Development of landslide susceptibility maps of Tripura, India using GIS and analytical hierarchy process

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Abstract

Landslides are one of the most extensive and destructive geological hazards in the globe. Tripura, a north-eastern hilly state of India experiences landslides almost each year during monsoon season causing casualty and huge economic losses. Hence it is required to assess the landslide susceptibility of the area that would support in short and long term planning and mitigation. Analytic hierarchy process (AHP) integrated with geospatial technology has been adopted for landslide susceptibility mapping in the state. Eight influencing factors such as slope, lithology, drainage density, rainfall, land use land cover, distance from riversand roads, and soil type were selected to map the landslide susceptibility. Landslide susceptibility index (LSI) was found to vary from6.205 during monsoon to 1.427 during post-monsoon season. The LSI values were classified intovery high, high, moderate, low and very low susceptibility. Landslide susceptibility maps for three different seasons, namely, pre-monsoon, monsoon and post-monsoon were prepared. The study showed that most of the areas of the state come under very low to moderate landslide susceptibility zones. Around 73.2% area of the state is found to be under low landslide susceptible zones during the pre-monsoon season, around 62% area is prone to landslides with moderate susceptibility during monsoon season and 68.5% area comes under landslides with low susceptibility zones during the post-monsoon season. The output of this study may be referred by the engineers and planners for the assessment, control and mitigation of landslides and development of basic infrastructure in the state.

Key words: Analytical hierarchy process, Consistency ratio, GIS, Landslide susceptibility maps, Landslide susceptibility index

Introduction:

Landslide is anatural hydro-geological hazardin which earth material is dislodged under the influence of gravity triggered byintense rainfall, earthquake, volcanic activity, changes in groundwater and anthropogenic activities. The occurrence of landslides is common in geo-dynamically sensitive zones and areas affected by frequent earthquakes and other tectonic activities (Bolt 1975). Landscape changes, threat to life, destruction of property and damage to natural resources are some of the major consequences of landslides. Environmental forcesareresponsible for such catastrophes that are mostly enforced by human induced activities such as deforestation and mining (Pour and Hashim2014; Hashim et al. 2014). Other human interventions such as construction of buildings, roads and railways, and hydropower projects also disturb the natural slopes thereby making the hills more susceptible to landslides. In recent times, the occurrence of landslides has increased both in intensity and frequency resulting from a combination of several such attributes causing instability in land slope. This trend is likely to continue in future also because ofrapid urbanisation, deforestation and increased regional precipitation intensity resulting from climate change in landslide-prone areas.

According to the CRED (2009), landslides accounted for about 4.4% of global natural disasters during 1990 - 2009,out of which about 2.3% of reported landslides occurred in Asia alone. Landslide and flooding are two most common natural hazards leading to huge economic losses and casualties in south-east Asia during the last few decades (Sharma and Priya 2001; Sanders 2007). About 12.6% of the total land of India (i.e. 42 million ha) is prone to landslides. According to a study by the Sheffield University, UK, the country was highly affected by human-triggered fatal landslides during theperiod 2004-2016 accounting to about 18% of global deaths.

Landslide activities are prevalent in the tectonically active north-easternhilly terrains of Indiathat lead to severe damagesto the roads and residential areas (Gurugnanam et al. 2012). These zones mostly fall under mega-earthquake prone zones and are worst affected by landslide problems of a bewildering category. According to EM-DAT (2009) about 10%population of India was affected by natural disasters in 2008, of whichabout 0.5% was affected by landslides. GSI (2009) reported that about 49 million ha area in India is vulnerable to landslide hazards, out of which 9.8 million ha is located in the north-eastern region of the country. Majority of the landslides in the country are mostly rainfall-induced. Other influencing factors are land slope, soil texture, percolation, seasonal changes in soil moisture and degree of saturation with depth.

Successful mitigation of disasters resulting from landslides requiresin-depth knowledge about the character, expected frequency and magnitude of the mass movement in an area (Pandey et al. 2008). Hence, the determination of high potential landslide areas is essential for better decision making and land-use planning. But the collection of data from inaccessible areas like hilly regionfor predicting landslide susceptibility becomes almost impossible. It can be solved with the help of remote sensing and geographic information system (GIS).GIS, a computer-based system having excellent spatial data handling and processing capacity, has extensive applications in disaster assessment (Carrara et al. 1999). Remote sensing plays important role in the development of landslide inventory and generation of landslide susceptibility maps of a region (Shahabi and Hashim 2015; Fell et al. 2008). It is gaining importance on landslide studies due to its wider coverage and increasing spatial and temporal resolution. Remote sensing has been widely adopted by government agencies as well as the research community for landslide mapping, which isessential for rapid response and recovery after the occurrence of the hazard. GIS integrated with remote sensing data has been an effective tool in geological analysis and the development of landslide susceptibility maps (Pradhan 2010; Pour and Hashim 2015;Arsyad and Hamid 2020). In recent timesaccessibility and availability of a variety of remote sensing data has made it been possible to prepare landslide hazard mapsusing thematic layers of landslide causative factors prepared using the GIS.

Analytical hierarchy process (AHP),a semi-quantitative multi-criteria decision making technique, is most often used for regional susceptibility studies. It is based on comparative judgement and synthesis of priorities among a set of causative factors (Saaty 1980;Yalcin and Bulut 2007;Yalcin 2008). The AHP allows the user to arrive at a preference scale drawn from a set of alternatives (Semlali et al. 2019). It generates weights for each criterioninvolved in the analysis according to the pairwise comparison of the criteria of the decision makers. The weigtage of any criterion decides its importance in the decision making process. The higher the weight the more important the corresponding criterion is.

Landslide susceptibility mapping or identification of landslide-prone areasis considered to be an integral part of landslide hazard management. It is one form of hazard zonation that includes the spatial distribution of various causative factors contributing to the instability processes. Landslide susceptibility maps help in determining landslide-prone areas without any temporal implication (Brabb and Pampeyan 1972). Both quantitative and qualitative approaches are involved in the development of landslide susceptibility maps(Aleotti and Chowdhury 1999). Quantitative methods involve numerical expressions of the landslide controlling factors (Guzzetti et al. 1999; Raman and Punia 2012), whereas qualitative methods depend on the opinions of experts and are often useful for regional assessment (Van Westen et al. 2003). Assessment of landslide hazard and risk reduction can be achieved only if accurate information on risk management is available. Landslide susceptibility mapsgenerated using remote sensing data has been proven to be an important source of information for the scientists and researchers associated with private and public sectors at the regional and international levels (Razak et al. 2013; Hashim et al. 2013; Shahabi and Hashim2015; Sura et al. 2020).

Occurrences of new landslides and reactivation of the old landslides are mainly responsible for frequent disturbancesin the National Highway of Tripura, which is considered to be the lifeline of the state (Ghosh et al. 2017). Tripura, being a hilly state receives a high average annual rainfall of about 2300 mm, which triggers most of the landslide incidents in the state. Hence, it is essential to identify vulnerable areas prone to landslides and prepare landslide susceptibility maps, which will help the scientists, researchers and the decision makers to undertake suitable measures to cope up with this natural cause. Keeping the above facts in view the present study has been undertaken to identify the critical factors causing landslides and to develop landslide susceptibility maps of the state of Tripura (India) using remote sensing, GIS and analytical hierarchy process (AHP).

Materials and methods:

Study area:

The state of Tripurais located in the north-eastern region of India (Fig. 1) and covers an area of about 10,492 km^2. It lies between the latitudes 22°56' –24°32' N and longitudes 91°09' – 92°20' E. The state has five hills running north to south, which are anticlinal.BetlingShib in the Jampui range is the state's highest point with an altitude of 939 m above mean sea level.The annual rainfall rangesbetween1,980 to 2,746 mm. The winter temperature ranges from 13 to 27 °C,whereas the temperature during summer falls between 24 and 36 °C.The soils of Tripura can be classified into five major groups.Red loam and sandy loam occupy 43.1% of the total area. Reddish yellow-brown sandy soils cover 33.1% area of the state.Other three groups namely,older alluvial soils, younger alluvial soils, and lateritic soils occupy less than 10%area each. In the study area, the main cause of landslides is the failure of slopesdue to high intensity rainfall during the monsoon season.

Fig. 1 Location map of the study area

Sources of data and Preparation of thematic maps

Different types of primary and secondary data were used to prepare the seasonal landslide susceptibility maps of Tripura state. Some of the data were generated from satellite imagery while some were developed or collected from potential sources. The development of landslide susceptibility maps of the study area involves the preparation of thematic layers of the landslide causative factors. Eight factors such as land slope, drainage density, distance from rivers, distance from roads, land use land cover (LULC), lithology, rainfall and soil types were chosen based on experts' opinions and past studies. These criteria have direct or indirect impact and can be considered as the triggering factors for the occurrence of landslides (Sarkar and Kanungo 2004; Ghoshet al.2017; Semlaliet al. 2019).

Convectional/existing layers such as lithology and soilmaps used in the study were obtained from different sources (Table 1). These maps were scanned and introduced into ArcGIS 10.6.1 for generation of thematic layers by properly following the rectification and digitalization process. LULC map was taken from the National Remote Sensing Centre (NRSC), Hyderabad. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was extracted from the US Geological Survey (USGS) website. The maps and the summary of their source and other details are given in Table 1. All the thematic layers were prepared using ArcGIS software.

The slope map anddrainage density map of the area understudy were generated from the SRTM DEM using spatial analyst tool in ArcGIS.Mapsshowing the distances from rivers and roads were generated from the DEM using the Euclidean distance tool in ArcGIS. Average rainfall maps for three different seasons such as pre-monsoon (March to May), monsoon (June to October) and post-monsoon (November to February) were prepared from the daily rainfall data of seven rain gauge stations (Agartala, Amarpur, Dharmanagar, Khowai, Sabroom, Sakhan, and Sonamura) within the study area. The rainfall data for a period of 22 years (1998 to 2019) was downloaded from the NASA Power Data Access Viewer website. The daily data was converted to seasonal data considering three seasons as stated above.Inverse distance weighting (IDW) interpolation technique in ArcGIS was used to prepare the seasonal rainfall maps.

Table 1 Summary of data sources

Sr. No.	Data	Source	Year	Scale/ Resolution
1	SRTM DEM	USGS Earth Explorer	2014	30 m
2	LULC map	National Remote Sensing Centre (NRSC), Hyderabad	2015-16	1:50,000
3	Geology map	Geological survey of India (GSI)	2018	1:50,000
4	Soil map	FAO harmonized world soil data base	2007	1:5,00,000
5	Road map	MapCruzin website	-	1:50,000
6	Daily Rainfall data	NASA Power data access viewer portal	1998-2019	-

Analytical Hierarchy Process (AHP):

Analytical hierarchy process (AHP) (Saaty 1980), a multi-criteria decision-making (MCDM) method, was used to assign weightage to different thematic layers based on their influence on the occurrence of landslides. The AHP is a method of measurement through pairwise comparison of landslide causative factors, which is based on experts' judgmentsfor deriving priority scales (Maheswaranet al. 2016). Human judgement is not always consistent. Hence, the MCDM method allows for some small inconsistency in judgment. Generally, AHP involves the following steps: (1) breaking down a complex unstructured problem into its components; (2) arranging the factors causing landslides in aorder following specific hierarchy; (3) assigning numerical values to each factor based on their relative importance; and (4) analyzing the judgments for determining priorities to be assigned to all the factors (Saaty and Vargas 2001).

In this method, relative weights were determined after consulting with the Experts and following the past studies.The weights were then assigned to different thematic layers and their features on the scale of 1 to 9 based on their influence on landslide susceptibility. Higher weights represent higher influences and the weight reduces with the reduction in landslide susceptibility. The criteria were then compared in pairs separately by constructing a pair-wise comparison matrix by rating every parameter against every other parameter by assigning values between 1 and 9. The reciprocal weights 1/2 to 1/9 were also used for inverse comparison. Table 2 shows the measurement scale of AHP as suggested by Saaty (1980).

Table 2 Measurement scale of AHP (Saaty, 1980)

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

In this hierarchical classification approach, the consistency of weights assigned to different layers was checked by calculating the consistency ratio (CR). This step was used to detect any inconsistencies in the comparison of the importance of each pair of criteria. The CR can be expressed as:

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

Where, CI is the consistency index and RI is the random consistency index.

The consistency index can be calculated as:

$$\mathrm{CI} = \frac{(\lambda_{max} - n)}{(n - 1)}$$

Where,λ_{max} is the principal eigenvalue and $n$represents the number of criteria or factors.

The RI is a value that depends on the size of matrix or the number of parameters used for pair-wise comparison (Table 3). According to Saaty (1980), the value of CR must be less than 10% for the weights to be consistent.Otherwise, re-evaluation of the corresponding weights should be done to avoid inconsistency.

Table 3 Random consistency indices for matrices of various sizes

Matrix size	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.21	1.24	1.32	1.41	1.45	1.49

Generation of landslide susceptibility maps

The landslide susceptibility maps of Tripura state were prepared using AHP technique. After generating the thematic layers, the landslide susceptibility index (LSI) value for each considered pixel was computed. LSI helps in indexing the probable landslide susceptible zones, which is a dimensionless quantity. The LSI value for each pixel was calculated by multiplying the eigenvector (weight of causative factors) with the eigenvector of the classes of the causative parameters. The cumulative LSI value was then calculated using the following expression.

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

Where, LSI = Landslide susceptibility index,

R_i = class weight (or rating value),

W_i = factor weight for factor i, and

n = total number of factors or parameters.

On the basis of LSI values, the study area was divided into five classes, namely very low, low, moderate, high, and very high zones susceptible to landslides. The landslide susceptibility maps for winter, pre-monsoon, monsoon and post-monsoon seasons were prepared using the weighted sum tool in ArcGIS software.

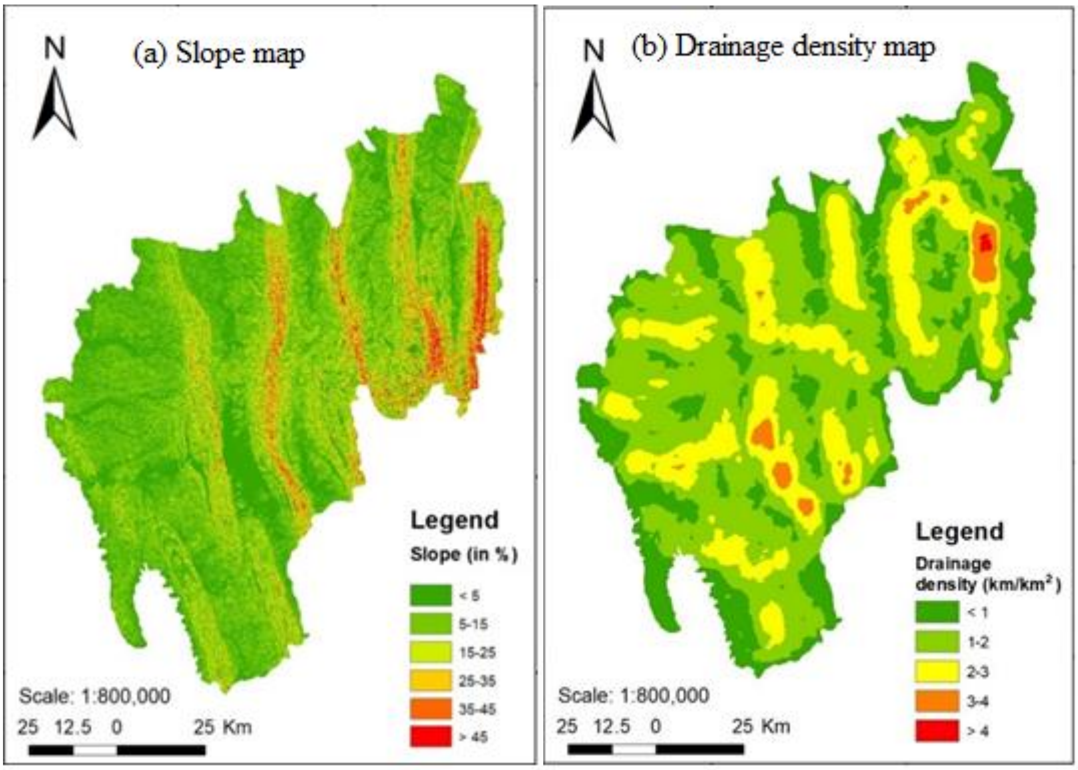
Results and Discussion

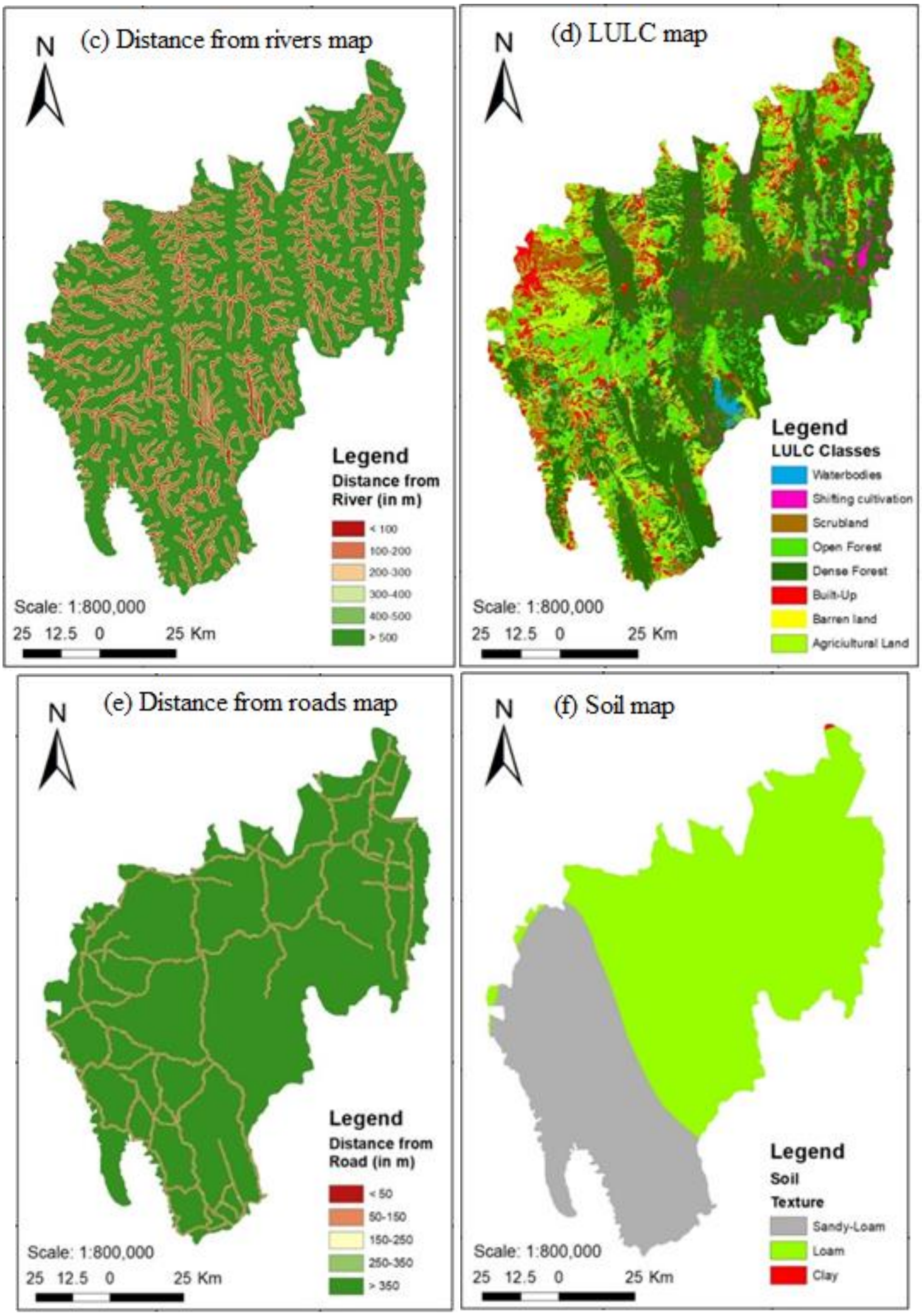
Thematic maps of Tripura State

The landslide susceptibility maps of Tripura State were prepared in the GIS platform considering eight landslide causative factors. The thematic maps of all the factors were generated.Pair-wise comparison matrices of all the factorswere prepared separately based on the weights assigned to different sub-classes. The weights in the scale of 1 to 9 (Saaty 1980) were assigned following past studies and the opinions of experts. As landslide susceptibility of different classes of any theme increases with increase in their weights, a weight value of one was assigned to the feature class having least landslide susceptibility. Accordingly, the CR values for individual factors were calculated. The weights of different classes or sub-themesof the causative factors were marginally modified till the value of CR in each case wasfound to be less than 10%.Accordingly, the influences of different sub-themes of all factors were predicted to prepare the maps of different features.

Slope map

The slope of any terrain makes the soil more vulnerable to landslides. In areas having gentle slope, the velocity of flow is low, which allows the runoff water to get absorbed into the soil, whereas steep slope areas facilitate high-velocity surface runoff and make the landmass susceptible to landslides (Choudhari et al. 2014).The slope map was further classified into six classes: <5, 5-15, 15-25, 25-35, 35-45 and >45% (Fig. 2a). The weights of the slope classes were assigned based on experts' opinions and past studies, that range from 1 to 9, where 9 means the highest susceptible area for landslide and 1 means the least susceptible area. Normalization of weights wasdone using AHP and the eigenvector technique. The influence of slopes of different classes on landslide susceptibility was found to vary from 46.2% for slopes more than 45% to 3.1% for slopes less than 5% (Table 4).





(c) Distance from rivers map
N
Legend
Distance from River (in m)
< 100
100-200
200-300
300-400
400-500
> 500
Scale: 1:800,000
25 12.5 0 25 Km
(d) LULC map
N
Legend
LULC Classes
Waterbodies
Shifting cultivation
Scrubland
Open Forest
Dense Forest
Built-Up
Barren land
Agriciultural Land
Scale: 1:800,000
25 12.5 0 25 Km
(e) Distance from roads map
N
Legend
Distance from Road (in m)
< 50
50-150
150-250
250-350
> 350
Scale: 1:800,000
25 12.5 0 25 Km
(f) Soil map
N
Legend
Soil
Texture
Sandy-Loam
Loam
Clay
Scale: 1:800,000
25 12.5 0 25 Km

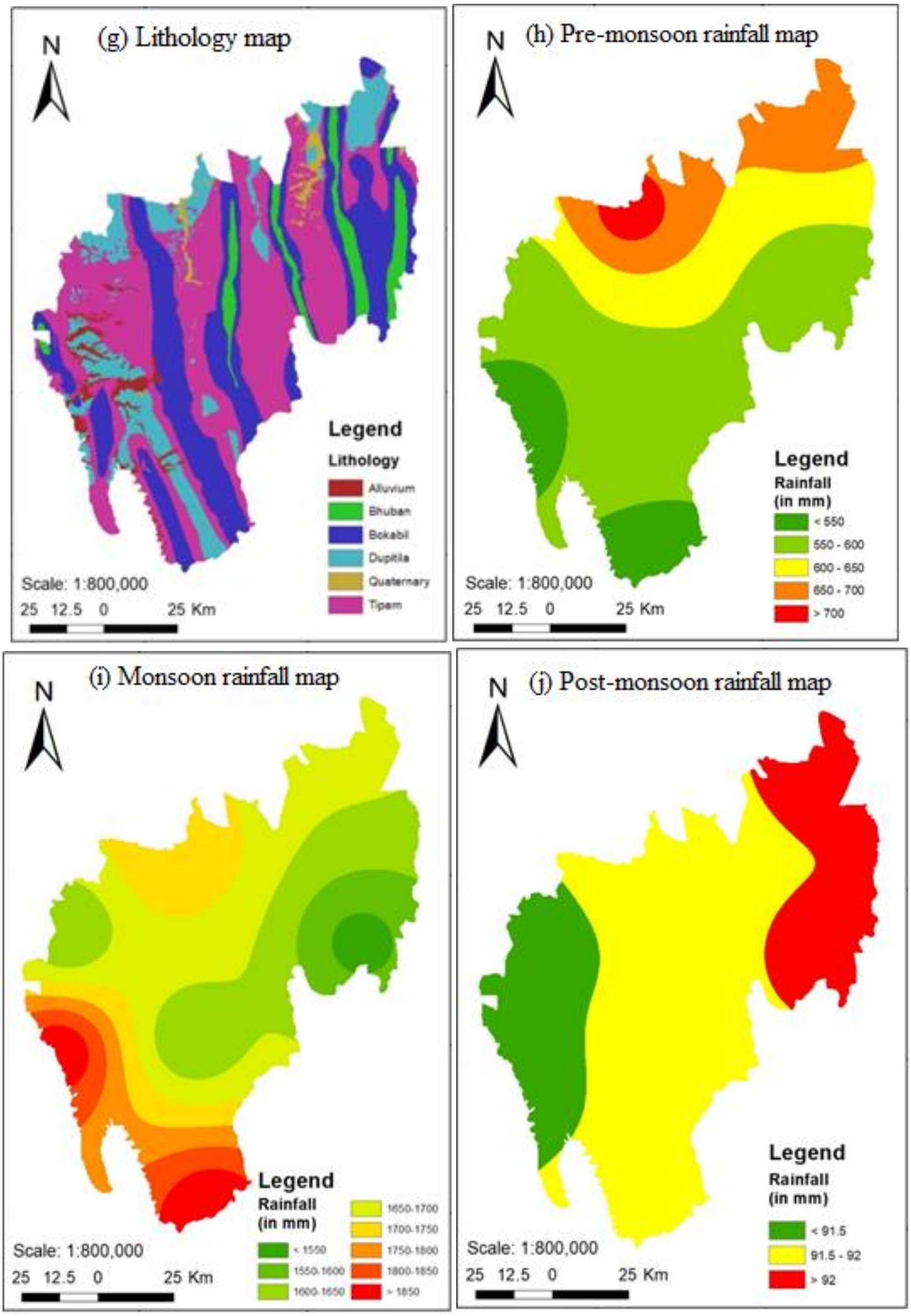


Fig. 2 Thematic layers of various landslide causative factors

Table 4 Normalized weight (NW) of different classes of landslide causative factors

Slope (%)	**NW**	**Drainage density (km/km^2)**	**NW**	**Distance from rivers (m)**	**NW**	**Distance from roads (m)**	**NW**
<5	0.031	<1	0.062	<100	0.389	<50	0.503

5-15	0.046	1-2	0.099	100-200	0.261	50-150	0.260
15-25	0.069	2-3	0.161	200-300	0.171	150-250	0.134
25-35	0.138	3-4	0.262	300-400	0.095	250-350	0.068
35-45	0.254	>4	0.416	400-500	0.051	>350	0.035
>45	0.462			>500	0.033		
Lithology	**NW**	**Soil**	**NW**	**Land Use Land Cover**	**NW**	**Rainfall (mm)**	**NW**
Alluvium	0.043	Clay	0.106	Water body (1)	0.021	<200	0.019
Quaternary	0.065	Loam	0.260	Dense forest (2)	0.029	200- 400	0.026
Dupitila	0.102	Sandy-Loam	0.633	Open forest (3)	0.041	400- 600	0.037
Tipam	0.160			Built-up (4)	0.080	600- 800	0.053
Bokabil	0.249			Agriculture (5)	0.112	800-1000	0.076
Bhuban	0.379			Scrubland (6)	0.160	1000-1200	0.109
				Barren land (7)	0.229	1200-1400	0.154
				Shifting cultivation (8)	0.328	1400-1600	0.218
						>1600	0.307

Drainage density map

The ratio of the total length of all streams within the watershed to the watershed area both measured in consistent units is called drainage density. It has been found that increased drainage density causes slope failure (Panigrahi 2013). Onda (1993) reported that the damage occurred by shallow seated landslide to the terrains having higher drainage density and thin soil layer was comparatively more pronounced.

The drainage density map was further classified into five categories such as <1.0, 1.0-2.0, 2.0-3.0, 3.0-4.0 and >4.0 km/km^2 (Fig. 2b). The weights were assigned to different classes based on the expert's opinion and theinformation available in the literature. The class defining the area of less drainage density got lower weight while the class representing more drainage density was assigned higher weight. The weights were normalized using AHP and eigenvector technique. The influence of drainage density of different classes on landslide susceptibility was found to vary from 41.6% for drainage density exceeding 4.0 km/km^2 to 6.2% for drainage density lower than 1.0 km/km^2 (Table 4).

Distance from rivers map

Distance from rivers controls the stability of slope. The degree of saturation of slope materials affectsthe stability of slope directly. Streams erode the slopes and affect the stability by saturating the lower part of the slope until the water level is increased (Dai et al. 2002; Sahaet al. 2005). The distance from river map was classified into six classes having varied distance from rivers such as <100, 100-200, 200-300, 300-400, 400-500 and >500 m (Fig. 2c). The weights given to different classes are based on the experts' opinions and past studies. The area nearer to the rivers are more susceptible to the landslide and hence, given highest weight while the area far from the river was assigned lowest weight as their influence on the occurrence of landslide is very less. The assigned weights were then normalized. The influence of distance from rivers of different classes on landslide susceptibility was found to vary from 38.9% for distance lower than 100 m to3.3% for values exceeding 500 m (Table 4).

Land Use and Land Cover map

Land use land cover (LULC) is another important factor responsible for the occurrence of landslides as the occurrence of a landslide is inversely related to the density of vegetation.Barren lands are more susceptible to landslide activity than forest areas. Changes in vegetal cover often lead to change inbehaviour of landslide (Glade 2003). There is a strong linkage between surface runoff and the agricultural land use (Srivastava et al. 2020). Modification in agricultural land use results in alteration in infiltration and surface runoff and thereby triggers landslide occurrence.Eight LULC classes such as water body, dense forest, open forest, built-up, agriculture, scrub land, barren land and shifting cultivation were considered (Fig. 2d). The weights assigned to different classes were used based past studies and the expert's opinions. The influence of shifting cultivation towards landslide susceptibility was found to be the highest at 32.8%, whereas it was least at 2.1% only for water bodies (Table 4).

Distance from roads map

The nature of topography is changed by construction of roads, and hence, the possibility of landslides increases on slopes intersected by roads. It reduces the shear strength at the toe of the slope and causes infiltration of water in the slopes. A drop-down road section is susceptible to landslides because it behaves like a wall, a net source or sink, or a corridor for water flow, depending on its location in the mountains (Ayalew and Yamagishi 2005; Yalcin 2008).

The study area was classified into five different categoriesthatmark the influence of roads on landslide susceptibility. The different classes such as <50, 50-150, 150-250, 250-350 and >350 m were given weights based on their distances from the roads (Fig. 2e). Higher weights were assigned to the class nearer to the roads and lower weights were giver to the class far from the roads. The influence of distance from roads of different classes on landslide susceptibility was found to vary from 50.3% for distance lower than 50 m to 3.5% for values exceeding 350 m (Table 4).

Soil map

The presence of loose surface soils increases landslides susceptibility. Landslide is activated when rainwater enter into the soil and get mixed with it. The topsoil cover on a slope has an influence on landslide occurrence as observed in the field. The study area was found to have three dominant soil textures such as sandy loam, loam and clay (Fig. 2f). Sandy loam soils are more susceptible to landslides compared to clay soils.Accordingly, weights were assigned to the different soil types based on their impact on the landslide. The influence of sandy loam, loam and clay soils were found to be 63.3, 26.0 and 10.6%, respectively (Table 4).

Lithology map

Lithology is one of the important factorsinvolved in landslide studies (Dai et al. 2001; Yalcin and Bulut 2007; Nefesliogluet al. 2008).Different lithological units have different degrees of susceptibility. It is widely accepted that lithology significantly influences the occurrence of landslides. This is due to the fact that the variations in lithology often lead to significant differences in the permeability and strength of rocks and soils.The map was classified into six classes, namely Tipam, Dupitila, Bokabil, Bhuban, Quaternary and Alluvium, which are the prominent classes available in the study area(Fig. 2g). The Bhuban lithological units were assigned maximum weight because this formation is characterized by a thinly bedded moderate to highly weathered sandstone shale. The weights were given to different formations based on the experts' opinions and past studies. The influence of Bhuban was found to be maximum at 37.9%, whereas the least influencing class was alluvium having 4.3% weight on landslide susceptibility (Table 4).

Rainfall maps

Rainfall is one of the important triggering factors for landslides. High intensity rainfall causes heavy runoff. Changes in soil moisture regime produce hydrostatic pressure. The mobilized shear resistance decreases with increase in pore water pressure, which is likely to cause shear instability. Average seasonal rainfall maps were prepared from the daily rainfall data that was collected for the last 22 years (1998 to 2019). It was found that the average seasonal rainfall ranges from 518.64 to 721.18 mm during pre-monsoon season (Fig. 2h). The study area experiences an average rainfall of 1534.67 to 1889.19 mm during the monsoon season (Fig. 2i)and the post-monsoon season receivesan average rainfall of 91.26 to 92.15 mmonly (Fig. 2j). The average seasonal rainfall was classified into nine classes such as <200, 200-400, 400-600, 600-800, 800-1000, 1000-1200, 1200-1400, 1400-1600 and >1600 mm, and weights were assigned to them (Table 4). The weights assigned were then normalized. The influence of average annual rainfall exceeding 1600 mm on landslide susceptibility was found to be maximum (30.7%). It reduced with decrease in average annual rainfall. The influence was only 1.9% at rainfall below 200 mm per annum (Table 4).

All the maps (thematic layers) were then arranged according to their impact on landslide, which was decided on the basis of relative weights derived based on experts' opinions and past studies. A pair-wise comparison matrix was prepared to find the influence of different factors on landslide susceptibility (Table 5). It can be seen from the table that the combined effect of land slope, lithology and soil has more than 70% influences on landslide susceptibility, with the land slope alone contributing about 33%. Soil and lithology has 16 and 23% influence on landslide susceptibility, respectively. All layers were then integrated to generate the final landslide susceptibility maps of the study area.The LSI values were calculated for different seasons using the AHP. It was found that the LSI has a minimum value of 1.427 during the winter season and a maximum value of 6.205 during the monsoon season. The LSI represents the relative susceptibility of a landslide. So, a higher LSI value denotes high landslide susceptible zone.

Table 5 Pair-wise comparison matrix of landslide causative factors

Landslide causative factors	Drainage density	Distance from rivers	LULC	Distance from roads	Rainfall	Soil	Lithology	Slope	Normalized weight	Influence
Drainage density	1	1/2	1/4	1/5	1/6	1/7	1/8	1/9	0.021	2.1
Distance from rivers	2	1	1/2	1/4	1/5	1/6	1/7	1/8	0.029	2.9
LULC	4	2	1	1/3	1/4	1/5	1/6	1/7	0.044	4.4

Distance from roads	5	4	3	1	1/2	1/3	1/4	1/5	0.079	7.9
Rainfall	6	5	4	2	1	1/2	1/3	1/4	0.112	11.2
Soil	7	6	5	3	2	1	1/2	1/3	0.159	15.9
Lithology	8	7	6	4	3	2	1	1/2	0.229	22.9
Slope	9	8	7	5	4	3	2	1	0.327	32.7
CR = 5.9%										

In order to prepare the landslide susceptibility maps using AHP and GIS, the LSI values were grouped into five different classes such as very low, low, moderate, high and very high. The study showed that most of the areas of the state come under very low to moderate landslide susceptibility zones (Table 6). During the pre-monsoon season 6.24, 73.19, 18.66, 1.80, and 0.11% of the total geographical area of the state comes under very low, low, moderate, high and very high landslide susceptible zones, respectively(Fig. 3a). It means that maximum percentage of area, i.e. 73.19% (around 7679 km^2) comes under low landslide susceptible during this season. During the monsoon season there is a shift of low landslide susceptibleareas towards moderate susceptibility covering 0.11, 29.27, 61.99, 8.30, and 0.34% of the state under very low, low, moderate, high and very high landslide susceptible zones, respectively(Fig. 3b). It depicts that around 62% (6504 km^2) area is prone to landslides with moderate susceptibility during monsoon seasonand the low landslide susceptible area reduces to about 29% (3071 km^2). As the monsoon recedes the susceptibility to landslides reduces following almost the similar trend as the pre-monsoon season (Fig. 3c) resulting in low to very low landslide susceptibility. Similarly, during the post-monsoon season, 21.12, 68.50, 9.78, 0.50, and 0.11% of the state comes under very low, low, moderate, high and very high landslide susceptible zones, respectively(Fig. 3c). It can be very well depicted from the figure that the valley regions of the state are highly prone to landslides.

Table 6 Distribution of landslide susceptibility zones

Landslide susceptibility zone	**Pre-monsoon**		**Monsoon**		**Post-monsoon**	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Very low	654.97	6.24	11.19	0.11	2215.34	21.12
Low	7679.07	73.19	3070.78	29.27	7186.63	68.50
Moderate	1957.38	18.66	6503.59	61.99	1026.35	9.78
High	188.61	1.80	870.34	8.30	52.24	0.50
Very high	11.66	0.11	35.80	0.34	11.13	0.11

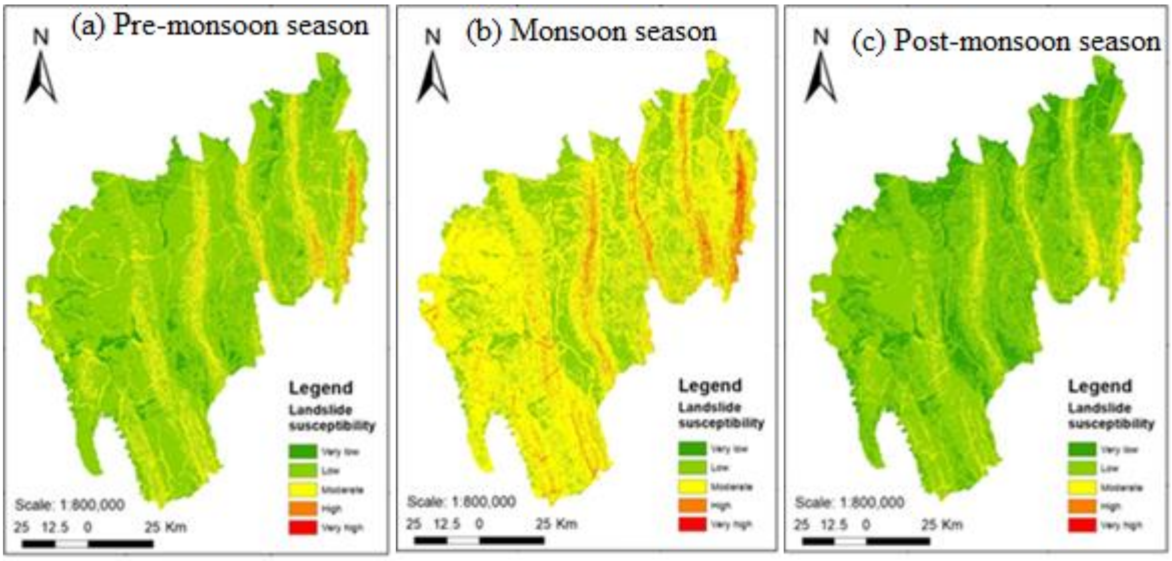


Fig. 3 Seasonal landslide susceptibility maps of Tripura state

Conclusions:

The landslide susceptibility study of the Tripura State of north-eastern India using GIS and AHP reveals that more than 40% of the study area has 5 to 15% slope and around 33% area has less than 5% slope. The highest slope for the study area is found to be about 69%. The drainage density of the area ranges from 0.059 to 4.29 km/km^2.The LULC map shows that more than 45% of the total geographical area of the state is covered with dense forest. The area under shifting cultivation, a triggering factor for the landslide, is 2.5%.The soil map represents that amongst the various types of soil found in the state, loam soil has the highest occurrence with 63% and clay soil has the lowest occurrence with 0.18%.

The study also depicts that around 45% of the study area has Tipam soil formations (containing ferruginous sandstone with siltstone and clay) and 30% area has Bokabil formations (containing sequence of sandy shale-sandstone-mudstone).During pre-monsoon season 73.2 and 18.7% of the area comes under low and moderate landslide susceptible zones covering about 7679 and 1957 km^2, respectively. During the monsoon season the susceptibility to landslide increases with the moderate landslide susceptible area increasing to about 62% and the low landslide susceptible area reduces to about 29%. Though the state is not highly susceptible to landslides, still its percentage is 8.3% during the monsoon season covering an area of around 870 km^2. As the monsoon recedes the susceptibility to landslides reduces following almost the similar trend as the pre-monsoon season resulting in low to very low landslide susceptibility.The landslide susceptibility maps will help the scientists/ planners to undertake precautionary measures to handle the hazard so that the possible cause of casualty and economic losses can be avoided up to certain extent.

Declarations

Funding – Not Applicable

Conflicts of interest/Competing interests – Not Applicable

Availability of data and material – All the data used in this study are available with the author(s)

Code availability – ArcGIS software has been used in this study, which is available with ESRI

Authors' contributions – All the authors have contributed significantly for the execution of this work

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Figures

Figure 1

Location map of the study area

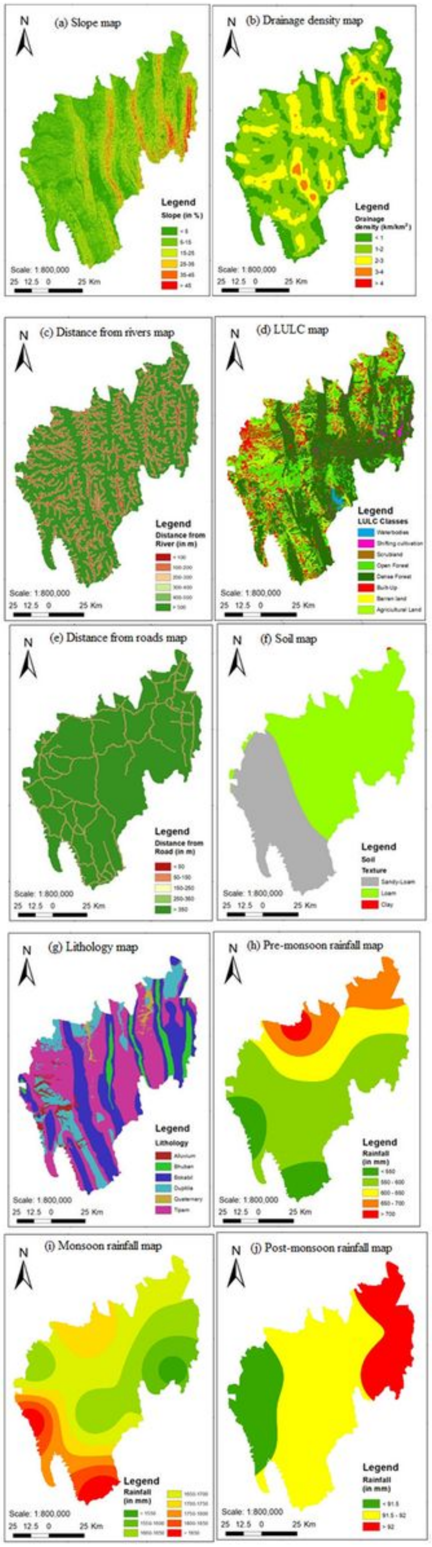

Figure 2

Thematic layers of various landslide causative factors

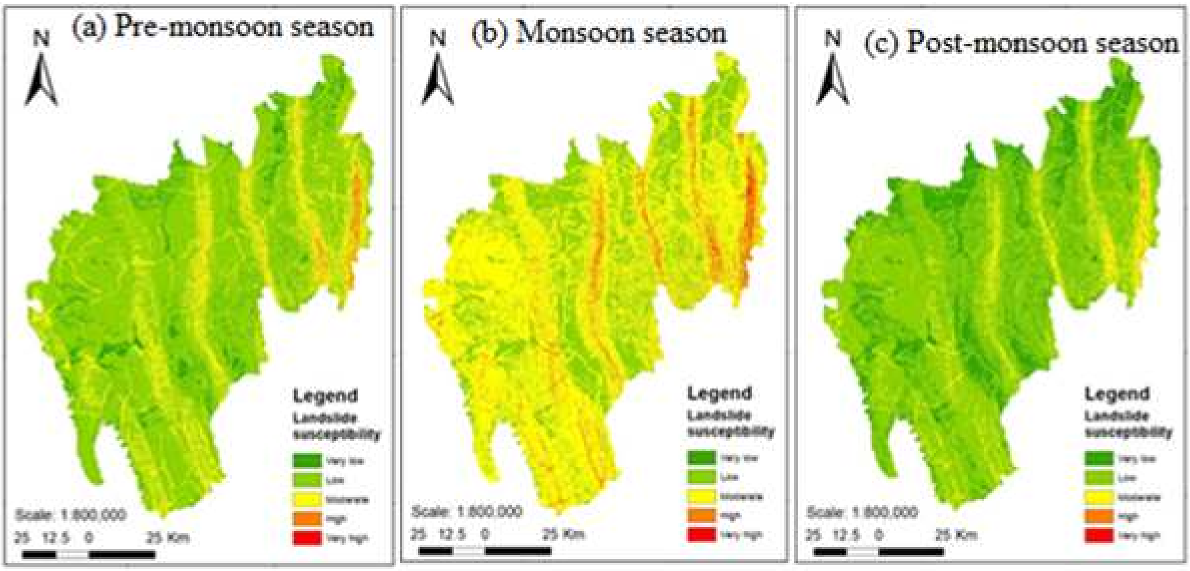

Figure 3

Seasonal landslide susceptibility maps of Tripura state