The Assessment of Landslide Vulnerability Levels in Ponorogo, Indonesia, Using Fuzzy Analytical Hierarchy Process: Natural Breaks

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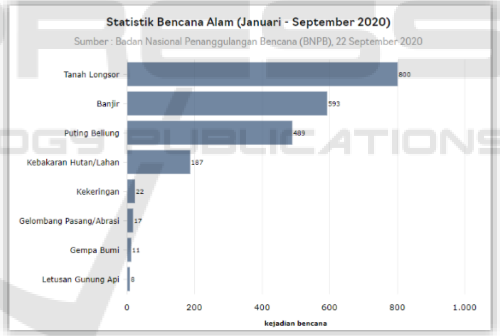
Abstract: Landslide is a natural phenomenon that turns into a landslide natural disaster when the landslide causes both losses of life and loss of property and human cultural products. Indonesia, which is partly hilly and mountainous, has caused parts of Indonesia to become areas prone to landslides. Although landslides are disasters that occur, repeated mitigation actions are often carried out spontaneously. This study proposes a new model for determining the level of vulnerability in Ponorogo Regency based on rainfall, land slope, elevation, land use, and soil type, using a fuzzy analytical hierarchy process (FAHP). FAHP produces priority weight values in 318 villages. The natural breaks classification method is used to classify the weight values into very low, low, medium, and high vulnerability values. The mapping results obtained were validated using the calculation of FAHP analysis and showed better results than AHP.

1 INTRODUCTION

Landslide is one of the natural disasters that often occur in Indonesia. The potential for landslides in Indonesia is a disaster that ranks first, with as many as 800 landslide events from January-September 2020. (Source: National Disaster Management Agency). Figure 1 shows statistical data on natural disasters that occurred in Indonesia from January – September 2020. Landslides are the most common disasters in Indonesia.

A landslide is a natural event that is currently increasing in frequency. This natural phenomenon turns into a landslide natural disaster when the landslide causes both losses of life and loss of property and human cultural products. Indonesia, which is partly hilly and mountainous, has caused parts of Indonesia to become areas prone to landslides. Landslides occur due to shear failure along the landslide, which is the limit of the movement of the soil or rock mass (Hardiyatno, 2012)

Ponorogo Regency is one of the regencies in East Java Province. This regency is located at geographical coordinates between 111° 17' - 111° 52' longitude and 7° 49' – 8° 20' latitude with an altitude of 92 to 2,563 meters above sea level and has an area of 1,371.78 km². Ponorogo Regency is varied, such as highlands and hills (Basofi et al., 2019).



Source: Katadata.co.id

Figure 1: Statistical data on Natural Disaster Events from January – September 2020.

Landslides in several villages in Ponorogo Regency caused damage to houses and public facilities and even claimed lives. The landslide disaster was caused by heavy rains that occurred on five consecutive days. The soil in the area results from weathering of thick rocks that absorb air and changes in land use from pine forests to agricultural land (Yuniarta et al., 2015).

Assessment of the level of vulnerability to landslides is needed as an effort for disaster early warning and decision support systems for

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stakeholders. The level of vulnerability to landslides is influenced by several factors that depend on the conditions of a particular area. The rainfall is the most significant factor in landslides in Ponorogo, followed by land slope, elevation, land use, and soil type (Basofi et al., 2017; Basofi et al.).

The analytical hierarchy process (AHP) is a decision support model developed by Thomas L. Saaty. This decision support model will describe a complex multi-factor or multi-criteria problem into a hierarchy. However, in reality, the AHP method has not been able to overcome vague or uncertain issues and is very dependent on the subjectivity of experts.

This study proposes a new model for determining the level of vulnerability in Ponorogo Regency based on rainfall, land slope, elevation, land use, and soil type, using a fuzzy analytical hierarchy process (FAHP). FAHP produces priority weight values in 318 villages. The natural breaks classification method is used to classify the weight values into very low, low, medium, and high vulnerability values.

2 METHODOLOGY

2.1 Model Development

In model development, several models will be developed using the FAHP method and carried out several experiments with a combination of several approaches. The development of the FAHP model consists of several stages, such as preparing a dataset, preprocessing, processing, and visualization.

A detailed description in Figure 2 of the system design for landslide-prone areas is as follows:

1. Landslide Data

The data needed in this application to determine landslide-prone areas are historical data from previous landslides, rainfall, and rain duration. This data is initial data in the form of raw data from related agencies that have not been processed. The information is from data obtained directly from the relevant agency, including the Disaster Management Agency of Ponorogo and the Department of Public Works of Ponorogo.

- Data History of landslides in 2015 was obtained from the Agency Ponorogo Disaster Management.

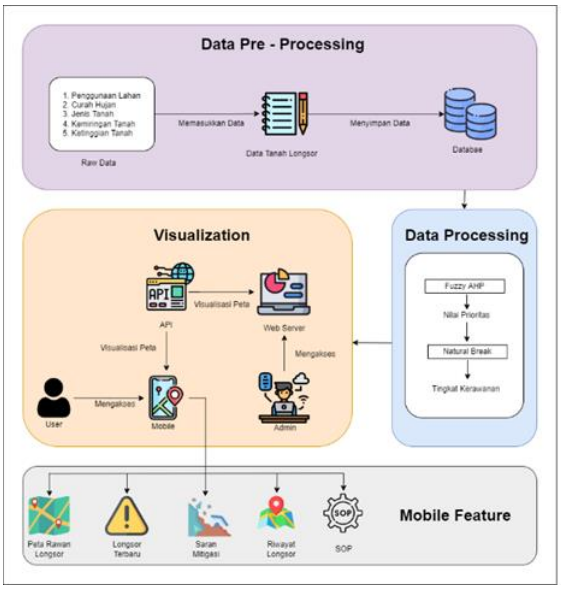

Figure 2: System Design.

- Variable data in the form of rainfall, land use, elevation, soil type, and land slope was obtained from Dinas Ponorogo Regency Public Works.

2. Databases

Landslide history data that has been collected will be prepossessed before being stored in the database. Prepossessing is the process of sorting data that aims to retrieve the required data. The database used is PostgreSQL.

3. Fuzzy Analytical Hierarchy Process (FAHP)

Preprocessing data such as village data and variables that affect landslide susceptibility will be processed. Then the process of collecting data from the database is carried out which is then carried out by the Statistical Analysis process which aims to find the correlation between the landslide history data and the variables that affect landslide susceptibility. In this application to produce flood-prone areas, calculations are carried out using FAHP (Intan et al, 2018).

4. Landslide Prone Area Data

The results of this correlation serve as a weighting reference to determine the ranking of priority variables that can cause landslides. Then the data processed from calculations using the FAHP method will be grouped in detail, then processed in the API.

5. API

The risk analysis results are provided in the form of an API that will be used on the mobile platform (android) and the website. After the modeling process is complete, a decision is made for landslide-prone areas. The user can access the output from regions that are prone to landslides.

6. Web Server
Information that has been processed regarding areas prone to landslides will also be displayed in the form of a spatial website that the admin will access.

7. Admin
In this application, the admin works on the server side, where the admin has access to add, read, update, and delete the data needed in this application.

8. Mobile
In this application, the user can use the application to view landslide data, landslide soup, and information about where the location is prone to landslides.

9. User
In this application, the user has a role on the client side where the user can view a map of landslide hazards, landslide history map, SOP for landslide disasters, and mitigation suggestions.

2.2 Hierarchy of Criteria

Figure 3 below shows that five criteria determine landslide-prone areas, namely land use, rainfall, land slope, soil type, and elevation.

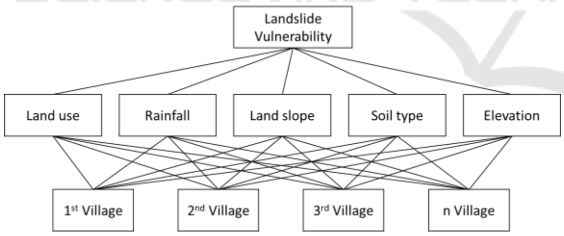

Figure 3: Hierarchy of criteria.

Each of the five criteria has sub-criteria: land use consisting of forests, non-rice fields, agriculture, rice fields, and settlements. Rainfall criteria consist of < 100 mm, 100-199 mm and > 200 mm. The land slope criteria consist of class 1 (0-8 degrees), class 2 (9-15 degrees), class 3 (16-25 degrees), class 4 (26-45 degrees), and class 5 (more than 45 degrees). The soil type or geology criteria consist of sub-criteria Alluvium, Limestone, Quaternary Volcanic, Young Quaternary Volcanic, Old Quaternary Volcanic, Pliosine Deposits, and Diosit. Then the land height criteria consist of 1000 mdpl, 1000-2000 mdpl, and > 2000 mdpl (Dzulkarnain et al., 2016).

2.3 FAHP Design

The flowchart of FAHP design for landslide assessment is shown in Figure 4. The following is an explanation of Figure 4 which consists of several stages, which are as follows:

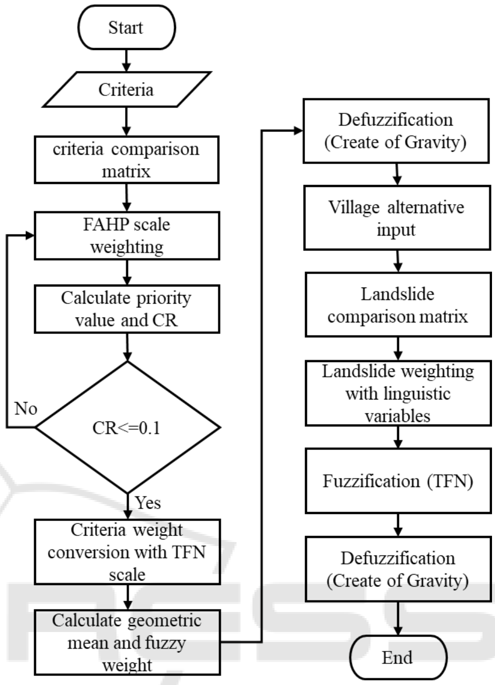

Figure 4: FAHP Flowchart.

1. Develop a comparison matrix (Pairwise Matrix Comparison / PCM) between all criteria and sub-criteria. Each element will be compared by giving weight to each comparison.
2. Calculate the Consistency Ratio (CR) value from the PCM calculation results to determine whether the PCM weighting has been consistent or not with the condition that the CR value is 0.1 by using the following formula

$$CI = (\lambda max - n) / (n - 1) \quad (1)$$

$$CR = CI / IR \quad (2)$$

where:
CI = Consistency Index
λmax = Maximum Eigen Value
n = Number of elements
CR = Consistency Ratio
IR = Index Ratio
3. The FAHP method uses a fuzzy ratio called Triangular Fuzzy Number (TFN) and is used in the fuzzification process. TFN consists of the

three membership functions, namely the lowest value (l), the middle value (m), and highest value (u). Change the results of the PCM weighting into the form of TFN using the scale as shown in Table 1.

Table 1: Triangular fuzzy number (TFN) scale.

AHP Scale	Linguistic Scale	TFN Scale (*l*; *m*; *u*)
1	Equal important	(1; 1; 1)
2	Intermediate important	(1/2; 1; 3/2)
3	Moderate important	(1; 3/2; 2)
4	Moderate plus important	(3/2; 2; 5/2)
5	Strong important	(2; 5/2; 3)
6	Strong plus important	(5/2; 3; 7/2)
7	Very strong important	(3; 7/2; 4)
8	Very strong plus important	(7/2; 4; 9/2)
9	Extreme important	(4; 9/2; 9/2)

4. Calculate the fuzzy geometric mean and fuzzy weight of each element using the formula:

$$r_i = a_{i1} \otimes a_{i2} \otimes \ldots \otimes a_{in} \quad (3)$$

$$wi = r_i \otimes (r_1 + \cdots + r_n)^{-1} \quad (4)$$

where:
a_{in} = synthetic pairwise comparison fuzzy value from element to *i*-*n*
r_i = geometric mean of *i*-th element
wi = fuzzy weight of the *i*-th element
n = Number of elements

5. The process of defuzzification of all elements (criteria and sub-criteria) using the Center of Gravity (COG) method.

$$BNP_i = \left\{\frac{(uR_i - lR_i) + (mR_i - lR_i)}{3}\right\} + lR_i \quad (5)$$

where:
BNP = Best Non-Fuzzy Performance
lR_i = the lowest value of the fuzzy weight of the *i*-th element
mR_i = the middle value of the fuzzy weight of the *i*-th element
uR_i = the highest value of the fuzzy weight of the *i*-th element

6. Determine the fuzzy priority for each alternative property by using linguistic variables. Integrating the weight of each criterion / sub-criteria and fuzzy performance values with fuzzy number calculations to get a fuzzy synthetic decision matrix using the formula:

$$R_i = E_i \otimes W_i \quad (6)$$

where:
R_i = *i*-th alternative fuzzy synthetic decision
E_i = alternative fuzzy performance value on the *i*-th element
W_i = total weight of fuzzy element *i*

7. Defuzzification of alternatives using the Center of Gravity method. The COG calculation results will be sorted based on the highest value to the lowest value to get the final result, which means the alternative that gets the highest value is the best alternative to be an investment choice (Xiong et al., 2017).

2.4 Natural Breaks Classification

The Natural Break method determines the points in the data by looking at the grouping and patterns of the data. The data used a range from the smallest to the largest. The data is then divided by the limits determined based on the value of the most extensive range. This natural breaks method is designed to select the best value settings for different classes (Sujatha et al., 2012).

This method seeks to reduce the variance within classes and maximize the variance between classes. Natural Breaks is the only method that finds the best ranges. The best ranges are the ranges where the area is like a grouping, which doesn't give the low-level areas the same color as the high-level areas. Natural Breaks minimize the variation within each color, so the areas within each color are as close to the same value as possible each other (Basofi et al., 2015) (Basofi et al., 2019).

Natural breaks iteratively calculate the squared deviation between classes (SDCM) and the squared deviation from the mean of each class (SDAM). After examining each SDCM, a decision was made to move one unit from the class with the largest SDCM to the class with the lowest SDCM. To test this classification method, the Goodness of Variance Fit (GVF) was calculated. GVF ranges from 0 to 1, which means from worst to very perfect.

3 RESULT

Experiments on 318 villages in Ponorogo regency used the following five criteria:

C1 = Rainfall
C2 = Land slope
C3 = Elevation
C4 = Land use
C5 = Soil type

The comparison matrix for each criterion can be seen in Table 2. Rainfall has the highest priority value, followed by land slope, elevation, land use, and soil type.

Table 2: Comparison matrix of each criterion.

	C1	C2	C3	C4	C5
C1	1	3	5	7	9
C2		1	3	5	7
C3			1	3	5
C4				1	3
C5					1

The results of the FAHP calculation are in the form of priority weight values for each alternative value (village). The priority weight values must be changed into high, medium, low, and very low categories. These categories are produced using the natural break classification. This method classifies 318 villages into four class categories. The GVF value from the classification results can be seen in Table 3. The GVF value analysis ranges from 0-1, where a value close to number 1 indicates a better classification result. The FAHP method produces a GVF value of 0.75, more significant than the classification results from the AHP priority weight value of 0.69.

Table 3: GVF Calculation Table.

	SDAM	SDCM 1	SCDM 2	SCDM 3	GFV
FAHP	3.97	1.73	0.99	1.29	0.75
AHP	4.50	2.00	1.38	1.46	0.69

The results of spatial mapping using FAHP and natural breaks for 318 villages in Ponorogo district can be seen in Figure 5. While spatial mapping using AHP and natural breaks can be seen in Figure 6. Areas in green indicate very low landslide susceptibility levels, blue color indicates low, yellow indicates medium, and red indicates high.

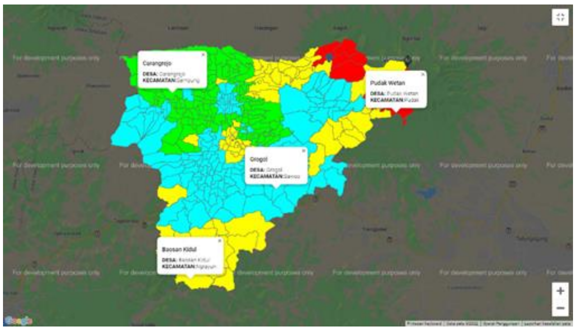

Figure 5: Result of FAHP Method.

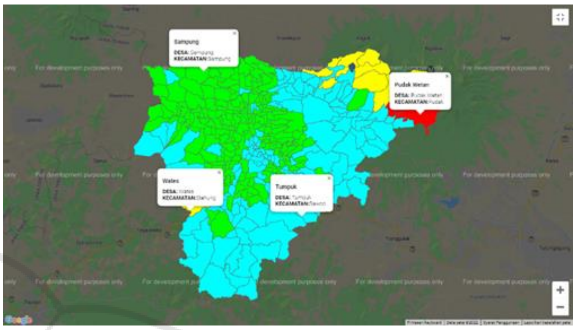

Figure 6: Result of AHP Method.

Then, the significant value and accuracy value were calculated using Pearson's Chi-squared test method. This trial is based on historical data on the number of villages with the number of landslide points that occur and the number of villages with the number of landslide points that do not happen in each classification of landslide vulnerability levels. Pearson's Chi-squared is used to calculate the accuracy value or significant value of the method It based on real area with landslide point data and area without landslide event on each classification category.

The formula used to get the Chi-squared value is

$$\frac{(Oi - Ei)^2}{Ei} \quad (7)$$

The value of *Oi* cell is the value derived from the landslide point data that already exists in each village. While *Ei* cell is a random value from the spatial distribution obtained from the formula *Ei* = (Total Oi × Total' *Oi*) / *Oi*. Then the Chi-squared cell is obtained from the calculation using the formula (7).

The value from Pearson chi-square ($\chi 2$) 80,016 have higher value and critical values. It show that the method has reasonably good accuracy in mapping landslide susceptibility in Ponorogo.

Table 4: Chi-Squared Result of FAHP Method.

Susceptibility area	**Class**				
	Very Low	***Low***	***Medium***	***High***	**Total**
Observed Number Cell (Oi)					
Without Landslide	188	43	44	2	277
With Landslide	3	8	24	6	41
Total	191	51	68	8	318
Expected Number Cell (Ei)					
Without Landslide	166,37	44,42	59,23	6,96	277
With Landslide	24,62	6,57	8,76	1,03	41
Total	191	51	68	8	318
Chi-Squared Value					
Without Landslide	2,810	0,045	3,917	3,542	10,316
With Landslide	18,991	0,308	26,466	23,933	69,699
Total	21,802	0,354	30,383	27,476	80,016

4 CONCLUSIONS

This study can determine the 318 Ponorogo village's vulnerability to landslides using the Fuzzy Analytic Hierarchy Process method based on five criteria, including rainfall, land height, land slope, land use, and soil type. The mapping results from the calculation of the FAHP method can be classified into four levels of vulnerability: areas with a level of vulnerability, landslides are high, medium, low, and very low.

The results of the landslide-prone areas are validated using natural-break calculation with data obtained when calculating FAHP and AHP. So the results of Fuzzy AHP give the best value compared to AHP, which shows a value of 0.75 rather than 0.69.

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