ISSN: 2278-0181
ICONNECT - 2k18 Conference Proceedings

Landslide Susceptiblity Zonation Using Remote Sensing and GIS

Vaishali R
PG student,
IRS, College of Engineering,
Guindy, Chennai 600025

Jayalakshmi S
Assistant Professor,
IRS, College of Engineering,
Guindy, Chennai 600025

***Abstract*— Landslides, a phenomenon of mass movement of debris, soil or rocks, are commonly occurring disasters in the areas where the natural slope exceeds the shearing angle of the soil. In India, the Himalayan ranges and the Western Ghats share a long history with the landslides, with numerous instances recorded since the time immemorial. Owing to minimize the loss of lives and widespread destruction of property and infrastructure, it is of utmost necessity to delineate the areas which are highly susceptible to the disaster. Landslide susceptibility aims to demarcate the area under study into different risk zones, based on the analysis of numerous landslide triggering factors. This study aims to formulate a landslide susceptibility zonation map for the Coonoor area, located in the Western Ghats, Tamil Nadu, India. A number of landslide triggering factors like soil, geology, geomorphology, etc. were considered as thematic inputs and the map was generated using fuzzy overlay, based on different fuzzy membership values while the validation of the map was carried out using past landslide occurrences in the area. The results showed that the majority of the study area fell in the classes of moderate risk (29.68%) and high risk (30.62%) zones, with 25 of the past 31 landslide occurrences considered for the validation following the same trend, falling in the moderate and high risk areas.**

Keywords*— *Landslide, susceptibility, thematic layers, zonation, fuzzy

I. INTRODUCTION

Landslide, a phenomenon characterised by the movement of soil, debris or rock down a slope, is one among the most destructive occurrences which cause widespread damages to infrastructure and loss of lives and habitat. In India, according to the research performed by the Defence Terrain Research Laboratory, the hazard accounts to over 0.4 million sq. km, which is about 15% of the country's total area [1]. Landslide susceptibility map, which delineates the area under study into different classes based on its susceptibility to the hazard, extends a helping hand in the decision making processes and policy framework, apart from playing a vital role in the planning processes, aiding in minimizing the impact of hazard on human life and infrastructure.

In the district of Nilgiris, landslide is a very common phenomenon, especially during monsoon season. Being located in the southern part of the country, owing to heavy rainfall activity, the study area is prone to the hazard during both the monsoons of the rainy season i.e., south-west and north-east monsoon, with former imposing a greater probability of occurrence. Due to turbulent nature of streams owing to highly rolling terrain and complex geomorphic structure of surface, the slopes are highly unstable with the threat of erosion looming during rains-weakening the soil slope stability.

With the advancements of science and technology in the fields of logical theory and reasoning, the application of artificial neural networks, fuzzy logic, decision tree analysis, Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchal Process (AHP) methods in the landslide zonation have turned out high levels of accuracy. This paper aimed to formulate a landslide susceptibility zonation map for the Coonoor area in the Nilgiris district, Tamil Nadu using fuzzy logic and delineated the area into five classes based on the susceptibility to the hazard, namely very low, low, moderate, high and very high.

II. STUDY AREA

The area considered for the study, Coonoor, is a town and municipality in the Nilgiris district, lying in the state of Tamil Nadu. It is situated at an average altitude of 1850m above sea level and the taluk extending between the geographic coordinates 11°13'N to 11°24'N latitude and 76°40'30''E to 76°52'E longitude. With the average temperature ranging between 13°C and 18°C across the year, the average precipitation accounts up to 1335mm annually.

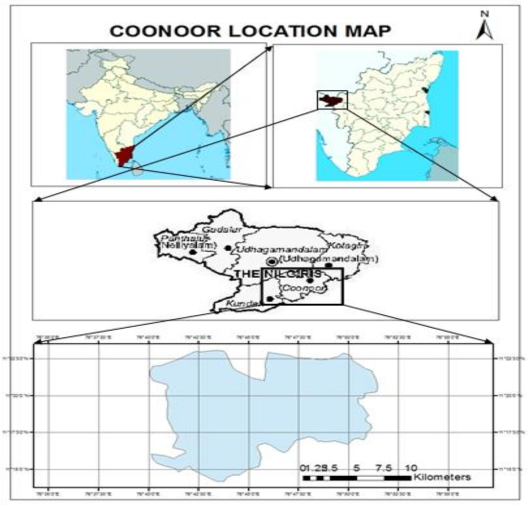


Fig 1 Location of study area

III. DATASETS AND METHODOLOGY

Typically, a landslide susceptibility map is generated for a given area by correlating the principal factors that contribute to the landslide disaster with the past distribution of the slope failures [2] [3] [4]. Till date, many techniques have been devised for generating landslide susceptibility maps [5], especially using GIS [6]. The available GIS methods can be broadly classified into qualitative and quantitative techniques, with the difference between the methods being in the properties they possess [7]. In this paper, the susceptibility map for the study area has been prepared by deriving fuzzy memberships for the causal factors and overlaying them using fuzzy overlay in ArcGIS 10.3 software. Figure 2 gives the methodology of the study.

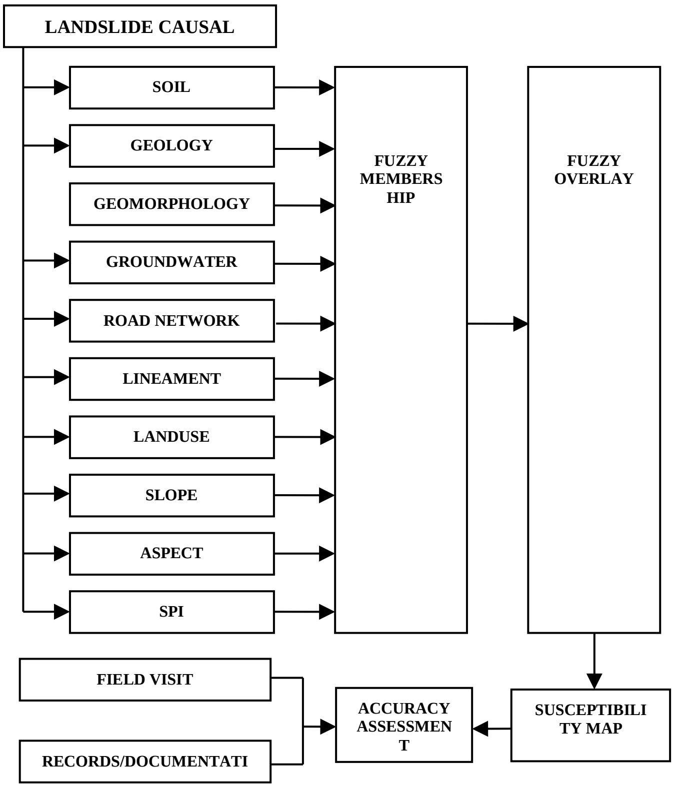


Fig 2 Methodology chart

A. Generation of thematic layers

Analysis of any spatial problem in a GIS domain involves integration, manipulation and drawing inference from different influencing factors, which are usually depicted as thematic layers. For the generation of landslide zonation map, landslide causal factors or triggering factors have to be identified. Although there are no universal guidelines for the selection of causal factors [7] [8], optimal selection of parameters have always been successful in providing better results. Redundant factors have been found to exercise difficulty in handling data, even though without much increase in the final accuracy but deficiency in data leading to inaccurate results and introduction of uncertainty in decision making. A total of ten causal factors, namely slope, aspect, soil, geology, geomorphology, lineament, road, land use land cover, groundwater potential and stream power index (SPI) are considered and generated in ArcGIS.

B. Soil

The soil makes up the uppermost part of the earth's crust, forming the run-away or sliding material during the landslide disaster. The texture of soil particles, which influences the stability of any slope, bears a direct relationship in triggering the landslide. In general, slopes made up of high cohesive soils are believed to be more stable than cohesionless or liquefiable counterparts.

C. Geology

Geology forms a major influencing factor in triggering landslide in an area. The rock formation in an area gives its relative stability against any type of movement. Areas made up of soft rocks are usually weathered when exposed and hence, are more susceptible to landslide than that of the harder rocks and unexposed ones. It could be viewed that the study area is primarily made up of charnockite, an assemblage of rocks formed by crystallisation of magma under high temperature and pressure, being more susceptible to landslides due to the presence of debris, fault, thrust, etc.

D. Geomorphology

Geomorphology of an area depicts the features in an area evolved from physical, chemical or biological processes on the earth's surface. The landscape of an area influences the occurrence of landslide in broader sense- steeper slopes and valleys pose a higher susceptibility while plain terrains have low risk. The geomorphology of the study area was digitized from the toposheets and Google earth at a scale of 1:50000.

E. Lineament density

A lineament gives information about the underlying geological formations such as faults and dykes. Thus, it essentially forms the region of penetration and seepage, which in turn influences the stability of soil lying over it. In general, the areas over fault plates and seismic zones are more vulnerable to landslides. The study area of Coonoor falls under the moderate seismic zone 3, with fault planes covering across the whole extent of Western Ghats and the lineament map was derived by digitizing from the toposheets covering the study area. The lineament density map depicts the density of the lineaments in an area and is calculated based on the population and search area of the neighbourhood.

F. Groundwater potential

The depth of groundwater in an area influences the stability of the soil covering an area. With the potential high in an area, the risk of triggering increases proportionally. The potential of the groundwater was derived by on-field survey and analysis.

G. Slope

Slope and aspect, two important derivatives of the Digital Elevation Model (DEM) of an area, form the most important factors controlling the triggering of the disaster. Slope, which is given as the percent rise or fall of each point on the ground, is derived from the CartoDEM product of the study area. In general, as the slope increases, the shear stress of the soil increases, thereby increasing the probability of landslides.

H. Aspect

Aspect denotes the direction of the slope fall. The more susceptible directions can be identified by understanding the environmental and climatic conditions like sunlit direction, precipitation amount and direction of runoff, etc.

I. Stream Power Index (SPI)

Stream Power Index is a factor which is used to describe the potential flow erosion at a given point on the topographic surface. It is computed by accounting for both slope geometry and site location, i.e., combining slope gradient and catchment area data. A higher value of SPI in an area indicates greater possibility of erosion occurring due to stream flow.

J. Road network

The distance to road is an important factor to be considered when a landslide zonation map is prepared. During landslides, roads are the most vulnerable features to be affected, hindering the transportation facilities and thereby affecting normal livelihood. With the flow of traffic and anthropogenic activities playing an important hand in triggering the disaster, buffers at different lengths were constructed to the digitized road layer, derived from google earth imagery of the study area.

K. Land use-land cover

One of the major factors which bring about changes to the existing natural conditions is the anthropogenic activity. The pattern of land usage in complementary with the existing land cover plays a major role in triggering the landslide in an area. The land use land cover map of the study area was generated using the maximum likelihood algorithm of supervised classification using the Sentinel-2 optical image (FCC using band8, band 4 and band 3 as Red, Green and Blue bands respectively) of 10m spatial resolution in ERDAS Imagine software.

L. Fuzzy Membership And Fuzzy Overlay

While the conventional algorithms and spatial image processing methods are based on the crisp value assessment to a feature pixel, in the real world, there exists ambiguity when two or more features are accommodated in a single pixel. This uncertainty can be handled using advanced methods like fuzzy logic, where the pixel value is defined by a membership function. With values ranging from 0 to 1, each pixel is related to the feature by means of a membership. The different thematic layers were reclassed on the basis of susceptibility towards the hazard and the membership values were accordingly allocated to each pixel.

An overlay analysis is carried out to derive an output by combining two or more layers, primarily to carry out suitability analysis, hazard and species mapping, etc. It can be carried out in the form of vector overlay (like identity, intersect, union, etc.) or raster overlay (weighted, fuzzy, weighted sum, etc.). An overlay essentially combines the value of each pixel/feature (in case of vector) from different layers based on the weightage/rank of each layer A fuzzy overlay is carried out based on the fuzzy membership values of different layers, with the help of a membership function. In ArcMap, a number of predefined fuzzy overlay functions are available, like sum, product, AND, OR and Gamma.

IV. ACCURACY ASSESSMENT

The accuracy of a map can be checked in both qualitative and quantitative methods- the qualitative methods involves cross-checking the map with past landslide occurrences in the study area while the quantitative methods perform assessment through statistical curves. Widely used quantitative method of validating a map is using the Receiver Operating Characteristic (ROC) Curve and computing the Area Under the Curve (AUC) parameter [5] [6] [9] [10]. In this study, the validation of the susceptibility map generated has been performed using the past landslide occurrences in the area.

V. RESULTS AND DISCUSSION

A. Generation of thematic layers

The land use-land cover map was generated using maximum likelihood classifier from Sentinel-2 data in ERDAS IMAGINE software and validated with Google Earth imagery and the layers slope, aspect and SPI were derived using GIS based tools available in ArcGIS using CartoDEM.

The soil type in the area was found to extend from ustisols to entisols and the reclassification was performed as per the increased susceptibility towards the hazard. Majority of the study area was found to be made of alfisols. Due to the origin of Western Ghats, the major geological type found was charnockite, with traces of gneiss. This could be attributed to the magma flow and metamorphic action over the years in the region. The highly dissected hills and peaks were the predominant geomorphological feature at the mapping scale of 1:50000, with traces of water bodies found at few regions.

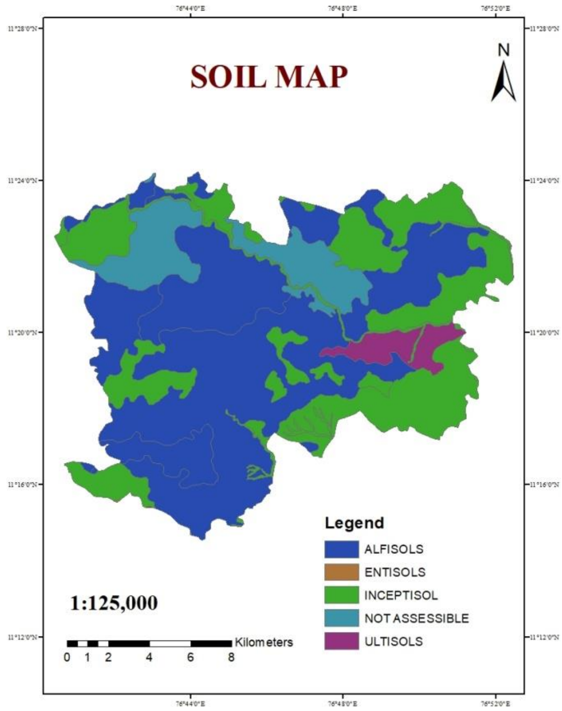


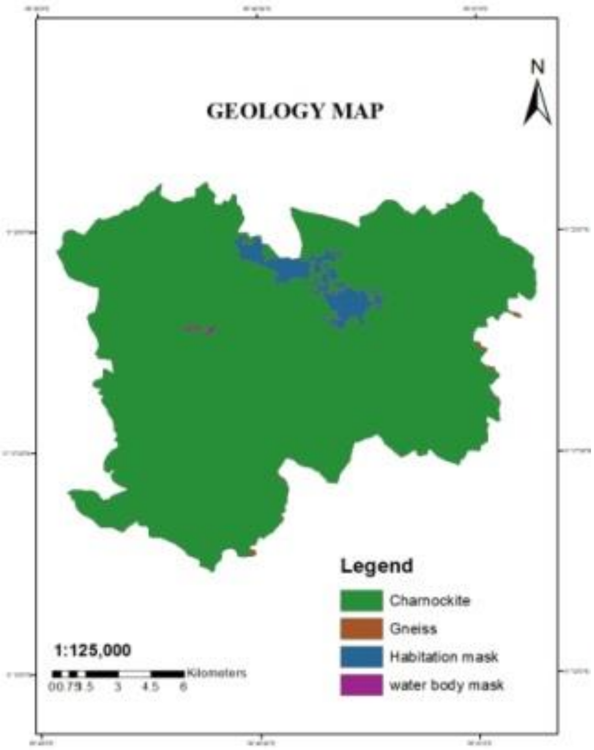
Fig 3(a) Soil map

The slope in the region was found to range from 0° to 88°, with majority of the peaks found at the south-east and western regions. The aspect in the study area ranged from -1 to 360° with -1 depicting the flat regions and 0°-360° denoting the eight directions. The lineament density was found to range from 0 to 0.0004 and was reclassed into 5 classes based on equal intervals. The Stream Power Index was generated using raster calculator using the flow accumulation and slope layer using raster calculator by expression stated as follows:

ISSN: 2278-0181

$$SPI = \ln(\text{flow\_accumulation} + 0.001) * (\text{slope} + 0.001)$$

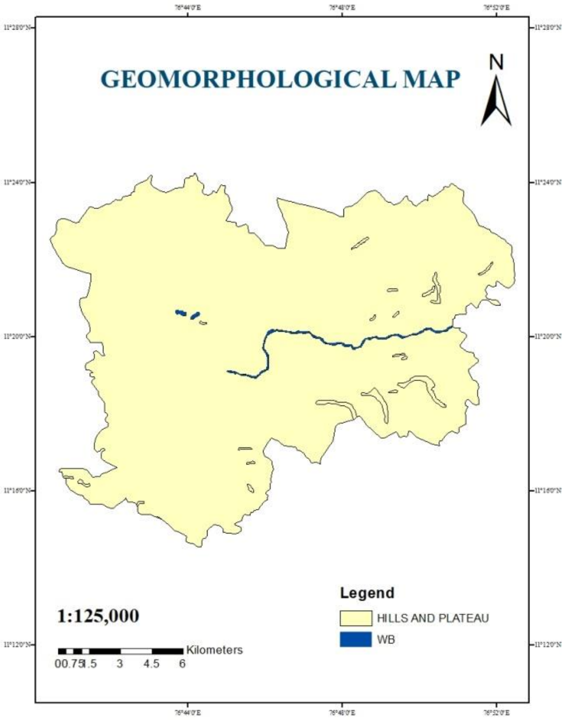
The direction of face of sunlight, presence of high peaks and precipitation activity knowledge was incorporated to reclass the aspect while the road buffers of lengths 7.5m, 10m, 20m, 30m, 50m, 100m and 1000m were constructed to perform the same. The ten thematic layers which have been considered for the susceptibility map generation for the study area are depicted in figure 3.

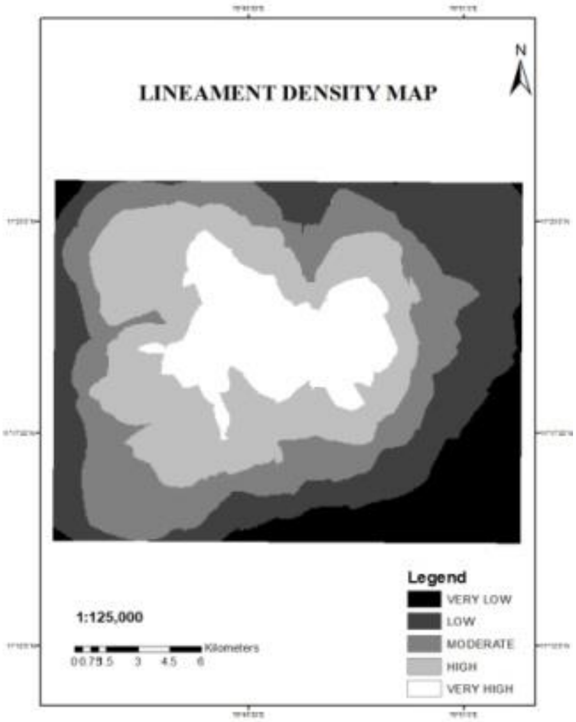


(a)

(b)

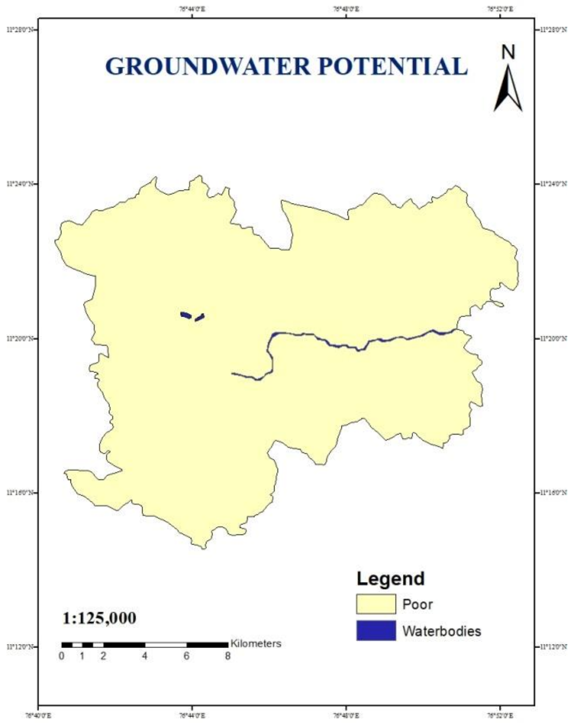
Fig 3 Different thematic layers used for the generation of landslide susceptibility map of the study area- (a) Soil (b) Geology

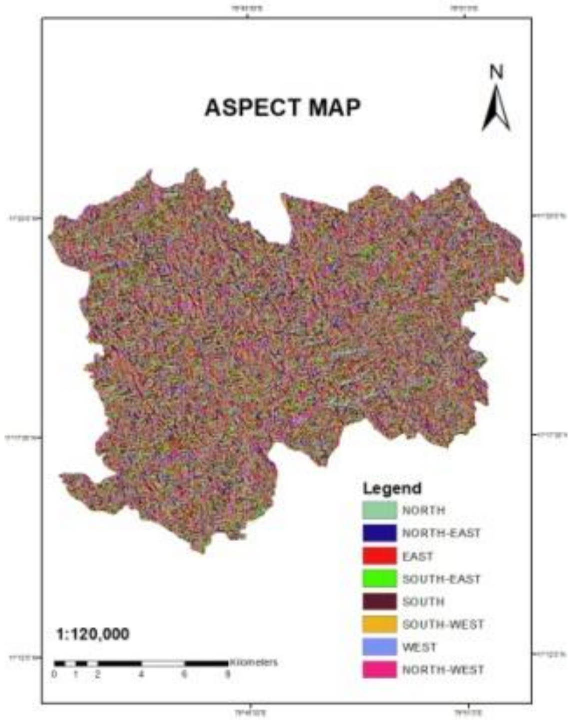


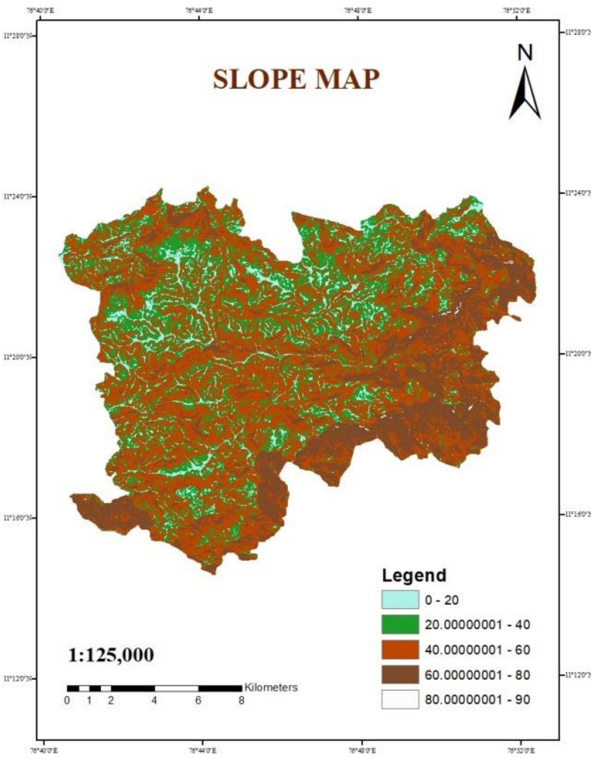


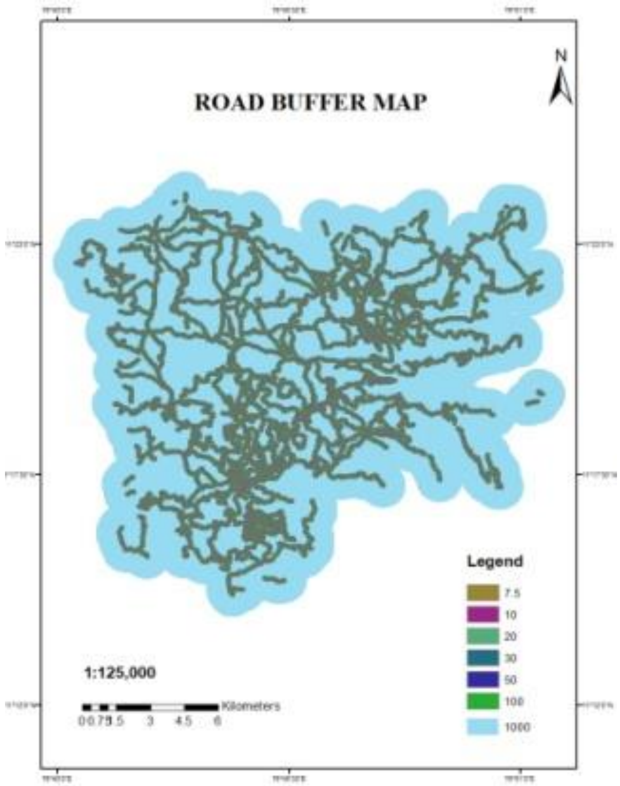
(c)

(d)









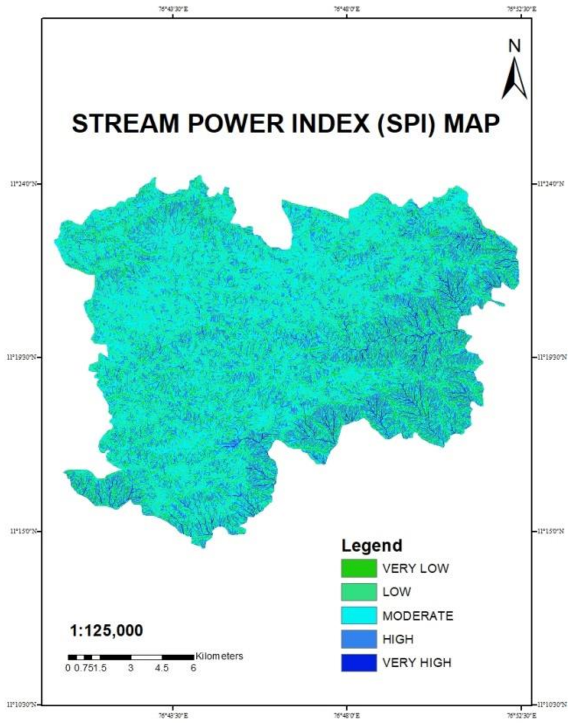
(e)

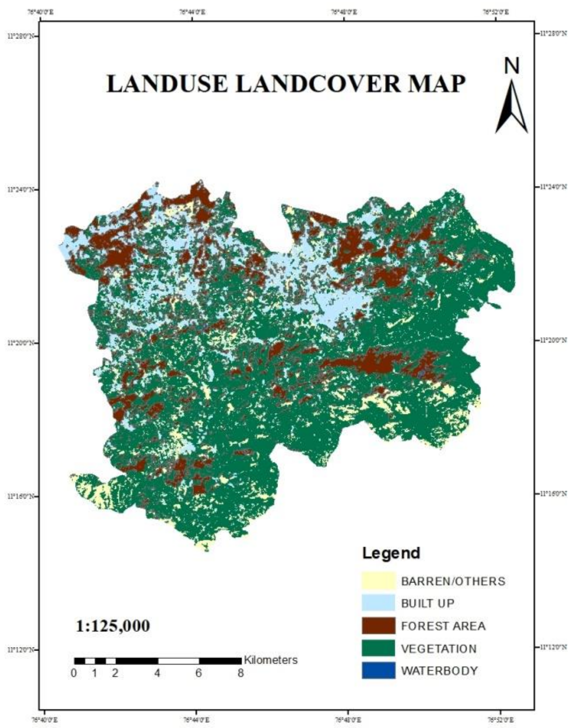
(f)

(g)

(h)

Fig 3 (contd.) (c) Geomorphology (d) Lineament density (e) Groundwater potential (f) Slope





(i)

(j)

Fig 3 (contd.) (g) Aspect (h) Road network (i) Stream Power Index (SPI) (j) Land Use Land Cover

B. Fuzzy membership and fuzzy overlay

The different thematic layers were reclassed on the basis of susceptibility ranks and the membership values were awarded. The fuzzy membership was provided in such a way that higher membership value depicts greater susceptibility to the hazard.

The resulting fuzzy membership layers were overlaid using fuzzy overlay by gamma function to generate the susceptibility map of the study area to the scale of 1:25000. Table 1 summarises the fuzzy membership ranges for each thematic layers while Figure 4 depicts the final susceptibility zonation map.

Table 1 Fuzzy membership values of reclassed thematic layers

SL.NO	LAYER	FUZZY MEMBERSHIP RANGE
1	Road	0.0574281-0.999024
2	Stream Power Index (SPI)	0.00190035-0.93673
3	Aspect	0.0632701-0.9981
4	Geology	0-1
5	Geomorphology	0-1
6	Groundwater	0.116364-0.808208
7	Landuse Landcover	0.00190035-0.93673
8	Lineament density	0.0721496-0.995902
9	Slope	0.00409836-0.92785
10	Soil	0.00409836-0.92785

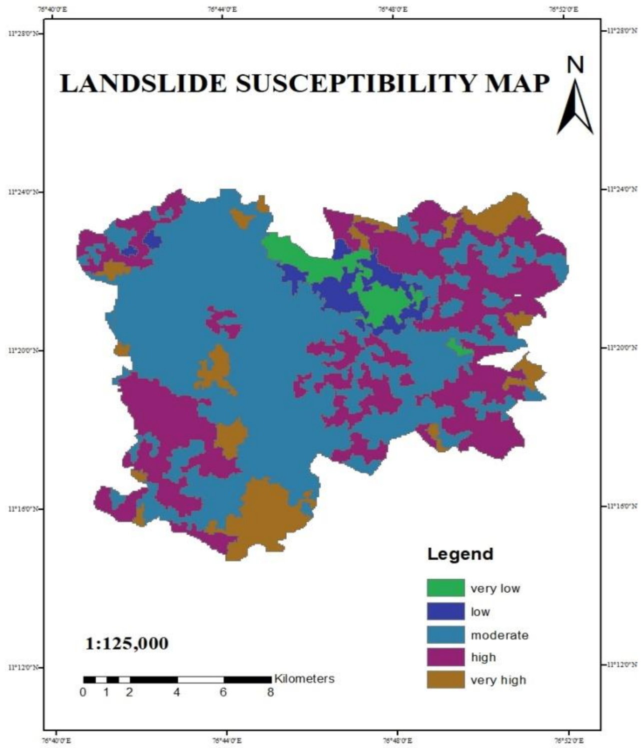


Fig 4 Landslide susceptibility map

The landslide susceptibility map generated for the study area using fuzzy overlay had an output membership value range of 0-0.751124024 and it was reclassed into five classes, namely, very low, low, moderate, high and very high based on the natural breaks method. Of the total area, it was evident that majority of the study area fell in the zone of moderately susceptible and highly susceptible zones.

C. Accuracy assessment of generated susceptibility map

It can be noted from the susceptibility map that 33.16% of the build up area falls under the low risk zone while the moderate and high risk zone of built up area accounts to 46.57%, indicating the possibility of influence of anthropogenic activities in triggering the landslide. It was further validated by assessing the past occurrences, which depicted that about 5 out of 9 past landslides in the built up area took place in moderate and high risk zones. Table 2 sums the percent area in each susceptible zone and the number of past occurrences in each zone.

Table 2 Areal extent of different susceptibility zones in the study area

ZONE	AREA (PERCENTAGE)	NO. OF LANDSLIDE OCCURRENCES
Very low	3.64	0
Low	22.4	3
Moderate	29.68	14
High	30.62	11
Very high	13.65	3

Similar trend could be observed in the forest areas wherein about 30.36% of area falls under high risk area while the moderate zone occupies 30.67%. About 48.73% of area occupied by vegetation falls into high and very high zones while the moderate and high risk zones accumulate to 57.93% of total area in the barren feature. Table 3 displays the percent areal extent of different features in different susceptible zones.

Table 3 Percent area occupied by different zones in different features

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
BUILT UP	12.82	33.16	26.99	19.58	6.2
VEGETATION	1.47	17.12	27.88	32.46	16.27
FOREST AREA	2.33	22.8	30.67	30.36	12.23
BARREN/OTHERS	3.16	24.8	30.25	27.68	9.86

It could be also inferred by correlating susceptibility map and slope map that most of the landslides, about 22 in numbers out of total 31 considered, have occurred in the range of 30°-60° while there was nil occurrences recorded in flat (0°-15°) and a minimal in very high slopes . Similar scenario was observed when the areas nearer to the road had more incidents recorded and downhill slopes of directions classified as high risk in aspect map falling in high and very high categories in the final susceptibility map. On correlating the final susceptibility map and past occurrences with the stream power index map, it could be observed that all the past occurrences and the areas of high and very high risk zones were classified as the zones of greater susceptibility in the SPI map. This further gave an indication of the accuracy of the generated susceptibility map, supported by the past occurrences to use as a tool for hazard management and developmental planning in the study area.

VI. CONCLUSION

In general, for the prediction of future landslide occurrences, it is believed that the areas in which the landslides have happened in the past, are likely to occur in the future i.e., under similar conditions [11] [12]. This has been the primary principle of the qualitative mapping methods of landslide hazard while the quantitative counterparts rely on the correlation between causal factors and the hazard. While the conventional methods were tough and time-investing, with the development of GIS and remote sensing technology, there has been a shift in emphasis occurred from local studies of single event or landslide to regional and synoptic assessment of regional susceptibility or risk.

With the optimal selection of causal factors, the outputs can be achieved with high accuracy than with the consideration of more number of factors. This paper, which aimed at formulating a landslide susceptibility map for the region of Coonoor and validating with past landslide occurrences, gave a fairly good qualitative correlation among the susceptible zones and past happenings recorded, and thus, presenting itself as an aid in planning and implementing the mitigation measures. Uncertainties happened to exist in terms of non-availability of past occurrences data due to unreported incidents, which ruled out the employment of quantitative analysis while scope could be extended in taking into consideration, other factors like precipitation, compound topographic index, depth of groundwater table, etc. and mapping at cadastral level to manage resources.

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