Landslide Susceptibility Mapping (LSM) in Kelud Volcano Using Spatial Multi-Criteria Evaluation

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Abstract. Mount Kelud eruption on February 2014 has a tremendous impact on the surrounding physical environment which ejected more than 200x10⁶m³ of material. Thus, triggered secondary hazard such as landslides in the surrounding area. The purpose of this study is to map landslides susceptibility using Spatial Multi-Criteria Evaluation (SMCE) approach in Kelud mountainous area in particular within KRB 1 and 2. The identification of landslide occurrence was conducted based on remote sensing data and field observation along with four considerations criteria; topography, hydrology, soil, and environmental characteristics. Each factor then reduced into several sub-criteria such as slope, aspect, topographic position index, topographic wetness index, stream power index, rainfall, soil texture, soil structure, COLE index and land use. The SMCE method was also engaged with expert judgment provided by academic university’ view and the BPBD agencies. The result showed that the river channel and surrounding areas categorized as landslide high prone area. Furthermore, eruption material found as the sources of landslides occurrences.

Keywords: Kelud Volcano, Landslides, Spatial Multi-Criteria Evaluation, Disaster

1. Introduction

Mount Kelud eruption on February 2014 with VEI 4 has a tremendous impact on the surrounding physical environment and affects the condition of agriculture, livestock, and fisheries. This physical environmental impacts are triggered by eruption material which ejected by Mount Kelud. The material such as ballistic bombs, volcanic ash, and pumice material reached more than 200x10⁶m³ of material [1]. Thus, triggered secondary hazard such as landslides in the surrounding area.

Landslides are described as mass movement of soil or rock that shear displacement along one or may be several slip surfaces [2-3]. Over the last two decades, researcher have investigated landslide hazard and construct maps portraying their spatial distribution [4]. Mapping landslide susceptibility is essential for proper land use planning and disaster management [5]. Different techniques and methods have been developed and applied in landslide susceptibility mapping using both the quantitative or qualitative approach [6] such as probabilistic models [7–12], the logistic regression model [13–17], and multi-criteria analysis [18–21,5]. In this study, the landslide susceptibility assessment employed spatial multi criteria model as a method. Four considerations criteria such as topography, hydrology, soil, and environmental characteristics were used. Each factor then reduced into several sub-criteria such as slope,
aspect, topographic position index, topographic wetness index, stream power index, rainfall, soil texture, soil structure, COLE index, land use, and distance from river. The SMCE method was also engaged with expert judgment provided by academic university’s view and the BPBD agencies.

2. Study Area

Mount Kelud is located at 7°56’00” South Latitude and 112°18’30” East Longitude with elevation level of 1731 m. Administratively Mount Kelud distributed within three districts in East Java, namely Blitar, Kediri, and Malang. It is categorized as high intensity of volcanic activity in Indonesia. The eruption characteristic of Kelud is explosive along with phreatic eruption [22]. It is characterized by spilling water that contained of mixed mud and material. In addition, freatomagmatic eruption of Mount Kelud produces ash-lapilli precipitate in the form of fall, then can be followed by flow of fall of pyroclastic material. The eruption period of Mount Kelud is relatively short with the eruption cycle in 20 years. In Fig. 1 shows the location of Mount Kelud.

![Location of Mount Kelud](image)

**Figure 1.** Location of The Study Area Showing Mount Kelud, East Java Province, Indonesia

3. Methodology

3.1. Input Data

This study used nine different GIS layers data to produce Landslide Susceptibility Map. All raster images (30m x 30m) were projected using Datum Universal Transverse Mercator (UTM), with WGS 84 zones. Then, each data layer is classified into several classes using Natural Breaks (Jenks) method.
Natural breaks class based on natural grouping attached to the data. It identifies the points of reference by choosing the class that breaks to the best group of value, same value and maximize the differences between classes [5]. Details of layers data used in this study are described as follows.

3.1.1 Altitude

A digital elevation model (DEM) is a digital model representing an earth’s surface. It is one of the important input in modelling dynamic natural phenomena such as landslides, mass-movement, and soil erosion. DEM describes information about morphological relief of earth’s surface on a digital format raster that height value on each pixel. To produce this parameter which controlled by several geologic and geomorphological processes [7,21,23,24], ASTER Global-DEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data was used. Figure 2 showed the spatial information related to the altitude/ elevation within research area.

![Figure 2. The elevation map.](image)

3.1.2 Slope

The most important parameter in the slope stability analysis is the slope (Lee and Min, 2001). The slope gradient is one primary geomorphometric parameter that figure of geomorphological process of earth’s surface. The slope is directly related and affected to the landslides and it is frequently used in preparing susceptibility maps [25–28]. Based on the ASTER GDEM data, the slope map was produced. Below figure showed the spatial distribution of slope gradient.
3.1.3 Topographic Position Index (TPI)

The Topographic Position Index (TPI) is calculated as the difference the cell elevation and the mean elevation of neighbouring cells [28]. Applied specific thresholds for TPI values allows for the identification of different topographic landforms, such as ridge, slope, and valley. Since the landslide scarps occur mostly on the ridges, the TPI index may be seen as one of landslide conditioning factor, and used for landslide susceptibility map [29,30]. TPI was calculated using Jennes, et al. (2013) implementation. The result of calculated TPI can be seen in figure 4.

Figure 3. The slope gradient map.
Figure 4. The Topographic Position Index (TPI) Map.

3.1.4 Stream Power Index (SPI)

The massive soil erosion describe the geomorphological process, and it’s have direct affect to potential landslide in an area. The Stream Power Index (SPI) used in this study (Fig. 5). This index is used to visualization potential flow erosion and related with landscape processes [31]. The SPI describes potential for flow erosion at the given point of the surface, and controls potential erosive power of water flow [28,31]. The SPI is calculated from following formula:

\[
SPI = As \times \tan \beta
\]  

(1)
3.1.5 Rainfall

We used rainfall data with the duration three years periods from Malang, Kediri, Blitar, Blitar City, Malang City, and Batu City rainfall station in processing landslide susceptibility map. Rainfall data can figure the accumulation of water that can transporting materials and soil, and also triggering the landslides. Spatial distribution of average of three annual rainfall data, we visualized in figure 6.
3.1.6 Topographic Wetness Index (TWI)

The Topographic Wetness Index (TWI) model is one of the criteria that indicate hydrological process, related to the accumulation of water flow based on the control of slope factor in an area [28–30]. The slope control of the hydrological process will be highly visible in areas with high relief configurations. Especially at the Mount Kelud area, the high slope configuration encourages control of hydrological processes, which relate to the process of accumulation of water flows. In Figure 7, its show the accumulation of water flows.

![Rainfall Map](image)

**Figure 6.** The Rainfall Map
3.1.7 Soil Texture

Soil texture describe the materials and physical characteristic in each soil profile. After catastrophic event, in 2014 Kelud eruption ejecting the amount of material, is important to make spatial distribution of soil texture. Soil texture data extracted from the laboratory analyses. The average percentage of soil texture in the study area were 70% sand, 20% silt, and 10% clay. Figure 8 contain the distribution of soil texture in the Kelud area.
3.1.8 COLE Index

The low percentage content of montmorillonite clay fraction causes a low of COLE index in this study area. The low COLE index will have an effect on low soil ability to retain water and soil ability to form aggregates. Figure 9 contain the information of distribution COLE index in research area.

Figure 8. The Soil Texture Map.
3.1.9 Land-Use

In this study, land use map was produced from the LANDSAT 8 OLI/TIRS satellite image, and applying a object-based classification scheme. There are eight types of land use are identified in the study area. In the landslides susceptibility modelling, land use map is important to produce information of human induce and environment condition in research area.

Figure 9. The COLE Index Map.
3.2. Research Processes

3.2.1 Landslide Inventory Map

Creation of landslide inventory maps is an important step in the process of determining and assessing the level of susceptibility. The landslides inventory map (see Fig. 11) can document the occurrence of landslide in an area [32]. The location of the incident, the volume and impact of a landslide can be represented and visualized through landslide inventory map [19]. A landslide inventory map is prepared for several scopes such as (i) documenting the occurrence of landslides in an area, (ii) as a first step towards the assessment of landslide susceptibility, and (iii) to investigate the distribution, type and pattern of landslides that occur [33].

Landslide inventory maps can be done with different techniques. The determination of the techniques used depends on the objectives of the landslide inventory process, the extent of the study area, the time available in the data collection process, the data sources used, and the experience of the researcher [32,34,35]. The selection of manufacturing techniques becomes very important, because it affects the processes and effort undertaken to produce landslide inventory maps that have a high degree of reliability.

The landslide delineation is carried out by visual interpretation using remote sensed data. Applied Google Earth for visual interpretation. In addition, Google Earth provides high-resolution imagery, the ability to display 3D earth surface has provided the ease and opportunity to detect and mapping landslide distribution in study area. Figure 11 showed the landslide interpretation that we digitized and marked where landslide occurred in this research area. The result of interpretation process, we used this information to validated, captured, and measured the materials of landslides in field observation process.
Field observation process is needed to know the landslide characteristic. Through field observation information will be obtained specifically related to the type and visual characteristics of landslide [34], as well as to determine the validation of landslide inventory maps that have been made. In the process of field observation, we observed the landslide event, and took a picture for every landslide that we found, showed in figure (a). In addition, we took the material of landslide (see figure b and c), and we classified the type of every landslide events that we found.
3.2.2 LSM Using SMCE

To solve spatial-based problems such as landslide phenomenon, GIS-based Spatial Multi-criteria Evaluation (SMCE) have been used. SMCE is a way of producing policy-relevant information about spatial decision problems for decision makers [21]. The basic steps is to divide the decision problem into small, understandable parts, analyse each of them, and integrate these parts in a logical manner to produce a meaningful solution [36]. SMCE process can be visualized in Figure 12 [21,37].

| CR | Spatial relationship between landslides events and landslide causing factors. |
|----|---------------------------------------------------------------------------|
| CR> 0.1 | Preferences from Expert Judgment |
| CR< 0.1 | Pairwise Comparison Matrix |
| CR | Raster Calculation |
| Validation | Landslide Susceptibility Map |

**Figure 13.** Landslide Susceptibility Process Using Spatial Multi-Criteria Evaluation (SMCE).

SMCE method in this study was also engaged with expert judgment provided by academic university’s view and the BPBD agencies. For these method, a pair-wise comparison based weighting was used. Pair-wise comparison method was established by Saaty (1987) in the context of the Analytical Hierarchy Process (AHP), showing in Table 1. According to Pourghasemi, et al., (2012) the AHP consists of three main steps; (1) generating the pair-wise comparison matrix, (2) computing the weigts of the criterion, and (3) estimating the consistency ratio. In making comparison matrix, the AHP method uses a scale with a range of values 0 – 9 to assess relative preferences for two criteria. The range value can be shown in table as followed:
### Table 1. The Range Value in AHP.

| Intensity of Importance | Definition | Explanation |
|-------------------------|------------|-------------|
| 1                       | Equal importance | Two activities contribute equally to objective |
| 3                       | Weak importance of one over another | Experience and judgment slightly favor one activity over another |
| 5                       | Essential or strong importance | Experience and judgment strongly favor one activity over another |
| 7                       | Demonstrated importance | An activity is strongly favored and its dominance demonstrated in practice |
| 9                       | Absolute importance | The evidence favoring one activity over another is the highest possible order of affirmation |
| 2, 4, 6, 8              | Intermediate values between the two adjacent judgments | When compromise is needed |

Source: Pourghasemi *et al.*, 2014

#### 3.2.3 Landslide Parameters

![Flowchart of the research](image)

**Figure 14.** The flowchart of the research

In the diagram above shows the landslide parameters of this research. In the process of assessment of landslide susceptibility have been used several parameters covering topography, hydrology, soil, and environment. Then, each parameter is reduced to several criteria including slope, TPI, altitude, TWI, SPI, rainfall, soil texture, soil COLE index, and Land Use. The layers from each data is then integrated in attempt to build a landslide susceptibility maps.
3.2.4 *Pairwise Comparison Matrix*

**Table 2.** Pairwise Matrix for Landslide Susceptibility Mapping.

| LSM Parameters | (1) | (2) | (3) | (4) | Eigen Value |
|----------------|-----|-----|-----|-----|-------------|
| Topography (1) | 1   | 1/2 | 3   | 3   | 0.308       |
| Hydrology (2)  |     | 1   | 3   | 3   | 0.433       |
| Soil (3)       |     | 1   | 3   |     | 0.165       |
| Land-Use (4)   |     |     |     | 1   | 0.094       |

Consistency Ration: 0.08

**Topography’s Criteria**

| Elevation | (1) | (2) | (3) | (4) | (5) | (6) | Eigen Value |
|-----------|-----|-----|-----|-----|-----|-----|-------------|
| 0 – 550 (1) | 1   | ½   | 1/2 | 1/2 | ½   | ½   | 0.085       |
| 551 – 700 (2) |     | 1   | 1/2 | 1/2 | ½   | ½   | 0.107       |
| 701 – 850 (3) |     |     | 1   | 1/2 | ½   | ½   | 0.135       |
| 851 – 1000 (4) |     |     |     | 1   | ½   | ½   | 0.169       |
| 1001 – 1250 (5) |     |     |     |     | 1   | 1/3 | 0.204       |
| 1251 – 1730 (6) |     |     |     |     |     | 1   | 0.300       |

Consistency Ration: 0.06

| Slope | (1) | (2) | (3) | (4) | (5) | (6) | Eigen Value |
|-------|-----|-----|-----|-----|-----|-----|-------------|
| 0 – 5 (1) | 1   | ½   | 1/3 | 1/3 | 1/3 | 1/3 | 0.059       |
| 6 – 15 (2) |     | 1   | 1/3 | 1/3 | 1/3 | 1/3 | 0.074       |
| 16 – 30 (3) |     |     | 1   | 1/3 | 1/3 | 1/3 | 0.117       |
| 31 – 50 (4) |     |     |     | 1   | 1/3 | 1/3 | 0.171       |
| 51 – 70 (5) |     |     |     |     | 1   | 1/2 | 0.258       |
| > 70 (6) |     |     |     |     |     | 1   | 0.322       |

Consistency Ration: 0.08

*Topographic Position Index (TPI)*
## Hydrology’s Criteria

### Stream Power Index (SPI)

| Factors | (1) | (2) | (3) | (4) | (5) | (6) | Eigen Value |
|---------|-----|-----|-----|-----|-----|-----|-------------|
| 0 – 20  | 1   | 3   | 3   | 3   | 3   | 3   | 0.350       |
| 20 – 40 | 1   | 3   | 3   | 3   | 3   | 3   | 0.241       |
| 40 – 60 | 1   | 3   | 3   | 3   | 3   | 2   | 0.166       |
| 60 – 80 | 1   | 3   | 2   | 2   | 1   | 1   | 0.107       |
| 80 – 100| 1   | 2   | 1   | 1   | 1   | 1   | 0.074       |
| >100    | 1   | 1   | 1   | 1   | 1   | 1   | 0.062       |

Consistency Ratio: 0.09

### Rainfall

| Factors | (1) | (2) | (3) | (4) | (5) | Eigen Value |
|---------|-----|-----|-----|-----|-----|-------------|
| 175     | 1   | 1/3 | 1/3 | 1/3 | 1/3 | 0.070       |
| 200     | 1   | 1/3 | 1/3 | 1/3 | 1/3 | 0.110       |
| 225     | 1   | 1/3 | 1/3 | 1/3 | 1/3 | 0.172       |
| 245     | 1   | 1/2 | 1   | 1   | 1   | 0.281       |
| 270     | 1   | 1   | 1   | 1   | 1   | 0.367       |

Consistency Ratio: 0.09

### Topographic Wetness Index (TWI)

| Factors | (1) | (2) | (3) | (4) | (5) | Eigen Value |
|---------|-----|-----|-----|-----|-----|-------------|
| 0 – 4   | 1   | 1/3 | 3   | 3   | 3   | 0.261       |
| 0 – 7   | 1   | 1   | 2   | 3   | 3   | 0.412       |
### Soil's Criteria

**Texture**

| Factors          | (1) | (2) | (3) | Eigen Value |
|------------------|-----|-----|-----|-------------|
| Loam (1)         | 1   | ½   | 1/3 | 0.157       |
| Loamy Sand (2)   | 1   | 1/3 |     | 0.249       |
| Sandy Loam (3)   | 1   |     | 1   | 0.594       |

### Land-Use’s Criterion

| Factors      | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | Eigen Value |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|-------------|
| Lahars       | 1   | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2    |     | 0.232       |

Consistency Ration: 0.06
Non-Vegetation 1 2 2 2 2 2 0.192
Bare Soil 1 2 2 2 1/2 0.141
Very Low-Veg. 1 2 2 2 0.134
Low-Veg. 1 2 2 0.110
Moderate-Veg. 1 2 0.091
High-Veg. 1 0.100

Consistency Ratio: 0.08
#### 3.2.5 Data Standardization

**Table 3. Spatial Relationship between Landslides and Landslide Causing Factors.**

| Factor | Class | No. of pixels in domain | No. of landslide | Percentage of landslide | FR | a    | b    | c    | d    |
|--------|-------|-------------------------|------------------|------------------------|----|------|------|------|------|
| Elevation | 550   | 389135                  | 2                | 2.35                   | 0.11 | 0.085 | 0.0091 | 0.249 | 0.308 | 0.0007 |
|         | 700   | 564495                  | 3                | 3.53                   | 0.11 | 0.107 | 0.0119 | 0.249 | 0.308 | 0.0009 |
|         | 850   | 374988                  | 20               | 23.53                  | 1.12 | 0.135 | 0.1506 | 0.249 | 0.308 | 0.0116 |
|         | 1000  | 226558                  | 32               | 37.65                  | 2.96 | 0.169 | 0.4994 | 0.249 | 0.308 | 0.0383 |
|         | 1250  | 153265                  | 21               | 24.71                  | 2.87 | 0.204 | 0.5848 | 0.249 | 0.308 | 0.0449 |
|         | 1730  | 69955                   | 7                | 8.97                   | 2.28 | 0.3   | 0.6844 | 0.249 | 0.308 | 0.0525 |
| Slope (deg) | 0 - 5 | 504856                  | 2                | 2.35                   | 0.08 | 0.59  | 0.0489 | 0.594 | 0.308 | 0.0089 |
|         | 6 - 15 | 459015              | 4                | 4.71                   | 0.18 | 0.074 | 0.0135 | 0.594 | 0.308 | 0.025 |
|         | 16 - 30 | 336505            | 11               | 12.94                  | 0.68 | 0.117 | 0.0800 | 0.594 | 0.308 | 0.0146 |
|         | 31 - 50 | 204188          | 10               | 11.76                  | 1.02 | 0.171 | 0.1750 | 0.594 | 0.308 | 0.0320 |
|         | 51 - 70 | 138069           | 25               | 29.41                  | 3.79 | 0.258 | 0.9767 | 0.594 | 0.308 | 0.1787 |
|         | > 70   | 134527                 | 33               | 38.82                  | 5.13 | 0.322 | 1.6514 | 0.594 | 0.308 | 0.3021 |
| TPI     | 0      | 179733                 | 17               | 20.00                  | 1.98 | 0.275 | 0.5442 | 0.157 | 0.308 | 0.0263 |
|         | 2      | 162564                 | 16               | 18.82                  | 2.06 | 0.218 | 0.4490 | 0.157 | 0.308 | 0.0217 |
|         | 4      | 429951                 | 10               | 11.76                  | 0.49 | 0.173 | 0.0842 | 0.157 | 0.308 | 0.0041 |
| Factor | Class | No. of pixels in domain | Percentage of domain | No. of landslide | Percentage of landslide | FR | a    | b    | c    | d    |
|-------|-------|-------------------------|----------------------|-----------------|------------------------|----|------|------|------|------|
|       |       |                         |                      |                 |                        |    |      |      |      |      |
|       |       |                         |                      |                 |                        |    |      |      |      |      |
| Rainfall | 175   | 132116                  | 11.67                | 2               | 2.35                   | 0.20| 0.7  | 0.1412| 0.594| 0.433| 0.03 |
|       | 200   | 186247                  | 16.45                | 10              | 11.76                  | 0.72| 0.11 | 0.0787| 0.594| 0.433| 0.02 |
|       | 225   | 237631                  | 20.98                | 17              | 20.00                  | 0.95| 0.172| 0.1639| 0.594| 0.433| 0.04 |
|       | 245   | 243707                  | 21.52                | 33              | 38.82                  | 1.80| 0.281| 0.5070| 0.594| 0.433| 0.13 |
|       | 270   | 332822                  | 29.39                | 23              | 27.06                  | 0.92| 0.367| 0.3379| 0.594| 0.433| 0.08 |
| TWI   | 0-4   | 757470                  | 43.02                | 22              | 25.88                  | 0.60| 0.261| 0.1570| 0.0157| 0.433| 0.00 |
| Layer | Texture | Loam | 0.01299 | 79561 | 6.87 | 16 | 18.82 | 2.74 | 0.128 | 0.3507 | 0.25 | 0.165 | 0.01 |
|-------|---------|------|---------|-------|------|----|------|------|-------|-------|-----|------|-----|
|       | Loamy   | Sand | 0.01384 | 41837 | 14.18 | 9  | 10.59 | 0.75 | 0.249 | 0.1859 | 0.75 | 0.165 | 0.02 |
|       | Sandy   | Loam | 0.02041 | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
| 0-7   | Loam    |      | 564669  | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
| 7-11  | Loamy   | Sand | 253185  | 41837 | 14.18 | 9  | 10.59 | 0.75 | 0.249 | 0.1859 | 0.75 | 0.165 | 0.02 |
| 11-15 | Loamy   | Sand | 137012  | 41837 | 14.18 | 9  | 10.59 | 0.75 | 0.249 | 0.1859 | 0.75 | 0.165 | 0.02 |
| 15-18 | Loamy   | Sand | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Loam    |      | 79561   | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
|       | Loamy   | Sand | 137012  | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Sandy   | Loam | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Loam    |      | 79561   | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
|       | Loamy   | Sand | 137012  | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Sandy   | Loam | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Loam    |      | 79561   | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
|       | Loamy   | Sand | 137012  | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Sandy   | Loam | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Loam    |      | 79561   | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
|       | Loamy   | Sand | 137012  | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Sandy   | Loam | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Loam    |      | 79561   | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
|       | Loamy   | Sand | 137012  | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Sandy   | Loam | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Loam    |      | 79561   | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
|       | Loamy   | Sand | 137012  | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Sandy   | Loam | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Loam    |      | 79561   | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
|       | Loamy   | Sand | 137012  | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Sandy   | Loam | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Loam    |      | 79561   | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
|       | Loamy   | Sand | 137012  | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Sandy   | Loam | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Loam    |      | 79561   | 48415 | 16.41 | 5  | 5.88  | 0.36 | 0.157 | 0.0563 | 0.75 | 0.165 | 0.00 |
|       | Loamy   | Sand | 137012  | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
|       | Sandy   | Loam | 48489   | 204820 | 69.41 | 71 | 83.53 | 1.20 | 0.594 | 0.7148 | 0.75 | 0.165 | 0.08 |
| Factor   | Class             | No. of pixels in domain | Percentage of domain | No. of landslide | Percentage of landslide | FR     | a      | b      | c      | d      |
|----------|-------------------|-------------------------|----------------------|------------------|-------------------------|--------|--------|--------|--------|--------|
| Landuse  | Lahar             | 86320                   | 7.01                 | 11               | 12.94                   | 1.85   | 0.232  | 0.4282 | 0.094  | 0.04025|
|          | Non-Vegetation    | 55602                   | 4.52                 | 6                | 7.06                    | 1.56   | 0.192  | 0.3001 | 0.094  | 0.02820|
|          | Bare Soil         | 7014                    | 0.57                 | 12               | 14.12                   | 24.78  | 0.141  | 3.4936 | 0.094  | 0.32839|
|          | Very Low Vegetation| 65521                   | 5.32                 | 3                | 3.53                    | 0.66   | 0.134  | 0.0889 | 0.094  | 0.00835|
|          | Low Vegetation    | 192981                  | 15.68                | 21               | 24.71                   | 1.58   | 0.11   | 0.1734 | 0.094  | 0.01630|
|          | Moderate Vegetation| 526222                  | 42.75                | 24               | 28.24                   | 0.66   | 0.091  | 0.0601 | 0.094  | 0.00565|
|          | High Vegetation   | 297322                  | 24.15                | 8                | 9.41                    | 0.39   | 0.01   | 0.0039 | 0.094  | 0.00037|

Domain: pixels in study area, domain (%): (domain/total pixels in study area)* 100, landslide: number of landslide occurrences, landslide (%): (landslide/ total number of landslide occurrences)* 100, frequency ratio: landslide (%) / domain (%).

a Normalized value.
b Parameter’s value.
c Group’s value.
d Final weight.
4. Result and Discussion

This study produces landslide susceptibility map which applied AHP method for determining the weight value of each parameter and criterion. The standardization stage of each criterion is based on frequency ratio calculation, where the percentage of landslide points in each class is divided by the number of pixels domains from each class within each criterion. We applied Natural Break (Jenks) classification to divide the susceptibility into several classes. The class of landslide susceptibility consists of “Very Low”, “Low”, “Moderate”, “High”, and “Very High”.

![Figure 15. Landslide Susceptibility Map](image-url)
Figure 16. The Pie Diagram of Percentage Landslide Occurrences

Total number of landslide point used in this study is 121, with landslide characteristic has area >100m2. Number of landslide in each class of susceptibility can be seen in the above figure. Based on the graph it is known that the area with very high level of susceptibility has a percentage of landslide incidence of 24.977%, then high susceptibility class is 27.957%, moderate susceptibility class is 27.660%, low susceptibility class is 15.288%, and very low class is 4.116%.

5. Conclusion

The phenomenon of landslide becomes a serious threat post eruption of Mount Kelud in 2014. This is in line with the mapping of landslide susceptibility that has been done. The area around Mount Kelud has a high landslide potential level. Based on research results of 24.977% of the area included into the class of very high susceptibility, and 27.957% including into high susceptibility class. The information generated from this research becomes important to reduce the impact of losses that can be caused by landslides.

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