and shear strength; gravelly soils and clayey textures often promote instability when saturated. Drainage density indicates the degree of surface runoff concentration, where higher densities may reduce infiltration but accelerate surface erosion, while lower densities may lead to pore pressure build-up during prolonged rainfall. Lineament density reflects the presence of structural discontinuities such as faults and joints, which act as zones of weakness that facilitate slope failure. Road density is a key anthropogenic factor, as unplanned or poorly engineered road cuts destabilize slopes, modify natural drainage, and increase the frequency of shallow slides.

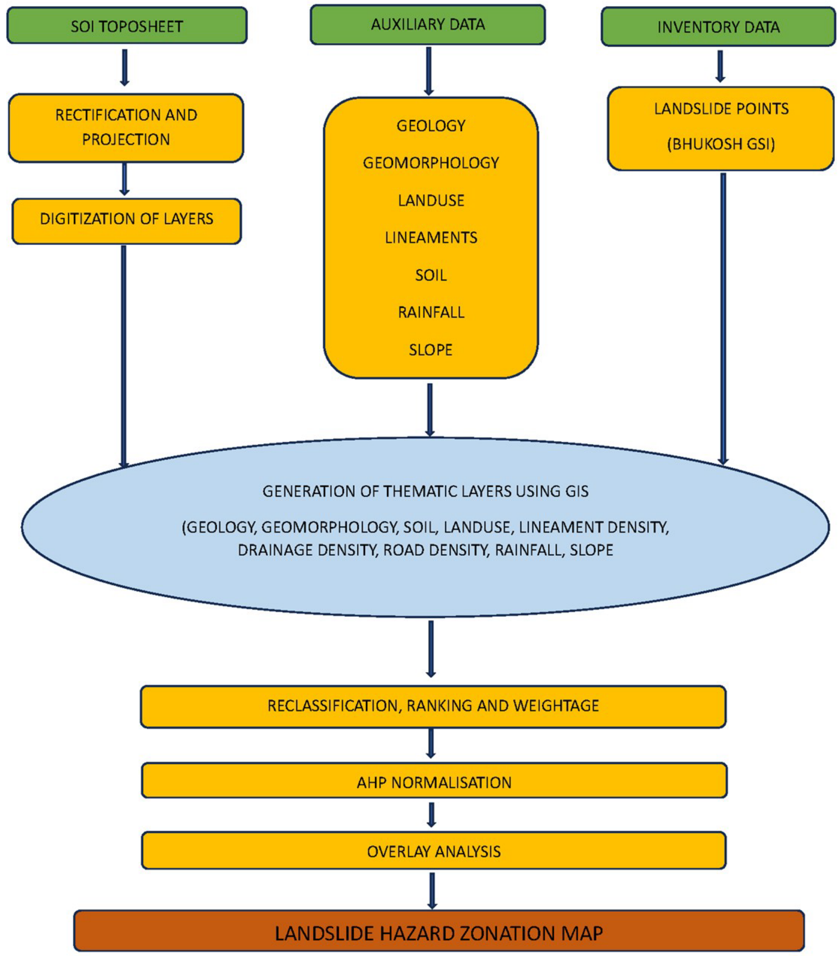

Fig .2 Methodology adopted for the study

Finally, rainfall is the primary triggering factor in the study area, where intense and prolonged monsoonal precipitation elevates pore water pressure, reduces soil strength, and frequently initiates shallow debris flows and translational slides. Together, these nine factors provide a comprehensive framework to capture the natural and anthropogenic processes influencing slope stability. Their integration within the AHP-GIS model ensures that both static predisposing conditions and dynamic triggering influences are represented in the hazard assessment.

The methodology adopted for the present study involved the preparation and integration of thematic maps using the ArcGIS 10.8 platform (Fig. 2). A Survey of India toposheet (1:50,000 scale) was used as the primary base map for delineating the boundary of the Valapattanam River Basin through digitization. The Shuttle Radar Topography Mission (SRTM) DEM data (30 m resolution) downloaded from the USGS Earth Explorer was used to derive the slope map by employing the Slope tool of the Raster Surface module under the 3D Analyst extension. Drainages processed from Survey of India toposheets covering the study area. These were processed through georeferencing, rectification, projection, and digitization. Subsequently, a 1 km × 1 km grid was prepared using the fishnet in ArcGIS platform. The grid points were then generated with the Feature to Point tool in Data Management tools, and interpolation was carried out using the Inverse Distance Weighted (IDW) method under the Spatial Analyst extension to obtain density surfaces. Geological, geomorphological, and lineament maps, as well as the landslide inventory data, were obtained from the Geological Survey of India (Bhukosh portal) and processed into thematic layers.

The soil map was prepared from the data provided by the Soil Survey of Kerala. Rainfall data for the year 2024, in NetCDF format, was sourced from the India Meteorological Department (IMD). Using the Make NetCDF Raster Layer tool under Multidimensional tools in ArcGIS, the NetCDF file was converted into raster format. The rainfall raster was further processed with the Cell Statistics tool and converted into point features, which were interpolated through the IDW method to generate the rainfall distribution map. For land use/land cover (LULC) analysis, Landsat 8-9 OLI C2 L2 satellite images were downloaded from the USGS Earth Explorer for the Kannur district. The study area was clipped, and supervised classification was performed to prepare the LULC map. All thematic maps were projected to WGS 1984 datum and UTM Zone 43N to maintain uniformity. Once prepared, the thematic layers were assigned ranks and weights based on expert knowledge and extensive literature review. The weightages were normalized through the Analytical Hierarchy Process (AHP) technique, ensuring logical consistency before integrating the layers in a GIS environment for weighted overlay analysis.

3.2 Analytical Hierarchy Process (AHP)

Multi-criteria decision making (MCDM) is the analytical hierarchy process (AHP). The approach provides a versatile and understandable means of examining complex issues by comparing the contributions of various factors pairwise using a matrix. Using this method, the factors or parameters taken into account in the study were arranged, and each factor or parameter was given a numerical value. (Mandal & Mandal, 2018; Appukuttan & Reghunath, 2022)

3.3 Selection of conditioning factors

The selection of appropriate conditioning factors is a critical step in landslide hazard zonation as these variables directly influence slope stability and landslide occurrence. In this study, nine conditioning factors were identified based on their relevance in previous research, expert judgment, and the availability of spatial data. These factors include geology, geomorphology, slope, land use/land cover (LULC), drainage density, lineament density, road density, soil type, and rainfall. Each factor plays a unique role in determining landslide susceptibility (Ajayakumar & Reghunath, 2025). For instance, geological formations influence rock strength and weathering characteristics; geomorphology reflects landform dynamics; and slope angle controls gravitational force acting on slope materials. Human-induced variables such as road density and LULC impact slope stability through land modification, while hydrological variables like rainfall and drainage density influence infiltration and pore water pressure. The comprehensive selection of these parameters ensures a multi-faceted understanding of landslide dynamics and forms the basis for reliable hazard modelling using the AHP-GIS integration framework.

3.4 Pairwise comparison matrix

For preparing pair wise comparison matrix, all the parameters which are used in the study is arranged in a hierarchical order and a numerical value is given for each parameter based on their relative importance. Saaty ‘s scale is used for this purpose (Saaty 2000). Saaty scale is represented in Table 1. This scale has values between 1 to 9, and each number in this scale represents the importance of parameters with respect to each other in a particular study.

3.5 Calculation of weights and consistency ratio

The priority weights, also known as eigenvector values or local weights, are obtained by normalizing the pairwise comparison matrix once it has been filled in, as indicated in Table 2. The final priority weights are obtained by calculating the average of each row in the normalized matrix that is produced by dividing each matrix element by the sum of its corresponding columns. Calculating the average of the normalized values in each row of Table yields the AHP weights or eigenvector values. Table 3 shows that the criteria weights for C1, C2, C3, C4, C5, C6, C7, C8and C9 are, in that order 30.2%, 25.9%,14.4%, 10.1%, 7.0%, 4.8%, 3.3%, 2.7% and 1.7%. As indicated in Table 3's final row, the sum of each column in the normalized matrix must equal 1.00 to guarantee the computations' accuracy.

The calculations should be re-examined for potential errors if the column totals differ from 1.00.(Thammaboribal et al., 2025). In the Analytic Hierarchy Process (AHP), consistency analysis checks whether the pairwise comparisons are logically coherent. This is measured using the Consistency Ratio (CR), calculated as

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{1}$$

where CI is the Consistency Index and RI is the Random Index. A CR of 10 % or less indicates acceptable consistency; higher values suggest the need to revise the judgments and consistency index is determined by the equation,

$$\mathrm{CI} = \frac{\lambda\mathrm{max}-1}{\mathrm{n}-1} \tag{2}$$

Where λmax is the principal eigenvalue of the pairwise comparison matrix (Thammaboribal, Tripathi, & Lipiloet, 2025). The consistency ratio obtained by using equation 1 is 5%, which is less than the threshold value of 10% so the weights assigned are consistent. λmax is 9.577.

Table 1: Scale of preference between two parameters in AHP (Saaty 2000)

Scales	Degree of preference	Explanation
1	Equally	Two activities contribute equally to the objective
3	Moderately	Experience and judgment slightly to moderately favor one activity over another
5	Strongly	Experience and judgment strongly or essentially favor one activity over another
7	Very strongly	An activity is strongly favored over another and its dominance is showed in practice
9	Extremely	The evidence of favoring one activity over another is of the highest degree possible of an affirmation
2, 4, 6, 8	Intermediate values	Used to represent compromises between the preferences in weights 1, 3, 5, 7, and 9
Reciprocals	Opposites	Used for inverse comparison

3.6 GIS-based Integration

The weighted overlay analysis is a clear and practical technique used to evaluate landslide hazards in a region. It is based on the idea that if the same conditions that triggered landslides in the past appear in other areas, landslides are likely to happen again. In this approach, each factor layer is reclassified according to a specific scale, highlighting the influence of each class on the potential for future landslides (Shano et al. (2020). For weighted overlay analysis, all the parameters were reclassified according to their allotted ranks with the help of reclassify tool of 3D analyst extension (Appukuttan & Reghunath, 2022). Then all are integrated with help of weighted sum tool of spatial analyst tool, in which corresponding weights for each criterion are entered. The weights assigned to each parameter are as follows: geology- 30.2, geomorphology - 25.9, slope - 14.4, land use - 10.1, drainage density - 7.0, lineament density - 4.8, road density - 3.3, soil - 2.7, rainfall -1.7.

3.7 Hazard zonation map preparation and validation

After Weighted sum, all the parameters are integrated to generate a landslide hazard zonation map, which was categorized into 5 classes; Very low hazard zone, low hazard zone, moderate hazard zone, high hazard zone and very high hazard zone. Validation of the study is done with the help of landslide inventory data which is downloaded from Bhukosh GSI website. Validation for the study is done with the help of ROC curve. To evaluate how well the above-mentioned methods can predict landslides, the Receiver Operating Characteristic (ROC) curve is one of the most commonly used and reliable techniques.

Table 2: Normalised pairwise comparison matrix for landslide hazard zonation map

#	GL	GE	SL	LU	DD	LD	RD	S	RF
GL	1	2	3	4	5	6	7	8	9
GE	0.5	1	3	4	5	6	7	8	9
SL	0.3	0.3	1	2	3	4	5	6	7
LU	0.3	0.3	0.5	1	2	3	4	5	6
DD	0.2	0.2	0.3	0.5	1	2	3	4	5
LD	0.2	0.2	0.3	0.3	1	1	2	3	4
RD	0.1	0.1	0.2	0.3	0	0.5	1	2	3
S	0.1	0.1	0.2	0.2	0	0.3	0.5	1	4
RF	0.1	0.1	0.1	0.2	0	0.3	0.33	0.25	1

NB: #: Parameters, GL: Geology, GE: Geomorphology, SL: Slope, LU: Land use and land cover, DD: Drainage density, LD: Lineament density, RD: Road density, S: Soil, RF: Rainfall

The ROC curve illustrates the relationship between correctly detected landslide areas (true positives) and incorrectly classified areas (false positives) as the probability threshold changes. By modifying the decision threshold, it's possible to control the balance between accurate and inaccurate predictions, allowing a systematic evaluation of the model's performance (Shano et al. (2020).

4. Results and Discussion

4.1 Thematic attributes

Geology

Geological map represents lithology, deposits and also the geological structures of a region or area. Geology investigation of an area helps to identify susceptible areas, assess slope stability, and inform land use planning. Research on landslide susceptibility worldwide shows that lithology is an important factor. Landslides are more likely to occur in younger, less consolidated rocks, while older, well solidified, and stronger rocks are less prone to landslides. For this reason, lithology is included as a key element in landslide models (Lin, Lin, & Wang, 2017). In cases where there is strong layering with depth such as a thin, heavily fractured, and weathered regolith layer overlying stronger bedrock large landslides are likely to appear in the seismic catalog only if the earthquake shaking is strong enough to destabilize the deeper layer (Valagussa, Marc, Frattini, & Crosta, 2019). Different colors are used to represent different rock types and unconsolidated materials. As we investigated the study area, the lithology of the area can be categorized into acidic rock, basic rock, Charnockite group of rocks, Khondalite group of rocks, high grade metasedimentary rocks, low grade metasedimentary rocks, laterite, meta basic and ultra basic rocks, migmatite complex, waterbody, peninsular gneissic complex, sand and silt, sandstone and clay with lignite intercalated type of rocks. Geology map of the Valapattanam river basin is represented in Fig.3a. The Peninsular gneissic complex is the most predominant rock type of the study area having an area of 610.23 sq.km followed by Charnockite group of rocks (384.28 sq.km), acidic rocks (47.39 sq.km), sand and silt (46.66 sq.km), high grade metasedimentary rocks (43.57 sq.km), low grade metasedimentary rocks (35.77 sq.km), Khondalite group of rocks (33.07 sq.km), laterite (32.36 sq.km), sandstone and clay with lignite intercalation (30.54 sq.km), Waterbody (26.92 sq.km), migmatite complex (23.02 sq.km), basic rocks (18.57 sq.km) and meta basic and ultrabasic rocks (5.76 sq.km).

Geomorphology

Landslide geomorphology studies are crucial for understanding the formation mechanisms of landslide, dynamic processes, and prevention and control measures (Qiu & Wei, 2025). Landslides are acknowledged as key drivers of mass wasting and shaping hillslopes locally, but their broader impact on the development of mountainous landscapes remains poorly understood (Korup, Densmore, & Schlunegger, 2010).The study area includes 3 physiographic units like coastal plains, lowland and central undulatory terrain. The geomorphic features of the Valapattanam river basin consists of classes like coastal plain, denudational hills, denudational structural hills, flood plain, marshy, pediplain, piedmont zone, plateau, residual hill, rock exposure and waterbody, Geomorphology of the Valapattanam river basin is represented in Fig.3b. The western part of the basin consists of coastal plains formed by the action of waves and tides, and the eastern part of the basin consists of denudational landforms formed by the weathering, mass wasting and erosion. The predominant geomorphic feature of the basin is plateau covering a large area of 578.12 sq.km, followed by denudational structural hills (283.31 sq.km), piedmont zone (186.45 sq.km), pediplain (146.50 sq.km), residual hills (68.60 sq.km), coastal plain (35.95 sq.km), waterbody (32.49 sq.km), floodplain (5.098 sq.km), Denudational hills (1.56 sq.km), marshy (0.057 sq.km) and rock exposure with an area of 0.011 sq.km.

Land use / Land cover

LULC is a significant factor in landslide studies. LULC map provides information about the human activities and the natural elements of a region. Human activities like unsustainable rural road construction, overgrazing, deforestation, monoculture farming, irrigation, mining, and creating cut slopes for buildings and other engineering projects can destabilize slopes by changing vegetation, weakening root support, reducing soil cohesion, and disrupting water movement due to alterations in root density, length, and depth (Hao et al., 2022). By using landcover map we can understand how the land is utilized by humans and how it affects the natural landscape, and we can take appropriate measures accordingly, to mitigate the effects of landslide. Land use map of the Valapattanam river basin comprises of agriculture or grassland, waterbody, forest, built-up, barren land and fallow land. Agriculture patterns are determined by climate and water availability. Land use map of the Valapattanam river basin is given in Fig. 3c. Agriculture/grassland covers large portion of basin having an area of 986.67 sq.km and forest (231.82 sq.km), followed by built-up (83.80 sq.km, waterbody (22.91 sq.km), fallow land (11.25 sq.km) and barren land (0.82 sq.km). Forest cover is seen in the eastern part of the basin which is a part of western ghats.

Slope

Slope plays crucial in the occurrence of the landslide. Steepness of the slope is represented as the slope angle. Slope map gives the elevation of the area. If the steepness of the area is higher, then the probability of landslide occurrence is high. This means that on steeper slopes, more material breaks apart even if the material has the same strength, leading to larger landslides (Chen, Liu, Chang, & Zhou, 2016). The tilting behaviour of slope surfaces, indicated by the linear increase of tilting angle with displacement, is independent of slope size, materials, and triggering factors and can serve as a sign of potential landslides (Xie, Uchimura, Chen, Liu, Xie, & Shen, 2019). Slope (in°) as estimated from DEM. Slope map of the Valapattanam river basin is given in Fig. 3d. The estimated slope degrees for the study area ranges from 0° to 66 ° and are classified into 4 classes .0°-7.26 °, 7.27 °-15.31°, 15.32 °-25.95°, 25.96°-66.18 °. Steep slope regions are found on the eastern side of the basin which indicates high runoff rate, so this region is highly susceptible to landslides and the western part of the study area mostly having a low slope range between 0° - 7.26°.

Soil

During the landslide, surface materials move downwards which leads to the soil erosion, resulting in the loss of fertility of the land, also mixing of the soil takes place. Landslide occurs as a result of soil erosion due to the detachment and transportation of soil by moving wind, water, or raindrops which transport materials between locations (Sharma, Patel, Debnath, & Ghose, 2011). Slope may become unstable as the soil is saturated during heavy rainfall. In slope failures, soil moisture plays a crucial role since water not only weakens the soil's strength but also adds extra stress to it (Ray & Jacobs, 2007). Soil type, texture and its composition determines the rate soil erosion. Soil map of the Valapattanam river basin is given in Fig. 3e. Soil map of the study area consists of 4 classes, they are clay, gravelly loam and gravelly clay. A large part of study area consists of gravelly clay with an area of 1158.058187 sq.km, which is followed by clay (102.73 sq.km), waterbody (46.46 sq.km) and gravelly loam (30.92 sq.km).

Lineament density

Lineaments are the largescale linear features seen on the surface, which are underlying faults or joints. Lineament are linear feature on the surface that can be mapped, which are aligned in a rectilinear or slightly curved manner differ from surrounding features and may reveal subsurface phenomena, (O'Leary, Friedman, & Pohn, 1976). Fractured zones or weak lines in the terrain tend to collect moisture and support vegetation, affecting surface materials, increasing weathering, and influencing slope stability and permeability, also the fragility of these zones is most evident in semi-arid regions, where weathering tends to focus along the lineaments (Ramli, Yusof, Yusoff, Juahir, & Shafri, 2010). There are two types of lineaments based on length; major and minor lineaments. Lineament density is calculated by total length of the lineaments per unit area. The region with high lineament density is highly susceptible to landslide. Lineament density of the study area ranges between 0 km/ sq.km - 2.00 km/ sq.km. These values are divided into 4 classes, they are 0-0.10, 0.11-0.34, 0.35-0.64, 0.65-2.00 km/ sq.km. Fig. 3f shows the lineament density map of the Valapattanam river basin. Major part of the study area has lineament density of 0-0.10 km/ sq.km. 0.65-2.00 km/ sq.km is the highest value of lineament density which means they are landslide prone locations.

Drainage density

Frequency of stream or drainage in land or in a basin is referred to as the drainage density. Drainage density is expressed as the total length of the streams divided by basin area and its unit is km/ sq.km. If infiltration rate of a region is lower compared to the rainfall, then area has high drainage density. Landslide occurrence is inversely proportional to drainage density. Water infiltration during intense rains and the resulting rise in pore pressure inside the overburden are the primary causes of landslides and also higher landslide incidence has been linked to poor drainage density in regions with high rainfall. This is because there is less surface runoff, which raises pore-water pressure and infiltration (Energy & Wetlands Research Group, 2009). Landslides and drainage networks interact in two main ways: landslides can initiate drainage networks (slope–fluvial relationship), while headward erosion drives stream incision that promotes landslide development (fluvial–slope relationship) (Ng, 2006). The study area is divided into 1km square grids, for deriving drainage density map and is calculated by the formula. Fig. 3g represents the drainage density map of the study area. The drainage density of the Valapattanam river basin ranges between 0-6.73 km/sq.km and this range is divided into 4 classes, they include 0-1.29, 1.30-2.32, 2.33-3.32, 3.33-6.73 km/sq.km. Higher drainage density value in the study area is 3.33-6.73 km/sq.km majorly found in SE part, here infiltration rate is low and in these locations landslide susceptibility is low, depending on the rainfall rate.

Road density

Construction of roads and other infrastructure is an important of part of urbanization, which would lead to the alteration of existing landscape. These constructions may lead to the instability of slopes. Especially unplanned roads constructed in mountain regions causing slope instability or is stressed resulting in landslide. The link between roads and landslides highlights how human activities can influence and even trigger slope failures. Roadside landslides become especially risky during the monsoon, as steepened slopes above the road and loose debris below can easily give way when heavy rains hit (McAdoo et al., 2018). Identifying areas at risk of landslides is crucial for road engineers, as road-induced landslides can lead to expensive repairs and even endanger lives. Understanding the potential impact of new road construction is essential, because landslides during building can significantly raise project costs (Skilodimou et al., 2018). Road density is expressed as the total length of the roads divided by basin area. It is expressed in km/ sq.km. For deriving road density map study area is divided into 1 Km^2 square grids. The road density of the study area ranges between 0-6.39 km/sq.km and are divided into 4 classes 0-0.50, 0.51-1.078, 1.079-1.75, 1.76-6.39 km/ sq.km. Road density map of the study area is represented in Fig. 3h.

Rainfall

Rainfall is one of the important factors which is directly linked to landslide. The moisture level on the land's surface greatly influences landslides. Soil moisture, representing the average amount of water in the soil, is a useful indicator of these conditions. Unlike average yearly rainfall, soil moisture is not easily affected by extreme weather, offering a clearer picture of slope stability over time and serving as a key factor in assessing landslide risk (Lin, Lin, & Wang, 2017). Most of the landslides are rainfall induced landslides, which is more common in Kerala. At times of heavy rainfall, if the area low drainage density, and ground is sufficiently saturated, then there is likelihood of landslide in that area. Rainfall can change the way water moves on and beneath the ground, making slopes less stable and increasing the risk of landslides. Such events can seriously threaten people and infrastructure, which is why being able to predict rainfall-induced landslides is so important (Guzzetti et al., 2020). Rainfall is measured in mm. Fig. 3i represents rainfall map of the Valapattanam river basin. From the figure, eastern side of the study area have low rainfall rate compared to western side. Rainfall rate of the study area ranges from 2750 mm to 4019 mm. These range is divided into 4 classes: 2750 mm-3124 mm, 3125 mm-3417 mm, 3418 mm-3676 mm, 3677 mm-4019 mm. Highest rainfall rate in the basin is 4019 mm on the western part of the basin.

4.2 Landslide hazard zonation

Following the weighted overlay analysis carried out in the GIS environment, a comprehensive Landslide Hazard Zonation (LHZ) map was generated for the Valapattanam River Basin (Fig.4). This map integrates multiple thematic layers, including geology, slope, rainfall, land use/land cover, drainage density, soil, and lineament density, into a composite spatial representation of landslide susceptibility. The integrated approach not only highlights the spatial variability of hazard-prone areas but also provides a scientific basis for identifying zones of vulnerability, thereby supporting informed decision-making for risk management and hazard mitigation. The final LHZ map categorizes the basin into five distinct hazard zones: very low, low, moderate, high, and very high (Fig.4). Quantitative analysis reveals that the very low hazard zone accounts for approximately 2% of the basin area, while the low hazard zone extends over 15%. The moderate hazard zone dominates the landscape, covering nearly 50% of the total area, followed by the high hazard zone, which encompasses 32%. The very high hazard zone represents about 1% of the basin. This distribution clearly indicates that a substantial proportion of the Valapattanam River Basin lies within the moderate to high hazard categories, underscoring the importance of targeted planning, continuous monitoring, and the implementation of mitigation measures in these critical areas. The spatial extent of each hazard class further emphasizes the dominance of moderate and high-risk zones. Specifically, the very high hazard zone occupies an area of 8.79 sq. km, while the very low hazard zone covers 19.54 sq. km. The low hazard zone extends across 201.91 sq. km, the high hazard zone spans 427.52 sq. km, and the moderate hazard zone accounts for the largest share, at 663.44 sq. km (Fig.5). The spatial distribution pattern reveals that the northern part of the Valapattanam River Basin is particularly prone to landslides, as high and very high hazard zones are predominantly concentrated in this region. This spatial clustering of susceptibility highlights the critical need for localized mitigation strategies, land-use regulation, and early-warning mechanisms to reduce the potential impact of future landslides in the basin.

4.3 Influencing factors

In case of geology, the major part of the basin is covered by Charnockite group of rocks and peninsular gneissic complex, i.e. region which is included in very high, high and moderate hazard zone. Charnockite rock and peninsular gneissic rock, when exposed to water loses its shear strength at the times of heavy rainfall and also it is weathered easily, which leads to occurrence of landslide. Also, Charnockite rock covers the very high and high hazard zone, so geology is a factor for landslide susceptibility. Denudational structural hills, piedmont zone, and residual hills covers the landslide prone areas of the Valapattanam basin. These features are the result of erosion and transportation. Although mass movements especially landslides are recognized as powerful agents shaping the landscape, their long-term and large-scale impact on landform development has often been overlooked (Crozier, 2010). Elevated hilly region is vulnerable to landslide. Drainage density, lineament density and road density greatly influence the occurrence of landslide. If the soil is less porous and permeable i.e. if the infiltration rate is low during heavy rainfall, drainage density will be higher. For the study area drainage density values are higher in the very high and high hazard zone so the drainage density does not influence the landslide in the Valapattanam region. Road density and lineament density greatly influence landslides in the study area as the road density and lineament density is high in very high, high and moderate hazard zones. High lineament density and road density increases the landslide frequencies. In case of lineament density, region with more faulting and jointing are landslide prone areas. Also unplanned and increased number of roads causes the instability of the slopes. Landslide occurrences are highest in regions with dense lineaments, indicating that areas with more morpho-tectonic features are more vulnerable to landslides (Sarkar & Kanungo, 2009). Most important factors which influence landslide occurrence are slope and rainfall. In case of slopes, its inclination plays a major role. Areas with higher slope gradient are highly vulnerable to landslide. Most of landslides are rainfall induced rainfall as the continuous and heavy rainfall always leads to landslide as the characteristics of the soil changes when it comes in contact with water.

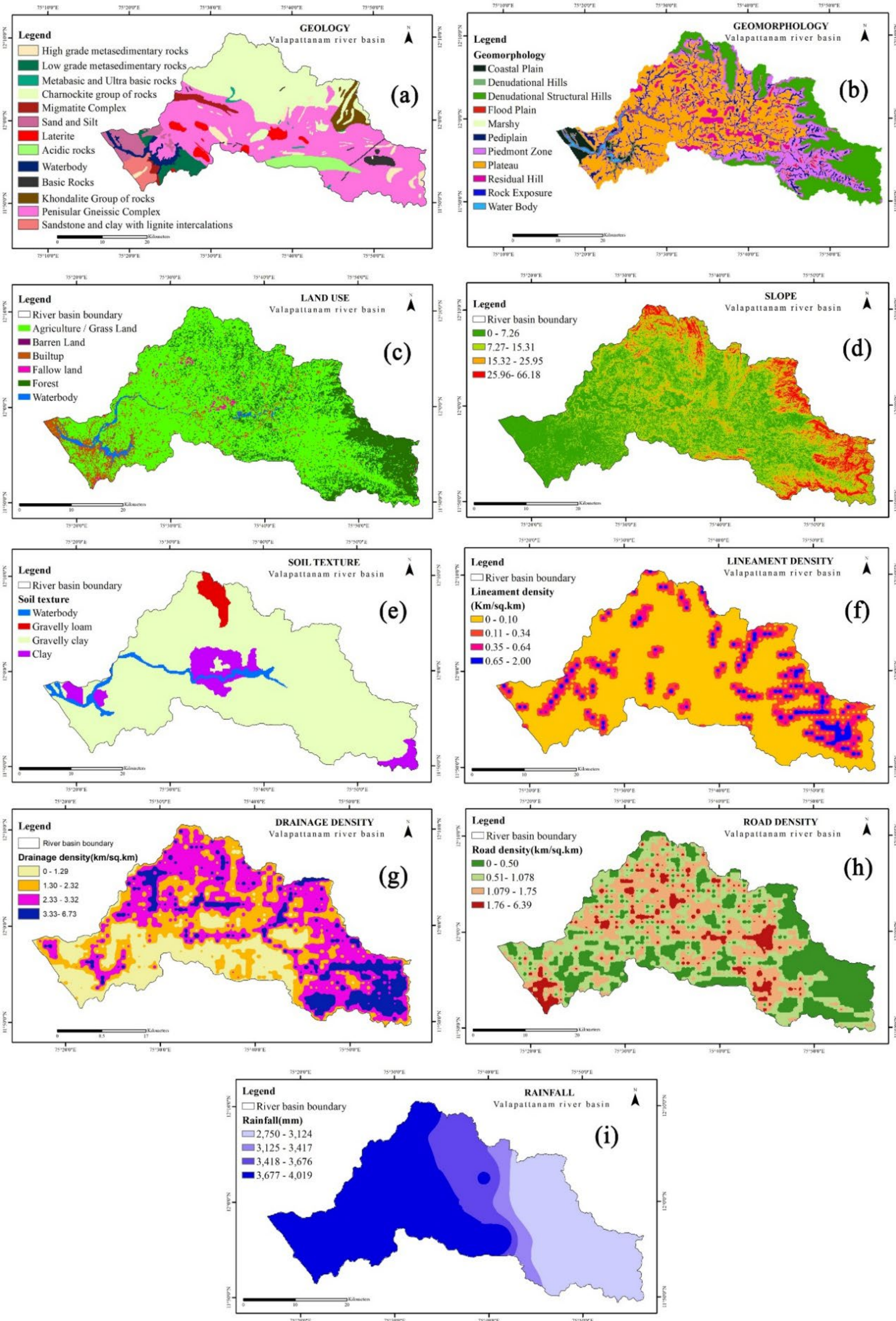

Fig. 3 The thematic layers used in the study (a to i)

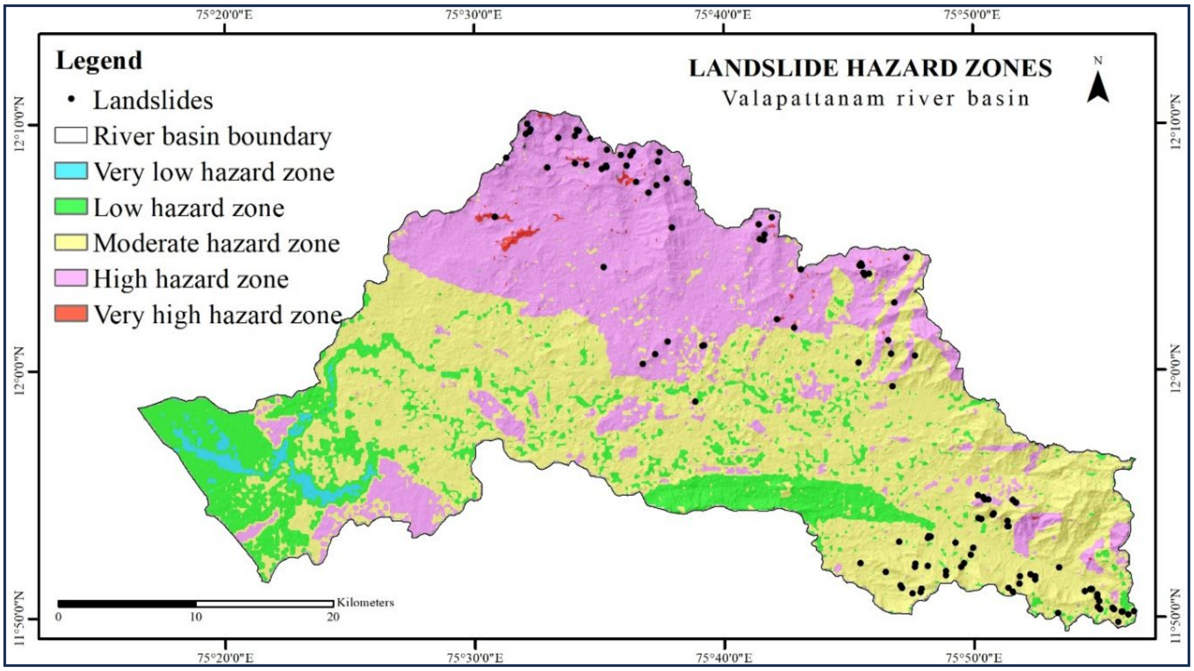

Fig. 4 The Landslide hazard vulnerable zones in the study area

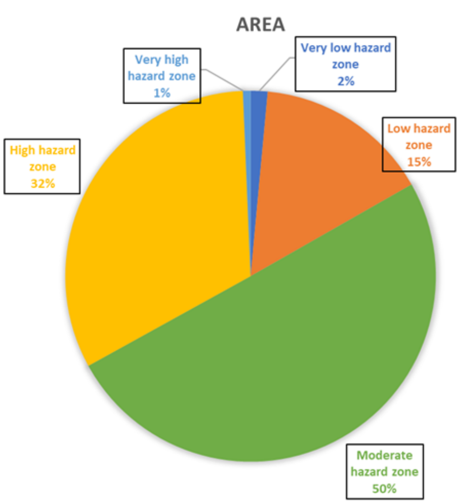

Fig.5 Pie chart representing area of hazard zones

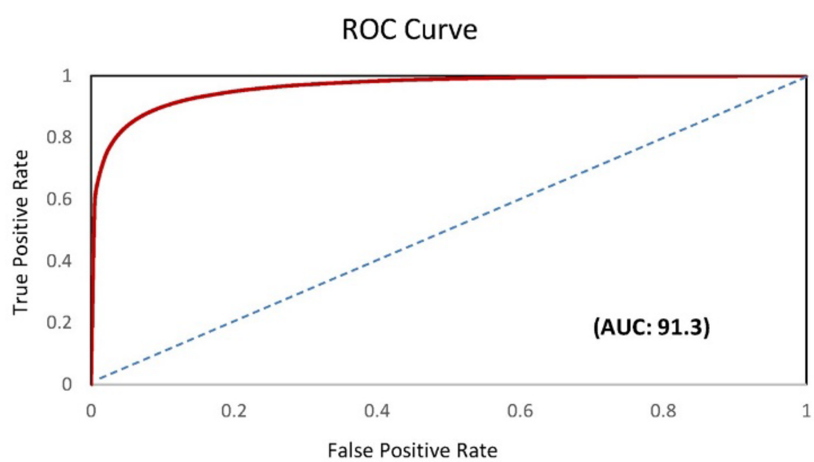

Fig. 6 ROC Curve used for validation

Rainfall-triggered shallow landslides are mainly influenced by the intensity and pattern of the rainfall, the steepness of the slopes, and the nature of the soil in the area (Liu, Deng, & Wang, 2021). In case of the study area, factors such as slope and rainfall are to be taken under consideration. As the slope gradient and rainfall rate are higher in the very high and high hazard zones. The high and very high hazard zone receives higher rainfall range of 3677 mm to 4019 mm according to the map. Land use is related to human activities which leads to change in natural landscapes. Land use and land cover (LULC) significantly influence how slopes respond to rainfall, often contributing to landslide occurrences. Many researchers have highlighted that alterations in land use or vegetation cover can raise the chances of landslide events by disrupting the natural balance of the terrain. Besides areas where agricultural activities have replaced forest cover, lands that were once used for cultivation and later abandoned are also at a higher risk of experiencing landslides (Quevedo et al., 2023).

The study area is dominantly covered by the class agriculture/grassland and also fallow lands covers the very high and high hazard zones. Soil is the other important factor which contributes to the landslide occurrence. The type of soil significantly influences how stable a slope remains. When rainfall and slope conditions were consistent, no landslides were observed in areas with silty or sandy soils. In contrast, landslides occurred where the soil was gravelly or a combination of different soil types (Liu, Deng, & Wang, 2021). This is due to the less cohesion between gravels. In case of the study area the moderate, high and very high hazard zones are covered with gravelly loam. Also, gravelly clay is present in high hazard zone which may lead to landslide. In this study, the landslide hazard zonation mapping for Valapattanam river basin was conducted using the integrated geospatial approach in a GIS platform. Hazard zones identified in this study was validated by ROC curve (Fig.6) in which true positive values are plotted against the false positive values, curve plotted shows 91.3 % accuracy.

5. Conclusions

The Landslide Hazard Zonation (LHZ) Mapping conducted for the Valapattanam River Basin offers a detailed understanding of how landslide risks are distributed across the region and what factors contribute to these risks. By combining the Analytical Hierarchy Process (AHP) with advanced geospatial analysis, the study successfully categorized the basin into five distinct hazard zones-very low, low, moderate, high, and very high hazard zone based on nine influencing factors: geology, geomorphology, slope, soil type, drainage density, lineament density, road density, rainfall, and land use/land cover. Very high hazard zone covers an area of 1%, high hazard zone covers 32%, moderate hazard zone covers 50%, low hazard zone covers 15% and very low hazard zone covers 2%. So, majority of area of the Valapattanam river basin is covered with moderate hazard zone, especially along the middle part of the basin, followed by high hazard zone which also covers a large part of northern portion of the basin, and within this high hazard zones, very high hazard zones are also seen, which covers small areas. Findings indicate that the northern and northeastern parts of the basin are more prone to landslides. These areas are having steep slopes, fragile rock types like Charnockite and Peninsular Gneiss, high lineament density and high road density. The analysis highlights that natural features such as terrain steepness, lithology, and soil texture along with unplanned infrastructure development like road construction plays a significant role in triggering landslides. In particular, the replacement of forested land with agriculture or fallow land has weakened slope stability, making these areas more susceptible to landslides. The type of soil also matters; landslides were more common in areas with gravelly loam and gravelly clay soils, which have lower cohesion when saturated during rainfall. Model validation through the Receiver Operating Characteristic (ROC) curve shows a high prediction accuracy of 91.3%, confirming the effectiveness of the approach. However, the method's dependence on expert judgment introduces some subjectivity, and since the map is static, it doesn't account for ongoing changes like seasonal rainfall patterns or shifts in land use. Importantly, the study found that many moderate to high-risk zones overlap with populated region, pointing to the urgent need for better land use regulations and disaster risk management. Integrating LHZ maps into local planning frameworks can help authorities make more informed decisions, reducing risks to both people and infrastructure. The AHP GIS model demonstrates strong potential as a practical and reliable tool for assessing landslide susceptibility, especially in areas where detailed data may be lacking. This approach can serve as a valuable reference for other regions facing similar geohazards.

CRediT authorship contribution statement.

Ajayakumar A: Writing–original draft, Visualisation Software. **Ananthu Sathish:** Software, Data curation, Methodology. **Rajesh Reghunath:** Supervision, Review & editing. **Anoop S**: Supervision Review & editing.

Declaration of competing interest

The authors declare that they have no known financial or personal conflicts of interest that could have influenced the work reported in this paper.

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