Landslide susceptibility assessment using frequency ratio technique – A case study of NH67 road corridor in the Nilgiris district, Tamilnadu, India

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Abstract: The purpose of this study is to develop landslide susceptibility mapping for NH67 road corridor in the Nilgiris district of Tamilnadu, India, using the Geographic information system (GIS) and multivariate statistical approach. In November 2009, North-East monsoon triggered numerous landslides in the Nilgiris district of Tamilnadu, resulting in a high death toll and considerable damage to property. The landslide-controlling parameters namely lithology, soil type, slope gradient, normalized difference vegetation index (NDVI), proximity to faults, and proximity to road, rainfall and streams were extracted from the spatial database, and the weight coefficient of each factor was computed. Then the landslide hazard was analyzed using the frequency ratio method. For verification of the model, the results of the analyses were then compared with the field verified landslide locations. It was concluded that about 3.86% and 16.23 % of the study area are in the very high and high susceptible zone. Based on this, landslide susceptibility map was then classified as very high, high, moderate, low and very low. In the course of model validation, the results were validated using the ROC curve. The AUC of Frequency ratio model was 67.5%. Therefore, the landslide susceptibility index map of the study area is considered valuable for the decision-makers of the landslide-prone region. This landslide susceptibility map can be used to carry out mitigation measures to reduce the susceptibility associated with landslide hazard.

1. Introduction
Landslides are known as too dangerous natural hazards that occur suddenly and cause considerable
damages to lives and property to a large extent. Over the last two decades, many governments and international research institutes in the world have investigated significant resources in assessing the landslide hazards and in attempting to construct maps portraying their spatial distribution [1].

Natural disasters have drastically increased over the last few decades. National and local government agencies are concerned with the loss of human life and damage to property caused by natural disasters such as hurricanes, earthquakes, erosion, tsunamis and landslides. Landslides represented approximately 9% of the natural disasters worldwide, which have occurred during the 1990s. This trend is expected to continue in the next decades too due to increased urbanization and development, continued deforestation and increased regional precipitation in the landslide-prone areas due to changing climatic patterns [2].

Among geological risks, landslides are those that cause the most damage, producing thousands of deaths every year and material losses of billions of dollars [3]-[4]. The measures that have been taken to reduce these losses include the creation of maps of susceptibility, danger and risk. Presentation of engineering geological data in the form of hazard map has served to be a useful tool for engineers for their urban planning. In recent years, geographical information systems (GIS) is gaining its potential for spatial data management and manipulation.

Several works have been carried out to delineate the hazard-prone zones all over the earth. As many techniques exist, researchers have adopted various methodologies and techniques to bring out promising solutions. The methods are broadly classified into quantitative and qualitative techniques [5]. The frequency ratio method takes a statistical approach quantitatively. Any system used to produce susceptibility maps involves the consideration of the causative factors inducing landslides. The correlation between landslide areas and associated factors that cause landslides can be brought out by providing the connections between region without past landslides and the landslide-related factors.

The probabilistic frequency ratio method had been widely adopted by various researchers in particularly for delineation of the landslides susceptible zones. Different landslide-prone areas have been studies using the frequency ratio method as it is a simple and understandable probabilistic model based on the observed relationship between the distribution of landslides and each landslide conditioning factor [6]. Over a decade some works have been published on frequency ratio model [7]-[8]-[9]-[10]-[11]-[12]-[13]-[14]-[15]-[16]-[17].

Because of the deficiencies centered around the pore water pressure development in the soils and their spatial and temporal distribution, some physically based models depicting the behavior of the pore water pressure have also been developed and produced by researchers. A popular physically based approach for assessing slope stability and hazards had been developed [18]-[19]. Statistical techniques require the collection of large amounts of data to produce reliable results. Statistical methods use sample data based on the relationship between the dependent variable, which may be the presence or absence of landslides, and the independent or explanatory variables. The combination of these parameter maps are treated statistically, and quantitative predictions are made for areas currently free of landslides but with similar conditions.

The primary purpose of this research to execute research over the landslide-prone area of Nilgiris using the statistical frequency ratio model and to validate its performance over the study area. The prediction capability of the adopted model would bring out efficient hazard map which would serve as the best tool for hazard experts and urban planners to carry out their duty, thereby executing mitigation measures in Nilgiris area.

2. Study Area
The study area includes a 25 km long section of a National Highway 67 road corridor alignment,
connecting Mettupalayam and Coonoor in the state of Tamil Nadu in southern India (Figure 1). The roadway and railway run almost parallel to the southern slopes of the Nilgiris plateau. These transportation routes cut through soil and laterite, underlain by charnockite and garnetiferrous quartzofelspathic gneisses belonging to the Charnockite Group of the Archaean age [20]. The regional strike of the foliation ranges from ENE–WSW to E–W direction with moderate to steep dips. The subtropical climate and intense physical and chemical weathering have resulted in a thick yellowish to the reddish-brown soil. The regolith thickness varies from <1 to 20 m, as observed in the cut slopes along the road and the railway. The contact between bedrock and weathering soil is often exposed in the cut slopes, which make them more susceptible to landslides due to the build-up of pore pressure on the contact. The soil depth in the region varies from place to place drastically.

The area concerned in the study has faced numerous landslides which have frequently occurred in the period from October to December due to the retreating monsoonal rainfall. For instance, on 4 October 1975, rainfall of 170 mm was recorded in 3 hours; on 12 November 1979, 150 mm in one day recorded at the Coonoor rain gauge; and on 11 November 1993, 177 mm in one night around Marapallam, resulting in numerous landslides. The rainfall event of 1979 has alone resulted in 200 landslides within the Nilgiris district. In the study area, landslides are mostly shallow translational debris slides triggered by rainfall.

The spatial distribution of the landslides has been depicted in figure 2. These landslides are individually small in size (1.5–2.0×10^5 m^3; average = 404 m^3, and median = 50 m^3) but occur in a large number and cause substantial damage to the railway and the roadway. Based on the historical records of the railway landslide maintenance department (from 1987 to 2007), a total of 790 landslides were identified within the 25 km² study area. About 94% of these landslides have occurred along the cut slopes and 6% in natural slopes. The majority of failures (97.2%) have been classified as shallow translational debris slides, and only 2.4% as debris flows. The inventory records claim that there had been at least one landslide event per year, except in 1995. The average rate of occurrence was 20 landslides per year. Major activities have been observed during 1992, 2001, 2006 and 2009.

![Study area map of National Highway 67, Mettupalayam to Coonoor.](image)

Figure 1. Study area map of National Highway 67, Mettupalayam to Coonoor.

3. **Database of landslide conditioning factors**

Though there exist various techniques to serve the purpose of the mapping landslide susceptible zone, all
of them incorporates specific causative factors that induce the occurrence of landslides in the region. Few researchers incorporate very few dominating condition parameters that influence landslides; some may include all possible factors providing them with lower weight. This study integrates eleven causative factor that potentially impacts the landslides in the Nilgiris area. The factors are elevation, slope, aspect, rainfall, land use/land cover, lithology, stream power index (SPI), topographic wetness index (TWI), distance to stream, distance to road and distance to lineament. Using the frequency ratio model, statistically, the influence of each factor has been incorporated in the susceptibility mapping.

The elevation (Figure 2a) is a frequently used causative factor for landslides. Slope gradient and elevation are found to be important to delineate flatlands that will in no way be subjected to slope failure [21]. The slope angle (Figure 2b) is also said to be a critical parameter as it evaluates the susceptibility to the developing earth flows. The interaction of slope angle with a friction angle of material, as well as permeability and cohesion, control the stability of the slope. The area which is at the large scale of susceptibility lies on mid-slope mountains where relatively weak rocks such as sandstone, mudstone and tuff are outcropping as one unit. No general decision could be given to the relationship between the slope aspect (Figure 2c) and landslides. However, landslides have always occurred in a specific direction for a given region; therefore, several types of research have taken the slope aspect as a causative.

The intensity of rainfall (Figure 2d) is directly proportional to the occurrence of landslides, which is a claim that is proposed with the knowledge from the inventory report of landslides. The Nilgiris region is highly prone to rainfall-induced landslides. Rainfall affects the slope stability using its influence on run-off and pore water pressure. The mountain topographic character influences the landslides to a reasonable extent. Deforestation, overgrazing and intensive agriculture, resulted by population pressure, are often the casual factors of soil erosion and mass movement. Thus land-use/land-cover has been taken as an important factor (Figure 2e) [22].

It is a widely accepted fact that landslides depend on the geology of the terrain, thereby making a lithology map (Figure 2f) to indeed be an alternative preferable for the most commonly available rough geological map. The characteristics of the soil play a vital role in the stability of the slope. The soil parameters and their slope characteristics determine the occurrence and type of landslides.

The stream power index (Figure 2g) is used to describe the potential flow erosion at a given point on a topographic surface. The stream power index is directly proportional to the erosion risk. As the catchment area and the slope gradient increases, the amount of water contributed to the up-slope areas, and the velocity of flow increases, thereby increasing the SPI. Also, the topographic wetness index (Figure 2h) is a steady-state wetness index and a secondary geo-morphometric parameter that exhibits the effect of the topography on the location and size of saturated source areas of run-off generation. Spatial patterns of high TWI values help to identify lines of preferential drainage of a landslide body. The index is determined as follows:

$$TWI = \ln \left( \frac{a}{\tan \beta} \right)$$  

(1)

The saturation degree of the soil (Figure 2i) is a critical factor to be taken into account in the study of landslides. The degree of saturation of the soil influences its pore water pressure and thereby its stability. The streams also play a vital role in eroding the materials, which also has its impact on the slope stability.

The construction of roads in hilly terrain causes an increase in stress on the back of the slope, thereby leading to tension cracks. The construction activity on the slope, itself acts as a factor that weakens the stability of the slope, causing a serious terrain of toe support and also affecting the topography of the terrain. Thus the distance to the road (Figure 2j) is considered as a causative factor in the study. Based upon the slope stability concerning the distance to the road the region is classified into six categories. Landslides spatial distribution has a strong correlation with the tectonic fractures. It was observed that landslides have occurred mainly along the faults and has decreased sharply with distance from it because faults make the
rocks heavily fractured and form a series of weak zones which are low in strength and high in permeability thereby negatively affecting the stability of the slope. The distance to lineament (Figure 2k) is calculated using the geological map.

**Figure 2.** (a) Elevation map (b) Slope map (c) Aspect map (d) Rainfall map (e) Landuse and landcover map (f) Lithology map (g) Stream power index (h) Topographic wetness index map (i) Distance to stream (j) Distance to road (k) Distance to lineament map.
4. Frequency-ratio model

In order to predict the landslide susceptible zones, it is necessary to assume that the landslide occurrence is based on its causative factors. To generate a landslide susceptibility map quantitatively, we can opt the frequency-ratio method. It is an applied method to determine the level of correlation between the location of the landslides in the study area and the conditioning factors. This model has been worked out, integrating with the GIS platform. The frequency ratio can be defined as the ratio of the area where landslides occurred in the total study area to the ratio of the landslide non-occurrence for a given attribute. The landslide susceptibility index (LSI) was calculated by a summation of each factor ratio value using the given formula equation

\[ LSI = \sum FR \]  

where LSI is the landslide susceptibility index, and FR is the frequency ratio of each factor type or class.

The frequency ratio of value 1 is an average value for the areas where landslides have occurred in among the total area. If the FR value is higher than 1, it denotes the higher correlation, which indicates a high probability of landslide occurrence and lower than 1 stated the lower correlation, which implies a low probability of landslide occurrence. The thematic layers were generated using ArcGIS 10.3 software, and Microsoft Excel sheet was used to calculate the frequency ratio of each layer. The landslide susceptibility map was finally constructed using the ArcGIS software, and the resultant map was indexed with four susceptible zones (high, moderate, low and very low).

5. Results and discussion

The causative factors are the backbone of the obtained result; each factor imparts a crucial impact in assessing the landslide susceptibility using the frequency ratio method. The correlation of each parameter to landslide occurrence has been calculated in this method which therefore emphasizes the importance of each parameter. The results thus obtained is a direct output of the combined correlation of all the eleven factors considered in the study.

The elevation of the study area ranges from 270 m to 1657 m. The landslide scarps are found dominantly in the mid-elevation region ranging between 536 m and 814 m. This does not pertain that region at high elevation are not susceptible to landslides. The elevation parameter is one of the factors that ascertain the hazard zone. The slope angle ranging from 20 to 37 degrees, is said to be susceptible to landslides. It is well known that flat terrain does not impart in the landslides. Steep terrain is prone to landslide considerably. The slope which is likely to construction and deforestation activities are highly prone to the landslide attack.

When considering the aspect factor of the slope, the landslides are highly susceptible in the NE, E and SE directions in the study area. The aspect of landslides considerably varies with localities. Not all landslides occur in this aspect. Based on the terrain and its topography, the aspect prone to landslide occurrence varies.

The prominent landslides in Nilgiris are a rainfall-induced avalanche or debris flow. The rainfall is the triggering factor for the occurrence of landslides in the region. Among all causative factors, rainfall seems to be the primary one. The maximum annual rainfall is taken into consideration in the study. The highest annual rainfall above 1584 mm has caused severe landslides in the study area. The rainfall may be a short-term rain-storm event or a continuous event; both serve to be influencing the landslide attack in the region.

The land cover of the study area is predominantly cropland, forest cover, built-up land and river. The susceptible land cover to landslides is forest and cropland. Many events have occurred in the forest cover of the study area. The study area has two types of lithology forms, mostly. Though quartz holds much weathering property than granite, the granite rocks in the region are detected to be highly susceptible to
landsides because of the other influencing and triggering parameters such as the land cover, topography and moisturizing property.

The stream power index ranges between -6,907.75 and 8,906.26. The SPI ranging from 100 to 1092 are highly prone to landslides. The topographic wetness index ranges between 2.79359 to 19.21530 and the TPI, which is proving susceptible to the occurrence of landslides ranges from 2.79 to 5.0. This claims that lower TPI values are highly correlated to landslides. Within 100 m distance to stream, the study area has faced considerable landslides. It is admissible that the region closer to the streams are remain saturated, and thus when it rains, the triggered landslide may occur. Same as the distance to streams, the distance to roads within 100 m are prone to landslides. The lineaments are topographic features which are unstable, and the distance to lineament within 50 m are susceptible to landslides. The claim proves correct as the faults are highly unstable, and when any triggering force happens, it raptures and landslide occur.

The resultant map obtained from the frequency ratio model has classified the study area into five landslide susceptible zones (figure 3). The study area has 3.86% very high, 16.23% high, 30.57% moderate, 33.98% low and 15.36% very low landslide susceptible zones.

6. Validation of the result
The overall performance of the model can be ascertained by computing the correctly classified cells in the resultant map. This requires a validation technique; there exist various validation procedures, but in this study, the Area Under the Curve (AUC) is generated to evaluate the accuracy. The Receiver Operating Characteristic (ROC) metric is adopted in this study to evaluate the output quality of the result using cross-validation. ROC curves typically feature true positive rate on the Y-axis and false positive rate on the X-axis. This means that the top left corner of the plot is the ideal point - a false positive rate of zero, and a true positive rate of one.

This is not very realistic, but it does mean that a larger area under the curve (AUC) is usually better. The obtained AUC of Frequency ratio model is 67.5% (Figure 4).

Table 1. Spatial relationship between each landslide conditioning factor and landslide by FR models
| Parameter                  | Class     | Number of pixels in class | % pixels in the class (%; PIF) | Number of landslide pixels | % landslide pixels (%; PLO) | Frequency ratio (FR) |
|----------------------------|-----------|---------------------------|--------------------------------|---------------------------|-----------------------------|----------------------|
| Distance to lineament (m)  | 50        | 8576                      | 57.852                         | 416                       | 33.441                      | 0.578                |
|                            | 100       | 1371                      | 9.249                          | 67                        | 5.386                       | 0.582                |
|                            | 150       | 1333                      | 8.992                          | 26                        | 2.090                       | 0.232                |
|                            | 200       | 1256                      | 8.473                          | 34                        | 2.733                       | 0.323                |
|                            | >250      | 2288                      | 15.434                         | 79                        | 6.350                       | 0.411                |
| Distance to road           | 50        | 5834                      | 39.355                         | 114                       | 9.164                       | 0.233                |
|                            | 100       | 2436                      | 16.433                         | 165                       | 13.264                      | 0.807                |
|                            | 150       | 1943                      | 13.107                         | 114                       | 9.164                       | 0.699                |
|                            | 200       | 1697                      | 11.448                         | 87                        | 6.994                       | 0.611                |
|                            | 250       | 2309                      | 15.576                         | 88                        | 7.074                       | 0.454                |
|                            | >250      | 605                       | 4.081                          | 89                        | 7.154                       | 1.753                |
| Slope aspect               | Flat      | 1692                      | 11.414                         | 42                        | 3.376                       | 0.296                |
|                            | North     | 1074                      | 7.245                          | 35                        | 2.814                       | 0.388                |
|                            | Northeast | 2455                      | 16.561                         | 111                       | 9.823                       | 0.539                |
|                            | East      | 2908                      | 19.617                         | 122                       | 9.807                       | 0.500                |
|                            | Southeast | 2677                      | 18.059                         | 113                       | 9.084                       | 0.503                |
|                            | South     | 1904                      | 12.844                         | 86                        | 6.913                       | 0.538                |
|                            | Southwest | 1139                      | 7.683                          | 56                        | 4.502                       | 0.586                |
|                            | West      | 235                       | 1.585                          | 40                        | 3.215                       | 2.028                |
|                            | Northwest | 740                       | 4.992                          | 17                        | 1.367                       | 0.274                |
| Distance to stream (m)     | 50        | 4894                      | 33.014                         | 5                         | 0.402                       | 0.012                |
|                            | 100       | 3806                      | 25.675                         | 437                       | 35.129                      | 1.368                |
|                            | 150       | 2624                      | 17.701                         | 110                       | 8.842                       | 0.500                |
|                            | 200       | 1560                      | 10.523                         | 49                        | 3.939                       | 0.374                |
|                            | >200      | 1940                      | 13.087                         | 21                        | 1.688                       | 0.129                |
|                            | 208-5     | 6298                      | 42.485                         | 289                       | 23.232                      | 0.547                |
|                            | 5.1-6.4   | 5947                      | 40.117                         | 164                       | 13.183                      | 0.329                |
|                            | 6.5-8.4   | 1598                      | 10.780                         | 79                        | 6.350                       | 0.589                |
|                            | 8.5-12    | 620                       | 4.182                          | 70                        | 5.627                       | 1.345                |
|                            | 13-19     | 361                       | 2.435                          | 20                        | 1.608                       | 0.660                |
| SPI                       | -6907.8   | 2000                      | 13.492                         | 43                        | 3.457                       | 0.256                |
|                            | -6907.07-100.02 | 1076 | 7.258 | 156 | 12.540 | 1.728 |
|                            | 100.03-1092.3 | 10602 | 71.519 | 343 | 27.572 | 0.386 |
|                            | 10924.4-3510.9 | 616 | 4.155 | 64 | 5.145 | 1.238 |
|                            | 3511-8906.3 | 530 | 3.575 | 16 | 1.286 | 0.360 |
|                            | 0-12      | 2918                      | 19.684                         | 148                       | 11.897                      | 0.604                |
|                            | 13-21     | 3669                      | 24.750                         | 203                       | 16.318                      | 0.659                |
|                            | 22-28     | 2099                      | 14.159                         | 113                       | 9.084                       | 0.642                |
|                            | 29-38     | 2390                      | 16.123                         | 87                        | 6.994                       | 0.434                |
|                            | 39-64     | 3748                      | 25.283                         | 71                        | 5.707                       | 0.226                |
| Parameter         | Class            | Number of pixels in class | % pixels in the class (%; PIF) | Number of landslide pixels | % landslide pixels (%; PLO) | Frequency ratio (FR) |
|-------------------|------------------|---------------------------|--------------------------------|----------------------------|---------------------------|---------------------|
| Lithology         | Quartz Vein      | 3938                      | 26.565                         | 219                        | 17.605                    | 0.663               |
|                   | Granite          | 10886                     | 73.435                         | 403                        | 32.395                    | 0.441               |
| Landuse/Landcover | Crop Land        | 7820                      | 52.752                         | 299                        | 24.035                    | 0.456               |
|                   | Forest           | 6837                      | 46.121                         | 325                        | 26.125                    | 0.566               |
|                   | Built-up Land    | 149                       | 1.005                          | 0                          | 0.000                     | 0.000               |
|                   | River            | 18                        | 0.121                          | 0                          | 0.000                     | 0.000               |
| Rainfall          | 1584.71-1599.37  | 5127                      | 34.586                         | 367                        | 29.502                    | 0.853               |
|                   | 1574.81-1584.71  | 1669                      | 11.259                         | 45                         | 3.617                     | 0.321               |
|                   | 1564.49-1574.81  | 2107                      | 14.213                         | 73                         | 5.868                     | 0.413               |
|                   | 1553.90-1564.49  | 2351                      | 15.859                         | 70                         | 5.627                     | 0.355               |
|                   | 1546.74-1553.96  | 3570                      | 24.083                         | 67                         | 5.386                     | 0.224               |
| Slope             | 0 - 11.957       | 2387                      | 16.102                         | 60                         | 4.823                     | 0.300               |
|                   | 11.958-20.675    | 4033                      | 27.206                         | 118                        | 9.486                     | 0.349               |
|                   | 20.676-28.398    | 4488                      | 30.275                         | 195                        | 15.675                    | 0.518               |
|                   | 28.399-37.863    | 3182                      | 21.465                         | 177                        | 14.228                    | 0.663               |
|                   | 37.864-63.521    | 734                       | 4.951                          | 72                         | 5.788                     | 1.169               |

Figure 4. AUC representing the quality of the model.
7. Conclusions

The Nilgiris region is one of the four prominent landslide occurring areas in India. This itself shows the necessity to work on the landslides of the region to bring out noticeable results that would help the district administration, hazard experts and urban planners. The frequency ratio model, which has incorporated eleven causative factors in this study, is proven to be a promising technique for providing 67.5% validation accuracy. This technique seems to a simple statistical method, which can give considerable results for hazard zonation mapping. The study area is prone to landslide attacks as 3.86% region falls in the very high landslide susceptible zone. Substantial measures have to be taken in order to mitigate the effects in those areas. The landslide susceptibility index map of the road corridor NH67 can be used by urban planners and disaster management department to carry out effective measures.

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