

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

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

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15

16 **Abstract**

17 Landslides are one of the most extensive and destructive geological hazards in the globe. Tripura, a north-
18 eastern hilly state of India experiences landslides almost each year during monsoon season causing casualty and
19 huge economic losses. Hence it is required to assess the landslide susceptibility of the area that would support in
20 short and long term planning and mitigation. Analytic hierarchy process (AHP) integrated with geospatial
21 technology has been adopted for landslide susceptibility mapping in the state. Eight influencing factors such as
22 slope, lithology, drainage density, rainfall, land use land cover, distance from rivers and roads, and soil type were
23 selected to map the landslide susceptibility. Landslide susceptibility index (LSI) was found to vary from 6.205
24 during monsoon to 1.427 during post-monsoon season. The LSI values were classified into very high, high,
25 moderate, low and very low susceptibility. Landslide susceptibility maps for three different seasons, namely,
26 pre-monsoon, monsoon and post-monsoon were prepared. The study showed that most of the areas of the state
27 come under very low to moderate landslide susceptibility zones. Around 73.2% area of the state is found to be
28 under low landslide susceptible zones during the pre-monsoon season, around 62% area is prone to landslides
29 with moderate susceptibility during monsoon season and 68.5% area comes under landslides with low
30 susceptibility zones during the post-monsoon season. The output of this study may be referred by the engineers
31 and planners for the assessment, control and mitigation of landslides and development of basic infrastructure in
32 the state.

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

35 **Introduction:**

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

48 According to the CRED (2009), landslides accounted for about 4.4% of global natural disasters during 1990 -
49 2009, out of which about 2.3% of reported landslides occurred in Asia alone. Landslide and flooding are two
50 most common natural hazards leading to huge economic losses and casualties in south-east Asia during the last
51 few decades (Sharma and Priya 2001; Sanders 2007). About 12.6% of the total land of India (i.e. 42 million ha)
52 is prone to landslides. According to a study by the Sheffield University, UK, the country was highly affected by
53 human-triggered fatal landslides during the period 2004-2016 accounting to about 18% of global deaths.

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

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

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

85 Landslide susceptibility mapping or identification of landslide-prone areas is considered to be an integral part of
86 landslide hazard management. It is one form of hazard zonation that includes the spatial distribution of various
87 causative factors contributing to the instability processes. Landslide susceptibility maps help in determining
88 landslide-prone areas without any temporal implication (Brabb and Pampeyan 1972). Both quantitative and
89 qualitative approaches are involved in the development of landslide susceptibility maps (Aleotti and Chowdhury
90 1999). Quantitative methods involve numerical expressions of the landslide controlling factors (Guzzetti et al.
91 1999; Raman and Punia 2012), whereas qualitative methods depend on the opinions of experts and are often
92 useful for regional assessment (Van Westen et al. 2003). Assessment of landslide hazard and risk reduction can

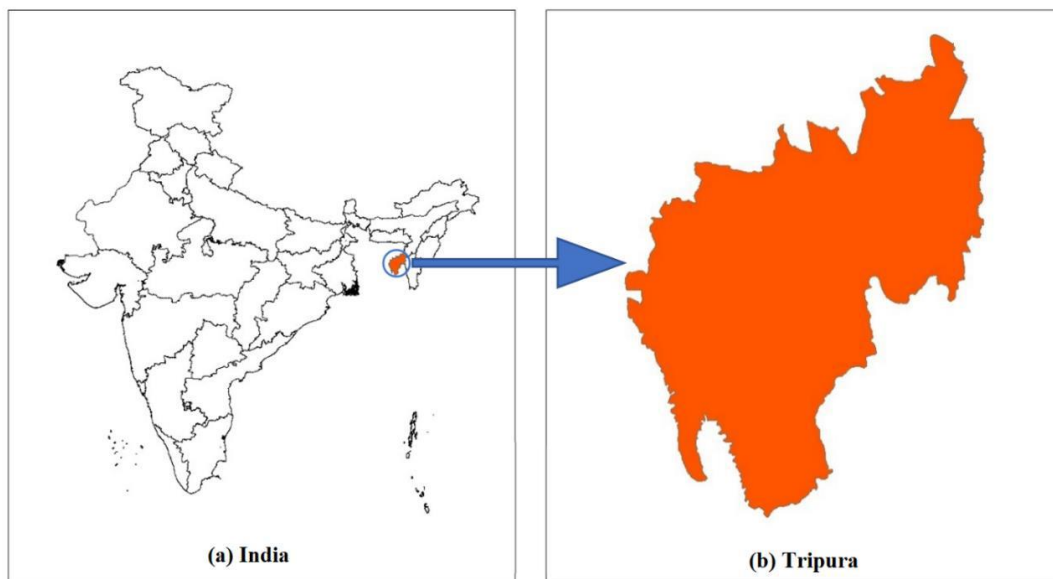
93 be achieved only if accurate information on risk management is available. Landslide susceptibility
94 maps generated using remote sensing data has been proven to be an important source of information for the
95 scientists and researchers associated with private and public sectors at the regional and international levels
96 (Razak et al. 2013; Hashim et al. 2013; Shahabi and Hashim 2015; Sura et al. 2020).

97 Occurrences of new landslides and reactivation of the old landslides are mainly responsible for frequent
98 disturbances in the National Highway of Tripura, which is considered to be the lifeline of the state (Ghosh et al.
99 2017). Tripura, being a hilly state receives a high average annual rainfall of about 2300 mm, which triggers most
100 of the landslide incidents in the state. Hence, it is essential to identify vulnerable areas prone to landslides and
101 prepare landslide susceptibility maps, which will help the scientists, researchers and the decision makers to
102 undertake suitable measures to cope up with this natural cause. Keeping the above facts in view the present
103 study has been undertaken to identify the critical factors causing landslides and to develop landslide
104 susceptibility maps of the state of Tripura (India) using remote sensing, GIS and analytical hierarchy process
105 (AHP).

106 **Materials and methods:**

107 **Study area:**

108 The state of Tripura is located in the north-eastern region of India (Fig. 1) and covers an area of about 10,492
109 km². It lies between the latitudes 22°56' – 24°32' N and longitudes 91°09' – 92°20' E. The state has five hills
110 running north to south, which are anticlinal. Betling Shib in the Jampui range is the state's highest point with an
111 altitude of 939 m above mean sea level. The annual rainfall ranges between 1,980 to 2,746 mm. The winter
112 temperature ranges from 13 to 27 °C, whereas the temperature during summer falls between 24 and 36 °C. The
113 soils of Tripura can be classified into five major groups. Red loam and sandy loam occupy 43.1% of the total
114 area. Reddish yellow-brown sandy soils cover 33.1% area of the state. Other three groups namely, older alluvial
115 soils, younger alluvial soils, and lateritic soils occupy less than 10% area each. In the study area, the main cause
116 of landslides is the failure of slopes due to high intensity rainfall during the monsoon season.



118 **Fig. 1** Location map of the study area

119

120 **Sources of data and Preparation of thematic maps**

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

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

135 The slope map and drainage density map of the area understudy were generated from the SRTM DEM using
136 spatial analyst tool in ArcGIS. Mapsshowing the distances from rivers and roads were generated from the DEM
137 using the Euclidean distance tool in ArcGIS. Average rainfall maps for three different seasons such as pre-
138 monsoon (March to May), monsoon (June to October) and post-monsoon (November to February) were
139 prepared from the daily rainfall data of seven rain gauge stations (Agartala, Amarpur, Dharmanagar, Khowai,
140 Sabroom, Sakhan, and Sonamura) within the study area. The rainfall data for a period of 22 years (1998 to
141 2019) was downloaded from the NASA Power Data Access Viewer website. The daily data was converted to
142 seasonal data considering three seasons as stated above. Inverse distance weighting (IDW) interpolation
143 technique in ArcGIS was used to prepare the seasonal rainfall maps.

144 **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	-

145 **Analytical Hierarchy Process (AHP):**

146 Analytical hierarchy process (AHP) (Saaty 1980), a multi-criteria decision-making (MCDM) method, was used
147 to assign weightage to different thematic layers based on their influence on the occurrence of landslides. The
148 AHP is a method of measurement through pairwise comparison of landslide causative factors, which is based on

149 experts' judgments for deriving priority scales (Maheswaran et al. 2016). Human judgement is not always
 150 consistent. Hence, the MCDM method allows for some small inconsistency in judgment. Generally, AHP
 151 involves the following steps: (1) breaking down a complex unstructured problem into its components; (2)
 152 arranging the factors causing landslides in order following specific hierarchy; (3) assigning numerical values to
 153 each factor based on their relative importance; and (4) analyzing the judgments for determining priorities to be
 154 assigned to all the factors (Saaty and Vargas 2001).

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

162
 163

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

164

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

$$168 \quad CR = \frac{CI}{RI}$$

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

170 The consistency index can be calculated as:

$$171 \quad CI = \frac{(\lambda_{max} - n)}{(n - 1)}$$

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

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

176

177 **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

178

179 **Generation of landslide susceptibility maps**

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

186
$$LSI = \sum_{i=1}^n (R_i \times W_i)$$

187 Where, LSI = Landslide susceptibility index,

188 R_i = class weight (or rating value),

189 W_i = factor weight for factor i , and

190 n = total number of factors or parameters.

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

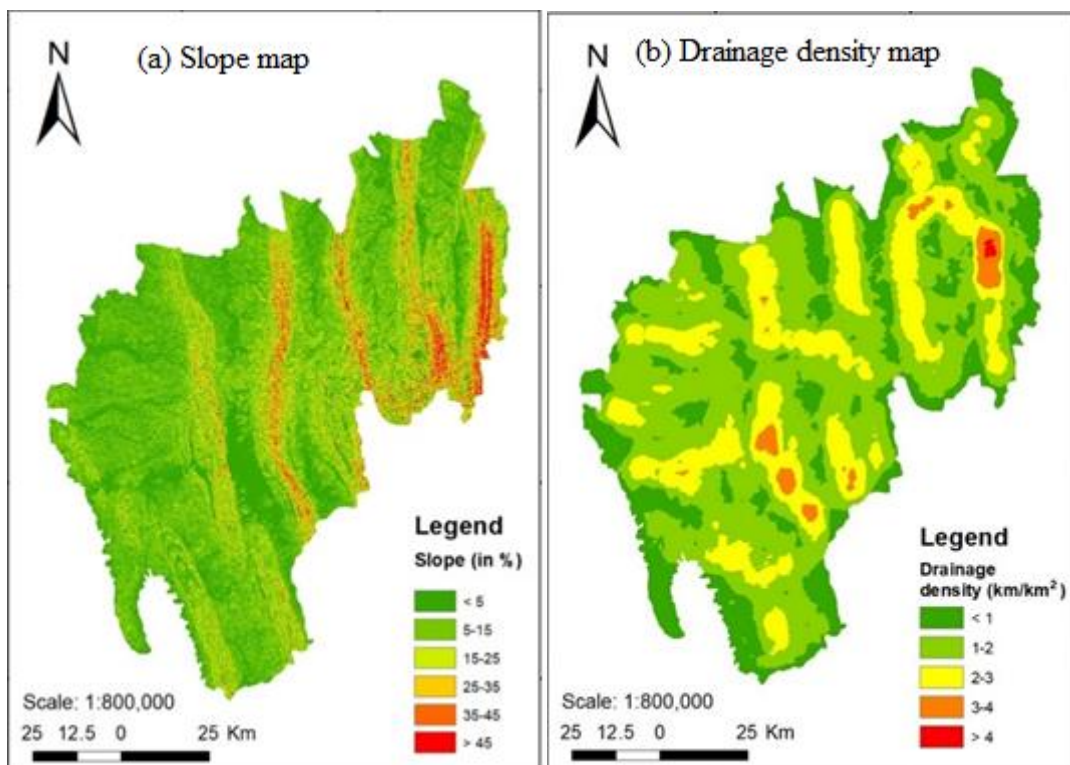
194 **Results and Discussion**

195 **Thematic maps of Tripura State**

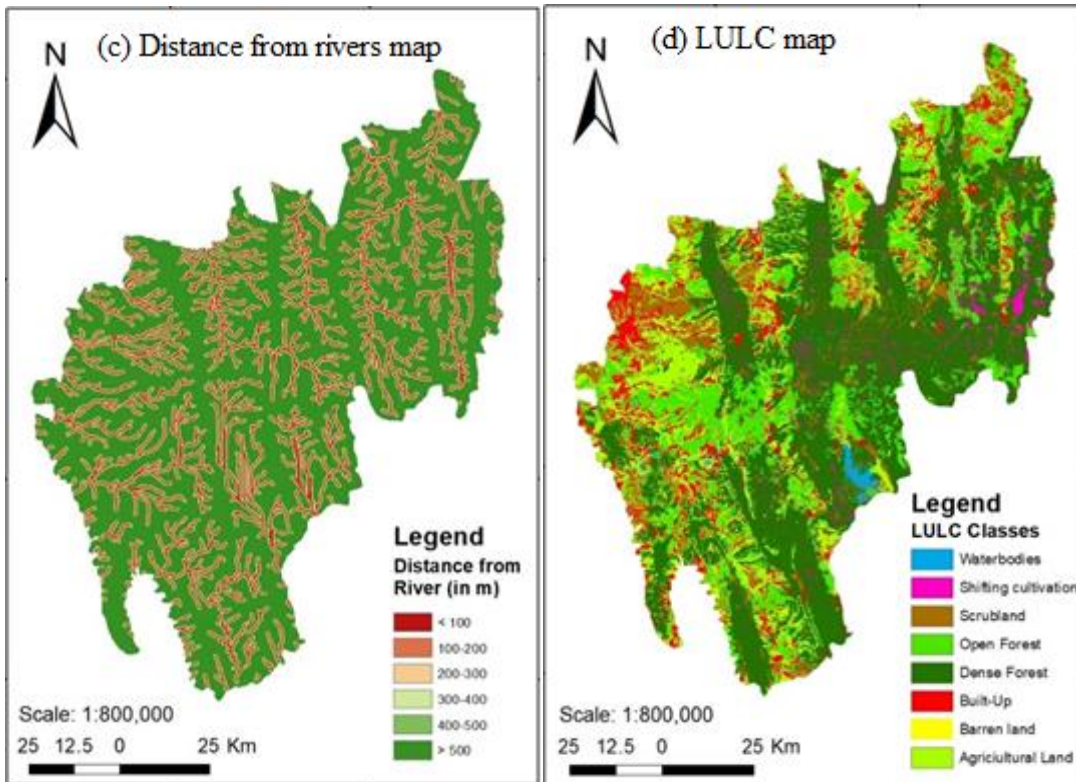
196 The landslide susceptibility maps of Tripura State were prepared in the GIS platform considering eight landslide
197 causative factors. The thematic maps of all the factors were generated. Pair-wise comparison matrices of all the
198 factors were prepared separately based on the weights assigned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

205 **Slope map**

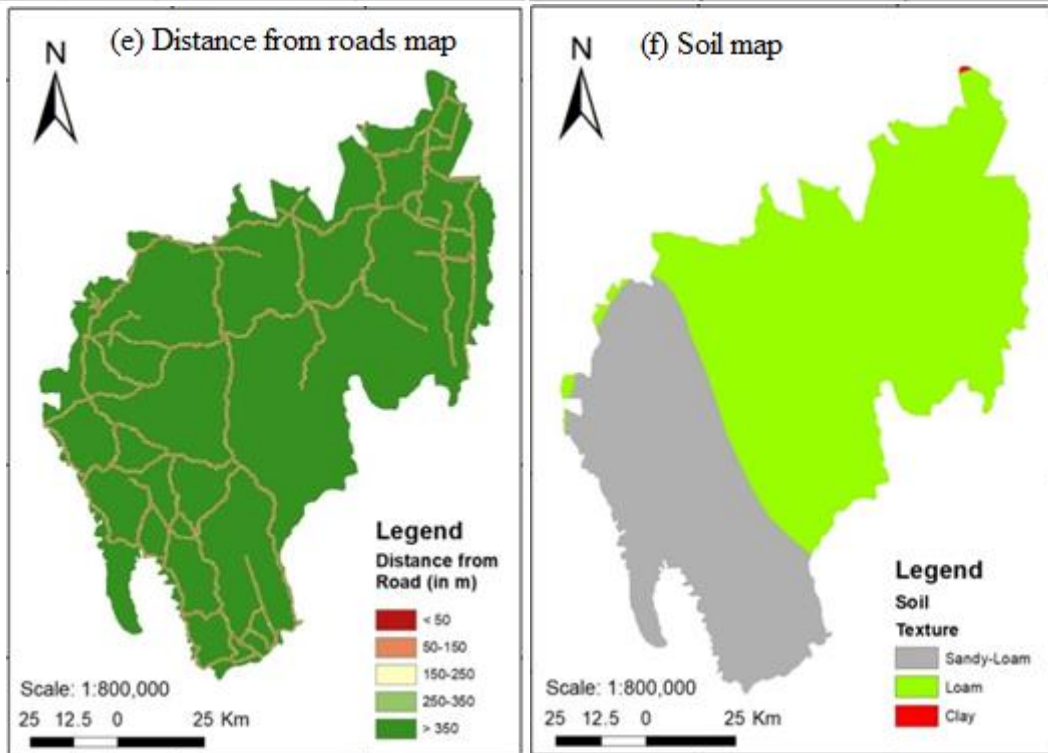
206 The slope of any terrain makes the soil more vulnerable to landslides. In areas having gentle slope, the velocity
207 of flow is low, which allows the runoff water to get absorbed into the soil, whereas steep slope areas facilitate
208 high-velocity surface runoff and make the landmass susceptible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



215

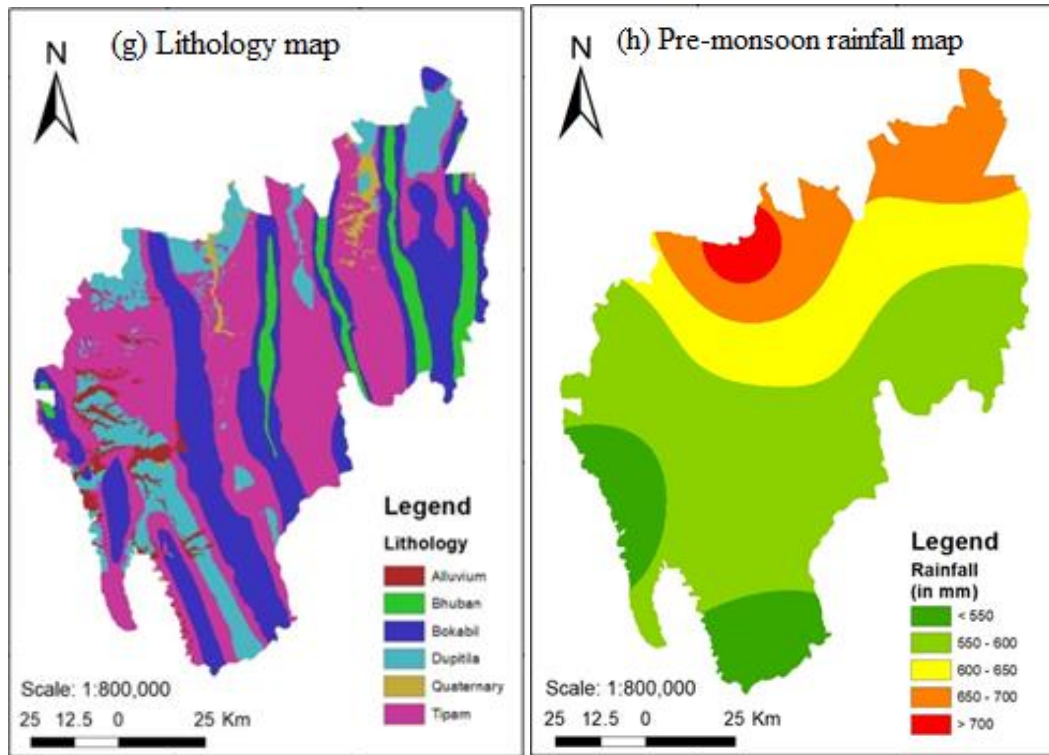


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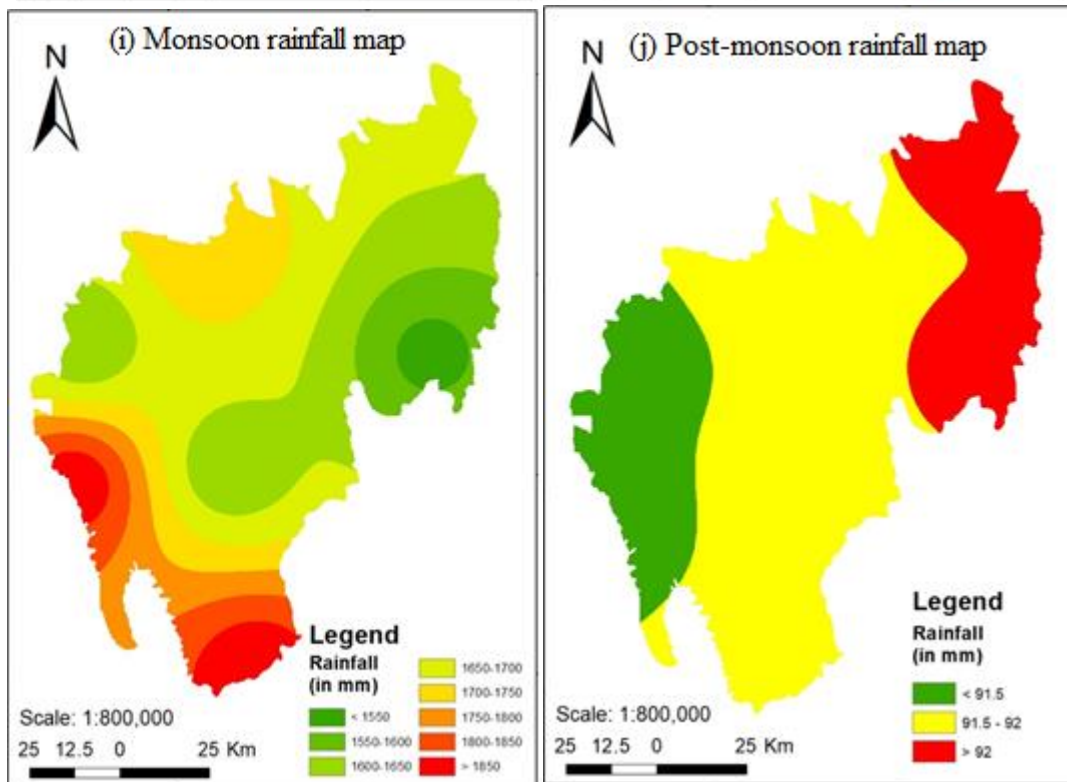


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219



220

Fig. 2 Thematic layers of various landslide causative factors

221

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

222

223 **Drainage density map**

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

228 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
 229 >4.0 km/km² (Fig. 2b). The weights were assigned to different classes based on the expert's opinion and
 230 the information available in the literature. The class defining the area of less drainage density got lower weight
 231 while the class representing more drainage density was assigned higher weight. The weights were normalized
 232 using AHP and eigenvector technique. The influence of drainage density of different classes on landslide
 233 susceptibility was found to vary from 41.6% for drainage density exceeding 4.0 km/km² to 6.2% for drainage
 234 density lower than 1.0 km/km² (Table 4).

235 **Distance from rivers map**

236 Distance from rivers controls the stability of slope. The degree of saturation of slope materials affects the
 237 stability of slope directly. Streams erode the slopes and affect the stability by saturating the lower part of the
 238 slope until the water level is increased (Dai et al. 2002; Saha et al. 2005). The distance from river map was
 239 classified into six classes having varied distance from rivers such as <100, 100-200, 200-300, 300-400, 400-500
 240 and >500 m (Fig. 2c). The weights given to different classes are based on the experts' opinions and past studies.
 241 The area nearer to the rivers are more susceptible to the landslide and hence, given highest weight while the area
 242 far from the river was assigned lowest weight as their influence on the occurrence of landslide is very less. The
 243 assigned weights were then normalized. The influence of distance from rivers of different classes on landslide
 244 susceptibility was found to vary from 38.9% for distance lower than 100 m to 3.3% for values exceeding 500 m
 245 (Table 4).

246 **Land Use and Land Cover map**

247 Land use land cover (LULC) is another important factor responsible for the occurrence of landslides as the
248 occurrence of a landslide is inversely related to the density of vegetation. Barren lands are more susceptible to
249 landslide activity than forest areas. Changes in vegetal cover often lead to change in behaviour of landslide
250 (Glade 2003). There is a strong linkage between surface runoff and the agricultural land use (Srivastava et al.
251 2020). Modification in agricultural land use results in alteration in infiltration and surface runoff and thereby
252 triggers landslide occurrence. Eight LULC classes such as water body, dense forest, open forest, built-up,
253 agriculture, scrub land, barren land and shifting cultivation were considered (Fig. 2d). The weights assigned to
254 different classes were used based past studies and the expert's opinions. The influence of shifting cultivation
255 towards landslide susceptibility was found to be the highest at 32.8%, whereas it was least at 2.1% only for
256 water bodies (Table 4).

257 **Distance from roads map**

258 The nature of topography is changed by construction of roads, and hence, the possibility of landslides increases
259 on slopes intersected by roads. It reduces the shear strength at the toe of the slope and causes infiltration of
260 water in the slopes. A drop-down road section is susceptible to landslides because it behaves like a wall, a net
261 source or sink, or a corridor for water flow, depending on its location in the mountains (Ayalew and Yamagishi
262 2005; Yalcin 2008).

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

269 **Soil map**

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

276 **Lithology map**

277 Lithology is one of the important factors involved in landslide studies (Dai et al. 2001; Yalcin and Bulut 2007;
278 Nefeslioglu et al. 2008). Different lithological units have different degrees of susceptibility. It is widely accepted
279 that lithology significantly influences the occurrence of landslides. This is due to the fact that the variations in
280 lithology often lead to significant differences in the permeability and strength of rocks and soils. The map was

281 classified into six classes, namely Tipam, Dupitila, Bokabil, Bhuban, Quaternary and Alluvium, which are the
 282 prominent classes available in the study area(Fig. 2g). The Bhuban lithological units were assigned maximum
 283 weight because this formation is characterized by a thinly bedded moderate to highly weathered sandstone shale.
 284 The weights were given to different formations based on the experts' opinions and past studies. The influence
 285 of Bhuban was found to be maximum at 37.9%, whereas the least influencing class was alluvium having 4.3%
 286 weight on landslide susceptibility (Table 4).

287 **Rainfall maps**

288 Rainfall is one of the important triggering factors for landslides. High intensity rainfall causes heavy runoff.
 289 Changes in soil moisture regime produce hydrostatic pressure. The mobilized shear resistance decreases with
 290 increase in pore water pressure, which is likely to cause shear instability. Average seasonal rainfall maps were
 291 prepared from the daily rainfall data that was collected for the last 22 years (1998 to 2019). It was found that the
 292 average seasonal rainfall ranges from 518.64 to 721.18 mm during pre-monsoon season (Fig. 2h). The study
 293 area experiences an average rainfall of 1534.67 to 1889.19 mm during the monsoon season (Fig. 2i)and the post-
 294 monsoon season receives an average rainfall of 91.26 to 92.15 mm only (Fig. 2j). The average seasonal rainfall
 295 was classified into nine classes such as <200, 200-400, 400-600, 600-800, 800-1000, 1000-1200, 1200-1400,
 296 1400-1600 and >1600 mm, and weights were assigned to them (Table 4). The weights assigned were then
 297 normalized. The influence of average annual rainfall exceeding 1600 mm on landslide susceptibility was found
 298 to be maximum (30.7%). It reduced with decrease in average annual rainfall. The influence was only 1.9% at
 299 rainfall below 200 mm per annum (Table 4).

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

310 **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%

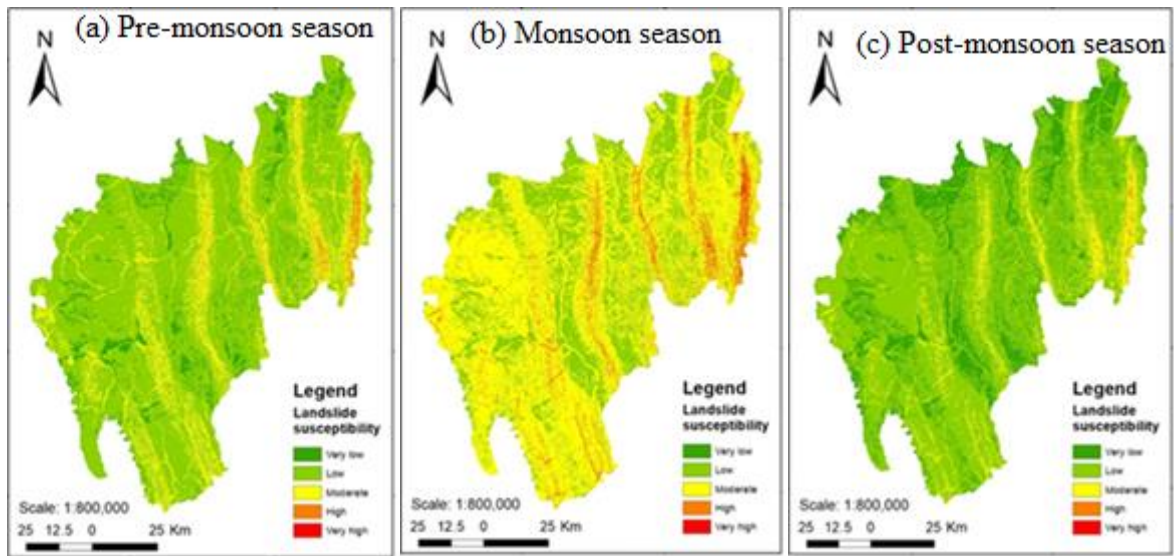
311

312 In order to prepare the landslide susceptibility maps using AHP and GIS, the LSI values were grouped into five
313 different classes such as very low, low, moderate, high and very high. The study showed that most of the areas
314 of the state come under very low to moderate landslide susceptibility zones (Table 6). During the pre-monsoon
315 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,
316 moderate, high and very high landslide susceptible zones, respectively(Fig. 3a). It means that maximum
317 percentage of area, i.e. 73.19% (around 7679 km²) comes under low landslide susceptible during this season.
318 During the monsoon season there is a shift of low landslide susceptible areas towards moderate susceptibility
319 covering 0.11, 29.27, 61.99, 8.30, and 0.34% of the state under very low, low, moderate, high and very high
320 landslide susceptible zones, respectively(Fig. 3b). It depicts that around 62% (6504 km²) area is prone to
321 landslides with moderate susceptibility during monsoon season and the low landslide susceptible area reduces to
322 about 29% (3071 km²). As the monsoon recedes the susceptibility to landslides reduces following almost the
323 similar trend as the pre-monsoon season (Fig. 3c) resulting in low to very low landslide susceptibility. Similarly,
324 during the post-monsoon season, 21.12, 68.50, 9.78, 0.50, and 0.11% of the state comes under very low, low,
325 moderate, high and very high landslide susceptible zones, respectively(Fig. 3c). It can be very well depicted
326 from the figure that the valley regions of the state are highly prone to landslides.

327

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



328

329

Fig. 3 Seasonal landslide susceptibility maps of Tripura state

330 **Conclusions:**

331 The landslide susceptibility study of the Tripura State of north-eastern India using GIS and AHP reveals that
 332 more than 40% of the study area has 5 to 15% slope and around 33% area has less than 5% slope. The highest
 333 slope for the study area is found to be about 69%. The drainage density of the area ranges from 0.059 to 4.29
 334 km/km². The LULC map shows that more than 45% of the total geographical area of the state is covered with
 335 dense forest. The area under shifting cultivation, a triggering factor for the landslide, is 2.5%. The soil map
 336 represents that amongst the various types of soil found in the state, loam soil has the highest occurrence with
 337 63% and clay soil has the lowest occurrence with 0.18%.

338 The study also depicts that around 45% of the study area has Tipam soil formations (containing ferruginous
 339 sandstone with siltstone and clay) and 30% area has Bokabil formations (containing sequence of sandy shale-
 340 sandstone-mudstone). During pre-monsoon season 73.2 and 18.7% of the area comes under low and moderate
 341 landslide susceptible zones covering about 7679 and 1957 km², respectively. During the monsoon season the
 342 susceptibility to landslide increases with the moderate landslide susceptible area increasing to about 62% and
 343 the low landslide susceptible area reduces to about 29%. Though the state is not highly susceptible to landslides,
 344 still its percentage is 8.3% during the monsoon season covering an area of around 870 km². As the monsoon
 345 recedes the susceptibility to landslides reduces following almost the similar trend as the pre-monsoon season
 346 resulting in low to very low landslide susceptibility. The landslide susceptibility maps will help the scientists/
 347 planners to undertake precautionary measures to handle the hazard so that the possible cause of casualty and
 348 economic losses can be avoided up to certain extent.

349 **Declarations**

350 **Funding** – Not Applicable

351 **Conflicts of interest/Competing interests** – Not Applicable

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

353 **Code availability** – ArcGIS software has been used in this study, which is available with ESRI
354 **Authors' contributions** – All the authors have contributed significantly for the execution of this work
355

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Figures



Figure 1

Location map of the study area

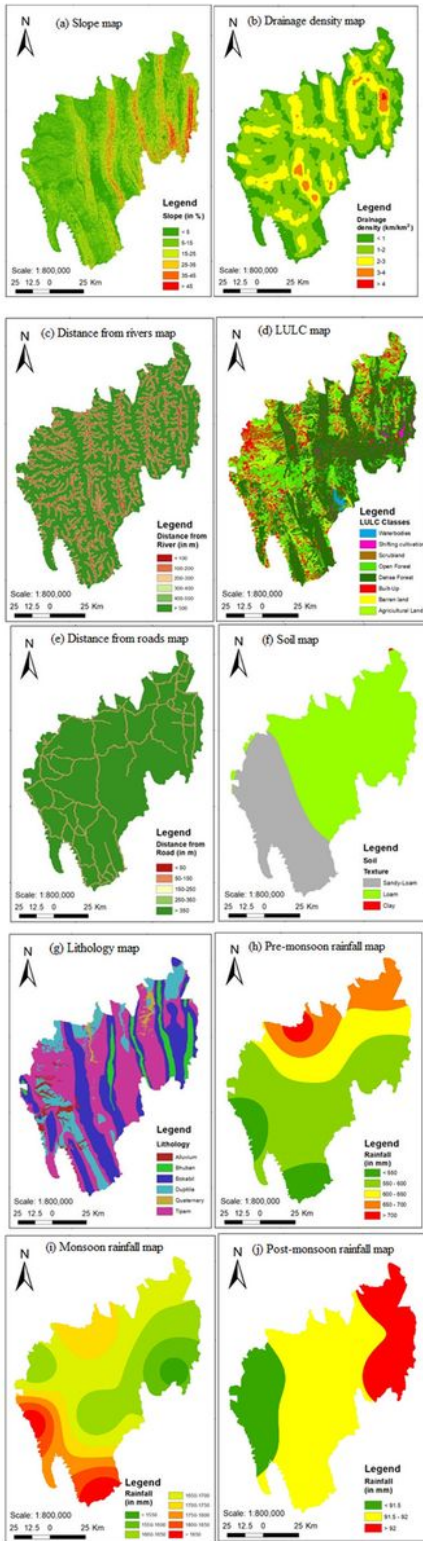


Figure 2

Thematic layers of various landslide causative factors

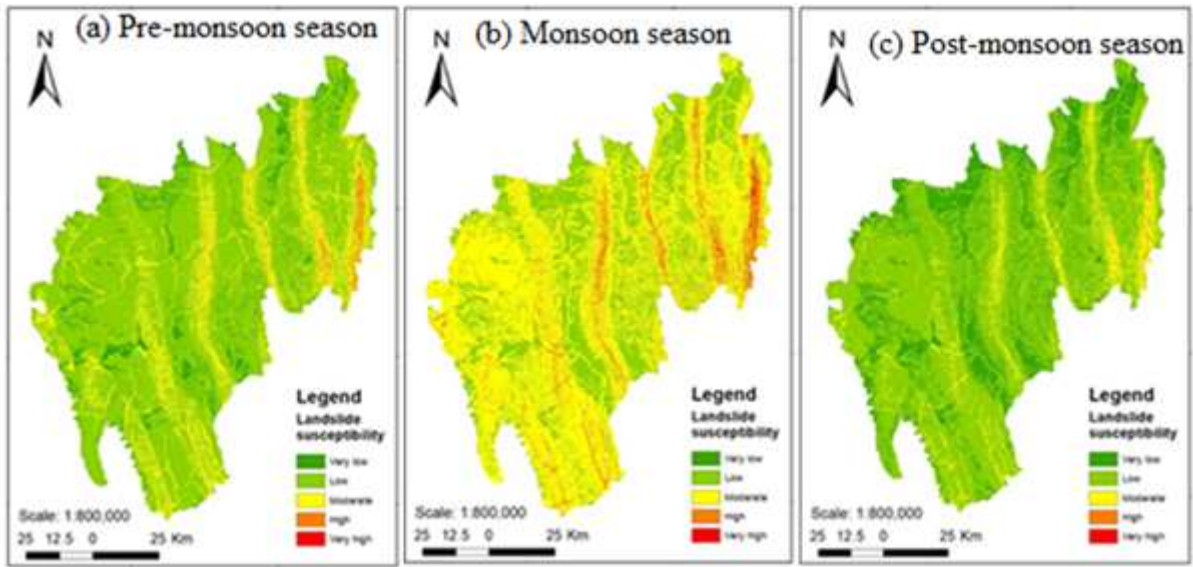


Figure 3

Seasonal landslide susceptibility maps of Tripura state