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Landslide Susceptibility Mapping of Menoreh Mountain Using Logistic Regression

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ABSTRACT. Menoreh mountain is one of the priority areas developed for tourism and to support sustainable development. Development must pay attention to disaster aspects, one of which is landslides. The map published by the Center for Volcanology and Geological Hazard Mitigation of Indonesia (PVMBG) has a regional scale; therefore, it is necessary to have a more detailed landslide susceptibility map in the Menoreh Mountains. The landslide susceptibility factors were identified and evaluated using logistic regression to build the zonation of the probability of landslide susceptibility. Field observation was conducted at 372 locations, including 129 landslides, and from a local disaster management agency (BPBD) for 200 landslide locations. Significant landslide conditioning factors include slope, lithology, distance to lineaments, distance to the river, and distance to the road. The results show that susceptibility zones were classified into low landslide susceptibility zone covering 39.82 %, moderate landslide susceptibility zone covering 25.86 %, and high landslide susceptibility zone covering 34.31 % of the whole area. Analysis using the logistic regression method has a model prediction accuracy rate of 90.5 %, indicating the high prediction accuracy for the landslide occurrence in the Menoreh Mountains.

Keywords: Landslide susceptibility map · Logistic regression · Landslide prediction.

1 INTRODUCTION

Menoreh Mountain has become one of the priority areas developed for tourism. It includes famous tourist destinations such as Borobudur temple, Suroloyo Peak, Nglinggo tea plantation, Puthuk Setumbu, Gereja Ayam, and others. Physical development must pay attention to disasters such as landslides to support sustainable development. In 2013, PVMBG released a regional scale of landslide hazard map that indicates Menoreh Mountain was at high risk of landslides. Two factors influence landslide occurrence: conditioning and triggering (Karnawati, 2005). Conditioning factors are attached to the slopes that can cause soil movements, divided into five types: geomorphology, soil and rock stratigraphy, geological structure, hydrological conditions, and some land use related to the slope. The conditioning factors of landslides might be different for different regions (Chau and Chen, 2005; Sinarta *et al.*, 2016). Therefore, it is necessary to have a detailed field investigation to know the conditioning factors that cause landslides in the study area. Proper mitigation and reducing the risk of landslides require a more detailed landslide susceptibility map in Menoreh Mountain. To make those maps, identification and evaluation

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of the landslide controlling factor must be done so that the zonation of the probability of landslide susceptibility can be made. The map can be created using a qualitative or quantitative approach (Ayalew and Yamagishi, 2005). The qualitative approach depends on the expert's opinions, whereas the quantitative approach is based on numerical expression. There are two methods of quantitative approach, namely bivariate, such as frequency ratio and weight of evidence (WoE), as well as multivariate, such as artificial neural network (ANN), support vector machines (SVM), and logistic regression. Logistic regression is the most commonly used to make a landslide susceptibility map, which is significant for classifying landslide susceptibility classes. Many researchers have used logistic regression for landslide susceptibility mapping, including Ayalew and Yamagishi (2005), Lee (2005), Lee and Sambath (2006), Pradhan and Lee (2006), Zhu and Huang (2006), Pradhan (2010), Bai *et al.* (2010), Oh *et al.* (2012) and Makealoun *et al.* (2014). This paper presents a landslide susceptibility map using logistic regression based on a landslide's conditioning factors. It determines the dominant conditioning factor that controls landslide occurrence in the study area

2 STUDY AREA

The study area is located on Menoreh Mountain; the surroundings are bounded by 395024 to 418736 and 9166301 – 9150468 UTM with datum WGS 1984 49S and have an extent of about 384 km² (Figure 1). It is about 35 km northwest of Yogyakarta City in Daerah Istimewa Yogyakarta, Indonesia.

The research area is located in the northern part of the Kulon Progo Mountains series. These mountains are superimposed old volcanic bodies, namely Mount Gadjah in the south, Mount Ijo in the middle, and Mount Menoreh in the north. The subduction process in southern Java, which is getting closer to the north, creates superimposed mountains where the farther north, the younger the hill (Barianto *et al.*, 2010). It is also characterized by changes in the minerals in those mountains.

The Menoreh Mountain area has an elevation ranging from 1012 masl to 86 masl. The morphology that develops is in the form of hills with strong reliefs. The river distribution pattern created in the research area was in the form of a trellis. The slope in the study area ranges from 0^o – 68^o, and in the mountainous part, it ranges from 18^o – 68^o. This morphology is formed due to the control of lithology and geological structure.

Several rock formations are exposed in the study area (Raharjo *et al.*, 1995). The oldest one is the Kebo Butak Formation, composed of volcanic materials such as andesite breccias, tuff breccias, tuffs, and breccias with lava flows. This formation was intruded by shallow intrusive rocks in andesite in the Late Oligocene-Early Miocene. Then, on top of that, the Jonggrangan Formation and the Sentolo Formation were deposited unconformably, dominated by shallow seas sedimentary rocks. This formation was then covered by the deposits of the quaternary volcanism activity of young volcanoes such as Mount Merapi, Mount Sumbing, and Mount Merbabu. Deposited materials include andesite breccia, tuffaceous sand, agglomerates, and tuff.

The geological structure that develops in the study area has a north-south trending main pattern, a Sundanese pattern (Pulonggono and Martodjojo, 1994). The main structure that cuts through the Menoreh Mountains is a sinistral shear fault or a left-lateral strike-slip fault (Widagdo *et al.*, 2018). In addition to the main structure that cuts through the Kulon Progo mountains, there is a descending fault with a west-east orientation. The deformation due to the fault is believed to cause the loss of morphology in the northern part of the Menoreh Mountains.

3 METHODOLOGY

One type of quantitative approach with multivariate methods considered relevant for analyzing landslide susceptibility is the logistic regression method (Dai and Lee., 2002; Ayalew and Yamagishi, 2005). This method involves more than one independent variable to predict the binary probability of the dependent variable (Hosmer and Lemeshow, 2000). A binary variable expresses the dependent variable on the probability of the occurrence of landslides. A binary variable expresses the dependent variable on the probability of landslides. A value of

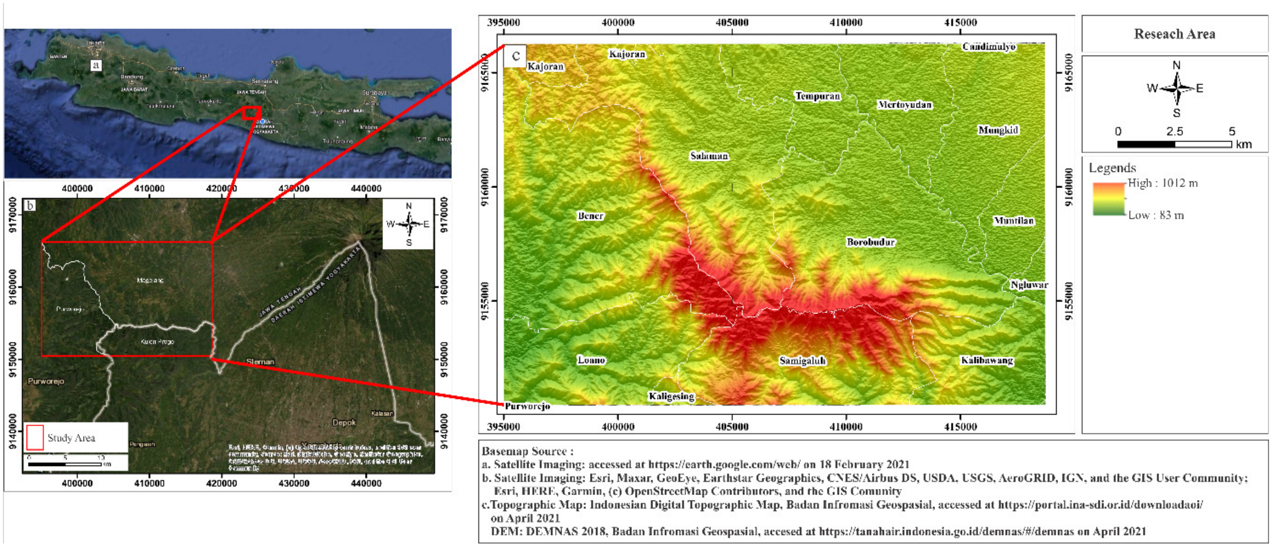

FIGURE 1. The study area.

0 shows no landslide, and a value of 1 indicates a landslide. Independent variables were the landslide's conditioning factors such as slope inclination, lithology, lineaments distance, river distance, and road distance. The data used have scale factors that have levels in each class. Then, those data were overlayed with GIS. Furthermore, probability can be estimated using Equation 1.

$$P_y = \hat{P} = \frac{e^z}{1+e^z} \tag{1}$$

where P probability of landslide occurring events, (0–1), z is linear logistic models ($z = b_0 + b_1x_1 + b_2x_2 + \cdots + b_nx_n$), b_0 is an intercept model or constant-coefficient, n is the number of independent variables, b_i is the coefficient of the regression model (i = 1, 2, 3, ..., n), and x_i is an independent variable.

The Pseudo R^2 value from the calculated logistic analysis can be used as how the model fits the dataset (Ayalew and Yamagishi, 2015). While using SPSS, Pseudo R^2 comes in term of Nagelkerke R^2. The value of 1 means that the model works well in predicted landslides, whereas 0 indicates no relationship between independent and dependent variables.

This study used primary data and secondary data. Primary data were collected by doing a field investigation. Field investigation consists of 372 locations, as shown in Figure 2. The collected data were geomorphology (Figure 3a-c), lithology (Figure 3d-f), and landslide (Figure 4). The data added to landslide data, including the type of landslide and geometry such as directions, elevations, length, and width. Local disaster management agency (BPBD) of Kulon Progo District, Magelang District, and Purworejo District provide secondary data on landslide occurrence. Based on those observations, almost all landslide has slide types (Figure 4a-d). Data such as slope inclination, lineaments, and rivers were extracted from DEM analysis, and roads' locations were extracted from this area's land-use map. The digital elevation model (DEM) and topographic map with a scale of 1:25000 are from the Indonesian Geospatial Agency (BIG, 2018).

A landslide susceptibility map was made using a probability equation provided by the logistic regression method. The probability calculation was done by creating a grid of 50 m × 50 m. That distance was considered to represent the study area thoroughly. Then, GIS performs interpolation using the kriging method to make the landslide susceptibility map of the study area. The kriging method was chosen because this interpolation accommodates a spherical model. The classification of landslide susceptibility zones is carried out following regulation of the head of the National Disaster Management Agency (Perka BNPB) No. 2 of 2012, divided into three classes of susceptibility zones with the equal interval method, namely high susceptibility zones, moderate susceptibility zones, and low susceptibility zones.

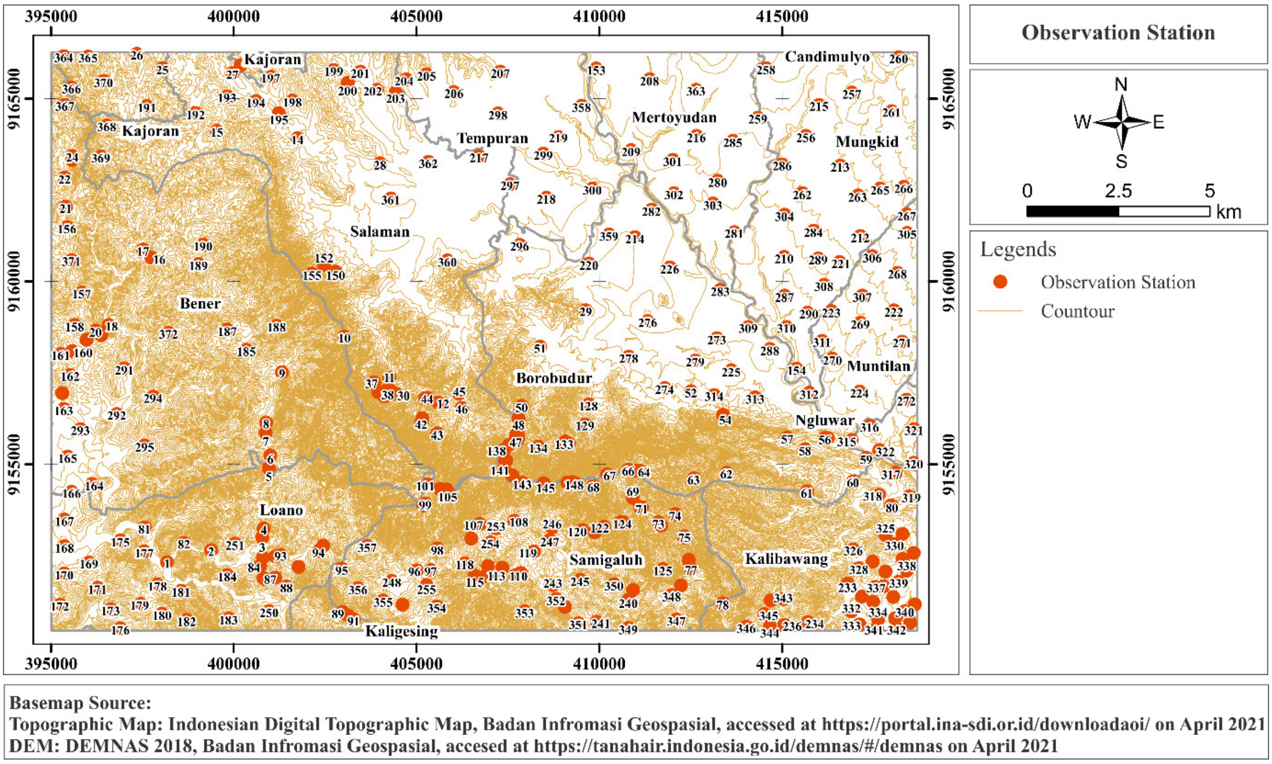

FIGURE 2. Field observation location.

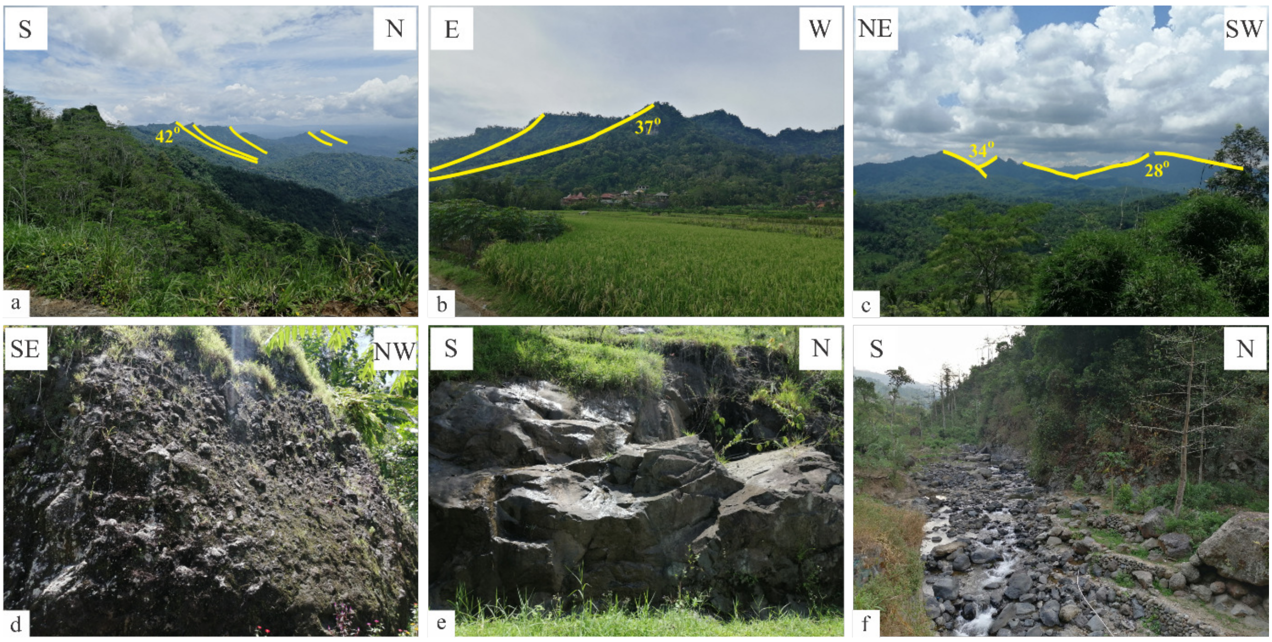

FIGURE 3. (a) high slope inclination in the mountainous part of the study area at station 67 and (b) station 52, and (c) station 21 for moderate slope inclination angle in the hilly part of the study area; (d) Volcanic breccia at station 42, (e) Andesite intrusion at station 49, and (f) Boulder-sand unit at station 165.

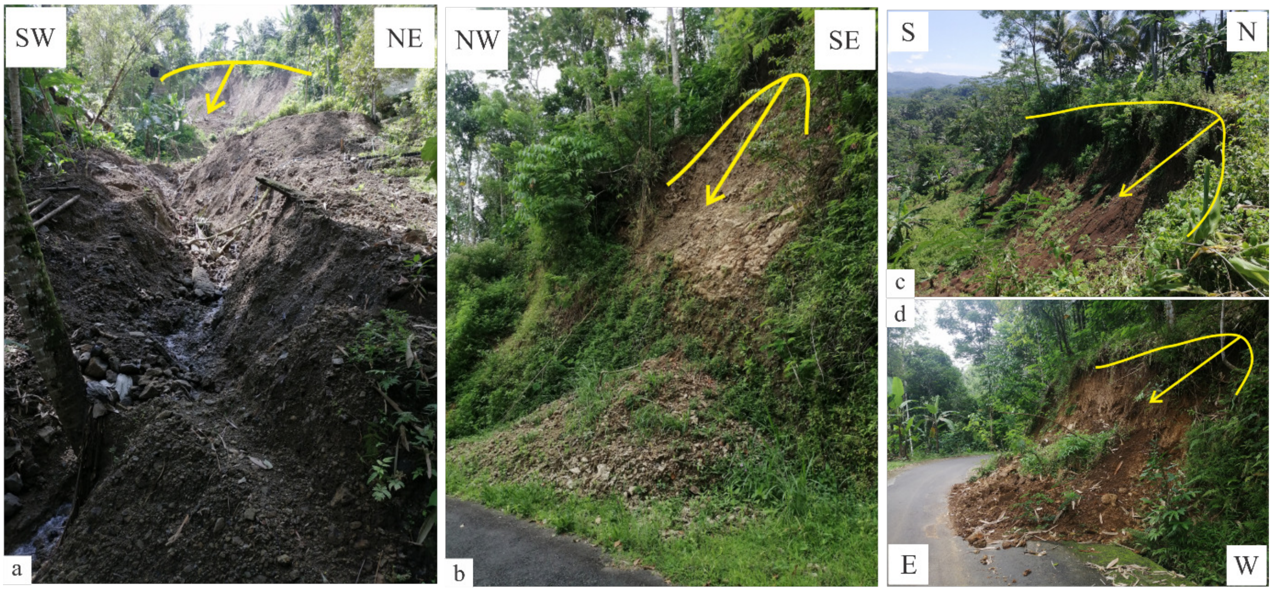

FIGURE 4. Landslide in the study area has slides type, shown at station (a) 34, (b) 70, (c) 15, and (d) 5.

4 RESULTS AND DISCUSSION

The geomorphological condition that mainly controls a landslide is slope inclination. The potential for landslide increases along with the increase in slope due to the greater driving force on steeper slope conditions. The degree of the slope was divided into three classes: low (0°–20°), medium (20°–40°), and high (>40°) (Karnawati, 2005), as shown in Figure 5. Analysis of slope inclination was conducted using DEM (BIG, 2018). The field investigation also verified that almost all landslide occurs at a slope angle of more than 40°.

The research area is composed of volcanic rocks from tertiary and quaternary volcanism. Field investigations also determine the lithological unit of the study area. Based on field observations, lithology can be divided into four units: Volcanic Breccia Unit, Andesite Intrusion Unit, Sand-clay Unit, and Boulder-sand Unit, as shown in Figure 6.

Lineament data extracted from DEM analysis were characterized by an abrupt change of morphology, deep valley, scarps, cliff, erosional pattern, and drainage pattern change. The lineaments influence landslide occurrence within 400 m from the lineaments (Oh *et al.*, 2012). So, buffer zones were made within 400 m from the lineament, assuming the closer the lineaments, the more intensive landslide occurred (Figure 7).

The hydrological condition is also one of the conditioning factors of landslides (Karnawati, 2005). Surface water flow causes erosion of rocks and soil on the surface. The extensive erosion process will affect the stability of the slopes where the slopes will tend to collapse easily (Barredo *et al.*, 2000) and on the river bank walls due to the weakening of the toe of the slopes (Zhu and Huang, 2006). Groundwater conditions closer to the river will also have a water-saturated zone closer to the surface. This will affect the strength of cohesion between soil particles. In addition, saturation at the foot of the slope will cause the groundwater level to rise. Thus, data on the river's distance can represent the field's hydrological conditions. Based on that, the divided influence of rivers on landslide occurrence into three classes, 0–50 m, 50–100 m, and more than 100 m (Varnes, 1984), as shown in Figure 8.

The last conditioning factor is the distance to roads. Roads can lead to instability due to reducing the rock mass strength (Zhu dan Huang, 2006). Cutting the slope that does not pay attention to the safety factor for the road makes the cut slope unstable. The construction of the road by cutting the slope also influences landslide occurrence (Ayalew and Yamagishi, 2005). Based on the results of statistical observations that have been carried out, the frequency of ground movements in intense mountainous areas occurs as far as 40 m to 80 m from road construction (Figure 9). This is because the road in

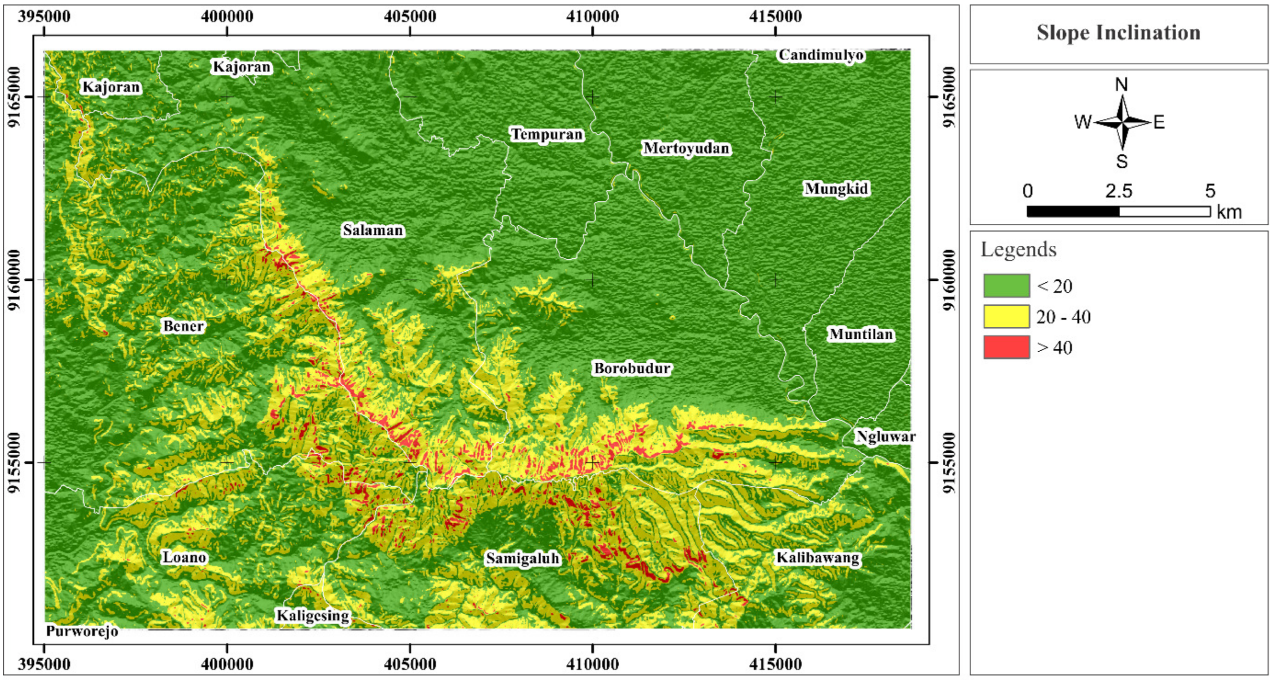

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FIGURE 5. Slope inclination map of the study area.

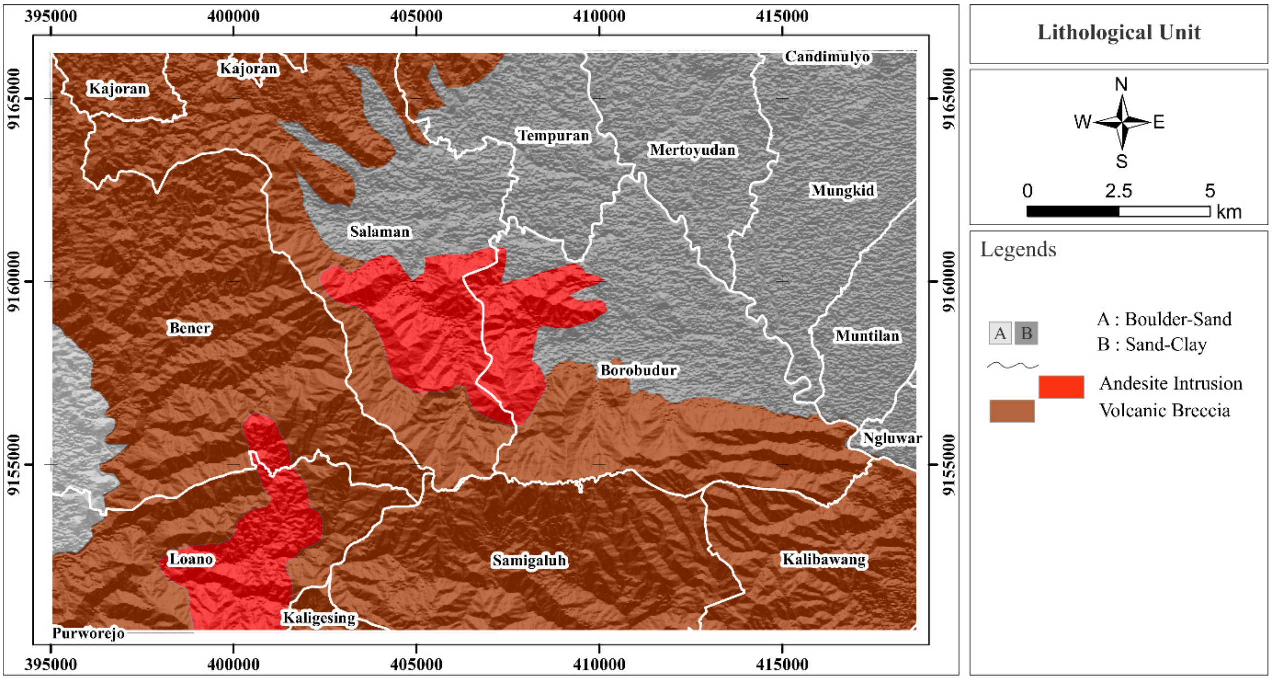

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FIGURE 6. Lithology map of the study area.

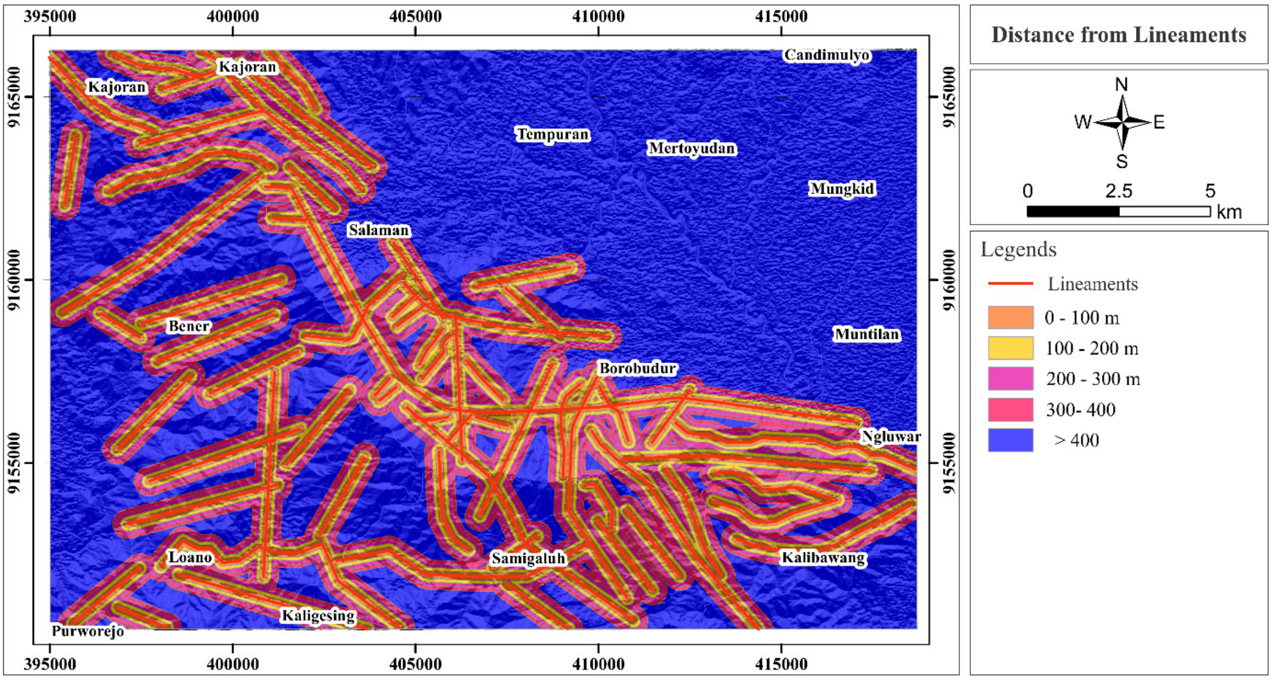

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FIGURE 7. Distance from lineaments map of the study area.

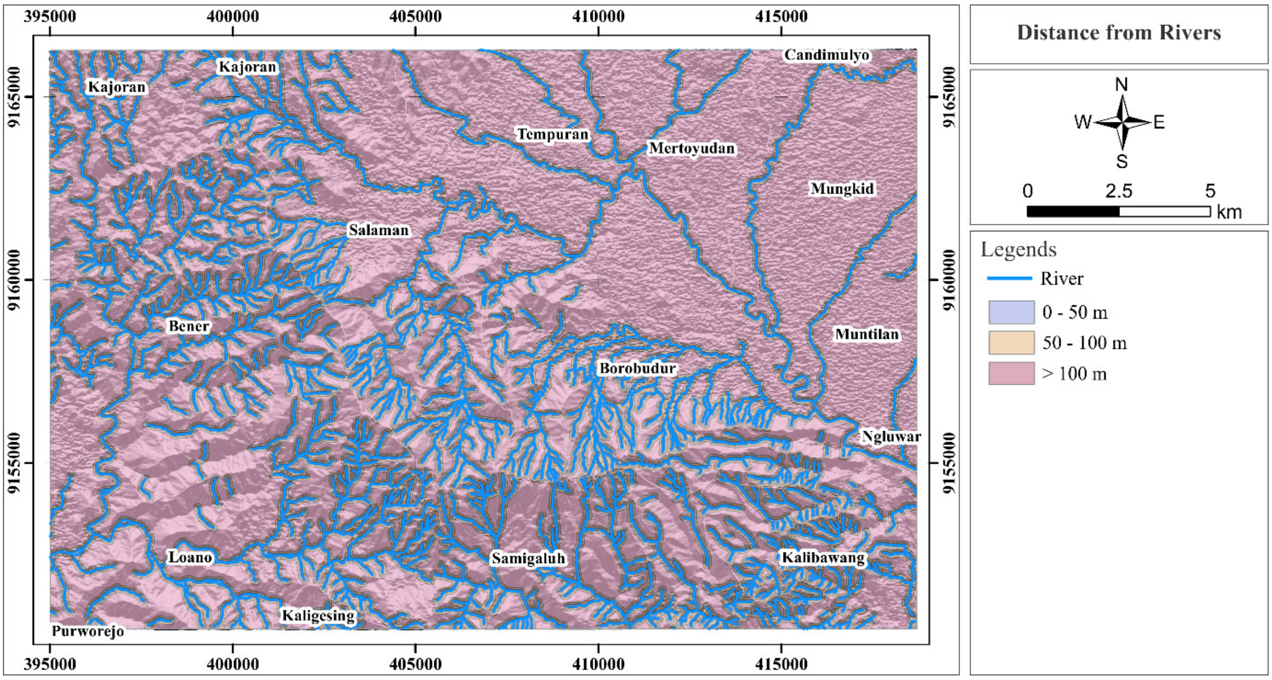

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FIGURE 8. Distance from rivers of the study area.

the mountains cuts the slope to have steep inclinations.

Landslide susceptibility mapping was then calculated by determining classes for each conditioning factor before using logistic regression. Controlling factors are slope inclination, lithology, distance from lineaments, distance from rivers, and distance from roads as independent variables (Table 1) and landslide occurrence as a dependent variable. Using 572 locations, including 329 landslide locations (Figure 10), logistic regression was then carried out to determine the relationship between independent and dependent variables in the form of a mathematical model.

The logistic regression calculation results are shown in Table 2, where each conditioning factor has a coefficient. The calculation for each grid is then conducted with those coefficients to Equation 1. The landslide probability map can be obtained in Figure 11, where it has a probability of landslide occurrence within 0 to 1.

The landslide susceptibility map is further divided into several classes of landslide susceptibility. Based on the Regulation of the head of the National Disaster Management Agency (Perka BNPB) No. 2 of 2012, the vulnerability zone is divided into 3 vulnerability classes. The classes are low, moderate, and high. The classes are divided based on an equal interval where the size of each class is 0.33. The low susceptibility class has a probability value range of 0–0.33, the moderate susceptibility class has a probability value range of 0.33–0.66, and the high susceptibility class has a probability value above 0.66. Based on the class division, the landslide vulnerability map can be seen in Figure 12.

The low landslide susceptibility class has an area of 149.09 km² or 39.81 % of the total area of the study area. There were 27 (8.20 %) recorded landslide occurrences in this class. This class is generally located northeast of the study area with moderate slopes to low slopes or less than 20° with lithology consisting of the sand-clay unit. This area is located more than 400 m from lineaments and more than 100 m from rivers. The moderate landslide susceptibility class has an area of 96.80 km² or 25.86 % of the total area of the study area's total area. There are 41 (12.50 %) recorded landslide occurrences in this class. This class is located in a hilly area of the study area with an inclination slope ranging from 10° to 40° and in a zone within 100 m from the river. The high landslide susceptibility class has an area of 128.47 km² or 34.32 % of the total area of the study area. There are 261 (79.30%) recorded landslide occurrences in this class. This class is located in a hill area with a steep inclination and a mountainous region with slope inclination ranging from 10° to more than 60°. This class is also within 100 m from lineaments, 40 m from roads, and 50 m from rivers. It also consists mainly of volcanic breccia and andesite intrusions. A histogram of landslide occurrence for each susceptibility zone can be seen in Figure 13.

Table 3 shows some results from a statistical calculation using logistic regression from the data set. The decreasing value of -2 Log-Likelihood block 0 to block 1 indicates that the calculation model has improved to be more fitting for independent variables to the regression calculation (Ayalew and Yamagishi, 2005). Hosmer-Lemeshow test has a P-value of 0.053. P-value has a value greater than 0.05, which means that the logistic regression model fits well in a predicted landslide in the study area. The Nagelkerke R^2 value from the logistic regression analysis shows that the independent variable used affects 76.50 % of the dependent variable. The remaining 23.40 % are other factors outside the determined independent variables affecting landslide occurrence. In addition, based on the predicted accuracy of the dataset, it was found that the model was able to anticipate events with an overall accuracy of 90.50%. Landslide occurrence in the low susceptibility zone and no landslide in several places that have a critical condition means that having probability nearing one can be caused by the presence of other conditioning factors such as the degree of weathering of the rocks, slip planes, and inappropriate land use, or even a triggering factors that affect landslide occurrence.

Each parameter's coefficient can determine the relationship between each conditioning factor and the landslide occurring. Except for lithology, all coefficients were positive, indicating that those variables were positively related to landslide occurrence. The slope inclination

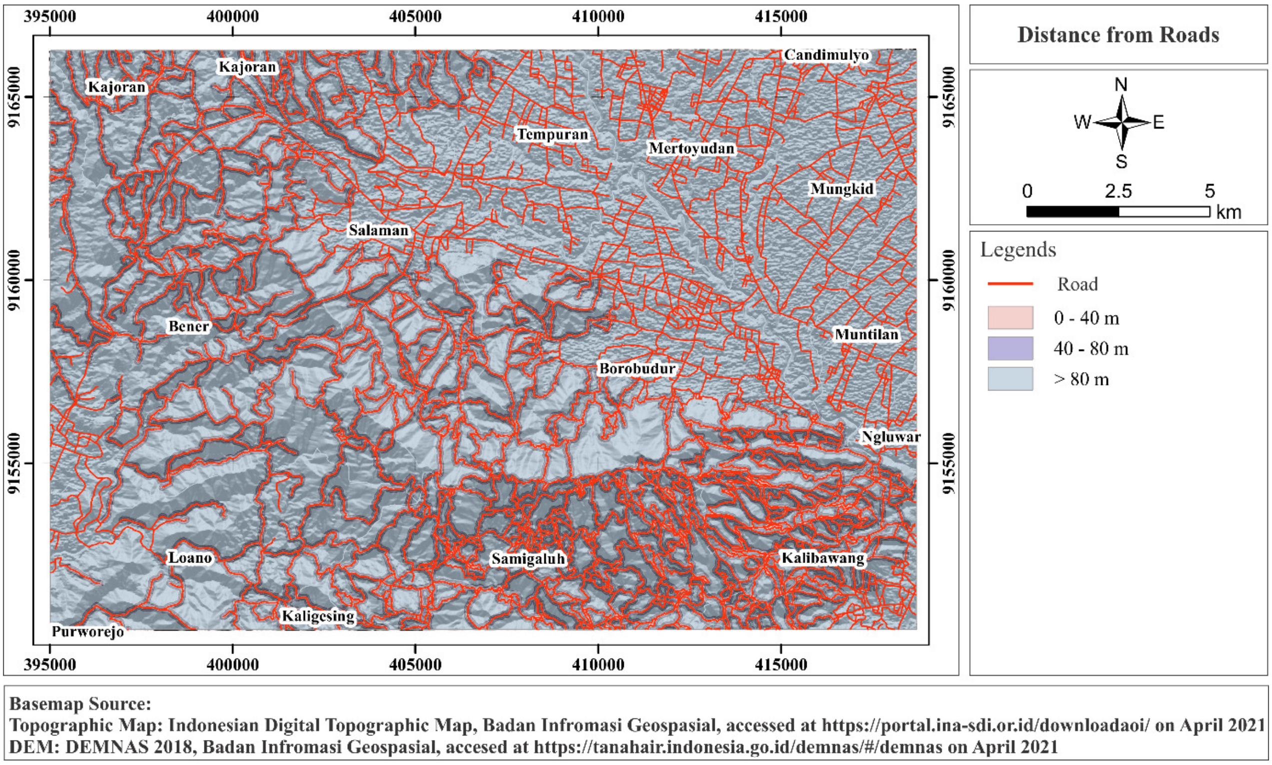

FIGURE 9. Distance from roads of the study area.

TABLE 1. Classes for each independent variable.

No.	Independent Variable	Independent Variable class	Score
1	Slope Inclination	0 – 20	1
		20 – 40	2
		>40	3
2	Lithology	Volcanic Breccia Unit	4
		Andesite Intrusion Unit	3
		Sand-Clay Unit	2
		Boulder-Sand Unit	1
3	Distance from Lineaments	0 – 100	5
		100 – 200	4
		200 – 300	3
		300 – 400	2
		> 400	1
4	Distance from Rivers	0 – 50	3
		50 – 100	2
		>100	1
5	Distance from Roads	0 – 40	3
		40 – 80	2
		>80	1

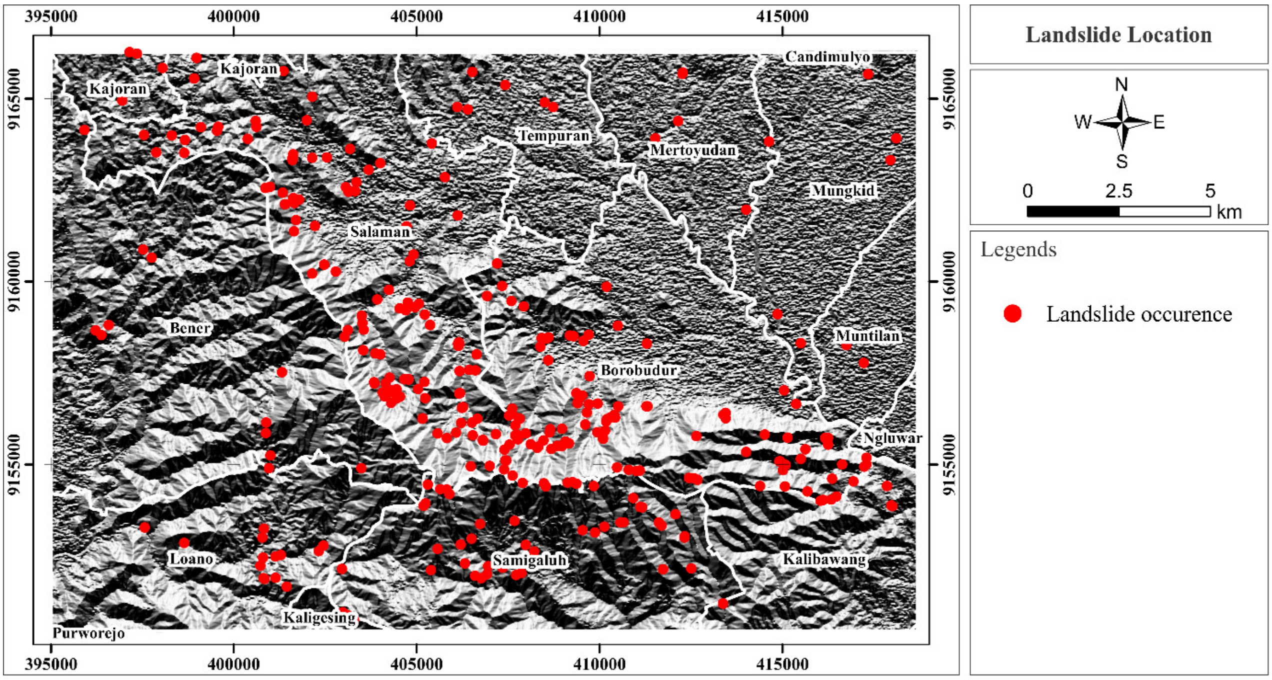

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FIGURE 10. Landslide occurrence map.

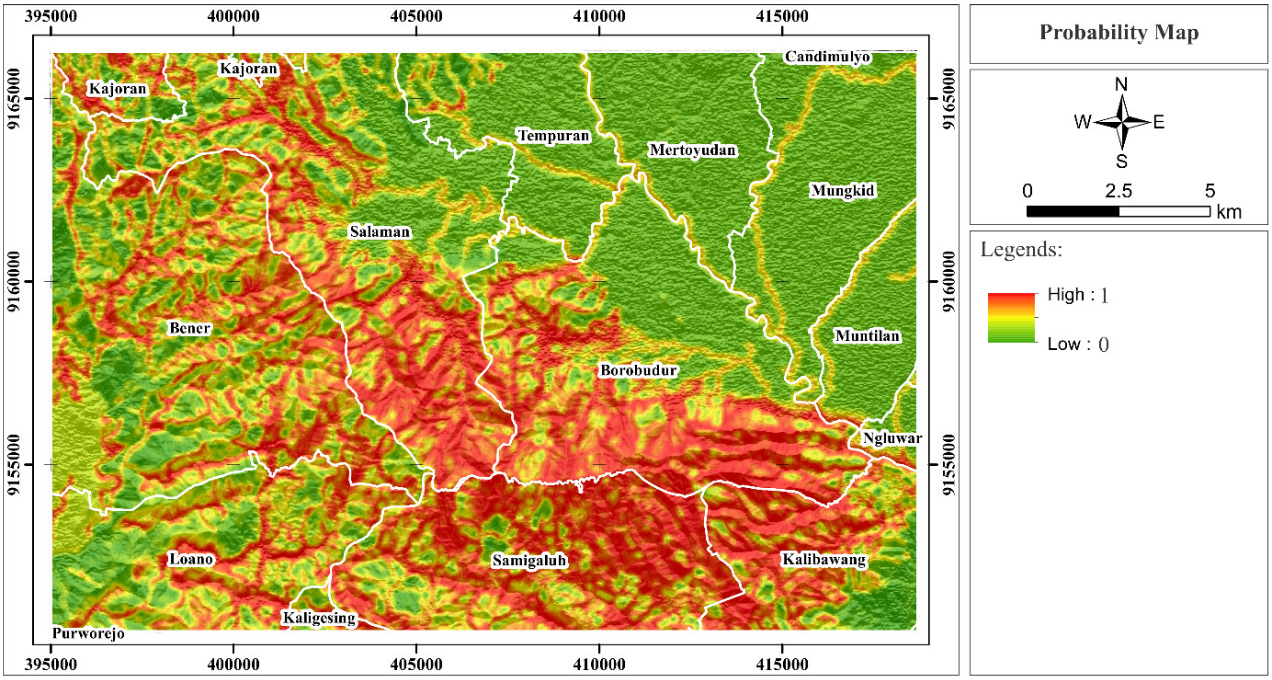

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FIGURE 11. Probability map obtained using logistic regression analysis.

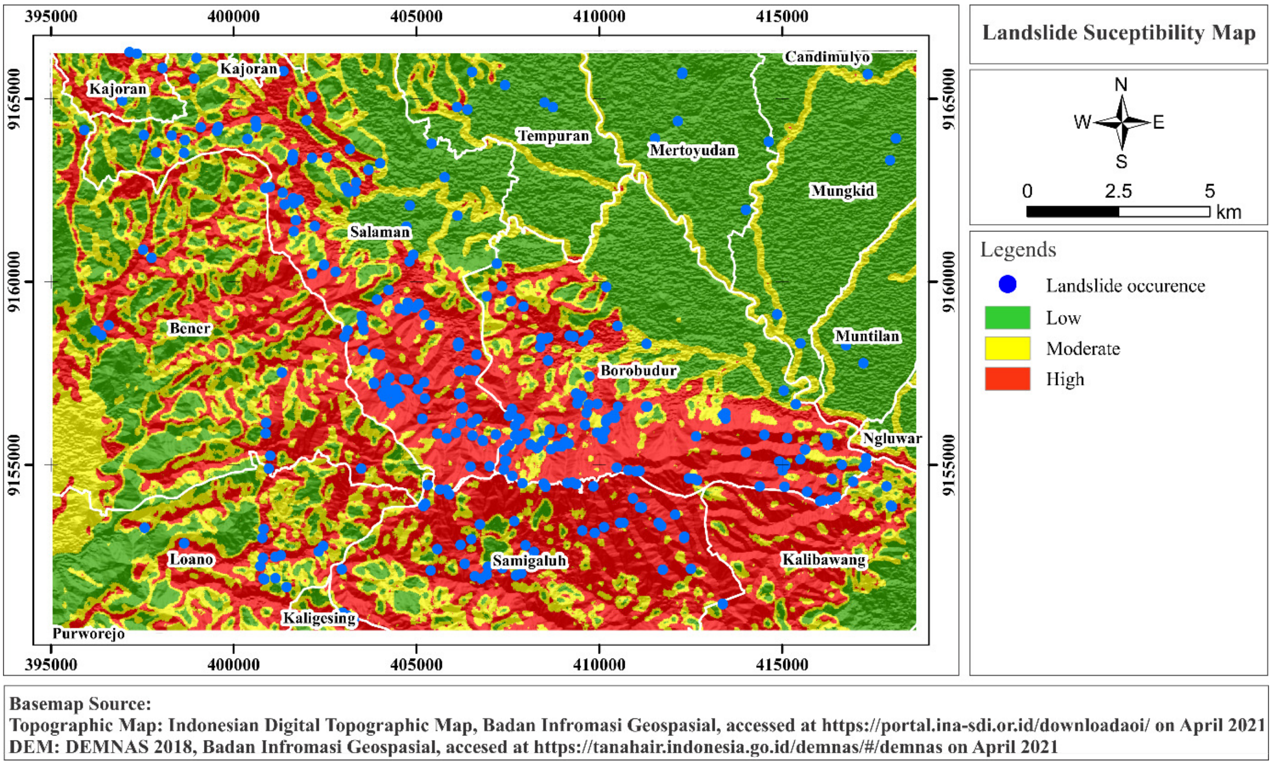

FIGURE 12. Landslide susceptibility map of Menoreh Mountain.

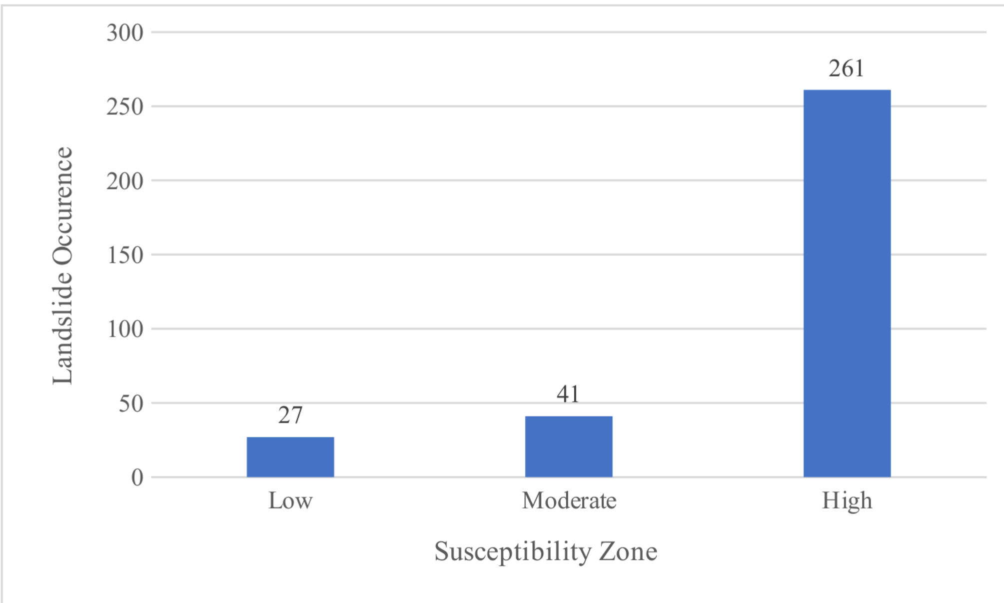

FIGURE 13. Histogram of landslide occurrence and susceptibility zone.

TABLE 2. Logistic regression model coefficient for each independent variable.

Independent Variable Class	B	S.E.
Slope Inclination	3.223	0.594
Lithology	-1.287	0.229
Distance from Lineaments	0.763	0.122
Distance from Rivers	1.315	0.286
Distance from Roads	2.700	0.318
Constant	-7.218	0.827

TABLE 3. Statistic results.

Statistic Result	Value
-2 Log likelihood block 0	751.963
-2 Log likelihood block 1	286.459
Pseudo R^2: Nagelkerke R^2	0.765
Hosmer-Lemeshow	0.053
Model Predicted Accuracy	90.50 %

angle having the highest number of coefficients means that most landslides occur because of the high slope angle. It follows by distance to roads, distance to rivers, then the distance to lineaments. A negative coefficient also decreases the chance of occurrence. That could happen because, in the lithology unit, volcanic breccia and andesite intrusion have a different rate of weathering where the rocks are found almost entirely weathered in some places. It is still fresh in some other areas, forming a massive rock mass that most likely will not collapse.

5 CONCLUSION

The landslide susceptibility map calculated with the logistic regression method has a 90.5 % accuracy rate in predicting the landslide occurrence. Susceptibility is then divided into three landslide susceptibility classes: low, moderate, and high, with an equal interval. Several areas with high landslide susceptibility are the northern part of Samigaluh District, the southern part of Borobudur District, the south part of Salaman District, the western part of Loano, and the Bener District. In contrast, the areas with low landslide susceptibility are Muntilan District, Mertoyudan District, Tempuran District, the Eastern part of Salaman District, and the northern part of Borobudur District. Based on the results of empirical calculations using logistic regression, the most dominant parameter in landslide occurrence is the slope inclination with a coefficient value of 3.223, followed by distance to the road with a coefficient of 2.700, then distance to rivers and distance to lineaments. Lithology has a negative coefficient causing the probability to decrease. It is because of the different rates of weathering where in some places, it is almost entirely weathered, and in some places, it is still fresh. On that note, logistic regression has proven reliable for landslide susceptibility mapping and can be used very well in the study area of Menoreh Mountain.

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REFERENCES

Ayalew, L., & Yamagishi H. (2005). The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains. Centre Japan: Geomorphology, 65(1–2): 15–31

Badan Nasional Penanggulangan Bencana (BNPB) (2012). Peraturan Kepala Badan Nasional Penanggulangan Bencana No. 02 Tahun 2012 tentang Pedoman Umum Pengkajian Risiko Bencana. Jakarta: Badan Nasional Penanggulangan Bencana.

Bai, S., Wang, J., Lü, G., Zhou, P., Hou, S., & Xu, S. (2010). GIS-based logistic regression for landslide susceptibility mapping of the Zhongxian segment in the Three Gorges area, China. Geomorphology 115 (2010): 23–31.

Barianto, D. H., Abboud, E., Setijadji, L. D. (2009). Structural analysis using Landsat TM, Gravity Data, and Paleontological Data from Tertiary Rocks in Yogyakarta, Indonesia. Memoirs of the Faculty of Engineering, Kyushu University, 69(2).

Barredo, J. I., Benavidez, A., Herhl, J., & van Westen, C.J. (2000). Comparing heuristic landslide hazard assessment techniques using GIS in the Tirajana basin, Gran Canaria Island, Spain: International Journal of Applied Earth Observation and Geoinformation, 2(1): 9-23.

Chau, K. T., & Chan, J. E. (2005). Regional bias of landslide data in generating susceptibility maps using logistic regression: case of Hongkong Island. Landslides, 2(4): 280-290.

Dai, F. C., & Lee, C. F. (2002). Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong. Geomorphology, 42(3-4): 213-228.

Badan Informasi Geospasial (BIG) (2018) DEMNAS, accessed on April 2021.

Hosmer, D.W., & Lemeshow, S. (2000) Applied Logistic Regression, Second Edition, John Wiley and Sons, Inc., New York, 375p

Karnawati, D. (2005) *Bencana Alam Gerakan Massa Tanah di Indonesia dan Upaya Penanggulangannya*. Jurusan Teknik Geologi Fakultas Teknik Universitas Gadjah Mada, Yogyakarta, 232p

Lee, S. (2005). Application of Logistic Regression Model and Its Validation for Landslide Susceptibility Mapping using GIS and Remote Sensing Data. International Journal of Remote Sensing, 26(7): 1477-1491

Lee, S., & Sambath, T. (2006) Landslide susceptibility mapping in the Damrei Romel area, Cambodia using frequency ratio and logistic regression models. Environmental Geology, 50(6): 847-855

Oh, H. J., Park, N. W., Lee, S. S., & Lee, S. (2012). Extraction of Landslide-Related Factors from ASTER Imagery and Its Application to Landslide Susceptibility Mapping. International Journal of Remote Sensing, 33(10): 3211-3231

Pradhan, B., & Lee, S. (2006). Landslide Hazard Mapping at Selangor, Malaysia Using Frequency Ratio and Logistic Regression Models. Landslide (2007) 4: 33-41

Pradhan, B. (2010). Landslide Susceptibility Mapping of a Catchment Area Using Frequency Ratio, Fuzzy Logic, and Multivariate Logistic Regression Approaches. Journal Indian Society Remote Sensing, 38: 301-320.

Pulunggono, A., & Martodjojo, S. (1994). *Perubahan Tektonik Paleogen-Neogen Merupakan Peristiwa Tektonik Terpenting di Jawa*. Preceedings Geologi dan Geotektonik Pulau Jawa Sejak Akhir Mesozoik Hingga Kuarter, Yogyakarta.

Pusat Vulkanologi dan Mitigasi Bencana Geologi (PVMBG) (2013). *Peta Zona Kerentanan Gerakan Tanah Kabupaten Magelang, Provinsi Jawa Tengah*, Jakarta, Kementerian Energi dan Sumber Daya Mineral.

Pusat Vulkanologi dan Mitigasi Bencana Geologi (PVMBG) (2013). *Peta Zona Kerentanan Gerakan Tanah Kabupaten Purworejo, Provinsi Jawa Tengah*, Jakarta, Kementerian Energi dan Sumber Daya Mineral.

Pusat Vulkanologi dan Mitigasi Bencana Geologi (PVMBG) (2013). *Peta Zona Kerentanan Gerakan Tanah Kabupaten Kulon Progo, Provinsi Daerah Istimewa Yogyakarta*, Jakarta, Kementerian Energi dan Sumber Daya Mineral.

Rahardjo, W, Sukandarrumidi, & Rosidi, H. M. D. (1995). Peta Geologi Lembar Yogyakarta, Skala 1 : 100.000, Bandung, Pusat Penelitian dan Pengembangan Geologi.

Satellite Imaging. accessed on 18 February 2021.

Satellite Imaging: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community; Esri, HERE, Garmin, (c) OpenStreetMap Contributors, and the GIS Comunity.

Sekarlangit, N. (2022). *Analisis Probabilitas Kerentanan Gerakan Tanah dengan Menggunakan Regresi Logistik, Studi Kasus: Lereng Utara Pegunungan Menoreh.* Yogyakarta. Unpublished Thesis. Yogyakarta: Universitas Gadjah Mada, p 153.

Sinarta I. N., Rifa'i, A., Fathani, T. F., Wilopo, W. (2016). Geotechnical Properties and Geologi Age on characteristics of landslide hazards of volcanic soils in Bali, Indonesia, International Journal of Geomate, 11(26): 2595-2599.

Topographic Map, Indonesian Digital Topographic Map, Badan Infromasi Geospasial, accessed on April 2021.

Widagdo, A., Pramumijoyo, S., & Harijoko, A. (2018). Morphotectono-Volcanic of Menoreh-Gajah-Ijo Volcanic Rock in Western Side of Yogyakarta-Indonesia. Journal of Geoscience, Engineering, environment, and Technology, 03(03): 155-163.

Varnes, D. J. (1978). Slope Movement Type and Processes, special Report 176; Landslide; Analysis and Control, Eds: R.L. Schuster dan R.j. Krizek, Transport Research Board, National Research Council, Washington, D.C., pp. 11-33.

Varnes, D. J. (1984). Landslide Hazard Zonation: A Review of Principles and Practice 3. UNESCO, Paris. 63 p.

Zhu, L., & Huang, J. (2006). GIS-based Logistik Regression for Landslide Susceptibility Mapping in Regional Scale. Journal of Zhejiang University SCIENCE A 7(12): 2007-2017.