Landslide vulnerability assessment using gis and remote sensing techniques: a case study from Garut – Tasikmalaya road

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Abstract. Road constructions, especially in mountainous topographical features, have been noted responsible for the significant increase of landslide occurrences. In the Garut – Tasikmalaya Road, numerous landslides have been recorded causing enormous losses. This road has a very important role as the main transportation connector between two regencies in West Java; those are Garut and Tasikmalaya Regency. To deal and control such problems, spatial distributions of landslide vulnerability need to be analyzed. The aim of this study was to assess the widespread landslide vulnerability zones along the Garut – Tasikmalaya Road. The landslide triggering factors, i.e. topographic slope, land use, lithology, distance to geological structure and distance to stream, were spatially evaluated and integrated using Analytical Hierarchy Process (AHP) and simple numerical rating method to determine the landslide vulnerability zones. The data of landslide triggering factors were derived from remote sensing data and processed using GIS technology. The data integration produced landslide vulnerability map along the Garut – Tasikmalaya Road, which delineates the research area into three zones of landslide vulnerability (high, moderate, and low). The landslide vulnerability map was validated using landslide inventory. The high vulnerability zones of landslide, that will affect the Garut – Tasikmalaya Road, are mainly located in the Salawu District.

1. Introduction

Landslide is one of the natural geological phenomena which most likely happen in mountainous areas. It contributes on the loss of life and damage of properties, including infrastructures such as roads, bridges, and houses. Risk of landslides rely on geomorphology (topography), geological condition, and meteorological aspects (climate, weather, rainfall rate), land uses, streams, water table, and loads above the slope [1]. Somehow, road construction contributes for triggering the possibility of landslides on a slope. When road construction is built by cutting mountain or a slope, it will create instability for the slope, so if there is no mitigation done on the slope, landslides will be most likely to happen as the slope needs to find a new equilibrium to be stable. As Indonesia has many mountainous topographical features, it cannot be denied that the potential of landslide occurrences is relatively high. The Garut – Tasikmalaya Road in West Java Province was recorded having numerous landslide events. Topography or geomorphology, tropical climate, high weathering rates of rocks, lithology types, geological structure, human interference in land use, and infrastructure development are being mentioned as what triggered the occurrence of landslides in this road. Road construction should take notes on the features of the slope to prevent landslides happening from when the construction began until after the construction ended to ensure the road is safe for people to use. Hence, there needs further analysis of slope stability for assessing landslide vulnerability in road construction.
The landslide vulnerability assessment was created by integrating information of the spatial distribution of the factors affecting slope instability [1]. The integrated factors would be shown as zonation of vulnerability classes presented on the landslide vulnerability map. Landslide vulnerability mapping included qualitative and quantitative approaches using the Analytic Hierarchy Process (AHP) and Simple Numerical Rating. The AHP was applied to assign the weighting factors of landslide triggering factors and the Simple Numerical Rating was applied to assign the weighting the different classes of triggering factors. Previous researchers used only AHP to assign the weighting of both triggering factors and their classes [2,3,4,5]. This study was for early prognosis, as the data that used in this study were all secondary data, and there was no field observation conducted in the study.

2. Study area
The study area is located on a segment of the Garut – Tasikmalaya Road, West Java Province, Indonesia. The study area has a total area of 1,365.2 km² with a segment of the Garut – Tasikmalaya Road being observed in the study is 55.8 km in length. The elevation of the study area ranges from 203 to 2,795 meters. The road is surrounded by mountainous topography (Figure 1) and located alongside streams and valleys. The geological conditions of the study area are quite complex. The lithology is mainly composed by volcanic rocks that have a relatively high degree of weathering, while the geological structures are intensively developed, cutting the study area [6,7].

Figure 1. Digital Elevation Model (DEM) of the study area

As the road is located in Indonesia, it has a tropical climate, which resulted in high weathering rates in the area. Based on monthly rainfall data from Meteorological, Climatological, and Geophysical Agency, the rainfall pattern in this area mostly ranges between low (0 – 100 mm per month) to medium (100 – 300 mm per month) in the dry season (May – September), and medium (100 – 300 mm per month) to high (300 – 500 mm per month) in the rainy season (October – April) [8,9]. The implications of all adverse conditions were the high number of landslide occurrence in the research area (Table 1) [10].
The Garut – Tasikmalaya Road is classified as a province road which connects 2 (two) districts in West Java, Garut and Tasikmalaya. As a province road, the regulation of this road is under the responsibility of the Regional Government of West Java. This road is very crucial as it is a primary connector between Garut and Tasikmalaya, so once landslides happen to the road, it will disconnect the major connector between these two big cities.

Table 1. Disaster history in the study area

| No | History      | Coordinate (Lon/Lat) | Location            |
|----|--------------|----------------------|---------------------|
| 1  | Landslides   | 107.909 -7.22791     | Garut Kota, Garut Regency |
| 2  | Landslides   | 107.912 -7.38621     | Banjarwangi, Garut Regency |
| 3  | Landslides   | 107.927 -7.3209      | Cilawu, Garut Regency |
| 4  | Landslides   | 107.901 -7.27803     | Cilawu, Garut Regency |
| 5  | Landslides   | 107.896 -7.41515     | Banjarwangi, Garut Regency |
| 6  | Landslides   | 107.927 -7.24937     | Garut Kota, Garut Regency |
| 7  | Landslides   | 108.039 -7.39906     | Salawu, Tasikmalaya Regency |
| 8  | Landslides   | 108.21  -7.33497     | Cihideung, Tasikmalaya Regency |
| 9  | Land subsidence | 108.214 -7.32795  | Cihideung, Tasikmalaya Regency |
| 10 | Landslides   | 107.989 -7.37785     | Salawu, Tasikmalaya Regency |
| 11 | Landslides   | 107.998 -7.36826     | Salawu, Tasikmalaya Regency |
| 12 | Landslides   | 108.112 -7.39141     | Mangunreja, Tasikmalaya Regency |
| 13 | Landslides   | 107.981 -7.37528     | Salawu, Tasikmalaya Regency |
| 14 | Landslides   | 108.15  -7.39106     | Tanjungjaya, Tasikmalaya Regency |
| 15 | Landslides   | 108.119 -7.24877     | Cisayong, Tasikmalaya Regency |

3. Relevant Data
The research began with collecting historical information of individual landslide events in the research area to establish the landslide inventory (Table 1). The distribution of historical landslide events was spatially evaluated to determine the most possible triggering factors in the research area. The triggering factors associated with the landslide occurrences in the research area were slope angle, land use, lithology, distance to geological structure/lineament and distance to stream. The data sources of landslide triggering factors were gained from remote sensing data and published maps served by the government (Table 2) [6,7,11,12].

Table 2. The data source of landslide triggering factors

| Thematic data maps                  | Data source                                                                                   | Original scale/resolution |
|-------------------------------------|------------------------------------------------------------------------------------------------|----------------------------|
| Slope angle                         | Digital Elevation Model (DEM) 1208-62, 1208-64, 1308-41, 1308-42, 1308-43, 1308-44 from Indonesia Geospatial Information Agency | 0.27-arcsecond             |
| Lithology and distance to lineament | Geological map of the Garut - Pameungpeuk and geological map of the Tasikmalaya from Geological Research and Development Centre | 1:100,000                  |
| Land use and Distance to stream     | Topographical map of Ciamis, Garut and Tasikmalaya from Indonesia Geospatial Information Agency | 1:25,000                   |

The data sources were digitized using GIS software to produce raster-based thematic digital maps of each landslide triggering factor with a resolution of 25 m x 25 m. The detailed information of each thematic map is described as follows.
3.1. Slope angle
Slope angle is typically considered to be one of the influential factors for landslide vulnerability study because it controls the shear forces acting on hill slopes [13]. In steep slope, the shear forces are usually greater than the shear strength, so it allows the soil/rock mass to move. The landslide potential will increase in direct proportion to the increasing slope angle. The data of the slope angle in the research area was derived from Digital Elevation Model (DEM) [11]. The research area was divided into three classes of slope angle (Figure 2); those are:
- Gentle slope ($0^\circ - 10^\circ$), symbolized by green coloured areas in the map. This slope class was located in the valley areas, obtaining about 45% of the study area.
- Moderate slope ($10^\circ - 25^\circ$), symbolized by yellow coloured areas in the map. This slope class was located in the hillside areas, obtaining about 30% of the study area.
- Steep slope ($25^\circ - 60^\circ$), symbolized by red coloured areas in the map. This slope class was located at the top of the hill areas, obtaining about 25% of the study area.

![Figure 2. Slope angle map](image)

3.2. Land use
Land use plays a big role in slope instability. Land use is the representation of anthropological activities that may contribute to land function and morphological changes. Based on the national topographical map produced by Indonesia Geospatial Information Agency, the research area was divided into five classes of land use those are forest, agricultural land, barren land, and built-up area (Figure 3) [12]. To know the order from the most to the least influencing classes, the distribution of historical landslide events was compared with the land use classes. The numbers of landslide events in built-up area, barren land, agricultural land, and forest, respectively, are 7, 4, 3, and 1. From this, we can see that the built-up area has the biggest influence to landslide potential, followed by barren land, agricultural land and the forest.
The distribution of land use classes is relatively following the morphology. Forest dominates the high terrain in the research area, meanwhile, the distribution of barren land is very limited and spotted randomly. Agricultural land and built-up areas, as the representation of human influence, are widely spread in low terrain.

Figure 3. Land use map

3.3. Lithology
Lithology, hereby, refers to the type of rock present in the research area. The lithology map was derived from regional geological maps of Garut – Pameungpeuk and Tasikmalaya. Necessary simplifications were incorporated to prepare the lithology map (Figure 4). Some of the rocks which have similar characteristics were regrouped into a class and named with the dominant lithology. Based on this classification, there were five classes of lithology in the research area [6,7]:

- **Alluvial deposit.** This class consists of a loose deposit of clay, silt, sand, gravel, and boulder. The alluvial deposit is quaternary sediment that is not consolidated. It is the weakest rock class that have biggest influence in landslide potential.
- **Limestone.** This class consists of sandy limestone, reef limestone, coral limestone. Limestone is the easiest rock class to be weathered in the research area because it tends to be dissolved by water.
- **Older volcanic rock.** This class consists of highly weathered of tertiary volcanic rock, i.e., volcanic breccia, flow breccia, tuff, tuff breccia, and andesitic lava. This class is the oldest rock class in the research area. It makes this class undergone the longest time of weathering.
- **Younger volcanic rock.** This class consists of quite intensive weathered of quaternary volcanic rock, i.e., volcanic breccia, lahar, andesitic to basaltic tuff and lava flow, and efflata.
- **Tuffaceous sandstone.** This class consists of tuffaceous sandstone, sandstone, calcareous sandstone, and conglomerate. This class is containing less volcanic product material than the others, so it is not easy to be weathered.
The information about geological structure and lineament were extracted from geological maps of Garut – Pameungpeuk, and Tasikmalaya published by the Geological Research and Development Centre. The presence of vary geological structures in research area indicates that the research area had undergone complex tectonic processes. Geological structure/lineament is responsible to the slope instability. It provides discontinuities in rock body that cut rock into pieces and enhance weathering. The landslide potential will increase when the distance to the geological structure is closer. In this study, the distance of slope to the geological structure/lineament was classified into three classes (Figure 5), i.e. close (0 – 400 m), nearby (400 – 700 m), and distant (700 – 1,000 m).

3.5. Distance to stream
Stream system in the research area is very intensive. Most streams are formed by surface runoff of rainfall water. The water flows down the slope, erodes the rock, leaves grooves, and then forms intermittent streams. Considering the phenomena, the presence of streams become one of factors causing slope instability. The closer the distance to the stream, the higher landslide potential will be. In this study, the distance of slope to the stream was classified into three classes (Figure 6), i.e. close (0 – 10 m), nearby (10 – 30 m), and distant (30 – 50 m).
Figure 5. Distance to lineament map

Figure 6. Distance to stream map
4. Methodology

The landslide vulnerability map was prepared by integration of the landslide triggering factors and their classes. Before being integrated, the data of landslide triggering factors and their classes, which presented in raster-based maps, were assigned based on the relative importance. The assignment was conducted in two processes using different multi-criteria decision-making, those are Analytic Hierarchy Process (AHP) and Simple Numerical Rating. The weight assignment of landslide triggering factors was determined using AHP approach, meanwhile, the weight assignment of classes of the triggering factors was determined using Simple Numerical Rating. After determining the weight of landslide triggering factors and their classes, the next step was integrating them using arithmetic overlay to get the Landslide Potential Index (LPI) as the basis of delineation of landslide vulnerability zone. All of the processes are explained as follow.

4.1. Analytic hierarchy process

The AHP is a semi-quantitative method of multi-criteria decision-making in which decisions are taken using weights through pairwise relative comparisons without inconsistencies in the decision process [14]. In this research, AHP was used to assign the weighting factors for landslide triggering factors. The AHP method was applied by following these steps [15]:

Step 1: Break down a complex problem into its component factors. The main problem in this research is to assess landslide vulnerability. To make the landslide vulnerability assessment being easily comprehended, the problem was decomposed into landslide triggering factors. The determination of landslide triggering factors needed a comprehensive study of the research area’s characteristics. The distribution analysis of historical landslide events was also incorporated into the research area study. The combination of both studies deduced that slope angle, land use, lithology, distance to geological structure/lineament, and distance to stream were the most relevant factors triggering the landslides in the research area.

Step 2: Arrange the component factors in a hierarchic order. The hierarchic structure of this research is shown in the Figure 7. The goal of this study, to determine landslide vulnerability zone, played as the root (first level) of the hierarchy. The leaf nodes (second level) are the landslide triggering factors and its classes.

![Figure 7. Hierarchic structure of the research](image)

Step 3: Assign numerical values showing the relative importance of each factor. The elements on the second level, the landslide triggering factors, were compared each other and rated based on relative importance of each factor with respect to the overall goal. The relative preferences of each factor were made using a scale, as shown in Table 3 [16]. The numerical values assignment for the present study is given in the Table 4.
Table 3. Scale for quantitative comparison [16]

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

Step 4: Construct a comparison matrix. The pairwise comparisons of the landslide triggering factors generated at step 3 are organised into a square matrix, as shown in the Table 4.

Step 5: Compute the eigenvector. The principal eigenvalue and the corresponding normalised right eigenvector of the comparison matrix give the relative importance of the various criteria being compared [17]. The final ranking of the landslide triggering factors is presented in the Table 4.

Step 6: Calculate the consistency index (CI). The AHP method provides a way to measure the inconsistency that probably happen from the subjective rating at step 3, defined as [18].

\[
CI = (\lambda_{\text{max}} - n) / (n - 1)
\]

Where, \(\lambda_{\text{max}}\) is the maximum eigenvalue of the judgement matrix and \(n\) is the order of the comparison matrix. If CR is greater than 0.1, the comparison matrix is inconsistent and should be revised.

Table 4. Pairwise comparison matrix

| Landslide triggering factors | (1) | (2) | (3) | (4) | (5) | Final Ranking |
|-----------------------------|-----|-----|-----|-----|-----|---------------|
| Slope angel                 | 1   | 1   | 2   | 3   | 3   | 31.3%         |
| Land use                    | 2   | 1   | 2   | 3   | 3   | 31.3%         |
| Lithology                   | 1/2 | 1/2 | 1   | 2   | 2   | 17.6%         |
| Distance to geological structure/lineament | 1/3 | 1/3 | 1/2 | 1   | 1   | 9.9%          |
| Distance to stream          | 1/3 | 1/3 | 1/2 | 1   | 1   | 9.9%          |

\[\lambda_{\text{max}} = 5.017; \ CR = 0.004\]

4.2. Simple numerical rating
The classes of the landslide triggering factors are assigned using simple numerical rating. The weight of each classes was assigned based on gradation scale between 0 to 9 in order of importance [1]. A higher weight implies that the class is more susceptible to landslide and a lower weight means that the class is less susceptible to landslide. The numerical rating of landslide triggering factors’ classes are given in Table 5. The consideration of weight assignment in the level of classes had been discussed at Section of Relevant Data.
Table 5. The numerical assignment of landslide triggering factors’ classes

| Causative factors       | Classes                     | Weight of classes |
|-------------------------|-----------------------------|-------------------|
| (1)                     | (2)                         | (3)               |
| Slope angle             | 25 – 60°                    | 9                 |
|                         | 10 – 25°                    | 7                 |
|                         | 0 – 10°                     | 3                 |
| Land use                | Built-up area               | 9                 |
|                         | Barren land                 | 7                 |
|                         | Agricultural land           | 3                 |
|                         | Forest                      | 1                 |
| Lithology               | Alluvial deposit            | 9                 |
|                         | Limestone                   | 8                 |
|                         | Older volcanic rock         | 7                 |
|                         | Younger volcanic rock       | 5                 |
|                         | Tuffaceous sandstone        | 3                 |
| Distance to geological structure/lineament | 0 – 400 m | 7 |
|                         | 400 – 700 m                 | 5                 |
|                         | 700 – 1,000 m               | 3                 |
| Distance to stream      | 0 – 10 m                    | 7                 |
|                         | 10 – 30 m                   | 5                 |
|                         | 30 – 50 m                   | 3                 |

4.3. Data integration

The landslide vulnerability map was generated by integrating the numerical data layers of landslide causative factors and their classes using arithmetic-based overlay tool, *Weighted Overlay*, in GIS software. The landslide vulnerability map was prepared in raster extension with a resolution of 25 m x 25 m. The integration of the causative factors and their classes had been demonstrated by Sarkar (2004) to produce Landslide Potential Index (LPI) using the following formula [1]. The final assignment of each classes using the LPI formula was given in Table 6. The landslide potential index ranged from 2 to 8 which was classified into three classes as shown in the Table 7.

\[
LPI = \sum_{i=1}^{5} (R_i \times W_{ij})
\]  (2)

where \( R_i \) denotes the rank for factor \( i \) and \( W_{ij} \) denotes the weight of class \( j \) of factor \( i \).

Table 6. Integration of landslide causative factors and their classes

| Causative factors       | Classes                     | Rank of causative factors | Weight of classes | Final weight |
|-------------------------|-----------------------------|---------------------------|-------------------|--------------|
| (1)                     | (2)                         | (3)                       | (4)               | (5)          |
| Slope angle             | 25 – 60°                    | 31.3%                     | 9                 | 2.817        |
|                         | 10 – 25°                    | 7                         | 2.191             |
|                         | 0 – 10°                     | 3                         | 0.939             |
| Land use                | Built-up area               | 31.3%                     | 9                 | 2.817        |
|                         | Barren land                 | 7                         | 2.191             |
|                         | Agricultural land           | 3                         | 0.939             |
|                         | Forest                      | 1                         | 0.313             |
Table 6. Integration of landslide causative factors and their classes (continued)

| Causative factors | Classes                          | Rank of causative factors | Weight of classes | Final weight (5) = (3) x (4) |
|-------------------|---------------------------------|---------------------------|-------------------|-----------------------------|
| Lithology         | Alluvial deposit                | 17.6%                     | 9                 | 1.584                       |
|                   | Limestone                       |                           | 8                 | 1.408                       |
|                   | Older volcanic rock             |                           | 7                 | 1.232                       |
|                   | Younger volcanic rock           |                           | 5                 | 0.880                       |
|                   | Tuffaceous sandstone            |                           | 3                 | 0.528                       |
| Distance to geological structure/lineament | 0 – 400 m | 9.9%                     | 7                 | 0.693                       |
|                   | 400 – 700 m                     |                           | 5                 | 0.495                       |
|                   | 700 – 1,000 m                   |                           | 3                 | 0.297                       |
| Distance to stream | 0 – 10 m                        | 9.9%                     | 7                 | 0.693                       |
|                   | 10 – 30 m                       |                           | 5                 | 0.495                       |
|                   | 30 – 50 m                       |                           | 3                 | 0.297                       |

Table 7. Classification of landslide potential index

| Landslide vulnerability class | LPI |
|-------------------------------|-----|
| Low                           | 2 – 3 |
| Moderate                      | 3 – 4 |
| High                          | 4 – 8 |

5. Result and discussion

The data integration produced landslide vulnerability map along Garut – Tasikmalaya Road as shown in Figure 8. The red, yellow, and green colours, respectively, represent the high, moderate, and low landslide vulnerability zone. The high vulnerability zones have all the adverse geological, hydrological, and anthropological factors, which make those areas are more susceptible to landslide. Meanwhile, the low vulnerability zones have the least possibility of landslide occurrences. The moderate vulnerability classes have only some of adverse factors that make the zones are more dangerous than the low vulnerability zones.

Before conducting further interpretation of landslide vulnerability in the research area, the map had to be validated to test the reliability. The data of historical landslide events (Table 1) and landslide vulnerability zone were compared to see the number of landslide occurrence in every zone. In this comparison, the number of landslides is matched with the vulnerability zone (Table 8). The high vulnerability zone has highest number of landslide occurrences, while the lowest vulnerability zone only possesses one landslide occurrence. It means that the landslide vulnerability map in the research area produced by combination of AHP and simple numerical rating is reliable.

Table 8. Distribution of landslide in vulnerability zone

| Landslide vulnerability class | Area km² | Area % | Number of landslides |
|------------------------------|----------|--------|----------------------|
| Low                          | 559.775  | 41     | 1                    |
| Moderate                     | 423.053  | 31     | 2                    |
| High                         | 381.828  | 28     | 12                   |
Finally, after getting the reliable landslide vulnerability map of the research area, the landslide potential which affect the Garut – Tasikmalaya Road could be evaluated. Most part of the Garut – Tasikmalaya Road, about 45%, pass through the moderate landslide vulnerability zone. About 30% of Garut – Tasikmalaya Road located in the high vulnerability zone and the 25% part is in low vulnerability zone.

The high vulnerability zones are mainly located in the Salawu District. By looking back to the landslide triggering factors, the Garut – Tasikmalaya Road in Salawu District is situated in adverse geological conditions. The road in Salawu District is located alongside the river, steep mountainous slope, composed by highly weathered volcanic rock and also occupied by normal fault and strike-slip fault. These combinations are sufficient to trigger landslide. The arrangement of landslide management strategies should be prioritized in Salawu District and implemented immediately. The construction of landslide-prevention infrastructure should fit to the geotechnical and geological characteristics. Furthermore, the implementation of early warning system is totally needed to monitor the relevance landslide parameters.

The landslide management strategies are also necessary arranged for landslide prevention in moderate vulnerability zones. The moderate vulnerability zones, which possible to affect the Garut – Tasikmalaya Road, mainly located in Cilawu and Cigalontang District. Considering the number of historical landslide events in every zone, the moderate vulnerability zone is not too dangerous. The construction of landslide-prevention infrastructures should be planned as feasible as possible. The main landslide management which should be considered to be applied in this zone is the implementation of early warning system.

6. Conclusion
The landslide vulnerability assessment alongside the Garut – Tasikmalaya Road using GIS technology and remote sensing data was proven effective to assess wide area. The resulting Landslides Potential Index (LPI) of the study area was classified into three classes of vulnerability zones: low, moderate, and
high. Combining the LPI classes into the historical landslide events in the study area, the number of landslides history is matched with the vulnerability zone. The high vulnerability zone has highest number of landslide occurrences, while the lowest vulnerability zone only possesses one landslide occurrence. In the Garut – Tasikmalaya Road, the most vulnerable slopes are located in Salawu District. The other vulnerable areas to landslide occurrence are located in the Cilawu and Cigalontong. The landslide managements considering the geotechnical condition had to be implemented immediately.

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