GIS-BASED LANDSLIDE SUSCEPTIBILTY MAPPING BY USING ANALYTICAL HIERARCHY PROCESS IN THE HYDROTHERMALLY ALTERED AREA AT SOUTHERN MOUNTAIN OF LOMBOK ISLAND, INDONESIA

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Abstract

Landslide disasters are abundant in the mountainous areas of Lombok Island, Indonesia. Most landslides frequently occur in areas intensively suffered by hydrothermal alteration including Pelangan Village at Southern Mountain, West Lombok Regency. The objective of this study are to identify the most important factors controlling landslide and also to analyze the landslide susceptibility zones in the hydrothermally altered area. For this purpose, it is necessary to prepare the landslide investigation and landslide susceptibility map. In this study, the AnalyticalHierarchyProcess (AHP) is used to develop landslide susceptibility map. The landslide susceptibility was analyzed by applying weighting and scoring on each factor controlling the landslide occurrence, such as hydrothermal alteration, slope inclination, distance to lineament, and landuse.The result shows that hydrothermal alteration and slope inclination are the most important parameters to landslide occurence (39.35%), and the least important factor are distance to lineament (13.76%), and landuse (7.54%). The high susceptible zones (HS) cover about 34.20% of the total study area. The moderate susceptible zones (MS) cover about 18.40% of the total area, while about 27.80% of the total study area were classified as being the low susceptible zone (LS), and about 19.60% of the total study area are classified as very low susceptible zone (VLS).

Keywords:*GIS, AHP, landslide susceptibility, hydrothermal alteration, Lombok Island Indonesia*

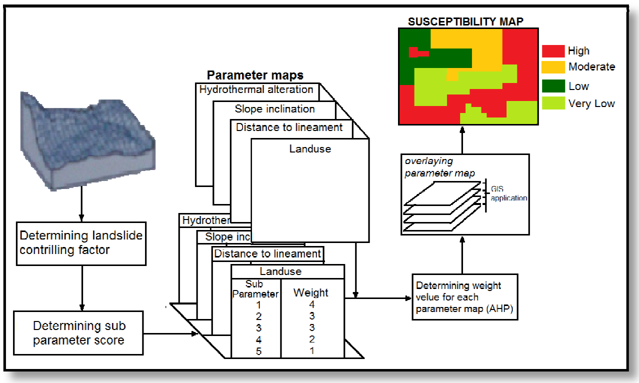
1. Introduction

Landslide is destructive natural disaster that fraquently lead to serious impacts, especially on the mountainous and hilly terrain with dynamic geological conditions such as in Indonesia. The natural conditions plays important role in controlling the susceptibility and trigerring the occurrence of landslides [1]. Generally, landslides are controlled by morphology, geology, deposits forming the slope, slope hydrology, and landuse conditions [1,2,3,4] and also triggered by water infiltration, seismic acceleration, and human activity [1,5,6].Most landslides frequently occur in areas intensively suffered by hydrothermal alteration including Pelanganarea, West Lombok Regency.Landslide investigations and landslide susceptibilitymapping (LSM) are crucial to support the landslide risk reduction efforts.

There are various methods for LSM such as AHP, fuzzy logic, and statistic methods.The AHP methodfor LSMhas been used by [7,8,9].AHP is a multicriteria decision making approach in which factors are decomposed into hierarchically structure and are given the weights according to their importance [10].The weighting of all the factors depending upon the scales of relative importance of each factor in controlling the landsliding. Many authors [7,9,11,12] generally agreed that weight of eachfactorsdepends on the judgment of expert, so that the more precise is the judgment, the more compatible is the developed landslide susceptibility map with reality.This paper attempts to describe the application of AHP for LSM in the hydrothermally altered area at Southern Mountain of Lombok Island.

2. Research Methods

This study is conducted by literature, engineering geological investigations, X-Ray Diffraction (XRD)analysis, data processing, and interpretation. Engineering geological investigations includes landslide inventory, mapping of landslide susceptibility, surface geology, hydrothermal alteration, and sampling of representative rock types and altered rocks.Landslide inventory is the form of landslide mapping. Landslide inventory map was eventually prepared using historical of landslide events and remote sensing imagery coupled with landslide inventory by global positioning system (GPS).The results of engineering geological investigations and XRD analysis were crucial to identify the controlling factors of landslide, and also to analyze the distribution and occurrence of landslides in the hydrothermally altered area.The landslide controlling factors were combined with landslide distribution to develop landslide susceptibility map.The AHP method proposed by [10] available in Geographic Information System (GIS) was used to develop landslide susceptibility map of the Pelangan area. The landslide susceptibility was analyzed by applying weighting and scoring on each factor controlling the landslide occurrencesuch as hydrothermal alteration, slope inclination, distance to lineament, and landuse. The weighting was defined by adapting the AHP method, depending upon the importance levels of each factor in controlling the landsliding. Meanwhile, the scoring was determined base on the level of unfavorable condition of the respective factor. Steps for analyzing the weighting to define the level of importance of each controlling parameter is illustrated in Figure 1.



Fgure 1. Steps for defining the weight value for each parameter, modified from [13]

3. Characteristics of the Study Area

Our study area, Pelangan, is located approximately 54 Km southwest of Mataram. The border of the study area is determinated by UTM coordinates X_1: 381000, Y_1: 9024000, X_2: 381000, Y_2: 9032000, X_3: 386000, Y_3: 9032000, X_4: 386000, Y_4: 9024000 as indicated in Figure 1.

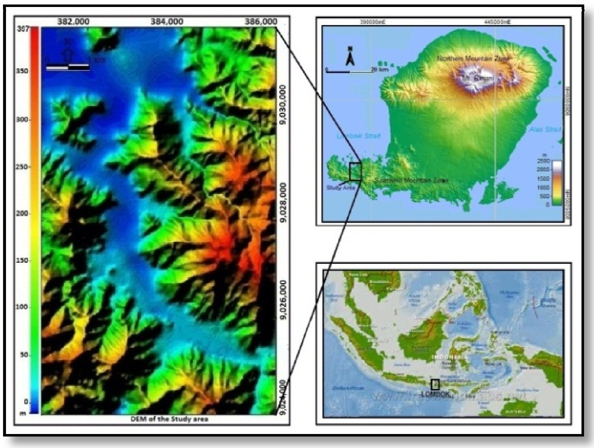


Figure 1. Research location map (on the right) and DEM of the study area (on the left)

The total area of the study is 40 km². The Pelangan area has different morphologies that the slope degree varies from 0° to 88° and the elevation varies from 0 to 394 meters above sea level. The moderate to very steep slope (15° - 88°) occupy 71.59% of the total area, whereas 28.41% is flat to gentle slope (<15°). This area is covered by andesitic breccia, andesitic tuff, andesite porphyry, dacite, diorite, limestone, and alluvium. The oldest rock unit in this area is Miocene PengulungFormation (Tomp) which composed of andesitic breccia and andesitic tuff. Limestone is a member of the Miocene EkasFormation (Tme). The youngestdeposits of the study area which is Holocene sedimentation (Qa) has been represented by alluvium.The andesite porphyry, dacite, and diorite intrusions are interpreted to be source of mineralization and hydrothermal alteration process. The younger volcanic wallrocks have been suffered by hydrothermal alteration. The valleys with moderate to very steep slopes extend along drainage with trending northwest to southeast and northeast to southwest trends.The study area has four types of landuse as follows forest, mix garden, agriculture, and settlement. Several people’s mining sites can be found in this area.

4. Results and Discussion

In this study, the AHP method is applied to develop landslide susceptibility map. For preparing the landslide susceptibility map, five layers including landslide inventory, hydrothermal alteration, slope inclination, distance to lineament, and landuse are considered. ArcGis software is used to develop the layer maps which are used in the development of the landslide susceptibility map.Finally, the map was verified using computation of landslide density.

4.1. Landslide Inventory

Landslide inventorieshave been conducted since September 2013 to Januari 2014. The location of all landslide were recorded by GPS. In total 12 landslides with size varying from 105 m² to 16000 m² were observed. The landslides cover about 27.84 km² of the total study area, and generally occur in hydrothermal altered rocks.Landslide investigation reveals that the Pelangan area experiences various types of landsliding. Debris slide, rock fall, and creep have been recognized. The debris slides mostly occur in altered andesitic tuff. Seven locations of debris slide are observed on the steep slopes within the range of 30° to 40°. Rock falls were occured in altered andesitic breccia, andesitic tuff, andesite porphyry, and jointed limestone. Four locations of rock fall can be found on very steep slopes where the inclination exceeds 40°. A creep occured on moderately slope with inclination 17°, which was covered by altered andesitic tuff. Distributionof landslides which vary in their types are shown in Figure 2.

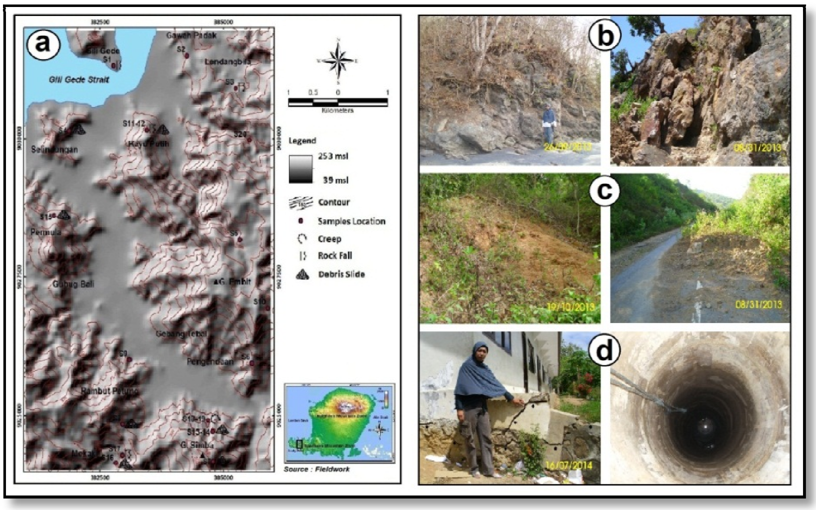


Figure 2. Distribution of landslides which vary in their types, (a) Landslide inventory map, (b) Rock fall in altered andesite porphyry (on the left)and alteredandesitic tuff (on the right), (c) Debris slide in altered andesitic tuff, (d) Impact of creep in altered andesitic tuff

4.2. Parameters for Landslide Susceptibility Assessment

After preparing landslide inventory map, hydrothermal alteration, slope inclination, distance to lineament, and landuse parameters were selected to develop the landslide susceptibility map of the Pelangan area (Table 1). The selection of these parameters is based on the availability of data forthe study area and the importance tolandslide occurrences.

Most landslides frequently occur in areas intensively suffered by hydrothermal alteration including Pelanganarea. The hydrothermal alteration produced clay minerals and made rocks become loose. The presence of those clay minerals especially associated with hydrothermal alteration zone become to be important lithological factor controlling the landslide occurrences within study area. Based on XRD analysis and fieldwork observation, zone of hydrothermal alteration was divided into advanced argillic zone, propylitic zone, and unaltered zone.

Generally, slope inclination have a large impact on landsliding in the Pelangan area. [2] reported that no landslides occurred on slopes less than 12º in Java. In Pelangan, no landslide occurrence is observed on the slope of less than 15º. A creep occured on moderately slope with inclination 17º. Debris slides can be observed on the steep slopes with inclination 30º - 40º. Rock falls can be found on very steep slopes that are greater than 40º.Based on those facts, the slope inclination is classified into four different classes 0º - < 15º, 15º - < 30º, 30º - 40º, and > 40º.

The distance to lineament is one of the main parameters in preparing landslide susceptibility map. Distance to lineament digital map was generated from the Digital Elevation Model (DEM) of the study area. In this study, distance to lineament was devided into three classes including 0 m - < 150 m, 150 m – 300 m, and > 300 m.

Landuse is one of the most important factors for slope instability in the study area. Landuse has effect on strength of slope materials against landsliding and control of water content of slope [1,6]. Based on a landuse map of the Sekotong area and fieldworkobservation, four landuse classes were considered consisting of forest, mix garden, agriculture, and settlement.

Table 1. The Input Parameters Use for AHP Analysis

Paramater	Sub Parameter
Hydrothermal Alteration	Advanced Argillic Zone Propylitic Zone Unaltered zone
Slope Inclination	0º - < 15º 15º - < 30º 30º - 40º > 40º
Distance to Lineament	0 m – 150 m 150 m – 300 m > 300 m
Landuse	Forest Mix Garden Agriculture Settlement

Each parameter map has been classified into a number of sub parameters based on their relatif influence on landslide occurrences (Figure 3).

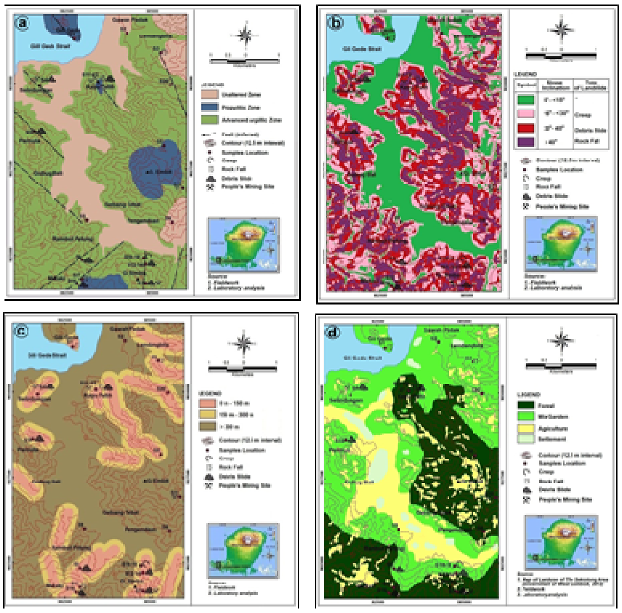


Figure 3. Landslide related parameters in the Pelangan area, (a) Hydrothermal alteration, (b) Slope inclination, (c) Distance to lineament, (d) Landuse

4.3. Parameter Weight Assigment

Landslide susceptibility map of the Pelangan area was eventually prepared using AHP method. AHP involves developing a hierarchy of landslide controlling parametersand then making comparisons between possible pair-wise in a matrix to give a weight for each parameter and consistency ratio (CR).In this method, pairwise comparison is based on the rating of relative preferences for two criteria at a time. Each comparison is a two-part question determining which criterion is more important and to what extent using a scale (Table 2). The values range from 9 representing the most important (than), to 1 for equal importance, and to 1/9 for least important (than), covering all the values in the set.

Table 2. The Saaty RatingScale for Pairwise Comparisons [10]

Intensity of Importance	Definition
1	First parameter is equally important as the second one
3	First parameter is moderately more important thanthe second one
5	First parameter is stronglymore important than the second one
7	First parameter is very strongly more important than the second one
9	First parameter is extremely more important the second one
2,4,6,8	Intermediate values between the two adjacent judgments
Reciprocals	Used for inverse comparison

In AHP, for measuring the level of consistency [10] proposed a consistency ratio (CR) which compares consistency index (CI) and the random index (RI).

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

The consistency index (CI) can be calculated using the principal eigenvalue λmax of the Saaty's matrix S.

$$CI = \frac{\lambda \max - n}{n-1}$$

Meanwhile, the random consistency index (RI) represents the avarage consistency index of randomly generated by Saaty's matrices of the dimension. A few first values can be found in Table 3.

Table 3. Random Consistency Index [14]

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53

For these matrices, the consistency ratio (CR) must be less than 0.1 [10]. The parameters with a CR greather than 0.1 were automatically rejected and should be re-evaluated. Meanwhile a CR less than 0.1 were automatically acceptable. This ratio indicates a reasonable level of consistency in their pair-wise comparison that was good enough to recognize the class weights.Calculated of each parameter has been normalized and converted to scale of Saaty in order to apply in ArcGis software (Table 4).

Table 4. Pairwise Comparison Matrix for Landslide Analysis

Parameter	1	2	3	4	Eigen Vectors
[1] Hydrothermal alteration	1.00	1.00	3.00	5.00	0.3935
[2] Slope inclination	1.00	1.00	3.00	5.00	0.3935
[3] Distance to lineament	0.33	0.33	1.00	2.00	0.1376
[4] Landuse	0.20	0.20	0.5	1.00	0.0754
Consistency ratio (CR) : 0.0021					

The resulting CR for the pairwise comparison matrix for four dataset layers was 0.0021 (Table 4). Based on the Table 2 and Table 4, hydrothermal alteration is equally important (1) as slope inclination. Hydrothermal alteration and slope inclination are moderately more important (3) than distance to lineament, and strongly more important (5) than landuse. This ratio indicates that the comparisons were perfectly consistent and that the relative weights were appropriate to be subsequently used in the landslide susceptibility model.Table 5 shows that the hydrothermal alteration is equally important as slope inclination to landslide occurrence. Hydrothermal alteration and slope inclination are 2.86 times bigger than distance to lineament, and 5.22 times bigger than landuse. Whereas distance to lineament is 1.83 times bigger than landuse. Consequently, the weight corresponding to hydrothermal alteration and slope inclination are the biggest (39.35%), whereas distance to lineamnet (13.76%) and landuse (7.54%) are the smallest (Table 4).

Table 5. Comparison of Priority Scalefor EachNormalized Parameter [10]

Comparison of Parameters	Score (X most biggest)
Hydrothermal Alteration : Slope Inclination	1.00
Hydrothermal Alteration and Slope Inclination : Distance to Lineament	2.86
Hydrothermal Alteration and Slope Inclination : Landuse	5.22
Distance to Lineament : Landuse	1.83

In the next step, on the basis of landslide distribution data andfactors controlling the occurrence of landslide,allsub parameter used in the landslide analysis were weighted. These sub parameter must be arranged in a hierarchic order and assigned numerical value to enable subjective judgment of relative importance of each sub parameter. The scoring were given to each sub parameter,orders from 1 (has relatively no influence on landslide occurrence), 2 (has relatively least influence on landslide occurrence), 3 (has moderate influence on landslide occurrence), and 4 (has strong influence on landslide occurrence). Table 6 shows the weighted score of each sub parameter for landslide analysis.

Table 6. The Weighted Score of Each Sub Parameters

Paramater	Sub Parameter	Score
Hydrothermal Alteration	Advanced Argillic Zone	4
	Propylitic Zone	2
	Unaltered zone	1
Slope Inclination	0º - < 15º	1
	15º - < 30º	4
	30º - 40º	4
	> 40º	1
Distance to Lineament	0 m – 150 m	4
	150 m – 300 m	1
	> 300 m	1
Landuse	Forest	3
	Mix Garden	4
	Agriculture	1
	Settlement	1

Finally, the landslide susceptibility map that was developed based on the AHP method depicted in Figure 4. According to [13], the resulting landslide susceptibility map of study area is classified into very low, low, moderate, and high susceptible zones. The high susceptible zones (HS) cover about 34.20% of the total study area, whereas moderate susceptible zones (MS), low susceptible zone (LS), and very low susceptible zone (VLS)cover respectively about 18.40%, 27.80%, and 19.60% of the total area (Table 4).

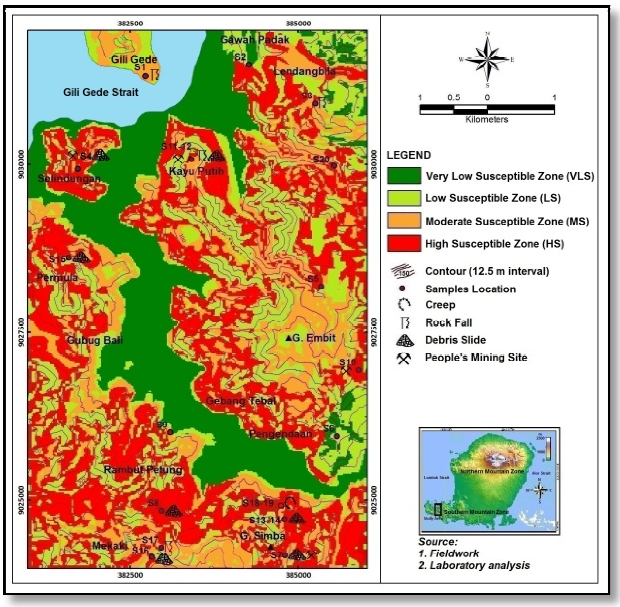


Figure 5. Landslide susceptibility map of the Pelangan area

5. Verification of The Landslide Susceptibility Map

There are different methods to verificate the landslide susceptibility map. In this study, the landslide susceptibility map was verified using computation of landslide density. Table 7 and Figure 6 shows that the landslide density forthe very low and low susceptibility zone are 0.0000 (0.00%). The landslide density for the moderate and high susceptibility zone are respectively 0.0207 (9.18%) and 0.2048 (90.82%). These results show that there is a gradual increase in landslide density from the very low to the high susceptibility zone. The number of landslide also increase from very low to high susceptibility zone are repectively 0 (0.00%), 0 (0.00%), 4 (33.33%) and 8 (66.67%). So, it can be concluded that the landslide susceptibility map of the Pelangan area very logic.

Table 7. Landslide Density in The Different Susceptibility Zones

Susceptibility Zones	Landslide		Area		Landslide Area		Landslide Density	
	Σ	%	km²	%	m²	%	Σ	%
Very low	0	0.00	7.38	19.60	0.00	0.00	0.0000	0.00
Low	0	0.00	10.45	27.75	0.00	0.00	0.0000	0.00
Moderate	4	33.33	6.94	18.41	0.0014	5.16	0.0207	9.18
High	8	66.67	12.89	34.24	0.026	94.84	0.2048	90.82

Figure 6. Distribution of landslide occurrences and landslide density in the landslide susceptibility zone

6. Conclusion

Four important geological factors controlling the landslide occurrence in the hydrothermally altered area at Pelangan area are identified including hydrothermal alteration, slope inclination, distance to lineament, and landuse. Based on the discussion above, hydrothermal alteration and slope inclination are the most important parameters to landslide occurrence, the second important parameter is distance to lineament, and the least important parameter is landuse. The obtained landslide susceptibility map indicate thatthe high susceptible zones (HS) cover about 34.20% of the total study area, whereas moderate susceptible zones (MS), low susceptible zone (LS), and very low susceptible zone (VLS)cover respectively about 18.40%, 27.80%, and 19.60% of the total area.Computation of landslide density proved that these landslide susceptibility map of the Pelangan area very logic.

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