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LANDSLIDE SUSCEPTIBILITY ASSESSMENT IN QUANG NAM PROVINCE USING STATISTICAL INDEX AND ANALYTICAL HIERARCHICAL PROCESS

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Abstract. More than 70% of the areas of Quang Nam province are mountainous terrain with heavy and seasonal rainfall. In recent years, economic activities and the work of humans have increased dramatically, destroying vegetation cover, and causing the natural environment to change significantly, which promotes the occurrences, development, and increase of landslides. This research uses the statistical index to determine the weight of each class in each factor and an analytical hierarchical process (AHP) to determine the weight of factors. A landslide susceptibility assessment map was established by integrating the factor maps. The result showed that landslide susceptibility in Quang Nam was categorized as 28.53% for low and very low; 39.66% for moderate, and 31.82% for high and very high.

Keywords: landslide, statistical index, analytical hierarchical process (AHP), Quang Nam province.

1. Introduction

Landslides are considered one of the common natural hazards in many parts of the world [1]. Globally, landslides cause billions of dollars worth of damage and thousands of deaths and injuries each year. In Vietnam, landslides often occur during the rainy season in the mountainous areas of the Northwest, Northeast, and Central regions, causing great damage to people, facilities, and the environment. In 2020, the country had 59 landslides and flash floods, causing 132 deaths or disappearances and about 527 billion VND worth of damage [2].

A landslide is the movement of soil and rock down the slope under the influence of gravity [3]. Landslides occur when the rock mass is unbalanced and the shear stress exceeds resistance. This situation often occurs when the material on the slope is saturated with water, the foot of the slope is lost, or underground erosion reduces the binding force between the permeable layer and the surface of the retaining layer. This often occurs in areas with significant moisture, lithology rich in clay material, and other favorable structural conditions.

Landslides have attracted the attention of many research scientists by introducing concepts, definitions, and classifications and identifying the causes of landslides [1], [4]-[7]. Assessing and zoning landslide risk is also the goal that research aims to achieve. In recent years, there have been many different landslide risk assessment methods, of which the group of statistical methods is the most widely used. Statistical methods are based on the analysis of the functional relationships between instability factors and existing landslides. Various statistical methods have been applied for slope instability such as bivariate approaches and multivariate approaches. The bivariate approaches for the study include five different methods: statistical index, certainty factor, landslide susceptibility analysis, probability method, and weight of evidence modeling. Multivariate approaches for landslide susceptibility mapping in the study include two methods: multiple linear regression and logistic regression analysis. Of the two groups of methods, bivariate approaches are relatively easy to use with the simpler analysis algorithm so they should be used in many research projects [8], [9].

In Vietnam, landslide studies also aim at zoning and predicting landslide risk. Studies have established zoning maps to predict landslide risk at different levels such as national scale [10], regional level [11], inter-provincial, provincial level [12], district level [13], and a route [14]. These studies have applied many modern methods such as analytic hierarchy process (AHP) methods [12], [14], [15], statistical index [12], the weight of evidence [13], [15], and certainty factor modeling [15].

Quang Nam, located in the center of the central region with diverse terrain including lowlands, midlands, mountainous areas, and a humid tropical climate, Quang Nam has many favorable conditions for socio-economic development. However, apart from these advantages, over 70% of the terrain is a mountainous area with steep slopes and deep divergence of dry-rainy climate that can cause natural hazards, including landslides. On the other hand, in recent decades, to meet the requirements of the reform process, the system of local infrastructure has been developed dramatically. Many roads have been maintained, repaired, and upgraded; hydropower projects have been built and operated; mineral mines have been expanded and exploited...Economic activities and the work of humans cause the natural environment to substantially change, quickly raising the development of slopes and causing increased landslides.

Reality shows that the landslide in Quang Nam takes place every year, causing great losses of people and property. Landslides can cause thousands of cubic meters of soil and stone to fall down and destroy homes, and work, threatening life or burying residents and damaging many roads. Therefore, assessing and identifying areas at risk of landslides in Quang Nam province to have solutions to prevent and minimize damage are very necessary and have scientific and practical significance.

Studies on landslides in Quang Nam in recent years have done quite a lot in different scales and aspects such as analysis and investigation of landslides [16], evaluation and forecast of the landslide risk in some areas, along the transport routes or in the entire province [12], [14]. However, the assessment of landslide risk in some studies is incomplete and not integrated. Determining the role of factors by assigning weights is subjective. In this study, landslide susceptibility in Quang Nam is evaluated according to an integrated perspective and systems approach. A combination of statistical index models and analytical hierarchy process (AHP) aims to increase objectivity in determining the weights for factors and the weights of each class in each factor, promoting reliability, accuracy, and quantification of assessment results. Furthermore, unlike most previous studies that mainly used the average annual rainfall index, in this study, the autumn precipitation indicator (cumulative rainfall in the 3 months of September, October, and November – rainfall in the rainy season) was selected for landslide analysis because in Quang Nam, the rainy season concentrates more than 60% of the annual total precipitation and most landslides occur during this period.

2. Content

2.1. Landslide susceptibility evaluating method

Landslide hazard assessment in Quang Nam province is based on the landslide susceptibility map; the integration of the various factors and classes in a single landslide susceptibility index (LSI) is accomplished by a procedure based on the weighted linear sum as follows:

$$LSI = \sum_{j=1}^{n} W_j w_{ij}$$

where,

LSI: Landslide susceptibility index;

W_j: weight value of parameter j;

w_{ij}: rating value or weight value of class i in parameter j;

n: number of parameters.

Based on the analysis of landslide inventory, nine relevant factors are selected as inputs for the models of landslide susceptibility mapping in this study, i.e. lithological composition, fault density, weathering crust, slope, deep dividing density, autumn rainfall, drainage density, land and distance from roads.

- *Method of defining the weight value for a parameter class* - *statistical index method.*

The statistical index method is a bivariate statistical analysis introduced by Van Westen for landslide susceptibility analyses. In this method, a weight value for a parameter class, such as a certain fault density unit or a certain slope class, is defined as the natural logarithm of the landslide density in the class divided by the landslide density in the entire map. This method is based on the following formula [8]:

$$wij = \ln\left(\frac{f_{ij}}{f}\right) = \ln\left(\frac{A^*_{ij}}{A_{ij}} \times \frac{A}{A^*}\right) = \ln\left(\frac{A^*_{ij}}{A^*} \times \frac{A}{A_{ij}}\right)$$

where,

w_{ij}: The weight is given to a certain class i of parameter j.
f_{ij}: The landslide density within class i of parameter j.
f: The landslide density within the entire map.
A^*_{ij}: Area of landslides in a certain class i of parameter j.
A_{ij}: Area of a certain class i of parameter j.
A^*: Total area of landslides in the entire map.
A: Total area of the entire map

Hence, the statistical index method is based on the statistical correlation of the landslide inventory map with attributes of different parameter maps. The wij value in this equation is only calculated for classes that have landslide occurrences. In the case of no landslide occurrences in a parameter class, the wij will be assigned to zero [8].

- Method of defining the weight value of the parameter - Analytical hierarchy process (AHP) method.

In reality, the influence of each factor differs; it is essential to quantify the relative weight of each contributing factor in a landslide. Factor weights are determined by a pair-wise comparison matrix using AHP. In the construction of a pair-wise comparison matrix, each factor is rated against every other factor by assigning a relative importance value between 1 and 9 to the intersecting cell. When the factor on the vertical axis is more important than the factor on the horizontal axis, this value varies between 1 and 9. Conversely, the value varies between 1/2 and 1/9 (Table 1) [17], [18].

Table 1. Scale of preference between two parameters in AHP [18]

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

Pair-wise comparison, however, is subjective and the results are highly dependent on the expert's judgment. Usually, the relevant importance between two factors is specified by sending questionnaires to different experts, who are asked to compare the relative importance between two factors with respect to the goal.

The analytical hierarchy process (AHP) method is its ability to evaluate quantitative and qualitative criteria so it is a semi-quantitative method.

2.2. Results and discussion

2.2.1. Landslide inventory mapping

Landslides are very common in this region, especially during the rainy season when rainfall is highly concentrated as typhoons are frequent in September, or when rainfall lasts for long periods (e.g., days or weeks) in October and November. In this study, the author conducted field surveys of landslide occurrences in several areas in the study area in October 2009. The field survey results have identified 157 sliding blocks, including 40 large sliding blocks, 50 medium sliding blocks, and 67 small sliding blocks. The author refers to the landslide inventory from the research by Dr. Pham Van Hung and his colleagues in 2010 with 528 landslides, including 264 large landslides, 90 moderate landslides, and 174 small landslides. The landslide inventory map for Quang Nam province was established after eliminating overlapping landslide points. The results show that there are 583 landslides of different sizes covering 10438.37 km^2 (Figure.1). The average density is about 5 cubic landslides,100 km^2 of which are 265 large landslides, accounting for 45.5%, 113 moderate landslides, accounting for 19.4% and 205 small landslides, accounting for 35.1%.

Landslides are distributed almost throughout the hilly area of the province, concentrating on greater density in medium mountain areas - low mountains of Dong Giang, Phuoc Son, Nam Giang, and Nam Tra My district. The landslide was also concentrated on a few low hills areas of Dai Loc, Duy Xuyen, Tien Phuoc, and North Tra My district.

Landslides occurred seriously in the area of ferosialite, sialferite weathering of metamorphic rock in Kham Duc formation, Tac Po formation, Upper - Lower A Vuong formation, and the intrusive magmatic rocks of Dai Loc complex, Ben Giang - Que Son complex, Chu Lai complex.

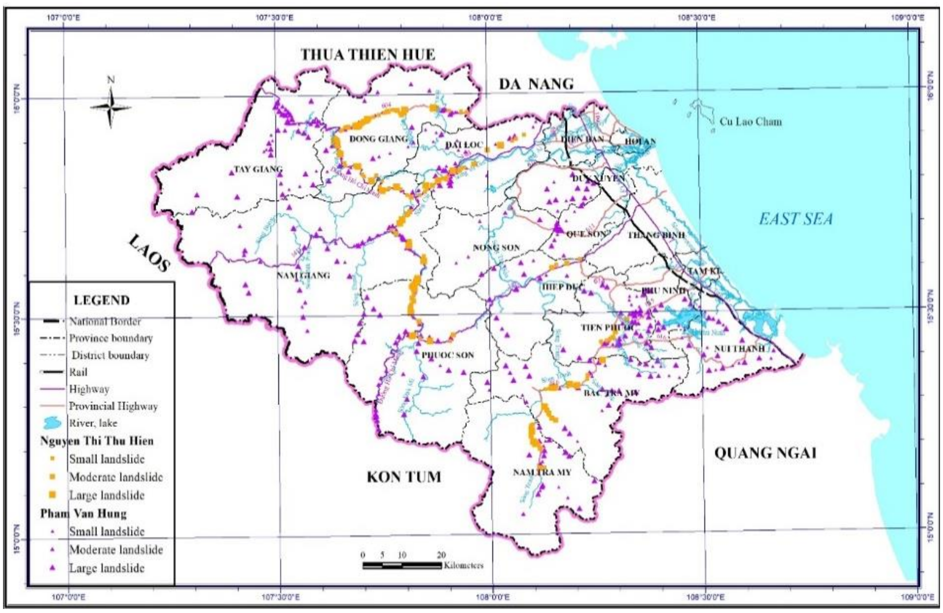

Figure 1. Landslide inventory map in Quang Nam province

The landslides also in the negative talus slopes and positive talus slopes along the traffic routes in Quang Nam are very common, especially during the rainy season. Landslides can cause cracking roads or drop down the road from hundreds to thousands of cubic meters of rock, giving rise to traffic jams for many hours and days. According to the annual report of the Committee of Quang Nam province, landslides occurred mainly in the rainy season, from September to November, and during, or after heavy rains. The large landslides with thousands of cubic meters bury houses, fields, roads and even kill people.

The 583 landslides were used for the evaluation of landslide susceptibility. To test the model, the authors used landslide points in Dr. Dinh Van Tien's research [14] and the collection of historical information on landslides from 2017 to 2023.

2.2.2. Landslide susceptibility assessment based on causative factors

*** Lithological composition**

The lithological composition of different rock groups is related to landslides through the durability, cohesion, and shear strength of rocks. Based on the geological map of Quang Nam province at a scale of 1/200,000 with 33 formations and complexes ranging in age from Proterozoic to Quaternary, the lithological composition was divided into 5 groups: Quaternary deposit, sedimentary and metamorphic rock, terrigenous sedimentary rocks, magmatic rock, and metamorphicrock (Figure 2).

The landslide inventory map is an overlaid lithological composition map. The result shows that the metamorphic rock groups have the highest weight value, corresponding to the highest susceptibility; then magmatic and terrigenous sediments have high and moderate susceptibility. Unconsolidated Quaternary sediment's landslide susceptibility is very low (Table 2).

Table 2. Classification of landslide susceptibility of lithological composition factor

Rock group	Area rate (%)	Landslide density (points/km^2)	Weight value	Susceptibility
Quaternary deposit	15.23	0.0105	-1.6531	Very low
Sedimentary and metamorphic rock	7.55	0.0225	-0.8939	Low
Terrigenous sedimentary rocks	12.94	0.0635	0.1426	Moderate
Magmatic rock	19.61	0.0662	0.1842	High
Metamorphic rock	44.67	0.0686	0.2195	Very high

**** Fault density***

Fault density is an important causative factor for landslide susceptibility mapping because highly faulted zones are areas of particularly high incidence of unstable slopes. Fault density was calculated as the total length of faults per 1 km^2 based on the Quang

Nam geological map, scale 1:200,000. Fault density was divided into 5 classes: < 200 m/km^2, 200 - 400 m/km^2, 400 - 600 m/km^2, 600 - 800 m/km^2, and > 800 m/km^2 (Figure 3).

Results of overlaying the landslide inventory map and fault density map show that in Quang Nam the susceptibility of landslide and fault density is linear relationship; the greater the density is, the higher the susceptibility of landslide is (Table 3).

Table 3. Classification of landslide susceptibility of fault density factor

Fault Density (m/km^2)	Area Percentage (%)	Landslide density (points/km^2)	Weight value	Susceptibility
< 200	53.3	0.0318	-0.5506	Very low
200 - 400	30.8	0.0666	0.1900	Low
400 - 600	12.6	0.0959	0.5547	Moderate
600 - 800	2.9	0.1636	1.0886	High
> 800	0.4	0.1815	1.1928	Very high

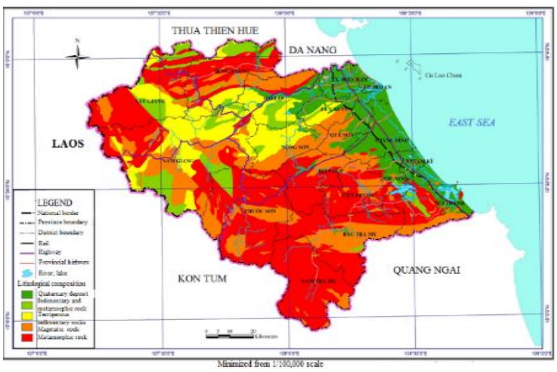

Figure 2. Lithological composition map

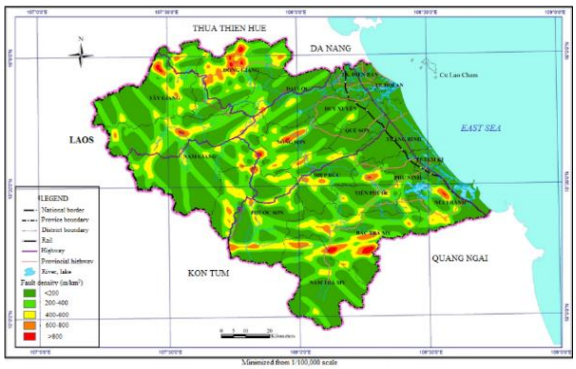

Figure 3. Fault density map

**** Weathering crust***

The type of weathering crust determines the thickness and associated mineral combination. On slopes, the thicker the weathered crust, and the more thorough the weathering, the greater the possibility of slipping. The clay mineral group of weathering products determines the water properties of the weathered crust.

On the basis of quantitative relationships of SiO2, Al2O3, and Fe2O3, the study area (except Quaternary deposits) can be classified into four weathering zones: Ferosialite (FSA), Sialferite (SAF), Silixite (SL), and Feralite (FA) (Figure 4).

Results of the overlaying weathering crust map and landslide inventory map show that the Ferosialite crust has the highest susceptibility. The Siaferite crust types have high landslide susceptibility. The Feralite crust types have the lowest weight value, which corresponds to a very low susceptibility level (Table 4).

Table 4. Classification of landslide susceptibility of weathering crust factor

Weathering crust type	**Area percentage (%)**	**Landslide density (points/ km^2)**	**Weight value**	**Susceptibility**
Ferosialite	54.7	0.0667	0.1912	Very high
Siaferite	25.2	0.0630	0.1343	High
Silixite	3.8	0.0319	-0.5451	Moderate
Quaternary deposits	13.6	0.0104	-1.6655	Low
Feralite	2.7	0.0035	-2.7435	Very low

**** Slope***

The slope is important with regard to landslide initiation. In most studies of landslides, the slope is taken into account as a principal causative or trigger factor. The topographic map of Quang Nam Province, on a scale of 1:50,000, showing topographic contours with intervals of 20 m, was digitized and a digital elevation model (DEM) of the study area with a pixel size of 30 m by 30 m was derived by inverse distance interpolation using ArcGIS software. A slope map was derived from the DEM using the slope function of ArcGIS, and slope classes were generated by separating the slope angles into five different classes: $<15^0$, 15^0 - 25^0, 25^0 - 35^0, 35^0 - $45^{0,}$ and $>45^0$ (Figure 5).

The slope map with these classes is overlaid with the landslide inventory map to determine the weight value for the slope level. The results show that in Quang Nam the higher the slope the greater the weight value and the higher the susceptibility (Table 5).

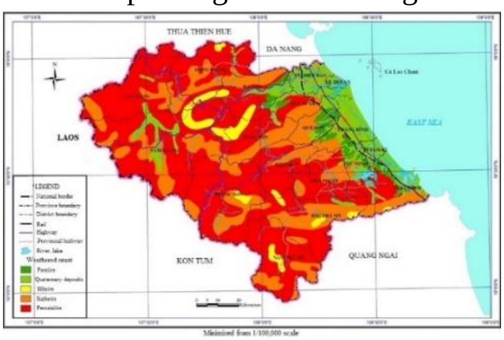

Figure 4. Weathering crust map

Figure 5. Slope map

Table 5. Classification of landslide susceptibility of slope factor

Slope	**Area Percentage (%)**	**Landslide density (points/ km^2)**	**Weight value**	**Susceptibility**
$< 15^0$	41.6	0.0397	-0.3262	Very low
15^0 - 25^0	30.4	0.0606	0.0961	Low
25^0 - 35^0	21.0	0.0665	0.1889	Moderate
35^0 - 45^0	6.3	0.0862	0.4485	High
$> 45^0$	0.7	0.1010	0.6065	Very high

**** Deep disruption density***

Deep disruption density in the research area is built based on digital elevation models (DEM) and is divided into 5 levels: < 25m/km^2, 25 - 50 m/km^2, 50 - 100 m/km^2, 100 - 200 m/ km^2 and > 200 m/km^2 (Figure 6).

The weight value of the deep dividing density factor increased from levels <25m to 100 – 200 m, and then it decreased. The highest landslide density is concentrated in areas with an average deep dividing density (100 - 200 m). Level 50 - 100 m corresponds to moderate landslide density. Levels < 25 m and 25 - 50 m correspond to very low and low susceptibility (Table 6).

Table 6. Classification of landslide susceptibility of deep disruption density factor

Deep disruption density (m/km^2)	Area percentage (%)	Landslide density (points/km^2)	Weight value	Susceptibility
< 25	13.67	0.0028	-2.9916	Very low
25 - 50	2.78	0.0408	-0.3005	Low
50 - 100	6.14	0.0785	0.3543	High
100 - 200	18.15	0.1072	0.6662	Very high
> 200	59.26	0.0494	-0.1085	Moderate

**** Autumn rainfall***

Unlike many previous studies that used average annual rainfall, in this study, we use autumn rainfall (cumulative rain in the three months of September, October, and November). In Quang Nam, autumn rainfall accounts for more than 60% of the annual rainfall and autumn is the peak period of the rainy season. Actual analysis of landslides in the study area shows that landslides mainly occur in the fall, during and after heavy rains.

Autumn rainfall map was established based on the results of interpolated rainfall data at 13 rain stations (period 1981 - 2015) and contour by Inverse Distance Weighted (IDW) method in ArcGIS. Accordingly, autumn rainfall in Quang Nam was divided into 5 levels: < 1500 mm, 1500 - 1700 mm, 1700 - 1900 mm, 1900 - 2100 mm, and > 2100 mm (Figure 7).

The analytical relationship results between autumn rainfall and landslide inventory show that weight values increased from areas where rainfall < 1500 mm to areas with rainfall > 2100 mm. That means the hazard of landslides increases with the increase of rainfall. The greater the autumn rainfall is, the higher the susceptibility of landslides is (Table 7).

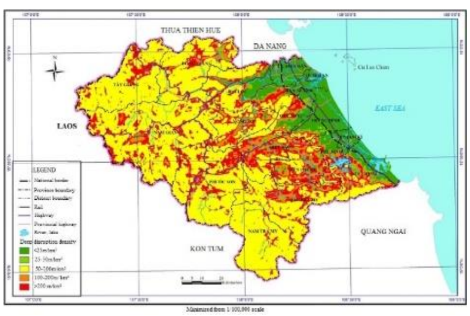

Figure 6. Deep disruption density map

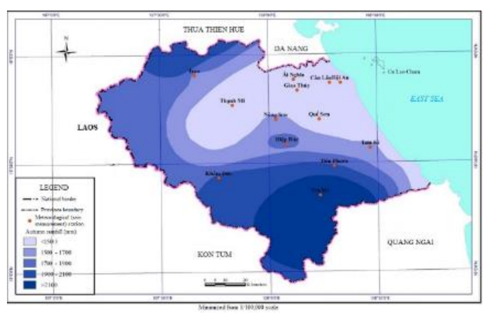

Figure 7. Autumn rainfall map

Table 7. Classification of landslide susceptibility of autumn rainfall factor

Autumn rainfall (mm)	Area Percentage (%)	Landslide density (points/km²)	Weight value	Susceptibility
< 1500	27.15	0.0527	-0.0431	Very low
1500 - 1700	16.25	0.0544	-0.0126	Low
1700 - 1900	26.53	0.0556	0.0094	Moderate
1900 - 2100	14.45	0.0563	0.0226	High
> 2100	15.62	0.0579	0.0507	Very high

**** River density***

Based on the river network with the help of GIS, we have developed the river density of Quang Nam province, which shows 5 different levels: < 0.5 km/km^2; 0. 5 - 1.075 km/km^2; 1.075 - 1.525 km/km^2; 1,525 - 2 km/km^2 and > 2 km/km^2 (Figure 8).

Very high landslide susceptibility is concentrated in areas where the river density is average (1.075 -1.525 km/km^2), followed by a high level of susceptibility to the density of 1.525 - 2 km/km^2. Areas with the highest river density (> 2 km/km^2) have the lowest weight value and lowest susceptibility (Table 8).

Table 8. Classification of landslide susceptibility of river density factor

River density (km/km²)	Area percentage (%)	Landslide density (points/km²)	Weight value	Susceptibility
< 0.5	7.5	0.0126	-1.4755	Low
0.5 - 1.075	56.2	0.0447	-0.2092	Moderate
1.075 - 1.525	31.1	0.0829	0.4095	Very high
1.525 - 2	5.0	0.0646	0.1591	High
> 2	0.2	0.0049	-2.4131	Very low

**** Land use***

While analyzing factors causing landslides, land use is considered in terms of the influence of vegetation cover. Plant cover has decreased rainwater, prevented erosion and mechanical destruction, strengthened soil cover, and increased soil resistance. The higher the vegetation cover, the greater the level of slope stability. Each type of tree creates a different level of canopy cover and therefore affects landslide hazards differently.

Based on the land use map in 2015, the author has divided it into 5 groups of land use, corresponding to the different levels of coverage: natural forests, planted forests, agricultural land, villages, built-up areas, and bare hills and shrubs.

Results overlay land use maps with landslide inventory show that bare hills and shrub areas have the highest susceptibility. Village and built-up areas have high susceptibility. Planted forests have average sensitivity levels, and agricultural land of natural forests are at very low levels (Table 9).

Table 9. Classification of landslide susceptibility of land factor

Landuse	Area percentage (%)	Landslide density (points /km^2)	Weight value	Susceptibility
Natural forests	38.41	0.0259	-0.7552	Very low
Agricultural land	26.48	0.0580	0.0521	Low
Planted forests	13.09	0.0743	0.2998	Moderate
Villages and built-up areas	8.82	0.0866	0.4525	High
Bare hills and shrubs	13.20	0.0979	0.5749	Very high

**** Distance to roads***

The process of building roads in mountainous areas increases the slope, the possibility of destabilizing the slope, causing landslides. Field surveys show that many landslides occur on talus. National highways 14E, 14D, 40B, Ho Chi Minh road, and provincial roads 604, and 611 are places where landslides often occur. Therefore, distance to roads is an important factor when landslide susceptibility is assessed.

Based on the road map of the traffic network of the research area, with the support of GIS, the author has developed a map of the distance to roads by Buffering tool with 5 levels: < 50 m, 50 - 100 m, 100 - 200 m, 200 - 400 m and > 400 m (Figure 9). Accordingly, < 50 m distance is only 2.12%, and 50 - 100m distance is only 2.07% of the total area. Distance which is the largest > 400 m covers most of the territory, at 84.4% of the total area.

Overlaying results showed that the nearer the road is, the higher the landslide susceptibility is (Table 10).

Table 10. Classification of landslide susceptibility of distance to roads factor

Distance (m)	Area percentage (%)	Landslide density (points/km^2)	Weight value	Susceptibility
< 50	2.12	0.2935	1.6733	Very high
50 - 100	2.07	0.2416	1.4785	High
100 - 200	3.99	0.2014	1.2965	Moderate
200 - 400	7.42	0.1121	0.7107	Low
> 400	84.40	0.0326	-0.5253	Very low

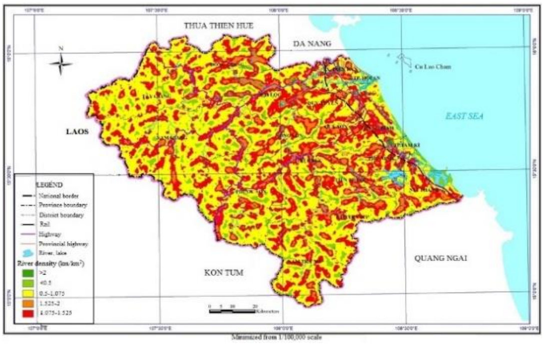

Figure 8. River density map

Figure 9. Distance to roads map

2.2.3. Evaluating landslide susceptibility in Quang Nam

**** Weight value of factors causing landslides***

Based on the opinions of 11 experts, the author has synthesized and calculated results in pair-wise comparisons of factors by the averaging method. Since then, the author shall build the correlation comparison matrix between factors arising from landslides in Quang Nam and calculate the weight value of each factor (Table 11). The results show that the slope factor and autumn rainfall have the greatest weight values, 0.271 and 0.235 respectively; representing two factors that have the greatest impact on the development process of landslides in Quang Nam. The next factors, lithological composition, weathering crust, and fault density which weighted 0.12; 0.112, and 0.96 respectively are the group's second most important factors. The river density factor weighted cross smallest (0.030) (Table 12).

Table 11. Correlation matrix between factors causing landslides in Quang Nam province

	Slope	Autumn Rainfall	Lithological composition	Fault density	Weathering crust	Deep disruption density	River density	Landuse	Distance to roads
Slope	1	2	4	5	4	5	7	5	6
Autumn rainfall	1/2	1	3	4	3	5	6	5	6
Lithological composition	1/4	1/3	1	2	1	4	4	3	4
Fault density	1/5	1/4	1/2	1	1	3	4	2	4
Weathering crust	1/4	1/3	1	1	1	3	4	3	4
Deep dividing density	1/5	1/5	1/4	1/3	1/3	1	2	2	3
River density	1/7	1/6	1/4	1/4	1/4	1/2	1	1/2	1/2
Landuse	1/5	1/5	1/3	1/2	1/3	1/2	2	1	2
Distance to roads	1/6	1/6	1/4	1/4	1/4	1/3	2	1/2	1

Table 12. Weight value matrix (Wi) of factors

	Slope	Autumn Rainfall	Lithological composition	Fault density	Weathering crust	deep disruption density	River density	Landuse	Distance to roads	Weight value
Slope	0.309	0.427	0.310	0.300	0.295	0.195	0.194	0.227	0.179	0.271
Autumn rainfall	0.155	0.214	0.310	0.300	0.295	0.244	0.194	0.227	0.179	0.235
Lithological composition	0.103	0.071	0.103	0.150	0.098	0.146	0.129	0.136	0.143	0.120
Fault density	0.077	0.053	0.052	0.075	0.098	0.146	0.129	0.091	0.143	0.096
Weathering crust	0.103	0.071	0.103	0.075	0.098	0.146	0.129	0.136	0.143	0.112
Deep dividing density	0.077	0.043	0.034	0.025	0.033	0.049	0.065	0.091	0.071	0.054
River density	0.052	0.036	0.026	0.019	0.025	0.024	0.032	0.023	0.036	0.030
Landuse	0.062	0.043	0.034	0.038	0.033	0.024	0.065	0.045	0.071	0.046
Distance to roads	0.062	0.043	0.026	0.019	0.025	0.024	0.065	0.023	0.036	0.036

**** Landslide susceptibility mapping***

Landslide susceptibility was established based on weighted overlaying 9 factors, including lithological composition, fault density, weathering crust, slope, deep dividing density, autumn rainfall, river density, land use, and distance to roads. The formula is as follows:

LSI = (lithological composition map × 0.12) + (fault density map × 0.096) + (weathering crust map × 0.112) + (slope map × 0.271) + (deep disruption density map × 0.054) + (autumn rainfall map × 0.235) + (river density map × 0.03) + (land use map × 0.046) + (distance to roads map × 0.036).

Factor maps in raster form are standardized and divided into pixels with each pixel size being 30x30m (11,763,164 pixels). Each pixel is assigned class weight values for each map. Integrated processing results obtained are a map of each pixel value of a corresponding value of LSI. LSI aggregated value across the entire study area ranges from -0,939305 to 0,421185. Landslide susceptibility index values were divided into five susceptibility classes (very high, high, moderate, low, and very low). The value between classes is determined according to the formula:

$$\Delta = \frac{LS\,\mathrm{Im}ax - LS\,\mathrm{Im}in}{5} = \frac{0,421185 - (-0,939305)}{5} = 0,272$$

The results of the landslide susceptibility map are shown in Table 13 and Figure 10.

Table 13. Classification of landslide susceptibility in Quang Nam

Class	**Susceptibility**	**LSI value**	**Area** (km^2)	**Area rate** (%)
Class 1	Very low	< -0.67	1555.51	14.90
Class 2	Low	-0.67 - (-0.40)	1422.56	13.63
Class 3	Moderate	- 0.40 - (-0.12)	4139.78	39.66
Class 4	High	-0.12 - 0.15	2979.65	28.55
Class 5	Very high	> 0.15	340.86	3.27
Total			**10438.37**	**100**

Very high landslide susceptibility areas only occupy 3.27% of the total area and it is distributed in some districts: Tay Giang, Dong Giang, Phuoc Son, and Nam Tra My. High landslide susceptibility areas are 28.55%. More than a third of the area of Quang Nam province (39.66%) has moderate landslide susceptibility and it is distributed in most mountainous areas of the province. Low landslide susceptibility areas occupy 13.63% and very low potential landslide susceptibility areas 14.9% of the total area in Quang Nam province.

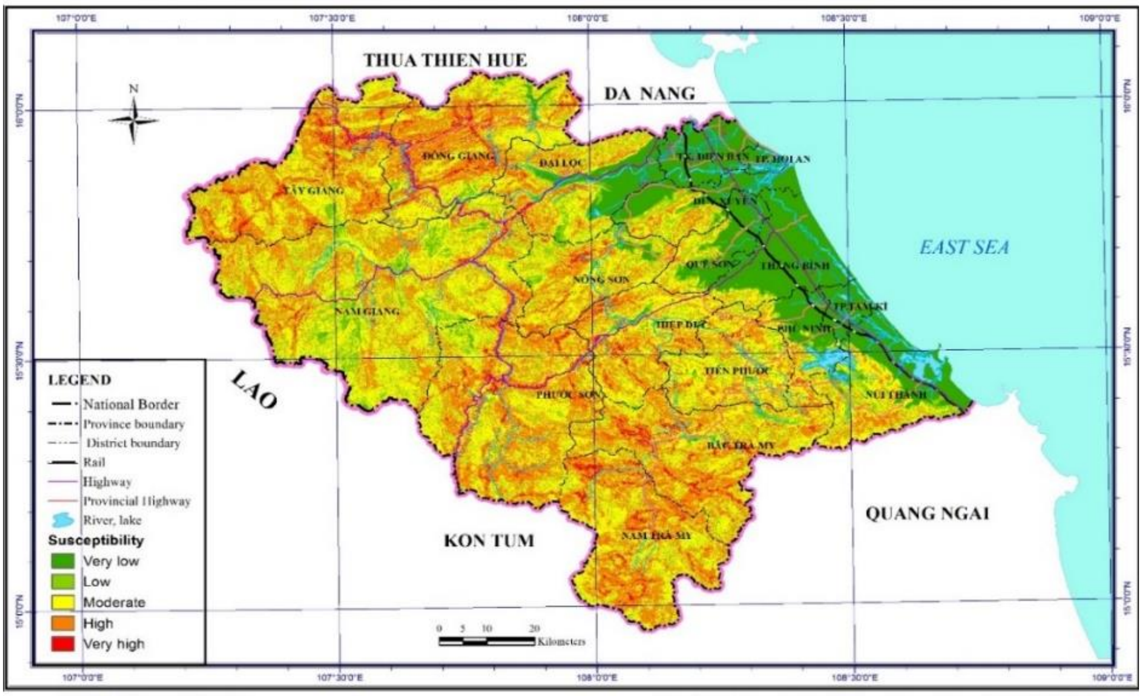

Figure 2. Landslide susceptibility map in Quảng Nam province

**** Identifying areas with high and very high susceptibility to landslides***

The high susceptibility area is 297,965 ha, located in 106 communes and towns. Phuoc Son district has the largest area of high susceptibility with 43373.74 ha, occupying 37.98% of the total area. Nam Giang and Nam Tra My have an area of 42767.92 ha and 36205.45 ha, respectively, covering about 23.45% and 44.41%.

In terms of the scale of commune level, each commune has a high susceptibility covering an area of about 2573.64 ha, occupying an average of 33.33% of the area. The most is in Phuoc Hiep commune of Phuoc Son district about 11572.25 ha are in high hazard of landslide, occupying 33.79% of the area. 11 other communes: Tra Giac, La ee, Lang, Tra Bui, Ca Dy, Tra Mai, Phuoc Kim, Zuoich, and TT. Thanh My, Dac Pring, and Ma Cooi have an area of high susceptibility to a landslide over 5000 ha /commune.

The very high susceptibility is 34086 ha, mainly in 104 communes and towns in the study area. Nam Tra My district has the largest very high susceptibility area, about 5809.01 hectares. In Bac Tra My, Tay Giang, Dong Giang, and Phuoc Son, the very high susceptibility areas are 5592.76 ha, 4986.67 ha, 4785 ha, and 4524.57 respectively.

For the commune level, on average, there are very high susceptibility of 325.41 ha in each commune in Quang Nam. Tra Bui commune of Bac Tra My district has the largest very high susceptibility area of 1868.05 ha, followed by Tra Giac (Bac Tra My), Ca Dy (Nam Giang), and Tra Mai (Nam Tra My), respectively 1340.88ha, 1237.82 ha and 1236.98 ha.

**** Model evaluation***

In this study, the author conducted a landslide susceptibility map assessment based on the consideration of the distribution of landslides in the hazard groups of the susceptibility map. The landslide inventory map by Dinh Van Tien in 2011 [14] overlapped with the above landslide susceptibility map. Results showed that: 79/110 landslides, accounting for 71.8%, fell into areas with high and very high susceptibility. In addition, the collected landslides that occurred in Quang Nam from 2017 to 2023 are concentrated in communes with high and very high susceptibility to landslides. That means the division of landslide susceptibility levels is in line with reality. The landslide susceptibility map proposed by the model is acceptable.

3. Conclusions

Landslides in Quang Nam province occur due to the combined impact of natural and human factors, including lithological composition, fault density, weathering crust, slope, deep dividing density, autumn rainfall, drainage density, land use, and distance from roads. In particular, slope and autumn rainfall are the two most important influencing factors on landslides.

Landslide susceptibility assessment in Quang Nam province is carried out based on the causative factors and integration assessment. The combined use of statistical index models and analytical hierarchy process (AHP) ensures the reliability of the evaluation results. The increasing trend of landslide density according to very low, low, medium, high, and very high susceptibility levels shows that the landslide susceptibility map built with this model is acceptable.

The assessment results show that the majority of the area (71.47%) in Quang Nam province has medium, high, and very high susceptibility to landslides. High and very high susceptibility accounts for 31.82% of the area, distributed mainly in the western mountainous areas such as Dong Giang, Tay Giang, Bac Tra My, Nam Tra My, Phuoc Son, Hiep Duc, and Tien Phuoc districts. Very low and low landslide susceptibility areas are concentrated in the coastal plains of Thang Binh, Dien Ban, Nui Thanh districts, Hoi An, and Tam Ky cities.

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