Determination of the level of seismic hazard in Yogyakarta using fuzzy simple additive weighting method

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Abstract. This study aims to obtain a mapping of seismic hazard vulnerability of Special Region of Yogyakarta (DIY) using the Fuzzy Simple Additive Weighting (FSAW) method. This mapping is serves as an act of mitigation for earthquake disasters to reduce the risk of earthquake disasters and minimize fatalities or losses in earthquake-prone areas. The factors used construct the mapping of earthquake-prone areas in Yogyakarta are social, physical, and economic vulnerabilities. Each factor has several variables. The data of this research were taken from the Central Bureau of Statistics (BPS) and the National Disaster Management Agency (BNPB) of the Special Region of Yogyakarta from 2014 to 2017. The FSAW method was used to determine the level of seismic hazard for each sub-district in DIY with a high, medium, or low vulnerability category. The steps taken in the FSAW method are (1) performing fuzzification for each variable, (2) normalizing, (3) determining the weight of each variable, (4) determining the classification of the result; whether it is categorized under high, medium, or low level. The result from this study is a map that shows areas in each district of Special Region of Yogyakarta with high, medium, and low seismic vulnerability. Based on the social, economic and physical vulnerability factors, it was found that every sub-district in Yogyakarta City were categorized under the high-level vulnerability, while the sub-districts in Bantul, Gunungkidul, Kulonprogo and Sleman Regencies had the average level of medium.

1. Introduction

Special Region of Yogyakarta is divided into 4 districts – Bantul Regency with 17 sub-districts, Gunungkidul Regency with 18 sub-districts, Kulonprogo Regency with 12 sub-districts, Sleman Regency with 17 sub-districts and a city called Yogyakarta City with 14 sub-districts. Topographically, 75.57% of the areas in Special Region of Yogyakarta are located on plains, 23.97% are on the slope/ridge, and the remaining 0.46 percent are in the valley or watershed [1].

The total population of Special Region of Yogyakarta was recorded around 3,762,167,000 people in 2017. For each regency and city, the total population in Bantul Regency was recorded at 995,264,000 people with an average population of around 58,544.941 people per district, Gunungkidul Regency at 729,364,000 people with an average population of around 40,520.222 people per district, Kulon Progo Regency at 421,295,000 people with an average population of around 35,107.916 people per district, Sleman Regency at 1,193,512,000 people with an average population of around 70,206.588 people per district, and Yogyakarta City at 422,732,000 people with an average population of around 30,195.142 people per district [1]. By comparing the population divided by the area, the population density of an area can be obtained. The population density on Special Region of Yogyakarta is 1,180.818 people per
Disasters are natural events or unexpected events that can cause damage to the environment and living creatures [2]. In Special Region of Yogyakarta, an earthquake measuring 5.9 on the Richter scale occurred in 2006 [3]. Seismic activity of a certain area can be determined by analyzing earthquakes that occur based on time period, frequency, power, and type of earthquake [4]. However, humans still can not predict the time for an earthquake to occur. Therefore, an earthquake is one of the disasters that can cause major damage to both the environment and human life [5]. Estimated losses resulting from earthquake disasters include: physical damage (schools, critical facilities and infrastructure), economic losses and social impacts [6].

According to the National Disaster Management Agency (BNPB), the criteria for an area to be said to be prone to earthquakes can be seen from three factors, namely social, physical, and economic vulnerability factors [7]. In the context of disaster mitigation, several studies on natural disasters have already been done. Research on potential locations for landslide evacuation using the simple additive weighting method has been conducted [8]. Fuzzy multi criteria decision making method has been used for another research to map the flood risk area [9]. Next, the mapping of earthquake risk levels around the Jayapura area has been conducted based on microtremor measurements [10]. Then, the determination of the tectonic earthquake disaster vulnerability zone in Malang district, southern region has also been performed [11]. Next, there is an analysis based on seismic data that shows an increase in earthquake power from 1973 to 2007 [12]. There is also an analysis of the earthquake disaster in the Philippines using the Twitter social media application [13]. An earthquake modeling research has also been carried out using the magnitude distribution [14].

The Simple Additive Weighting (SAW) method is one of the simplest, natural and most widely used multi-criteria evaluation methods in research [15]. The basis of the SAW method is the overall ranking index for each alternative which is calculated as the number of criteria and suitable alternative objectives. The SAW method makes an assumption for the decision results controlled by weights which express the importance of the criterion [16]. This method was developed to help make decisions on several alternative decisions to get an accurate and optimal decision [17]. If the information obtained cannot be presented completely and contains uncertainties, then the fuzzy multi attribute decision making method can be used to solve the problem [18]. Fuzzy logic is a multi-value logic derived from fuzzy set theory relating to human reasoning ranging from "almost certain" to "very unlikely" with membership values ranging between 0 and 1 [19]. The advantage of the Fuzzy Simple Additive Weighting (FSAW) method is that it can be used for decision making based on data that contains uncertainty [20], [21], [22], [23], [24]. Based on previous research, research on seismic hazard level mapping in Special Region of Yogyakarta using the FSAW method has not been performed. Therefore, in this study, a seismic vulnerability area mapping for each sub-district in Special Region of Yogyakarta will be carried out using the FSAW method.

2. Method
In this study, three aspects were used, namely social aspects, physical aspects and economic aspects. Social aspects include population density (people per hectare), gender ratio (percent), age dependency ratio (percent), poverty ratio (percent), and disabled population ratio (percent). Physical aspects include housing (million rupiah), public facilities consisting of road costs (million rupiah), public transportation (million rupiah) and waterways (million rupiah) as well as critical facilities such as hospitals (million rupiah). The economic aspect includes productive land variables consisting of forests (million rupiah), rice fields (million rupiah) and plantations (million rupiah), as well as GRDP (million rupiah). Data for each district is taken from the BPS-Statistics of D.I. Yogyakarta [1] and the Disaster Management National Agency (BNPB) [25]. The data used are the data from 2014 to 2017. The steps to determine the level of seismic hazard using the FSAW method can be seen in Figure 1.
In more detail, the steps in Figure 1 are carried out as follows:

2.1. Fuzzy Set
The fuzzy set for each variable is constructed using an upward and downward representation [26]. The determination of the type of fuzzy set for each variable is based on the variable type, whether it is a benefit or a cost variable [27].

2.1.1. Social Aspects is divided into 5 variables, namely: population density (C1), gender ratio (C2), age dependency ratio (C3) poverty ratio (C4) and ratio of disabled population (C5). This variable is expressed by the membership function as follows:

\[
\mu_{c1} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{208} & 0 \leq x \leq 208 \\
1 & x \geq 208 
\end{cases}
\]  

(1)

\[
\mu_{c2} = \begin{cases} 
0 & x \leq 0 \\
\frac{109 - x}{109} & 0 \leq x \leq 109 \\
0 & x \geq 109 
\end{cases}
\]  

(2)

\[
\mu_{c3} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{100} & 0 \leq x \leq 100 \\
1 & x \geq 100 
\end{cases}
\]  

(3)

\[
\mu_{c4} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{100} & 0 \leq x \leq 100 \\
1 & x \geq 100 
\end{cases}
\]  

(4)

\[
\mu_{c5} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{100} & 0 \leq x \leq 100 \\
1 & x \geq 100 
\end{cases}
\]  

(5)

The graph of the membership functions C1, C2, C3, C4 and C5 can be seen in Figure 2 to Figure 6.
2.1.2. Physical Aspects

is divided into 5 variables, namely: houses (P1), road costs (P2), public transportations (P3), waterways (P4) and hospitals (P5). This variable is expressed by the membership function as follows.
The graph of the membership functions $P_1$, $P_2$, $P_3$, $P_4$ and $P_5$ can be seen in Figure 7 to Figure 11.

\[
\mu_{P_1} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{2700} & 0 \leq x \leq 2700 \\
1 & x \geq 2700 
\end{cases} \tag{6}
\]

\[
\mu_{P_2} = \begin{cases} 
7000 - x & 0 \leq x \leq 7000 \\
7000 & x \geq 7000 \\
0 & x \leq 0 
\end{cases} \tag{7}
\]

\[
\mu_{P_3} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{152000} & 0 \leq x \leq 152000 \\
1 & x \geq 152000 
\end{cases} \tag{8}
\]

\[
\mu_{P_4} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{3304} & 0 \leq x \leq 3304 \\
1 & x \geq 3304 
\end{cases} \tag{9}
\]

\[
\mu_{P_5} = \begin{cases} 
552223 - x & 0 \leq x \leq 552223 \\
552223 & x \geq 552223 \\
0 & x \leq 0 
\end{cases} \tag{10}
\]
2.1.3. Economic Aspects is divided into 4 variables, namely: forestry (E1), rice fields (E2), plantations (E3), and GRDP (E4). This variable is expressed by the membership function as follows.

\[
\mu_{E1} = \begin{cases} 
0 & 0 \leq x \leq 11211000 \\
\frac{x}{11211000} & x \geq 11211000 
\end{cases} 
\]

(11)

\[
\mu_{E2} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{17360000} & 0 \leq x \leq 17360000 \\
1 & x \geq 17360000 
\end{cases} 
\]

(12)

\[
\mu_{E3} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{205322000} & 0 \leq x \leq 205322000 \\
1 & x \geq 205322000 
\end{cases} 
\]

(13)

\[
\mu_{E4} = \begin{cases} 
0 & x \leq 0 \\
\frac{x}{2360000} & 0 \leq x \leq 2360000 \\
1 & x \geq 2360000 
\end{cases} 
\]

(14)

The graph of the membership functions E1, E2, E3, and E4 can be seen in Figure 12 to Figure 15.
2.2. Data Normalization
Next, the degree of membership for each data is normalized by formula (15) [27].

\[
    r_{ij} = \begin{cases} 
    \frac{x_i}{\text{Max } x_j} & \text{Benefit} \\
    \frac{x_j}{\text{Min } x_i} & \text{Cost} 
    \end{cases} 
\] 

(15)

2.3. Determining the seismic hazard index
The value of the Seismic Hazard Index (IKG-Indeks Kerawanan Gempa) is calculated as follows [27].

\[
    V_i = \sum_{j=1}^{n} w_j r_{ij} 
\] 

(16)

Where \( V_i \) is the preference value of the alternative, \( w_j \) is the weighted value of the \( j \) criterion and \( r_{ij} \) is the normalized value of the \( i \) alternative and the \( j \) criterion The social vulnerability index (IKS-Indeks Kerawanan Sosial), physical vulnerability index (IKF-Indeks Kerawanan Fisik) and economical vulnerability index (IKE-Indeks Kerawanan Ekonomi) are calculated with the following formula [25].

\[
    IKS = (0,6 \times C1) + (0,1 \times C2) + (0,1 \times C3) + (0,1 \times C4) + (0,1 \times C5) 
\] 

(17)

\[
    IKF = (0,4 \times P1) + (0,1 \times P2) + (0,1 \times P3) + (0,1 \times P4) + (0,3 \times P5) 
\] 

(18)

\[
    IKE = (0,2 \times E1) + (0,2 \times E2) + (0,2 \times E3) + (0,4 \times E4) 
\] 

(19)

Furthermore, the IKG value is calculated by formula (16) and is obtained:
IKG = (IKS \times 0.4) + (IKF \times 0.3) + (IKE \times 0.3) \quad (20)

2.4. IKG Classification
After getting the IKG value for each district, the classification is continued according to Table 1 [25].

| IKG Value       | Level     |
|-----------------|-----------|
| IKG < 26        | Low       |
| 26 \leq IKG \leq 70 | Medium    |
| IKG > 70        | High      |

2.5. Mapping
This study uses three classifications of seismic hazard levels, namely low hazard (green), medium hazard (yellow) and high hazard (red). Each district is then mapped according to its level of vulnerability.

3. Result and Discussion
In this discussion, we will determine the level of seismic hazard using the FSAW method using the steps as shown in Figure 1. The following will give an example of calculating the level of earthquake vulnerability in Srandakan sub-district in 2017.
(i). We determine the value of Social Vulnerability Index (IKS). The values of the social vulnerability variable in Srandakan sub-district in 2017 were respectively S1 = 16.01, S2 = 98.01, S3 = 31.42, S4 = 16.76 and S5 = 0.19. Variables S1, S3, S4 and S5 are benefit variables so they use upward representation functions, while S2 is a cost variable, so it uses a downward representation function. The normalized value for the IKS variable is then calculated as follows.

\[
C_1 = \frac{0.076}{0.998} \times 100 = 7.708
\]

\[
C_2 = \frac{0.003}{0.1008} \times 100 = 3.002
\]

\[
C_3 = \frac{0.314}{0.345} \times 100 = 90.989
\]

\[
C_4 = \frac{0.167}{0.189} \times 100 = 88.647
\]

\[
C_5 = \frac{0.001}{0.022} \times 100 = 8.585
\]

Next, by using formula (17), the IKS for Srandakan sub-district is obtained as

IKS = 23.747

(ii). We determine the value of Physical Vulnerability Index (IKF). The following is the value data from the physical vulnerability variable of Srandakan sub-district in 2017 with the values of F1, F2, F3, F4, and F5 respectively 300; 2755.01; 3773; 45.75; and 1111.4. The variables F1, F3, and F4 are benefit variables so they use upward representation functions, while the variables F2 and F5 are cost variables, so they use downward representation functions. The normalization value for the IKF variable is then calculated as follows.

\[
P_1 = \frac{0.111}{1} \times 100 = 11.111
\]

\[
P_2 = \frac{0.004}{0.606} \times 100 = 0.726
\]
Next, by using formula (18), the IKF for Srandakan sub-district is obtained as 

$$IKF = 4.904$$

(iii). We determine the value of Economic Vulnerability Index (IKE). The following is the value data of the economic vulnerability variable for Srandakan sub-district in 2017 with the values of $E_1$, $E_2$, $E_3$, and $E_4$ respectively 350000; 2315000; 430000; and 1331396. The variables $E_1$, $E_2$, $E_3$, and $E_4$ are all benefit variables so that the linear upward membership function is used. The normalized value for the IKE variable is then calculated as follows.

$$E_1 = \frac{0.031}{1} \times 100 = 3.121$$

$$E_2 = \frac{0.133}{0.846} \times 100 = 15.748$$

$$E_3 = \frac{0.002}{0.1} \times 100 = 2.094$$

$$E_4 = \frac{0.564}{0.999} \times 100 = 56.46$$

Next, by using formula (19), the IKE for Srandakan sub-district is obtained as 

$$IKE = 26.777$$

After obtaining the IKS, IKF and IKE values from Srandakan sub-district in 2017, then the Earthquake Vulnerability Index value (20) was determined with the IKS, IKF and IKE weigh respectively 0.4; 0.3 and 0.3 and the GI values are obtained as follows.

$$IKG = 19.003$$

Afterwards, by using the Fuzzy SAW method, the IKG value is established as 19.003. The IKG calculation results based on the method used by BNPB do not have an upper limit so that the results can exceed 100. In the FSAW method, the data undergo normalization so that the results only range from 0 to 100. To resolve this, the equivalent value is calculated by dividing the maximum value of IKG from the BNPB method by the value the maximum IKG of the FSAW method. Then, the result will be multiplied by the IKG from the FSAW method, and the equivalent value is obtained. The maximum value of the IKG from the method used by BNPB in 2017 is 212. With this, we can now determine the equivalent value of the Srandakan subdistrict.

$$EquivalentValue = \frac{212}{100} \times 19.003 = 40.287$$

Thus, the IKG value for Srandakan sub-district in 2017 is 40.287 which is categorized under the moderate hazard classification. In the same way, seismic hazard classification was performed in the Special Region of Yogyakarta from 2014 to 2017. The following graphs show the number of sub-districts for each category of seismic hazard in districts or city in the Special Region of Yogyakarta Each graph from Figure 16 to Figure 20 represents the graph for each regency or city.
Figure 16. Graph of Number of Sub-Districts for each Seismic hazard Level in Bantul Regency

Figure 17. Graph of Number of Sub-Districts for each Seismic hazard Level in Gunungkidul Regency

Figure 18. Graph of Number of Sub-Districts for each Seismic hazard Level in Kulonprogo Regency
The classification results for each district from Special Region of Yogyakarta in 2017 can be seen in Table 2.

**Table 2. Classification Results using the FSAW Method in 2017**

| Sub-District   | Level | Sub-District   | Level | Sub-District   | Level |
|----------------|-------|----------------|-------|----------------|-------|
| Srandakan      | Medium| Ponjong        | Medium| Mlati          | High  |
| Sandeh         | Medium| Karangmojo     | Medium| Depok          | Medium|
| Kretak         | Medium| Wonisari       | Medium| Berbah         | High  |
| Pundong        | Medium| Playen         | Medium| Prambanan      | Medium|
| Bambanglipuro  | Medium| Patuk          | Medium| Kalasan        | Medium|
| Pandak         | Medium| Gedangsari     | Medium| Ngemplak       | Medium|
| Bantul         | Medium| Nglipar        | Medium| Ngaglik        | Medium|
| Jitis          | Medium| Ngawen         | Medium| Sleman         | Medium|
| Imogiri        | Medium| Semin          | Medium| Tempel         | Medium|
| Dlingo         | Medium| Temon          | Medium| Turi           | Medium|
| Pleret         | Medium| Wates          | Medium| Pakem          | Medium|
| Piyungan       | Medium| Panjatan       | Medium| Cangkringan    | Medium|
| Banguntapan    | Medium| Galur          | Medium| Mantrijeron    | High  |
| Sewon          | Medium| Lendah         | Medium| Kraton         | High  |
Table 2. Seismic hazard level mapping is constructed for each sub-district or city as shown in Figure 21 to Figure 24.

| Sub-district   | Level | Sub-district   | Level | Sub-district   | Level | Sub-district   | Level |
|---------------|-------|---------------|-------|---------------|-------|---------------|-------|
| Kasihan       | Medium| Sentolo       | Medium| Mergangsan    | High  | a             |
| Pajangan      | Medium| Pengasih      | Medium| Umbulharjo    | High  | hazard        |
| Sedayu        | Medium| Kokap         | Medium| Kotagede      | High  |               |
| Panggang      | Low   | Girimulyo     | Medium| Gondokusuman  | High  |               |
| Purwosari     | Medium| Nanggulan     | Medium| Danurejan     | High  |               |
| Paliyan       | Medium| Kalibawang    | Medium| Pakualaman    | High  |               |
| Saptosari     | Medium| Samigaluh     | Medium| Gondomanan    | High  |               |
| Tepus         | Medium| Moyudan       | Medium| Ngampilan     | High  |               |
| Tanjungsari   | Medium| Minggir       | Medium| Wirobrajan    | High  |               |
| Rongkop       | Medium| Seyegan       | Medium| Gedongtengen  | High  |               |
| Girisubo      | Medium| Godean        | Medium| Jetis         | High  |               |
| Semanu        | Medium| Gamping       | Medium| Tegalrejo     | High  |               |

Figure 21. Mapping of Classification Results in Bantul Regency

Figure 22. Mapping of Classification Results for Gunungkidul Regency
Comparison of classification results with the FSAW method and the BNPB method and the SAW method can be seen in Table 3.
Table 3. Percentage of Similarity Level of Results

| Year | FSAW with BNPB | FSAW with SAW |
|------|----------------|---------------|
| 2014 | 93.58          | 91.02         |
| 2015 | 93.58          | 92.3          |
| 2016 | 98.71          | 92.3          |
| 2017 | 100            | 84.61         |

Based on table 3, the level of similarity between the FSAW and BNPB methods ranges from 93.58% to 100%, meaning that the FSAW method can be used as an alternative method of determining the level of earthquake vulnerability. Table 4 shows several sub-districts that change classification of seismic hazard levels in 2014 to 2017.

Table 4. Changes in Classification of seismic vulnerability using the FSAW Method

| Sub-District | 2014 | 2015 | 2016 | 2017 |
|--------------|------|------|------|------|
| Mlati        | High | High | Medium | Medium |
| Prambanan    | High | High | Medium | Medium |
| Ngemplak     | Medium | High | Medium | Medium |
| Ngaglik      | High | High | High | Medium |

Based on table 4, Mlati sub-district experienced a decrease in the hazard class from 2015 to 2016. In 2015 the IKG value of Mlati sub-district was 72.86 which was in the high hazard category, then in 2016 it experienced a decline of 65.15 which was included as medium hazard category. This was due to the decline in the IKF value, which was originally 19.06 then decreased to 12.69. The decrease in IKF was caused by the critical facility variable, namely the hospital. In 2016 the number of hospitals and health centers in Umbulharjo District increased, this caused a decrease in the minimum limit value of the hospital variable in this study. Prambanan Sub-district also experienced a decrease in the hazard category from 2015 to 2016. This was due to the decreasing IKF value. The IKF value decreases due to the decrease in the minimum limit of the hospital variable. Ngemplak sub-district experienced a decrease in the hazard category from 2015 to 2016. The cause was due to the decrease in the minimum limit of the hospital variable.

Ngaglik sub-district experienced a decrease in the hazard class from 2016 to 2017. This was due to the decrease in the IKG value in 2016 reaching 72.19 which is included as high hazard class. Then the IKG in 2017 decreased to 69.03 which was included as moderate hazard class. This was due to a decrease in the IKE and IKF values.

4. Conclusion
This research has resulted in a mapping of seismic hazard levels for each sub-district in the Special Region of Yogyakarta using the FSAW method from 2014 to 2017. According to the FSAW method from 2014 to 2017, the province of Yogyakarta Special Region is dominated by medium hazard levels with a percentage above 70%.

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