DOI: 10.21120/LE/17/1/2 **Landscape & Environment 17 (1) 2023. 11-32**

LANDSLIDE SUSCEPTIBILITY MAPPING USING THE ANALYTICAL HIERARCHY PROCESS AND GIS FOR IDUKKI DISTRICT, KERALA, INDIA

ARUNKUMAR K.S.[1], ANOOP K.G.[1], JOBIN THOMAS[2]

[1] Department of PG Studies & Research in Geology, MES College Ponnani, Malappuram-679586, Kerala, India
[2] Department of Geological and Mining Engineering and Sciences, Michigan Technological University, Houghton, MI 49931, USA
*Email: ksarunenv@gmail.com

Received 18 November 2022, accepted in revised form 29 January 2023

Abstract
This study demonstrates the application of the analytical hierarchy process (AHP) technique for landslide susceptibility mapping of Udumbanchola and Devikulamtaluks of Idukki district (Kerala, India). The landslide conditioning factors, such as lithology, geomorphology, slope angle, slope aspect, relative relief, drainage properties, land use/ land cover, and lineament characteristics,are derived using remote sensing data and GIS. The landslide susceptibility of the region is estimated using the weights derived by the AHP method. The analysis indicates the controls exerted by the structural and fluvial process and relief characteristics on the landslide activity of the region.The landslide susceptibility map of the region suggests that the high and severe susceptible zones cover about 10.68% of the area, and another 9.40% falls under the moderate susceptibility zone. The results highlight the significance of implementing various structural and non-structural measures in the moderate to severe susceptibility zones to mitigate the impacts of landslides.

Keywords: Landslide susceptibility, AHP, GIS, Western Ghats, Kerala

1. Introduction

Landslides, a geomorphic process operating along hillslopes, are one of the major natural hazards occurring in mountainous terrains across the world and cause significant changes to natural and anthropogenic landscapes. Landslides are typically driven by either geological, metereological or hydrological processes or a combination of both. Although the landslides take place mostly in the mountainous regions, the catastrophic events cause thousands of victims and deaths, damages and environmental losses worth hundreds of billions of dollars every year (Aleotti and Chowdhury, 1999; Gutiérrez, 2020;OFDA/ CRED, 2018;Tiranti and Cremonini, 2019). The terminology "landslide" represents a broad spectrum of mass wasting processes and debris flow is a the common type of mass movement occurring as a result of extreme rainfall events on steep slopes with saturated overburden (USGS, 2004).

The global distribution of landslides is heterogeneous, where the majority (75%) of the fatal landslide events (excluding those triggered by earthquakes) between 2004 and 2016 occurred in Asia (Froude and Petley, 2018). It is also reported that roughly 16% of the rainfall-triggered landslides worldwide occur in India, especially along the Himalayan Arc and the Western Ghats.

The Western Ghats is a unique orographic feature of Peninsular India and contributes to a climate divide between the humid to per-humid western coastal belt and the semi-arid to arid eastern inland country zone (Gunnell, 1998). It is estimated that nearly 80% of rainfall-triggered landslide events in India take place during the Indian summer monsoon rainfall (June-September) (Froude and Petley, 2018). The westward slopes of the Western Ghats are generally prone to the occurrence of landslides and the southern Western Ghats (i.e., in Kerala) experience several types of landslides of which debris flows are the most common.The extreme rainfall events in Kerala during August 2018 alone caused more than 5000 landslides of varying extents (Martha et al., 2019)followed by numerous landslides during the extreme rainfall events in 2019 (Wadhawan et al., 2020) which led to enormous damages across the western slopes of the Western Ghats. However, the landslide occurrences were mostly confined with in a few districts, viz., Idukki, Malappuram, Kozhikode, Wayanad and Kannur. In general, the landslides in Kerala are typically triggered by prolonged and/or intense rainfall and consequent pore pressure variations (Kuriakose et al., 2009). However, in the regional context, other factors, such as degradation of natural vegetation,changes in the land use/ land cover pattern, mining activities, soil piping, etc., also increase the probability of landslide occurrences(Kuriakose, 2009; SoE, 2017; KSDMA 2019, ESSO-NCESS, 2020).As Kerala is one of the most densely populated states of India (Census, 2011), with a population density of 859 persons km-2, the population pressure on the Western Ghats has drastically increased over the years leading to activities that modify local slope and topography, intensification of agricultural/tourism activities and alteration of the natural vegetation patterns.The population growth and consequent demand for land are high in Kerala, where the per-capita availability of land area was only 0.012 ha in 2001(SoE, 2007). However, the repeated extreme rainfall events in Kerala for four consecutive years (2018, 2019 2020 and 2021) and associated landslides call for the implementation of appropriate mitigation measures to reduce the risk.

One of the essential components of landslide risk management is landslide susceptibility mapping, which enables the identification of landslide-prone zones (Fell et al. 2008) using the factors influencing the occurrence of landslides. The factors are broadly classified into two, viz., preparatory and triggering, where the former makes the slope susceptible to sliding due to gravity, while the latter causes immediate changes in the strength/stress of the slopes to initiate the movement (Crozier, 1986; Griffiths, 1999; Fourniadis et al., 2007; Nguyenet al., 2014; Liu et al., 2016). The different approaches employed in landslide susceptibility mapping include qualitative, semi-quantitative and quantitative methods. The qualitative methods involve geomorphologic mapping, heuristic and other subjective judgement approaches (e.g., Zimmerman et al. 1986; Anbalagan 1992; Nagarajan et al.1998; Gupta et al.1999; Saha et al. 2002), whereas the quantitative methods estimate the probabilities of the occurrence of landslide phenomena (Guzzetti et al. 1999). However, one of the most widely employed approaches is the semi-quantitative methods, such as analytical hierarchy process (AHP), fuzzy logic, combined landslide frequency ratio & fuzzy logic and weighted linear combination (Kumar &Anbalagan, 2016;Ercanoglu and Gokceoglu, 2004; Pradhan and Lee, 2009; Ayalew, 2004). Among these methods, the AHP is a popular tool for multi-criteria decision-making, by reducing complex decisions to a series of comparative pairs and synthesizing the results.The AHP disaggregates a complex decision problem into different hierarchical levels and allows quantifying opinions and transforming them into a coherent decision model (Saaty, 1980). Further, the AHP has been used for landslide susceptibility mapping in different geoenvironmental settings worldwide (e.g., Hong et al., 2015; Shahabiet al., 2015; Sangchini et al., 2016; Althuwaynee and Pradhan, 2016; Kumar &Anbalagan, 2016).The present study demonstrates the application of the GIS and AHP to predict the landslide susceptibility zones (LSZs) of the Udumbanchola and Devikulam taluks of Idukki district, Kerala (India). The study area is chosen primarily due to (1) the numerous occurrences of landslide events during the Indian summer monsoon season of 2018, 2019 and 2020 and (2) the geodiversity and population characteristics of the region.

Study area

The LSZs of the Udumbanchola and Devikulam taluks of the Idukki district of Kerala, India, were mapped in this study. The taluks cover an area of 2196 km^2 and extends mainly across the western slopes of the southern Western Ghats between North latitudes 9° 38' to 10° 20' and East longitudes 76° 30' to 77° 30' (Fig. 1). The region represents a dissected hilly landscape with narrow and steep valleys encompassing different geological regimes. The study region experiences a tropical humid climate, where the average annual rainfall is between 3,800 and 5,200mm and the average annual temperature varies between 13 and 29°C. However, the average annual rainfall in the eastern leeward slopes of the Western Ghats (in Devikulamtaluk) is less than 1,000 mm and the mean annual temperature exceeds more than 30°C.

The study area forms a part of the Madurai Block of the high-grade metamorphic southern granulite terrain of Peninsular India (Koshimoto et al., 2004) and is located between the Palghat-Cauvery shear zone in the north and the Achankovil shear zone in the south. The major lithological types of the study area consist of hornblende gneiss

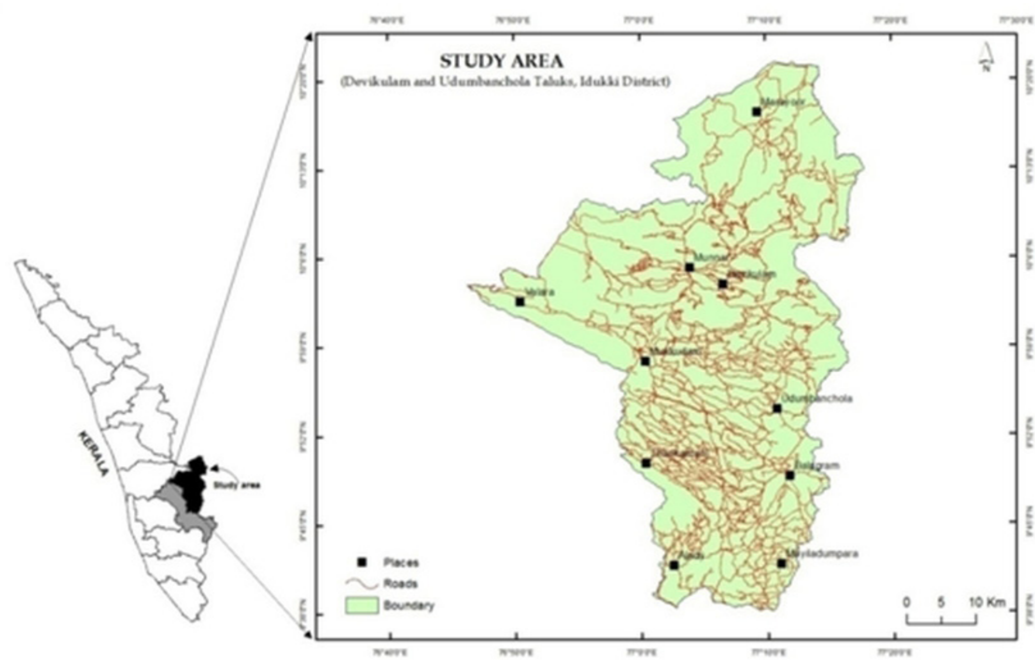

Fig. 1. Location map of the study area

(hornblende-biotite and quartz-mica gneiss composite) and pink granite gneiss (including granite), traversed by bands of pyroxene granulites, calc-granulites, quartzites and quartz magnetites of differing dimensions. The hornblende gneiss is formed by the retrogressive metamorphism of charnockites due to the emplacement of Munnar granite (Rajan et al., 1984). The general mineral assemblage of the gneiss comprises quartz, K-feldspar, oligoclase, biotite and hornblende. The Munnar granite, on the other hand, is emplaced within the Precambrian gneisses and spatially related to the intersection zone of the NE-SW trendingAttur lineament (Santosh et al. 1987). This flesh-coloured rock is characterized by a granulitic texture with quartz, orthoclase and biotite as major minerals (Sajinkumar et al., 2011).Different types of soil series cover the region, viz., Pampadumpara, Anamudy, Venmany, Thommankuthu and Chinnar series (SSO, 2007), which differ significantly among their properties. The study area experienced a large number of landslides compared to many other regions along the flanks of the Western Ghats.

According to the Geological Survey of India landslide database, debris flow, rock slide and complex slide are the dominant landslide types in Devikulam taluk. During the extreme rainfall events of 8-9 August2018, nearly 10 major failures along fringe slopes of rugged hills bordering the Munnar plateau were reported with damaged buildings, roads, and agricultural land (GSI, 2018). In Devikulam Taluk 28 major landslides occurred between June and August 2018 (Kalaranjini & Ramakrishnan, 2020).

2. Materials and methods

The landslide susceptibility zones of the study area were demarcated based on different factors influencing the stability of the regional slope and the occurrence of landslides.A set of twelve geoenvironmental variables, viz., lithology, geomorphology, slope, aspect, relative relief, drainage density, drainage frequency, distance from drainage, land use/ land cover, lineament density, distance from lineament, and lineament frequency were used in the study. The geoenvironmental variables were derived from multiple data sources, including the Survey of India (SoI) topographic maps (1:50,000 scale) and remote sensing data (IRS P6 LISS III mage) (Table 1). Further, all the factors were rescaled to a spatial resolution of 20 m x 20 m, which is comparable to the spatial resolution of the satellite image and contour interval of the SoI topographic maps.

Table1. Factors used (and their sources) for computing LSZs of the region

Factor	Source
Geomorphology	IRS P6 LISS III, SoI topographic map
Slope	SoI topographic map
Aspect	SoI topographic map
Relative relief	SoI topographic map
Distance fromdrainage	SoI topographic map
Drainage frequency	SoI topographic map
Drainage density	SoI topographic map
Distance from lineament	SoI topographic map
Lineament frequency	SoI topographic map
Lineament density	SoI topographic map
Lithology	SoI topographic map
Land use/ land cover	IRS P6 LISS III

Since extreme rainfall events triggered the vast majority of the landslides that occurred in the study area, the present study assumed a nearly uniform effect of rainfall on the landslide susceptibility of the region.

The digital elevation model (DEM) of the study area was generated from the contours (at an interval of 20 m) digitized from the SoI topographic maps. The terrain derivatives, viz., slope, aspect and relative relief were generated from the DEM. The geomorphological features of the study area were identified using the topographic map, satellite image (IRS P6 LISS III) and DEM.

The AHP method (Saaty, 1980) was used to derive the relative weights of the different factors and relative ranks between the features of individual factors of the study area. The process involves a matrix-based pair-wise comparison of the contribution of different factors to the occurrence of landslides. The pair-wise comparison matrix is generated by comparing the relative dominance of each factor against every other factor using a scale between 1 and 9 (Table 2). The relative dominance of each factor is computed by normalizing the eigenvector associated with the maximum Eigen value of the pair-wise comparison matrix. The consistency associated with the pair-wise comparison of the matrix was analyzed by calculating the consistency ratio (CR), which is the ratio between the consistency index of the matrix and the consistency index of a random matrix of the same order. A lower value of CR (i.e., close to 0) implies consistent pair-wise judgements, while the comparisons with the CR greater than 0.1need to be rejected and the exercise must be repeated (Saaty, 1980, 1994). In this study, the CR values of the pair-wise comparison matrices were significantly lesser than 0.1, implying consistency in the pair-wise comparison judgements.

Following the computation of the relative weights and ranks of the different factors and features, the landslide susceptibility of the region was estimated using a weighted linear sum procedure (Vooged, 1983). The landslide susceptibility index (LSI) was computed in ArcGIS using the weights derived by the AHP technique (Eq. 1):

$$LSI = \sum_{i=1}^{n}(W_i \times R_i) \qquad (1)$$

where Wi is the weight of the factor and Ri is the rating of the feature class.

3. Results and discussion

The LSZs of the Udumbanchola and Devikulam taluks were delineated using the twelve causative factors, viz., lithology, geomorphology, slope, aspect, relative relief, drainage density, drainage frequency, distance from drainage, land use/ land cover, lineament density, distance from

Table 2. Scale of preference between two parameters in AHP (Saaty, 2000)

Scale	Degree of preference	Explanation
1	Equally	Two factors contribute equally to the objective
3	Moderately	Experience and judgment slightly to moderately favouronefactor over another
5	Strongly	Experience and judgment strongly or essentially favour one factor over another
7	Very strongly	A factor is strongly favoured over another and its dominance is shown in practice
9	Extremely	The evidence of favouring one factor 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

Table 3. The pair-wise comparison matrix, factor weight, class weight (rating) and consistency ratio used in this study

Lithology	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	Rating
[1] Charnockite/ charnockite gneiss	1	3/6	3/1	3/3	3/1	3/1	3/1	3/1	3/4	3/1	3/1	3/4	0.118
[2] Hornblende-biotite gneiss	6/3	1	6/1	6/3	6/1	6/1	6/1	6/1	6/4	6/1	6/1	6/4	0.225
[3] Pink granite	1/3	1/6	1	1/3	1/1	1/1	1/1	1/1	1/4	1/1	1/1	1/4	0.039
[4] Pyroxene granulite	3/3	3/6	3/1	1	3/1	3/1	3/1	3/1	3/4	3/1	3/1	3/4	0.118
[5] Quartz vein	1/3	1/6	1/1	1/3	1	1/1	1/1	1/1	1/4	1/1	1/1	1/4	0.039
[6] Quartzite	1/3	1/6	1/1	1/3	1/1	1	1/1	1/1	1/4	1/1	1/1	1/4	0.039
[7] Granite	1/3	1/6	1/1	1/3	1/1	1/1	1	1/1	1/4	1/1	1/1	1/4	0.039
[8] Biotite gneiss	1/3	1/6	1/1	1/3	1/1	1/1	1/1	1	1/4	1/1	1/1	1/4	0.039
[9] Calc granulite	4/3	4/6	4/1	4/3	4/1	4/1	4/1	4/1	1	4/1	4/1	4/4	0.133
[10] Magnetite quartzite	1/3	1/6	1/1	1/3	1/1	1/1	1/1	1/1	1/4	1	1/1	1/4	0.039
[11] Dolerite	1/3	1/6	1/1	1/3	1/1	1/1	1/1	1/1	1/4	1/1	1	1/4	0.039
[12] Garnet biotite gneiss/migmatite	4/3	4/6	4/1	4/3	4/1	4/1	4/1	4/1	4/1	4/1	4/1	1	0.133
Consistency ratio: 0.00154													

Geomorphology	[1]	[2]	[3]	[4]	[5]	[6]	[7]	Rating
[1] Denudational structural hill	1	5/1	5/1	5/4	5/3	5/2	5/1	0.306
[2] Residual hill	1/5	1	1/1	1/4	1/3	1/2	1/1	0.061
[3] Pedimont zone	1/5	1/1	1	1/4	1/3	1/2	1/1	0.061
[4] Pediplain	4/5	4/1	4/1	1	4/3	4/2	4/1	0.210
[5] Barren rock	3/5	3/1	3/1	3/4	1	3/2	3/1	0.183
[6] Flood plain	2/5	2/1	2/1	2/4	2/3	1	2/1	0.118
[7] Waterbody	1/5	1/1	1/1	1/4	1/3	1/2	1	0.061
Consistency ratio: 0.0008								

Slope	[1]	[2]	[3]	[4]	[5]	[6]	[7]	Rating
[1] ≤ 5	1	1/2	1/3	1/4	1/5	1/7	1/9	0.032
[2] 6-10	2/1	1	2/3	2/4	2/5	2/7	2/9	0.074
[3] 11-15	3/1	3/2	1	3/4	3/5	3/7	3/9	0.095
[4] 16-25	4/1	4/2	4/3	1	4/5	4/7	4/9	0.135
[5] 26-35	5/1	5/2	5/3	5/4	1	5/7	5/9	0.158
[6] 36-45	7/1	7/2	7/3	7/4	7/5	1	7/9	0.222
[7] > 45	9/1	9/2	9/3	9/4	9/5	9/7	1	0.285
Consistency ratio: 0.00520								

Relative relief	[1]	[2]	[3]	[4]	[5]	[6]	Rating
[1] ≤ 75	2/1	1	2/4	2/6	2/8	2/9	0.067
[2] 76-150	4/1	4/2	1	4/6	4/8	4/9	0.133
[3] 151-300	6/1	6/2	6/4	1	6/8	6/9	0.200
[4] 301-600	8/1	8/2	8/4	8/6	1	8/9	0.267
[5] 601-1000	2/1	1	2/4	2/6	2/8	2/9	0.067
[6] >1000	4/1	4/2	1	4/6	4/8	4/9	0.133
Consistency ratio: 0.000180							

Aspect	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	Rating
[1] Flat	1	1/2	1/1	1/3	1/5	1/7	1/9	1/6	1/4	0.027
[2] N	2/1	1	2/1	2/3	2/5	2/7	2/9	2/6	2/4	0.054
[3] NE	1/1	1/2	1	1/3	1/5	1/7	1/9	1/6	1/4	0.027
[4] E	3/1	3/2	3/1	1	3/5	3/7	3/9	3/6	3/4	0.077
[5] SE	5/1	5/2	5/1	5/3	1	5/7	5/9	5/6	5/4	0.134
[6] S	7/1	7/2	7/1	7/3	7/5	1	7/9	7/6	7/4	0.188
[7] SW	9/1	9/2	9/1	9/3	9/5	9/7	1	9/6	9/4	0.224
[8] W	6/1	6/2	6/1	6/3	6/5	6/7	6/9	1	6/4	0.161
[9] NW	4/1	4/2	4/1	4/3	4/5	4/7	4/9	4/6	1	0.108
Consistency ratio: 0.00323										

Drainage density	[1]	[2]	[3]	Rating
[1] Low	1	9/5	9/1	0.803
[2] Moderate	5/9	1	5/1	0.164
[3] High	1/9	1/5	1	0.033
Consistency ratio: 0.00637				

Drainage frequency	[1]	[2]	[3]	Rating
[1] Low	1	7/4	7/1	0.583
[2] Moderate	4/7	1	4/1	0.333
[3] High	1/7	1/4	1	0.083
Consistency ratio: 0.14258				

Distance from drainage	[1]	[2]	[3]	[4]	[5]	Rating
[1] ≤ 100	1	8/7	8/4	8/2	8/8	0.363
[2] 101-300	7/8	1	7/4	7/2	7/1	0.318
[3] 301-600	4/8	4/7	1	4/2	4/1	0.181
[4] 601-900	2/8	2/7	2/4	1	2/1	0.090
[5] > 900	1/8	1/7	1/4	1/2	1	0.045
Consistency ratio:0.01069						

Lineament density	[1]	[2]	[3]	Rating
[1] ≤ 1000	1	2/4	2/7	0.090
[2] 2500-5000	4/1	1	4/7	0.181
[3] > 5000	7/2	7/4	1	0.318

Consistency ratio: 0.00316

Lineament frequency	[1]	[2]	Rating
[1] Low	1	1/4	0.200
[2] High	4/1	1	0.800

Consistency ratio:0.0016

Distance from lineament	[1]	[2]	[3]	[4]	Rating
[1] ≤ 1000	1	8/6	8/4	8/1	0.421
[2] 1001-2000	6/8	1	6/4	6/1	0.315
[3] 2001-5000	4/8	4/6	1	4/1	0.210
[4] > 5000	1/8	1/6	1/4	1	0.052

Consistency ratio:0.00357

Land use	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	Rating
[1] Built up land	1	1/1	1/1	1/4	1/5	1/2	1/6	1/1	1/1	1/5	1/8	1/7	1/2	1/4	1/3	0.019
[2] Crop land	1/1	1	1/1	1/4	1/5	1/2	1/6	1/1	1/1	1/5	1/8	1/7	1/2	1/4	1/3	0.019
[3] Fallow land	1/1	1/1	1	1/4	1/5	1/2	1/6	1/1	1/1	1/5	1/8	1/7	1/2	1/4	1/3	0.019
[4] Forest evergreen	4/1	4/1	4/1	1	4/5	4/2	4/6	4/1	4/1	4/5	4/8	4/7	4/2	4/4	4/3	0.077
[5] Forest deciduous	5/1	5/1	5/1	5/4	1	5/2	5/6	5/1	5/1	5/5	5/8	5/7	5/2	5/4	5/3	0.097
[6] Forest plantation	2/1	2/1	2/1	2/4	2/5	1	2/6	2/1	2/1	2/5	2/8	2/7	2/2	2/4	2/3	0.039
[7] Land with scrub	6/1	6/1	6/1	6/4	6/5	6/2	1	6/1	6/1	6/5	6/8	6/7	6/2	6/4	6/3	0.116
[8] Barren rock	1/1	1/1	1/1	1/4	1/5	1/2	1/6	1	1/1	1/5	1/8	1/7	1/2	1/4	1/3	0.019
[9] River/ waterbody	1/1	1/1	1/1	1/4	1/5	1/2	1/6	1/1	1	1/5	1/8	1/7	1/2	1/4	1/3	0.019
[10] Grass land	5/1	5/1	5/1	5/4	5/5	5/2	5/6	5/1	5/1	1	5/8	5/7	5/2	5/4	5/3	0.097
[11] Rubber	8/1	8/1	8/1	8/4	8/5	8/2	8/6	8/1	8/1	8/5	1	8/7	8/2	8/4	8/3	0.276
[12] Mixed crop	7/1	7/1	7/1	7/4	7/5	7/2	7/6	7/1	7/1	7/5	7/8	1	7/2	7/4	7/3	0.135
[13] Cardamon	2/1	2/1	2/1	2/4	2/5	2/2	2/6	2/1	2/1	2/5	2/8	2/7	1	2/4	2/3	0.003
[14] Tea	4/1	4/1	4/1	4/4	4/5	4/2	4/6	4/1	4/1	4/5	4/8	4/7	4/2	1	4/3	0.005
[15] Coffee	3/1	3/1	3/1	3/4	3/5	3/2	3/6	3/1	3/1	3/5	3/8	3/7	3/2	3/4	1	0.058

Consistency ratio: 0.00535

Data layers	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	Rating
Geomorphology	1	7/1	7/3	7/9	7/3	7/5	7/6	7/2	7/5	7/4	7/2	7/3	0.002
Lithology	1/7	1	1/3	1/9	1/3	1/5	1/6	1/2	1/5	1/4	1/2	1/3	0.003
Land use	3/7	3/1	1	3/9	3/3	3/5	3/6	3/2	3/5	3/4	3/2	3/3	0.018
Slope	9/7	9/1	9/3	1	9/3	9/5	9/6	9/2	9/5	9/4	9/2	9/3	0.083
Aspect	3/7	3/1	3/3	3/9	1	3/5	3/6	3/2	3/5	3/4	3/2	3/3	0.040
Relative relief	5/7	5/1	5/3	5/9	5/3	1	5/6	5/2	5/5	5/4	5/2	5/3	0.074
Drainage density	6/7	6/1	6/3	6/9	6/3	6/5	1	6/2	6/5	6/4	6/2	6/3	0.128
Drainage frequency	2/7	2/1	2/3	2/9	2/3	2/5	2/6	1	2/5	2/4	2/2	2/3	0.054
Distance from drainage	5/7	5/1	5/3	5/9	5/3	5/5	5/6	5/2	1	5/4	5/2	2/3	0.168
Lineament density	4/7	4/1	4/3	4/9	4/3	4/5	4/6	4/2	4/5	1	4/2	4/3	0.162
Lineament frequency	2/7	2/1	2/3	2/9	2/3	2/5	2/6	2/2	2/5	2/4	1	2/3	0.097
Distance from lineament	3/7	3/1	3/3	3/9	3/3	3/5	3/6	3/2	3/5	3/4	3/2	1	0.171

Consistency ratio: 0.00492

lineament, and lineament frequency, which are discussed in the subsequent sections. The relative weights of the various factors and the relative ranks of the different feature classes of individual themes are given in Table 3.

Lithology

Lithology is a key factor conditioning the occurrence of landslides because different lithologic types have differing sensitivities to active geomorphological processes, such as landslides (Carrara et al. 1991).Hence, numerous researchers considered lithology as an input factor to assess landslide susceptibility in different geological settings (e.g., Yalcin 2008; Lee and Pradhan 2007; Akgun et al. 2008, Althuwaynee and Pradhan 2016).The major rock types of the study area include charnockite/charnockites gneiss, hornblende-biotite gneiss, granite gneiss, pyroxene-granulite,quartzite, granite, biotite gneiss, calc-granulite, magnetite quartzite, dolerite, and garnet-biotite gneiss/migmatite (Fig.2a). However, the dominant lithological units are charnockite/charnockite gneiss, granite gneiss, hornblende-biotite gneiss, biotite gneiss and granite. Based on the pair-wise comparison matrix, hornblende-biotite gneiss has the highest rank (0.225), implying higher susceptibility, followed by calc-granulite (0.133) and garnet-biotite gneiss/migmatites (0.133) (Table 3).

It is demonstrated that lithology considerably influences the occurrence of landslides because lithological variations result in varying levels of strength and permeability of rocks as well as the intensity of weathering processes. The hornblende-biotite gneiss rocks are relatively highly vulnerable to landslides because of the presence of well-developed foliation plains and joints. The hornblende-biotite gneiss in the study area is highly jointed and weathering is found to be extensive along these joints. Moreover, the preponderance of feldspar content in this rock type and subsequent alteration through intense chemical weathering in the humid climate of the southern Western Ghats has resulted in the formation of clay with reduced physical and geotechnical properties.

Geomorphology

Geomorphology is one of the prime factors controlling the occurrence of landslides. The geomorphic diversity of the region indicates that the major landforms of the area are denudational-structural hill,

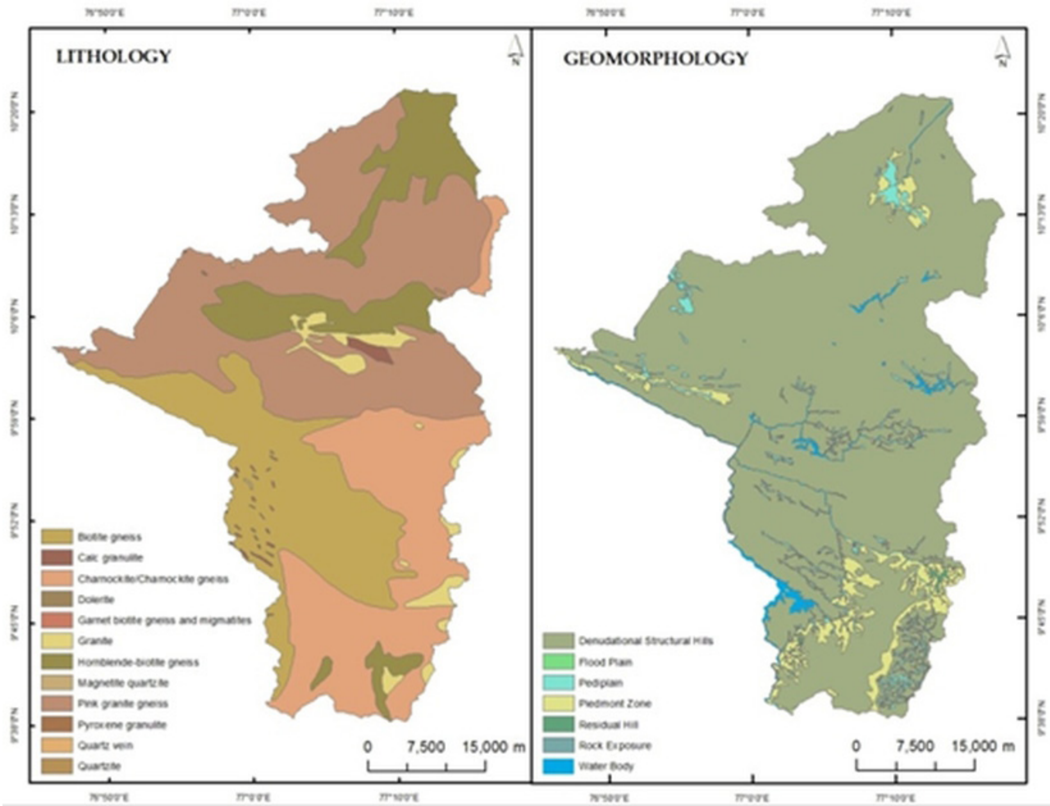

Fig. 2. Landslideconditioning factors of the study area:(a) lithologyand (b) geomorphology

residual hill, pediment zone, pediplain, barren rock, flood plain and waterbody (Fig. 2b). However, the prominent landform of the area is the denudational-structural hill, which is developed independently across the lithology. Based on the matrix (Table 3), the denudational structural hill (0.306) is more susceptible to landslide occurrence, followed by the pediment zone (0.21), whereas the floodplains including flat valleys of the region are less susceptible to occur landslides. The geomorphic features which are of denudational origin are more prone to landslides than those that are formed by processes (Agun, 2012). In the study area, the denudational-structural hills are characterized by steeply sloping, highly weathered hills, and are significantly prone to landslides. However, landforms such as pediplain and plateau are relatively stable and are devoid of landslides.

Slope

The slope angle is an important factor determining slope stability and hence, is used in landslide susceptibility studies (Lee and Min, 2001; Pachauri et al. 1998; Saha et al. 2002). It is observed that landslides mostly occur at certain ranges of critical slope angles (Gokceoglu and Aksoy 1996; Uromeihy and Mahdavifar 2000; Lee and Min 2001; Fernandes et al., 2003). The elevation of the study area varies from 40 to 2680 m above MSL (Fig. 3a). The steepness of the slope of the study area ranges between 0 and 80° (Fig.3b) and has been classified into seven slope angle categories (Table 3). The pair-wise comparison of the different slope classes implies a relatively higher rank to slopes greater than 45°(i.e., 0.285), while the rank gradually decreases towards the lower slope classes. The variability of the ranks

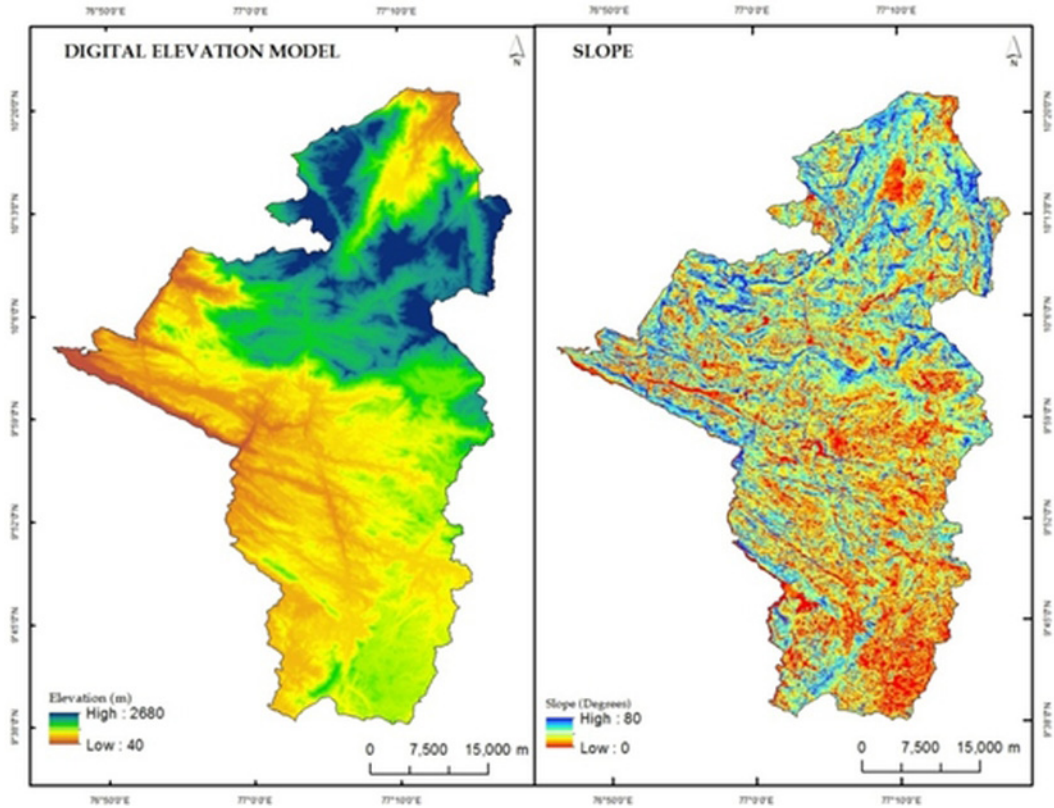

Fig. 3. Landslide conditioning factors of the study area:(a) DEMand (b) slope

indicates that the landslide susceptibility increases with the increase in the slope angle. Among the different slope classes of the study region, most of the highly susceptible area is observed in very high and high slope angle classes. In general, landslide frequency increases with an increase in slope angle due to the increase in downslope shear stress.

Aspect

The direction of the slope or the slope aspect is an important factor determining landslide susceptibility as the exposure to sunlight, winds (dry or wet), rainfall (degree of saturation), soil moisture have a vital control on the occurrence of landslides (Cevik and Topal, 2003; Komac, 2006; Carrara et al., 1999; Guzzetti et al., 1999; Saha et al., 2002; Cevik and Topal, 2003; Lee et al., 2004; Yalcin, 2008). The aspect of the study area was classified into nine classes, viz., north, northeast, east, southeast, south, southwest, west, northwest and flat slopes (Fig. 4a). The slopes towards the southwest (0.224) and southeast (0.180) directions have relatively higher ranks.South-facing slopes of the study area, which receive relatively higher insolation and high rainfall, fall under higher susceptibility classes. Incidentally, a large number of agricultural terraces are present on the southwest-facing slopes leading to more instability.

Relative relief

The relative relief represents the variation of altitude in a unit area with respect to its local base level and implies the ruggedness of the terrain. The relative relief of the study area ranges from 13 to 1053m (Fig. 4b). The Devikulam taluk shows relatively higher relative relief than the Udumbanchola taluk (Fig. 2f), where the higher values of relative

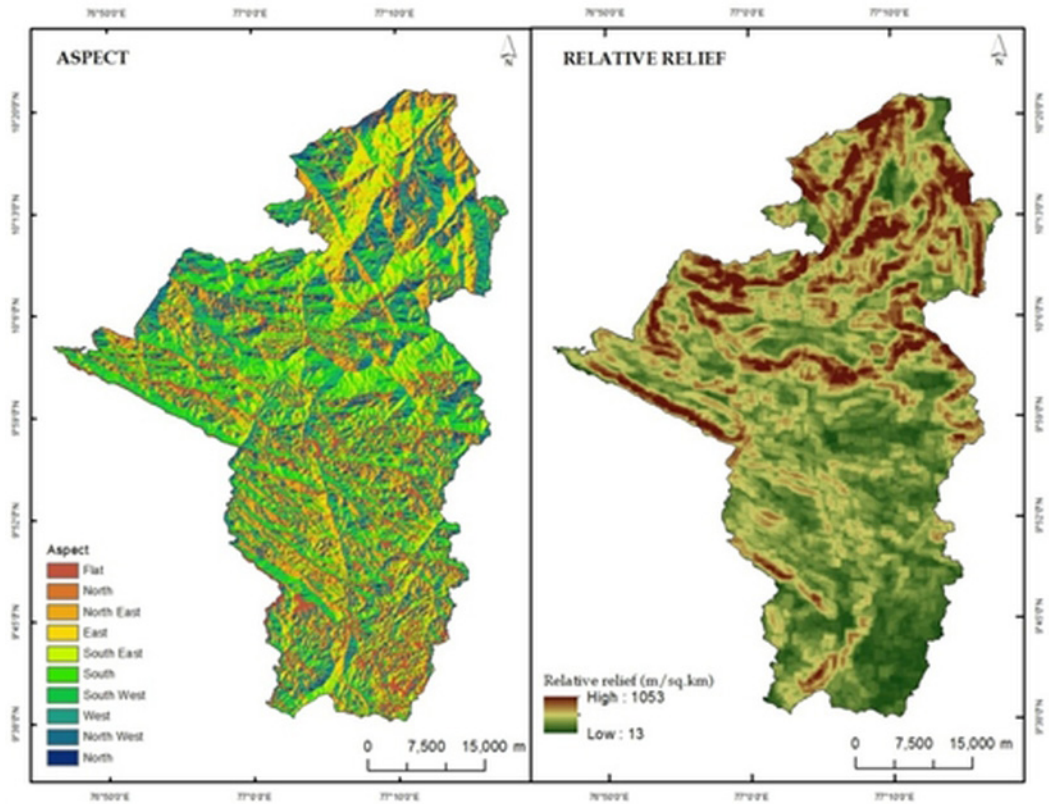

Fig. 4. Landslide conditioning factors of the study area:(a) aspect and (b) relative relief

relief mostly represent the scarps of the Munnar plateau. The pair-wise comparison of the different classes of relative relief indicates that the areas having a relative relief of greater than 1000m are more susceptible to landslides (0.30) followed by the relative relief ranging between 601- 1000m and 301-600m. Since the relative relief is the variation in elevation in a unit area, relatively higher values imply rugged and steep surfaces, which are often rendered unstable by the influence of various triggering factors, such as extreme rainfall.

Drainage characteristics

Drainage characteristics are usually considered an important factor determining landslide susceptibility as landslides generally occur in steeper valley slopes and on the banks of rivers, wherein the toe of the bank is subject to downcutting. Further, modification of the slopes caused by gully erosion may also influencelandslide initiation (Dai and Lee 2002; Bui et al. 2011). Similarly, low drainage density and drainage frequency imply a higher soil infiltration rate and perched groundwater on hillslopes developed during storm periods, suggesting a high susceptibility for shallow landslides (Onda et al., 2004). The drainage network of the study area, in general, shows a NE-SW trend (Fig. 5a). Although the dominant drainage pattern is parallel, implying the controls of the slope, dendritic, trellis and rectangular patterns also co-exist. The present study considered the drainage characteristics, such as drainage density, drainage frequency and distance from drainage for landslide susceptibility mapping.

The drainage density of the taluks ranges between as low as 0 to 4.44km km-2(Fig. 5b), which was classified into low, moderate and high density (Table 3). The matrix shows that the areas having low drainage density (0.803)

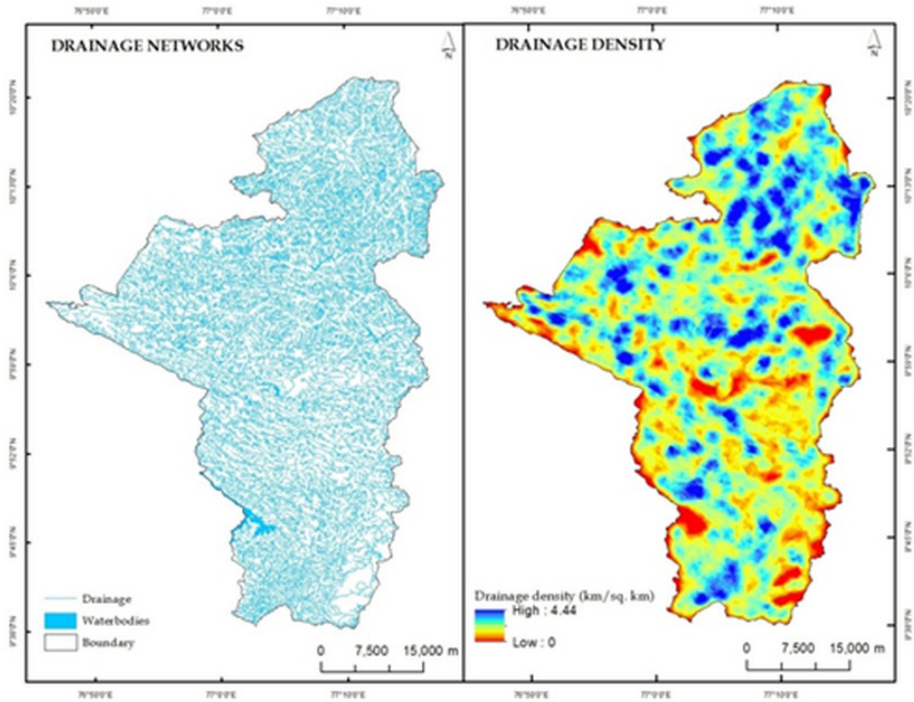

Fig. 5. Landslide conditioning factors of the study area:(a) drainage network and (b) drainage density

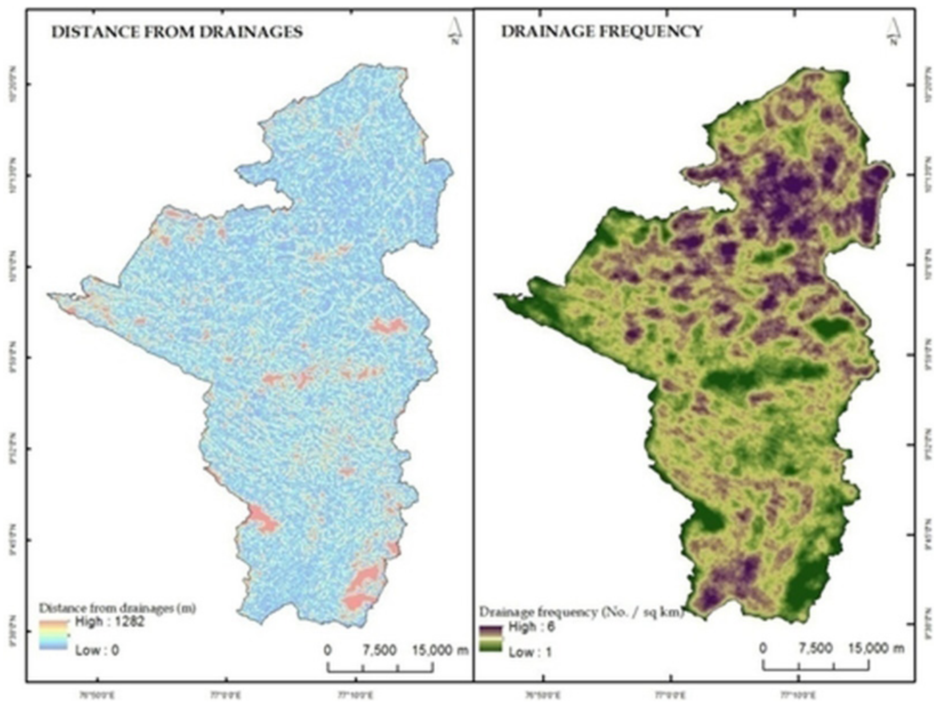

Fig. 6. Landslide conditioning factors of the study area:(a) distance from drainage and (b) drainage frequency

are more susceptible to landslides than the areas having moderate (0.164) and high (0.033) drainage density. We hypothesized that the areas having relatively higher drainage densities (in hard rock terrains) would facilitate faster water movement from hillslopes into stream channels, whereas the areas of lower drainage densities cause more water soil water storage due to increased infiltration and a corresponding increase in the porewater pressure.

The drainage frequency of the study area ranges from 0 to 6 km-2, which was reclassified into low, moderate and high. The drainage frequency of Devikulamtaluk is relatively higher than the Udumbancholataluk (Fig. 6b), which is attributed to the differences in the topographic variability between the taluks. The areas with low drainage frequency (0.583) are more susceptible to landslides than the areas with moderate and high drainage frequencies. The distance from the drainage channels in the study area ranges from nearly 0 to more than 1.2 km (Fig. 2i), which was reclassified into five classes (Table 2). The pair-wise comparison of the different classes indicates that the areas proximal to drainage (i.e., between 0 and 100 m) are more susceptible to landslides (0.363) than the areas distant from the drainage channels (Table 3).

Land use/ land cover

Land use/ land cover is considered a significantfactor in mapping landslide susceptibility as healthy vegetation cover and the anchorage offered by their root network tend to prevent landslide occurrence (Gray and Leiser, 1982; Dahal et al., 2008). In contrast, degraded barren slopes are more prone to landslides. The changes in the land use/ land cover pattern due to population

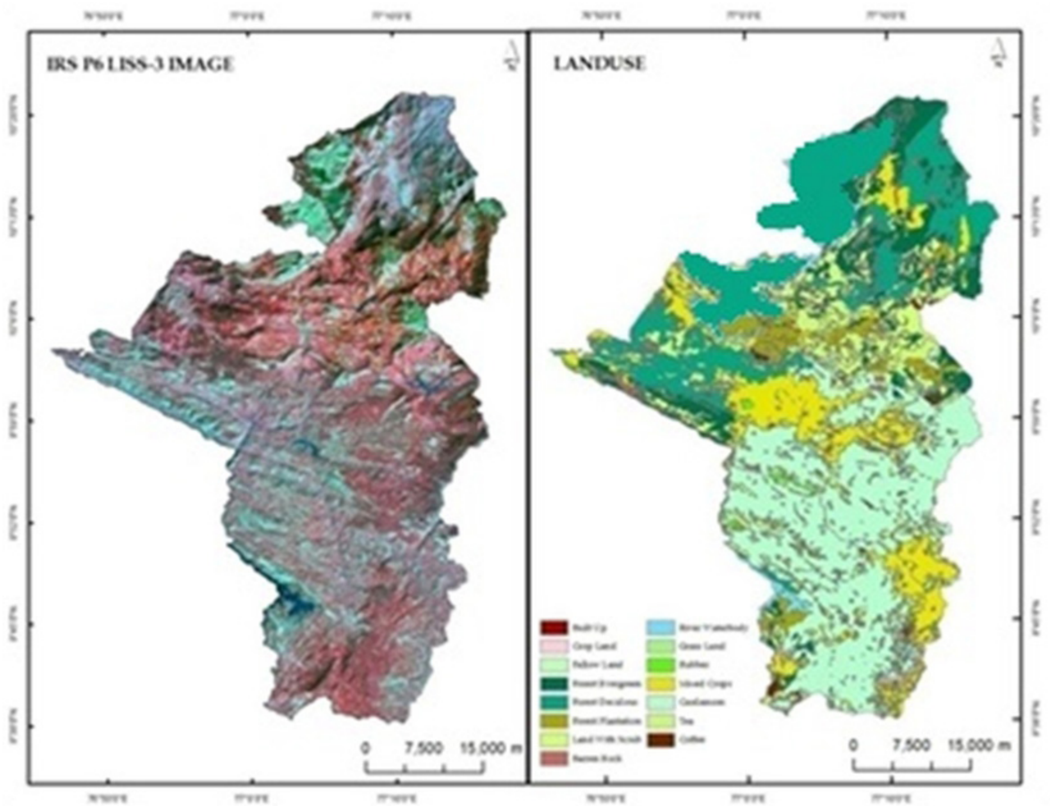

Fig. 7. Landslide conditioning factors of the study area:(a) IRS P6 LISS-3 image, and (b)landuse/land cover

growth and economic development, such as the conversion of natural vegetation to monoculture plantations, increase the probability of landslides. The land use/ land cover map of the area was prepared from the IRS P6 LISS III image (Fig 7a). The landuse/ land cover types of the area includebarren rock, built-up land, cropland, fallow land, grassland, forests, forest plantation, land with scrub, mixed crop, plantations (e.g., cardamom, tea, coffee and rubber) and river/ water bodies(Fig.7b). Plantations crops and forests are the major land use/ land cover classes in the study area. Coverage of natural vegetation is critical for slope stability and hence, slopes with dense vegetation cover should be less prone to the occurrence of landslides than barren (or non-vegetated) slopes, while all other parameters remain constant (Fig. 7b). From the matrix, the areas covered with rubber plantations (0.276) are more susceptible to landslides followed by land with shrubs (0.135) (Table 3).

Lineaments

Lineaments are linear or curvilinear features in a landscape representing theunderlying geological structures. The lineaments indicate the planes of weakness, where the chances for the occurrence of landslides are relatively high. The lineament map of the study area is given in Fig. 8a. The present study estimated lineament density, lineament frequency, and distance from lineaments for the landslide susceptibility mapping.

The lineament density ofthe study area ranges from 0 to 20,544mkm-2 (Fig. 8b) and is classified into low (≤1,000), medium (2,500-5,000) and high (>5,000). The analysis shows (Table 3) that the areas having highlineament density (0.318) are highly susceptible to the occurrence of landslides,

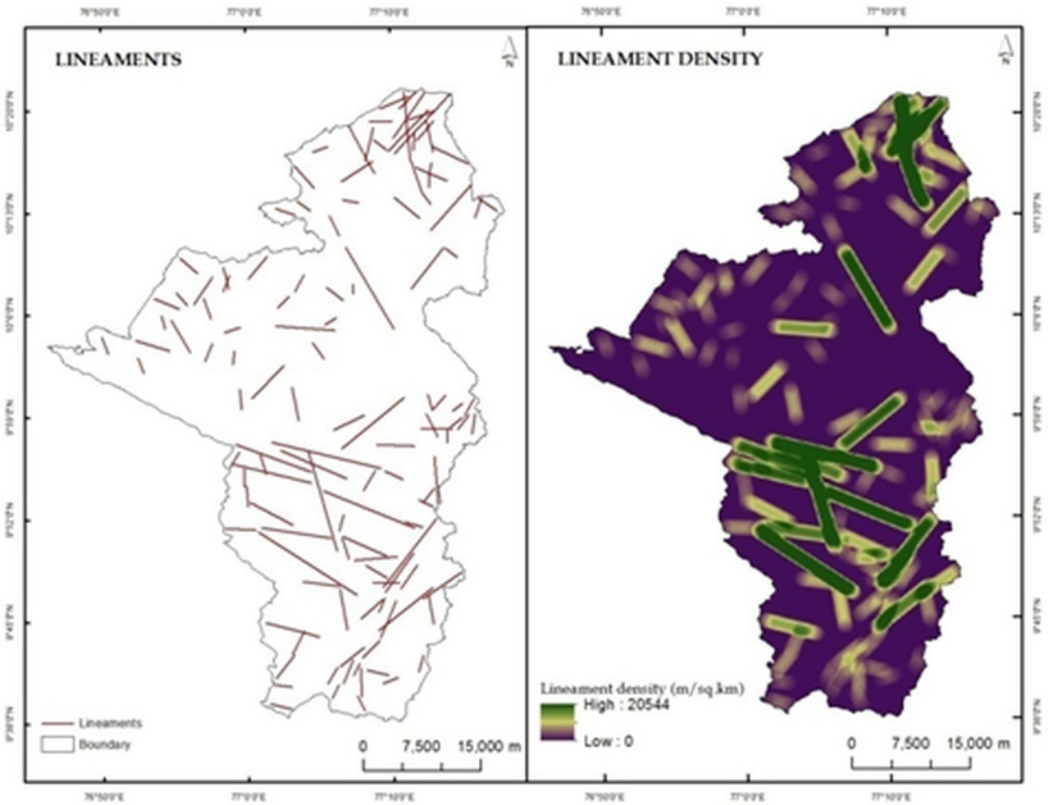

Fig. 8. Landslide conditioning factors of the study area:(a) lineaments, and (b) lineament density

while the areas having low lineament density are relatively less susceptible. The distance from the lineament has been generated to consider the probable seismic origin of the landslides (Demoulin and Chung, 2007). The distance from the lineament (Fig. 9a) of the area was divided into four classes (Table 3). The possibility of landslides in the area with a distance to lineaments less than 1,000 m (0.421) is relatively higher than that of the areas distant from lineaments, e.g., > 5,000 m(0.052).The lineament frequency of the study area (Fig. 9b) shows frequencies ranging between 0 and 2, which is divided into two, i.e., low and high frequencies(Table 3). The landslide susceptibility is directly related to the lineament frequency and the landslide susceptibility increases with increasing lineament frequency. The lineament frequency of the region shows that the Udumbanchola taluk has a comparatively higher lineament frequency than the Devikulam taluk.

The pair-wise comparison of the landslide causative factors of the study area indicates that major factors controlling the occurrence of landslides are the distance from lineament (0.171), distance from drainage (0.168), lineament density (0.162), and drainage density (0.128), whereas lineament frequency (0.097), slope (0.083), relative relief (0.074), drainage frequency (0.05), and landuse/ land cover (0.018) also exerts substantial controls on the occurrence of landslides (Table 3). However, geomorphology (0.002), lithology (0.003) and slope aspect (0.04) have only secondary controls on the landslide occurrences.

However, in certain cases, some of these less critical pre-conditioning factors could have a triggering effect under specific conditions

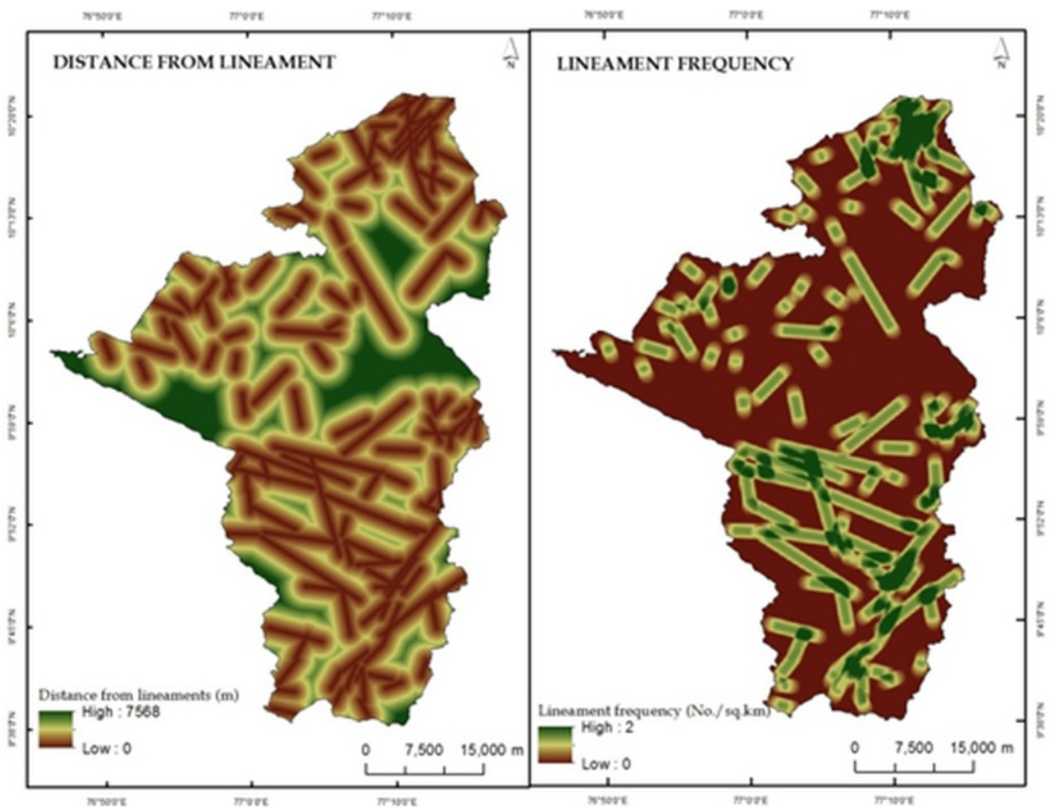

Fig. 9. Landslide conditioning factors of the study area:(a) distance from lineament, and (b) lineament frequency

(He and Beighley, 2008). For instance, a new road excavation or further construction on the land may activate landslide occurrence.

Landslide susceptibility index (LSI)

The LSI of the study area was derived using theweighted linear sum procedure (Eq. 1) and classified into five classes, viz., nil, low, moderate, high, and severe susceptibility (Fig. 10). The spatial variability of the LSI of the study area indicates that roughly 11% of the study area is high to severely susceptible to the occurrence of landslides (Table 4). Approximately, 50% of the study area is fairly stable. The high to severe landslide susceptibility zones of the study area are spatially distributed as two major clusters, one near Mukkadam, and the other along the scarps of the Munnar plateau. In addition, localized high to severe landslide susceptibility zones are noted around Valara, Balagram, Devikulam and near Mattuppetty (i.e., about 10 km northwest of Munnar). The moderate to severe susceptibility of zones, covering about 20% of the study area requires immediate interventions for landslide risk management.

Humans continuously alter the topography and the land use/ land cover pattern of the region for infrastructure development and agricultural activities. The unscientific land use/ land cover practices, for example, conversion of natural vegetation into monoculture plantations, terracing and blocking of lower order drainage channels on steep slopes, and construction of roads and buildings across unfavourable slopes can contribute toincreased occurrences of landslides. In the Idukki district, the area covered by natural vegetation was 2,049 km^2 in 1998 compared to 4,352 km^2 in 1966-67 (Jha et al. 2000). Conversion of natural vegetation into plantations (i.e., rubber in midlands and tea, cardamom and coffee in highlands) is a common practice in Kerala. The unscientific practice of water conservation measures (e.g., rain pits) and the use of machinery for agricultural/plantation

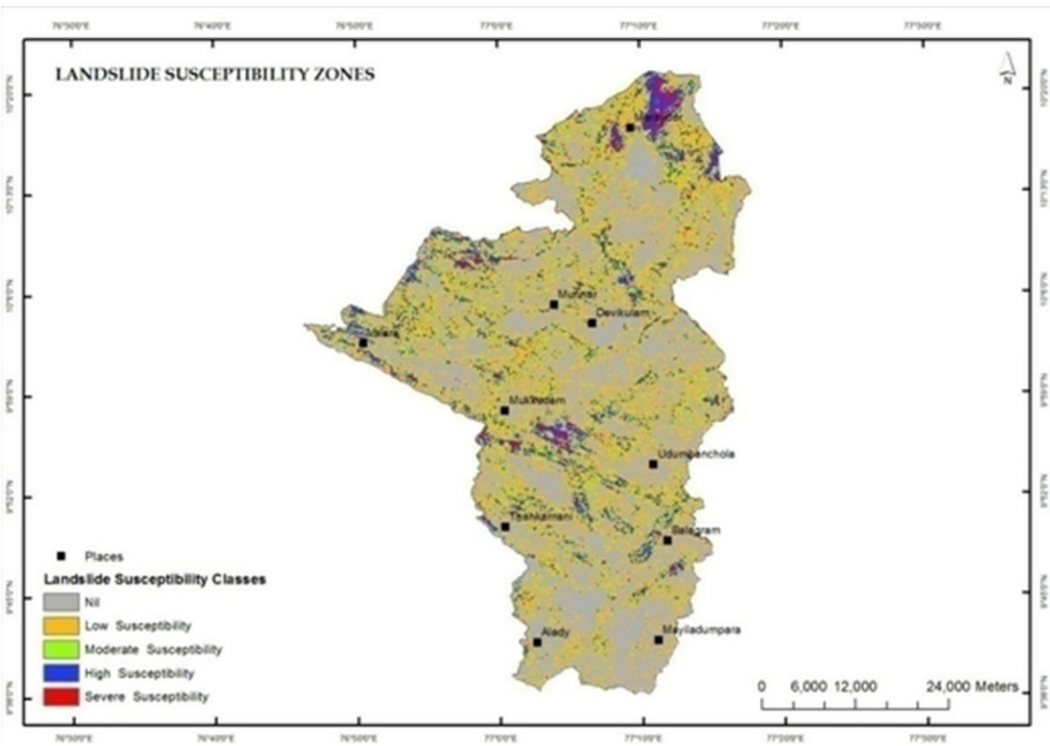

Fig. 10. Landslide susceptibility map of the study area

Table 4: Areal extent of different landslide susceptibility classes in the study area

Sl. No.	Landslide Susceptibility	Area (km^2)	Area (%)
1	Nil	1109.88	50.55
2	Low	644.85	29.37
3	Moderate	206.33	9.40
4	High	214.39	9.76
5	Severe	20.16	0.92
Total area		2195.61	100

operations in steep slopes elevates the slope instability. Such factors were crucial in the recent landslide occurrences in the region. In addition, blocking lower-order stream channels or redirecting to a more hazardous slopemostly associated with agricultural practices on steep slopes also enhances slope instability.

The reduction of the areal extent of the natural vegetative cover by about 50% in three decades indicates that land use/ land cover changes occurred at a faster rate in the study area, which may be attributed to the development of human settlement clusters and associated agricultural/plantation activities. The change of areal coverage of the natural vegetation cover estimated using topographic maps, satellite data and field verifications shows that 34% of the conversion occurred within 25 years (1978-2002). The reduction of natural vegetation cover might have adversely affected the equilibrium of the environment, leading to accelerated soil erosion and landslide occurrences. Various studies demonstrated the implications of removing the natural vegetative cover on landslide susceptibility, where an increase in the landslide frequency was observed due to the mass removal of forest cover (e.g., Derose et al., 1993; Vasanthakumar and Bhagavannulu, 2008). Deforestation reduces soil cohesion, which increases the occurrence of landslides. The consequential defacing of deforested areas is extreme during a landslide as the volume of debris generated might be considerably higher due to thick regolith cover. The sediment delivery rate is also higher in the landslides that occurred in deforested areas than in forested landscapes (Fluente et al. 2002).

The hilly area of Kerala is characterized by a thin veneer of unconsolidated soil, resting above the massive Precambrian crystalline rocks except for the plateau regions, such as Munnar and Nelliyampathy (Sajinkumar and Anbazhagan 2015). Usually, the glide plane of the landslides will be the contact plane of these two units (Istiyanti et al. 2021), which is evident from the exposed bedrock after the slope failure. Hence, along with the understanding of landslide susceptibility, the soil thickness of the area and the saturation capacity of the soil column have to be investigated. The contact between these two units is stable in a plain or gentler slope whereas it will be in a meta-stable position in a steep slope (Getachew and Meten 2021; Puente-Sotomayor et al. 2021). This equilibrium will be lost when the soil column is saturated by water during the monsoon season.The comparatively higher rainfall during the Indian summer monsoon season may saturate the soil column and the extreme rainfall events are sufficient enough to trigger landslides. Hence, the present study calls for the development of comprehensive landslide risk management plans with particular reference to sustainable land use/ land cover management.

4. Conclusion

Landslides in mountainous terrains cause loss of life and property,and landslide susceptibilityzonation mapping is one of the primary steps to mitigate the impacts. This study demonstrates the application of theAHP technique and GISto develop a landslide susceptibility map of the Udumbanchola and Devikulam taluks of the Idukki District (Kerala, India). Twelve landslide conditioning factors, viz., lithology, geomorphology, slope angle, slope aspect, relative relief, drainage properties, land use/ land cover, and lineament characteristics,were used to identify the regions susceptible to the occurrence of landslides. The analysis indicates that the major factors influencing landslide activity in the region are drainage and lineament properties, as well as the relief characteristics.The relative rating of the dominant factors is the proximity of lineament (0.171) and drainage (0.168), lineament and drainage densities (0.162 and 0.128, respectively), slope (0.083) and relative relief (0.074).The landslide susceptibility map of the region suggests that high and severe susceptible zones cover about 10.68% of the area, and another 9.40% falls under the moderate susceptibility zone. The areas belonging to moderateto severe susceptibility zones need urgent attention to implement appropriate mitigation measures, such as management of natural vegetation, and drainage correction to ensure proper drainage.

Acknowledgements

The author would like to express thanks to HEAD, Hazard Vulnerability Risk Assessment Cell (HVRAC) for providing facilities for data analysis in the HVRAC Cell, ILDM, Govt. of Kerala, India.

5. References

Akgun A (2012). A comparison of landslide susceptibility maps produced by logistic regression, multi-criteria decision, and likelihood ratio methods: a case study at İzmir, Turkey. Landslides 9:93–106

Akgun, A., & Dag, S, & Bulut, F. (2008). Landslide susceptibility mapping for a landslide-prone area (Findikli, NE of Turkey) by likelihood-frequency ratio and weighted linear combination models. Environmental Geology. 54. 1127-1143. 10.1007/s00254-007-0882-8.

Anbalagan, Rathinam. (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. Engineering Geology. 32. 269-277. https://doi.org/10.1016/0013-7952 (92)90053-2.

Aleotti, P., Chowdhury, R. (1999). Landslide hazard assessment: summary review and new perspectives. Bull Eng Geol Env 58, 21–44 https://doi.org/10.1007/s100640050066.

Al-Thuwaynee, Omar & Pradhan, Biswajeet & Ahmad, Noordin. (2014). Landslide susceptibility mapping using decision-tree based CHi-squared automatic interaction detection (CHAID) and Logistic regression (LR) integration. IOP Conference Series: Earth and Environmental Science. 20. 012032. 10.1088/1755-1315/20/1/012032.

Alfonso Gutierrez Martin (2020). A GIS-physically-based emergency methodology for predicting rainfall-induced shallow landslide zonation. Geomorphology, Volume 359,107121,https://doi.org/10.1016/j.geomorph.2020.107121.

Ayalew, L., Yamagishi, H. &Ugawa, N. (2004). Landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugawa area of Agano River, Niigata Prefecture, Japan. Landslides 1, 73–81 https://doi.org/10.1007/s10346-003-0006-9

Census (2011), Primary Census Abstracts, Registrar General of India, Ministry of HomeAffairs,GovernmentofIndia,Availableat:www.censusindia.gov.in/2011cenus/PCA/pca_highlights/pe_data.html.

Çevik, E. & Topal, Tamer. (2003). GIS-based landslide susceptibility mapping for a problematic segment of the natural gas pipeline, Hendek (Turkey). Environmental Geology. 44. 949-962. 10.1007/s00254-003-0838-6.

Crozier, M J (1986) ."Landslides: Causes, Consequences and Environment," Croom Helm Australia Pty. Ltd., London, 252 p.

ESSO-NCESS (2020). Report on Studies on land disturbances due to soil piping affecting the critical zones in Western Ghats of Kerala. Submitted to State Disaster Management Authority, Government of Kerala.

Ercanoglu, Murat &Gokceoglu, Candan. (2004). Use of fuzzy relations to produce landslide susceptibility map of a landslide prone area (West Black Sea Region, Turkey). Engineering Geology. 75. 229-250. 10.1016/j.enggeo.2004.06.001.

Fourniadis IG, Liu JG, Mason PJ (2007) Landslide hazard assessment in the three gorges area, China, using ASTER imagery: Wushan–Badong.

Geomorphology 84:126–144. doi:10.1016/j.geomorph.2006.07.020

Gupta, R &Saha, Ashis& Arora, Manoj & Kumar, A. (1999). Landslide Hazard Zonation in a part of the Bhagirathi Valley, Garhwal Himalayas, Using Integrated Remote Sensing – GIS. Himalayan Geology. 20. 71-85.

Gupta, R.P. and Joshi, B.C., (1990) Landslide Hazard Zonation using the GIS Approach - A case Study from the Ramganga Catchment, Himalayas, Engineering Geology, 28, 119-131.

Gokceoglu C. and Aksoy H., 1996. Landslide susceptibility mapping of the slopes in the residual soils of the Mengen region (Turkey) by deterministic stability analyses and image processing techniques. Engineering Geology, 44 (4): 147-161.

Guzzetti, Fausto & Galli, Mirco & Paola, Reichenbach & Ardizzone, Francesca & Cardinali, Mauro. (2006). Landslide Hazard assessment in the Collazzone area, Umbria, Central Italy. Natural Hazards and Earth System Sciences. 6. 115-131. 10.5194/nhess-6-115-2006.

Griffiths, J. (1999). Proving the occurrence and cause of a landslide in a legal context. Bull Eng Geol Env 58, 75–85. https://doi.org/10.1007/s100640050070.

Istiyanti ML, Goto S, Ochiai H (2021) Characteristics of tuf breccia-andesite in diverse mechanisms of landslides in Oita Prefecture, Kyushu Japan. Geoenviron Disasters 8(1):1–14

Hong, H., Xu, C., Bui, D. (2015). Landslide Susceptibility Assessment at the Xiushui Area (China) Using Frequency Ratio Model. Procedia Earth and Planetary Science. 15. 513-517. 10.1016/j.proeps.2015.08.065.

Kalaranjini, V & S.S, Ramakrishnan. (2020). Landslide investigation using SAR Interferometry on selected regions of Idukki district, Kerala, India. Indian Journal of Geo-Marine Sciences. 49. 882-888.

Koshimoto, S., Tsunogae, T. and Santosh, M. (2004) Sapphire and Corundum bearing ultra-high temperature rock from the Palghat-Cauvery shear system, Southern India. Jour. Mineral. Petrol. Sci., v.99, pp.298–310.

Kumar, R., Anbalagan, R. Landslide susceptibility mapping using analytical hierarchy process (AHP) in Tehri reservoir rim region, Uttarakhand. J Geol Soc India 87, 271–286 (2016). https://doi.org/10.1007/s12594-016-0395-8

Kuriakose, Sekhar & Sankar, G. & Muraleedharan, C. (2008). History of landslide susceptibility and a chorology of landslide-prone areas in the Western Ghats of Kerala, India. Environmental Geology. 57, 1553–1568https://doi.org/10.1007/s00254-008-1431-9.10.1016/j.geomorph.2005.07.005.

Lahai YA, Anderson KF, Jalloh Y, Rogers I, Kamara M (2021) A comparative geological, tectonic and geomorphological assessment of the Charlotte, Regent and Madina landslides, Western area Sierra Leone. Geoenviron Disasters 8(1):1–17

Lee, Saro& Min, Kyungduck. (2001). Statistical analysis of landslide susceptibility at Yongin, Korea. Environmental Geology. 40. 1095-1113. 10.1007/s002540100310.

Lee, S., Pradhan, B. Landslide hazard mapping at Selangor, Malaysia using frequency ratio and logistic regression models. Landslides 4, 33–41 (2007). https://doi.org/10.1007/s10346-006-0047-y

Liu, C.C., Luo, W., Chen, M.C. et al. A new region-based preparatory factor for landslide susceptibility models: the total flux. Landslides 13, 1049–1056 (2016). https://doi.org/10.1007/s10346-015-0620-3

Nagarajan, R., Mukherjee, A., Roy, A. And Khire, M.V. (1998). Temporal remote sensing data and GIS application in landslide hazard zonation of part of Western Ghats, India. Int. Jour.Remote Sens., v.19, pp.573–585

Nguyen HT, Wiatr T, Fernández-Steeger TM (2012). Landslide hazard and cascading effects following the extreme rainfall event on Madeira Island (February 2010). Nat Hazards 65:635–652. doi:10.1007/s11069-012-0387-y

Omar F. Althuwaynee, Biswajeet Pradhan &Saro Lee (2016) A novel integrated model for assessing landslide susceptibility mapping using CHAID and AHP pair-wise comparison, International Journal of Remote Sensing, 37:5, 1190-1209, DOI: 10.1080/01431161.2016.1148282

OFDA/CRED (2018). International Disaster Database. Brussels: UniversitéCatholique de Louvain. Available online at: www.emdat.be (Accessed August 9, 2018).

Pradhan, Biswajeet & Lee, Saro. (2009). Landslide risk analysis using artificial neural network model focusing on different training sites. International journal of physical sciences. 4. 1-15.

Rajan, P.K., Santosh, M. and Ramachandran, K.K. (1984) Geochemistry and petrogenetic evolution of the diatexites of Central Kerala, India. Proc. Indian Acad. Sci. (Earth Planet. Sci.), v.93 (1), pp.57–69.

State of Environment report (SoE)-Kerala, (2007). Kerala State Council for ScienceTechnology and

Environment (KSCTE), Government of Kerala.

Saha, Ashis& Gupta, R. & Arora, Manoj. (2002). GIS-based Landslide Hazard Zonation in the Bhagirathi (Ganga) Valley, Himalayas. International Journal of Remote Sensing - Int J Remote Sens. 23. 357-369. 10.1080/01431160010014260.

Saaty TL (1980) the analytic hierarchy process. McGraw-Hill, New York.

Shahabi, Himan & Hashim, Mazlan. (2015). Landslide susceptibility mapping using GIS-based statistical models and Remote sensing data in tropical environment. Scientific Reports. 5. 15. 10.1038/srep09899.

Sangchini, E.K., Emami, S.N., Tahmasebipour, N. (2016). Assessment and comparison of combined bivariate and AHP models with logistic regression for landslide susceptibility mapping in the Chaharmahal-e-Bakhtiari Province, Iran. Arab J Geosci 9, 201 (2016). https://doi.org/10.1007/s12517-015-2258-9

Santosh, M., Iyer, S.S. and Vasconcellos, M.B.A. (1987) Rare earth element geochemistry of the Munnarcarbonatite, Central Kerala. Jour. Geol. Soc. India, v.29, pp.335-343.

Saha, Ashis& Gupta, R. & Arora, Manoj. (2002). GIS-based Landslide Hazard Zonation in the Bhagirathi (Ganga) Valley, Himalayas. International Journal of Remote Sensing - INT J REMOTE SENS. 23. 357-369. 10.1080/01431160010014260.

Sajinkumar, K.S., Anbazhagan, S., Pradeepkumar, A.P., Rani, VR (2011) Weathering and landslide occurrences in parts of Western Ghats, Kerala. Jour. Geol. Soc. India, v.78 (3), pp.249–257.

SSO (2007) Benchmark soils of Kerala. Soil Survey Organization,

Tiranti Davide, Cremonini Roberto (2019). Landslide Hazard in a Changing Environment, Front. Earth Sci., Volume 7; pp1-3. SN-2296-6463 https://doi.org/10.3389/feart.2019.00003

Geological Survey of India, World Wide Web electronicpublication. https://www.gsi.gov.in/ version (10/2018).

Saaty, T. L. (1994). How to Make a Decision: The Analytic Hierarchy Process. Interfaces, 24, 19-43.https://doi.org/10.1287/inte.24.6.19

Saaty, T.L. (2000) Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process (Analytic Hierarchy Process Series, Vol. 6). RWS Publications, Pittsburgh.

Pachauri, A. K., Terrain Analysis for Landslide Hazard Zonation (LHZ) (October 7, 2009). The IUP Journal of Earth Sciences, Vol. 3, No. 4, pp. 7-35, October 2009, Available at SSRN: https://ssrn.com/abstract=1484358

Puente-Sotomayor F, Mustafa A, Teller J (2021) Landslide susceptibility mapping of urban areas: logistic regression and sensitivity analysis applied to quito Ecuador. Geoenviron Disasters 8(1):1–26

USGS(2004). Landslide Types and Processes URL: https://pubs.usgs.gov/fs/2004/3072/

Uromeihy, A., Mahdavifar, M. Landslide hazard zonation of the Khorshrostam area, Iran. Bull Eng Geol Env 58, 207–213 (2000). https://doi.org/10.1007/s100640050076

Fernandes, Nelson & Guimarães, Renato & Gomes, Roberto & Vieira, Bianca & Montgomery, David & Greenberg, Harvey. (2004). Topographic controls of landslides in Rio de Janeiro: Field evidence and modeling. CATENA. 55. 163-181. 10.1016/S0341-8162(03)00115-2.

Marko, Komac. (2006). A landslide susceptibility model using the Analytical Hierarchy Process method and multivariate statistics in perialpine Slovenia. Geomorphology. 74. 17-28.

Carrara, A., Guzzetti, F., Cardinali, M. et al. Use of GIS Technology in the Prediction and Monitoring of Landslide Hazard. Natural Hazards 20, 117–135 (1999). https://doi.org/10.1023/A:1008097111310

Lee S, Ryu JH, Won JS, Park HJ (2004) Determination and application of the weights for landslide susceptibility mapping using an artificial neural network. Eng Geol 71(3–4):289–302

Dai, F.C & Lee, C.F. (2002). Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong. Geomorphology. 42. 213-228. 10.1016/S0169-555X (01)00087-3.

Bui, Dieu &Löfman, Owe &Revhaug, Inge & Dick, Øystein. (2011). Landslide susceptibility analysis in the Hoa Binh province of Vietnam using statistical index and logistic regression. Natural Hazards. 59. 1413–1444. 10.1007/s11069-011-9844-2.

Gray, D. H., and A. T. Leiser. 1982. Biotechnical Slope Protection and Erosion Control. Van Nostrand Reinhold Company. New York.

Froude, Melanie & Petley, David. (2018). Global fatal landslide occurrence 2004 to 2016. Natural Hazards and Earth System Sciences Discussions. 1-44. 10.5194/nhess-2018-49. DOI:10.5194/nhess-2018-49

Dahal, Ranjan & Hasegawa, Shuichi &Nonomura, Atsuko & Yamanaka, Minoru & Masuda, Takuro& Nishino, Katsuhiro. (2008). GIS-based weights-of-evidence modeling of rainfall-induced landslides in small catchments for landslide susceptibility mapping. Environmental Geology. 54. 311-324. 10.1007/s00254-007-0818-3.

Demoulin, Alain & Chung, Chang-Jo. (2007). mapping landslide susceptibility from small datasets: A case study in the Pays de Herve (E Belgium). Geomorphology. 89. 391-404. 10.1016/j.geomorph.2007.01.008.

He, Y.P. and Beighley, R.E. (2008) GIS-Based Regional Landslide Susceptibility Mapping: A Case Study in Southern California. Earth Surface Processes and Landforms, 33, 380-393.

https://doi.org/10.1002/esp.1562

Jha, Chandra & Dutt, C. & Bawa, Kamaljit. (2000). Deforestation and land use changes in Western Ghats, India. Current science. 79. 231-238.

64.De Rose, R. C., Trustrum, N. A., & Blaschke, P. M. (1993). Post-deforestation soil loss from steeplandhill slopes in Taranaki, New Zealand. Earth Surface Processes and Landforms, 18, 131– 144.

Kumar, S. & Bhagavanulu, Dvs. (2008). Effect of Deforestation on Landslides in Nilgiris District - A Case Study. Journal of the Indian Society of Remote Sensing. 36. 105-108. 10.1007/s12524-008-0011-5.

Gunnell, Y. and Fleitout, L. (1998), Shoulder uplift of the Western Ghats passive margin, India: a denudational model. Earth Surf. Process. Landforms, 23: 391-404. https://doi.org/10.1002/(SICI)1096-9837(199805)23:5<391::AID-ESP853>3.0.CO;2-5

Martha, Tapas & Roy, Priyom & Khanna, Kirti &Kotteeswaran, Mrinalni&vinod Kumar, Kumranchat. (2019). Landslides Mapped using Satellite Data in the Western Ghats of India after Excess Rainfall During August 2018. Current science. 117. 804-812. DOI:10.18520/cs/v117/i5/804-812.

Wadhawan, S.K., Singh, B. & Ramesh, M.V. Causative factors of landslides 2019: case study in Malappuram and Wayanad districts of Kerala, India. Landslides 17, 2689–2697 (2020). https://doi.org/10.1007/s10346-020-01520-5

Getachew N, Meten M (2021) Weights of evidence modeling for landslide susceptibility mapping of Kabi-Gebro locality, Gundomeskel area central Ethiopia. Geoenviron Disasters 8(1):1–22

Government of Kerala, Thiruvananthapuram.

Sajinkumar KS, Anbazhagan S (2015) Geomorphic appraisal of landslides on the windward slope of Western Ghats, southern India. Nat Hazards 75(1):953–973

Yalcin, Ali. (2008). GIS-based Landslide Susceptibility Mapping Using Analytical Hierarchy Process and Bivariate Statistics in Ardesen (Turkey): Comparisons of Results and Confirmations. Catena. 72. 1-12. 10.1016/j.catena.2007.01.003.

Zimmerman, M., Bichsel, M., Kienholz, H., 1986. Mountain hazards mapping in the Khumbu Himal, Nepal, with prototype map, scale 1:50,000. Mountain Research and Development 6 (1), 29-40.