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Improving Landslide Susceptibility Using Groundwater Parameter in Samigaluh and Kalibawang Subdistricts

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ABSTRACT. Landslide susceptibility maps are crucial in disaster risk management, and they can be used for regional development plans. Landslide susceptibility maps can be made by analyzing parameters that are assumed to affect landslides such as gradient slopes, geology, soil, and climate. Selection of landslide controlling parameters influences the accuracy of landslide susceptibility map. This study evaluates the effect of parameter that's rarely used, which is groundwater. The study area of this research was Kalibawang and Samigaluh Subdistricts, Kulonprogo, Special Region of Yogyakarta, Indonesia. Frequency ratio was used for the method along other parameters which is slope gradient, lithology, lineament density, land use, soil thickness. The result shows that groundwater parameter increased the accuracy by 22.29%. This study suggests that groundwater should be highly considered in landslide susceptibility mapping. In the other hand, groundwater depth mapping remains a challenge because most remote sensing methods only detect shallow groundwater. Further research is necessary to develop better methods for groundwater mapping using remote sensing or other indirect methods.

Keywords: Disaster management · Environmental geology · Frequency ratio · Groundwater · Landslide susceptibility.

1 INTRODUCTION

Mapping of landslide susceptibility is required for the preparation of regional development plan that is based on disaster risk reduction. Landslides may result in material and immaterial losses and hence should be avoided if landslide-prone zones can be identified (Rahman & Mapjabil, 2017). Landslide susceptibility maps must be accurate so that regional development activities take place in locations that are safe from the threat of landslides.

Research on relative susceptibility is usually only based on a few parameters, namely gradient slopes, geological characteristics, land cover, and soil. This is due to parameters that are relatively universal, and which can be investigated in any place are those parameters (Reichenbach *et al.*, 2018). The depth of groundwater is one of the landslides controlling parameters whose role still needs further investigation. The groundwater depth parameter is rarely accounted for because it is not found in all places (Neuhäuser & Terhorst, 2007). Therefore, groundwater depth parameter research is more often employed in a detailed scale on a slope unit. Detailed scale research on one

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slope unit can show the effect of the presence of groundwater because it calculates the effect of permeability (Carrara *et al.*, 1991). Groundwater depth parameters are rarely accounted for in semi-detailed or regional scale analysis and therefore, its effect on the landslide susceptibility accuracy still needs further investigation.

This study aims to evaluate the effect of groundwater depth parameter on the accuracy of landslide susceptibility map. The susceptibility map produced will be compared with susceptibility map without groundwater depth in order to evaluate the effect of groundwater depth parameters to its accuracy.

2 GEOLOGICAL SETTING/SITE CHARACTERIZATION

The study area is located in the Kalibawang and Samigaluh Subdistricts, Kulon Progo Regency, Special Region of Yogyakarta, Indonesia. Geological formations that can be found in the study area are Colluvium (Qc), Young Volcanic Deposits of Merapi Volcano (Qmi), Sentolo Formation (Tmps), Jonggrangan Formation (Tmj), Kebobutak Formation (Tmok), Nanggulan Formation (Teon), and Andesite (a) (Rahardjo *et al.*, 1995) (Figure 1).

From the youngest, Colluvium (Qc) that can be found in the foothills consist of unsorted debris from Kebobutak Formation. Young Volcanic Deposits of Merapi Volcano (Qmi) that can be found in the east side of the research area consist of undifferentiated tuff, ash, breccia, agglomerate, and lava flows. Sentolo Formation (Tmps) that also found in the east side of research area consist of Limestone and marly sandstone. Jonggrangan Formation (Tmj) which can be found in hilly area consist of conglomerate, tuffaceous marl, and calcareous sandstone with intercalations of lignite seams, limestone, and coralline limestone. Kebobutak Formation (Tmok) as the dominating geological formation in the research area consists of andesitic breccia, tuff, lapilli tuff, agglomerate, and intercalations of andesitic lava flows. Nanggulan Formation (Teon) that found in the south side of the research area consist of sandstone, sandy marl, and claystone. Andesite (a) that can be found on the west side of the research area consist of hypersthene andesite to hornblende-augite andesite and trachyandesite.

The hydrogeological settings on the location are aquifer in which flow is intergranular and aquifers of poor productivity and regions without exploitable groundwater (Effendi, 1985). Aquifer in which flow is intergranular can be found in the lowland while aquifers of poor productivity and regions without exploitable groundwater mostly found in the highland.

3 METHODOLOGY

The data that was used in this study comprises of primary and secondary data. The primary data that was gathered through field surveys consists of past and present landslide occurrence, lithology, soil thickness, and groundwater depth. Secondary data that was used were contour line and land use, which both data obtained from Geospatial Information Agency of Republic of Indonesia. The contour line was used to generate slope and lineament density. Land use data was updated by field survey and Google satellite imagery.

Lineament density analysis was divided into 10 classes equally as in general landslide susceptibility studies using the frequency ratio method (Avinash & Ashamanjari, 2010; Pradhan & Lee, 2010; Wang *et al.*, 2016). Data on soil thickness and depth of groundwater from field measurements were plotted on semivariogram charts. Plotting the data on a semivariogram graph was applied to find suitable kriging method interpolation according to data distribution (Kisaka *et al.*, 2016).

Landslide controlling parameters data were presented in the form of slope gradient map, lithology map, density lineament map, land use map, soil thickness map, and groundwater depth map. The parameters were further analyzed using frequency ratio using landslide occurrence data (Lee & Pradhan, 2007). Area of landslide occurrence were plotted into susceptibility parameter maps to get the area ratio in each susceptibility parameter class using Equation 1.

$$FR = \frac{D_i / A_i}{\sum_{i=1}^{N} D_i / \sum_{i=1}^{N} A_i} \tag{1}$$

Notes:

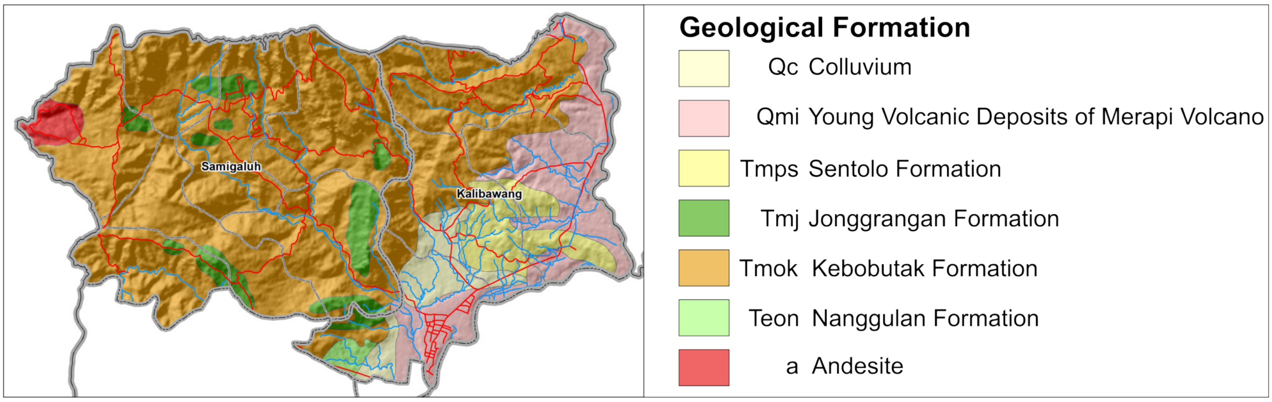

FIGURE 1. Regional geological map (Rahardjo *et al.*, 1995).

FR : Frequency Ratio
D_i : Landslide area in one class in one parameter
A_i : Area of a class in one parameter
$\sum D_i$: Cumulative area of all landslides
$\sum A_i$: Overall research area

The results of the frequency ratio calculation for each susceptibility parameter were summed and classified into 10 classes of LSI (Landslide Susceptibility Index) based on the equal distance method. The total value of the frequency ratio was calculated using Equation 2. Regions that have high LSI values describe high levels of vulnerability and vice versa (Avinash & Ashamanjari, 2010).

$$LSI = FR_1 + FR_2 + \cdots + FR_n \qquad (2)$$

There are two susceptibility maps created through this research, i.e. landslide susceptibility map created without and with groundwater parameters. Accuracy evaluation of both maps was carried by using Area Under Curve (AUC) method. The curve was created by drawing it in graphical form, with the X axis being the cumulative area of the LSI class and the Y axis being the cumulative area of the landslide (Samodra *et al.*, 2017).

4 RESULTS AND DISCUSSION

The results of the landslide survey in October to December 2019 found 227 locations of landslides. About 50% of the landslide data is applied for the model building and another 50% is applied for the accuracy evaluation. Distribution of the number of landslides are 50,22% for modeling and 49,78% for accuracy evaluation, as close as possible to 50% because the landslide amount is imbalance. The total area of landslides used to build the model is 12,876 m2 and data used for the accuracy evaluation test is 17,063 m2. Figure 2 shows the distribution of landslide data being used for modelling and for accuracy evaluation.

4.1 Slope gradient and lithology

Slope gradient has become the main parameter when making landslide susceptibility maps or models. Models that were made only by slope were far more accurate compared to models that were made only by geological or others parameter (Marchesini *et al.*, 2014). Figure 3A shows the slope gradient in the field. In this study, slope gradient is classified based on (Samodra *et al.*, 2017) which consists of 5 classes. The classification is gentle (00–80), moderately steep (80–150), steep (150–250), very steep (250–450), and extremely steep (>450). This classification was used as the base as the research were based on studies that considered characteristics of terrain in tropical and tectonically active region, such as Indonesia.

Frequency ratio analysis of slope gradient (Table 1) showed that most landslides can be found in class of moderately steep (80–150). This landslide occurrence represented by the highest FR value at 2.40. On the other hand, other classes do not have high FR value. All slope classes except moderately steep have less than 1 FR value. Landslides that occurred in low slope angle (less than 150) are usually caused by weathering zone increases in these angles which increases its susceptibility (Çellek, 2022).

Lithology plays an important role in deter-

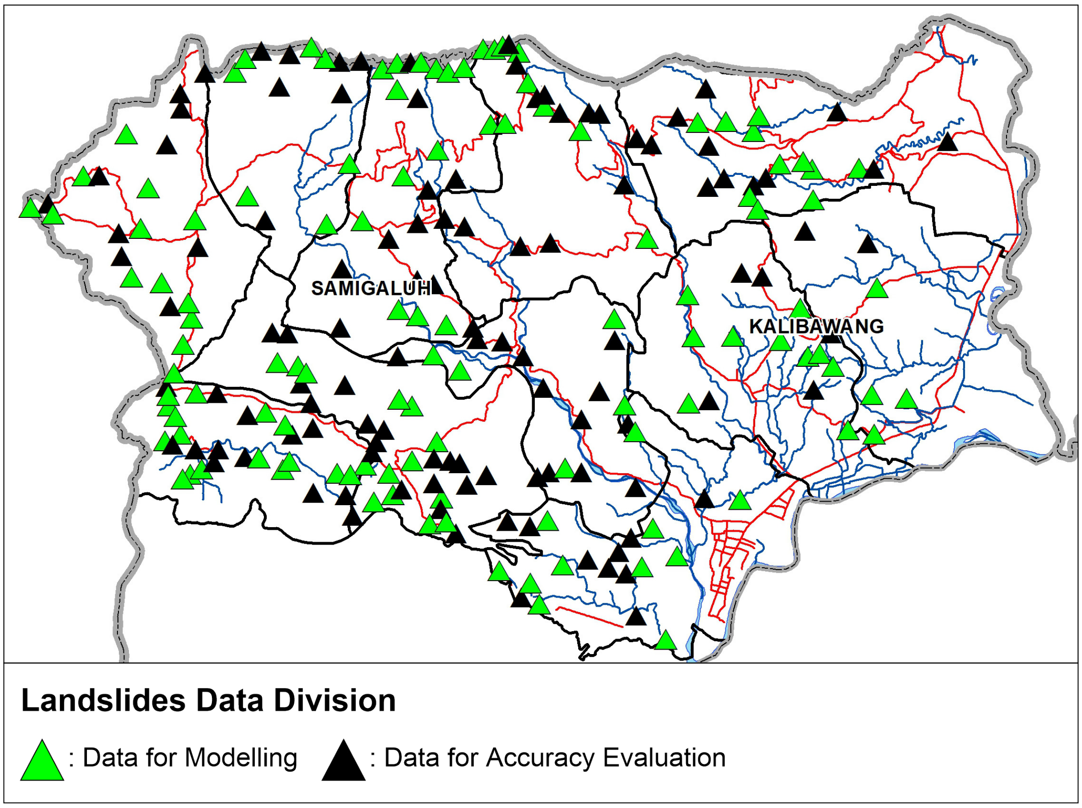

FIGURE 2. Landslide data in the research area.

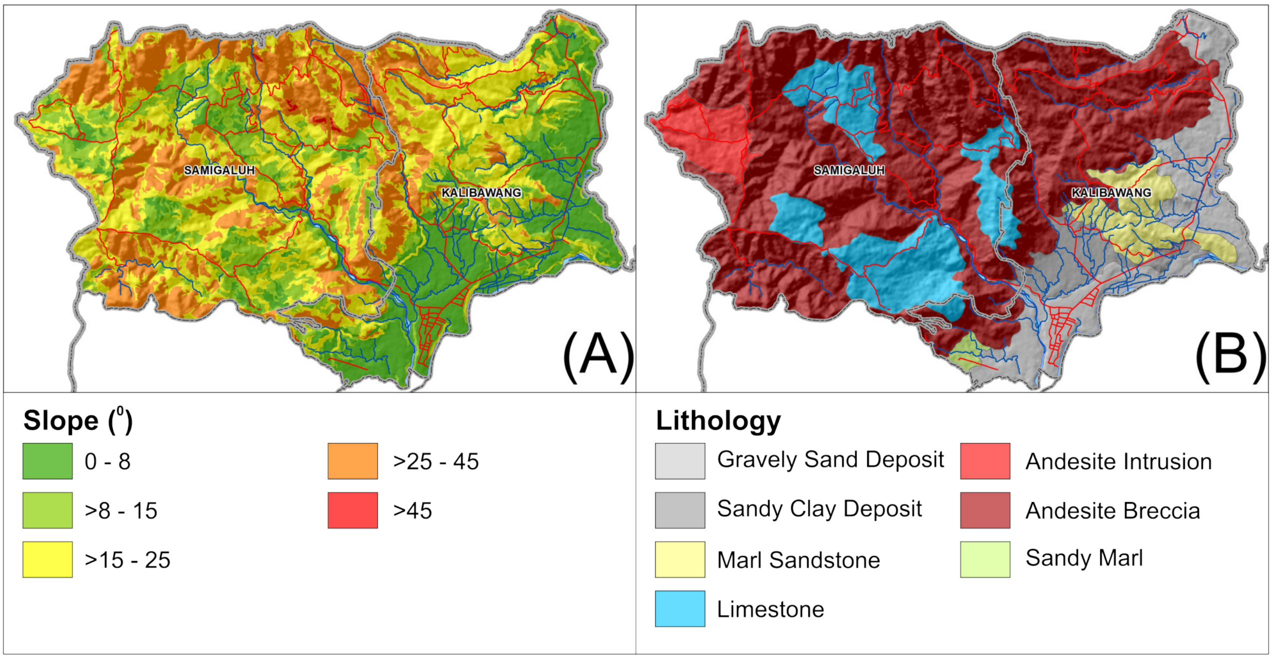

FIGURE 3. (A) Slope gradient map based on topography data (Geospatial Information Agency of Republic of Indonesia, 2018); (B) Lithology map.

mining landslide susceptibility maps because of its physical characteristics, like strength, resistance toward weathering, and permeability (Yu *et al.*, 2021). Highly weathered and porous rocks are prone to landslides because water infiltration is increasing which can reduce cohesion and increase pore water pressure (Guzzetti *et al.*, 2008). On the other hand, more compact and resistant rock such as andesite is likely less landslide prone (Figure 3B). The lithology

TABLE 1. Frequency ratio value of slope gradient.

Classes (°)	Area of Landslide (m^2)	Area of each class (m^2)	Total area of landslide (m^2)	Total Study Area (m^2)	Frequency Ratio Value
0 – 8	2,158	226,003,255	12,835	117,779,716	0.76
>8 – 15	5,285	20,195,723	12,835	117,779,716	2.4
>15 – 25	3,802	41,292,782	12,835	117,779,716	0.84
>25 – 45	1,590	30,106,712	12,835	117,779,716	0.48
>45	-	181,244	12,835	117,779,716	-

that was found in the research area was gravely sand deposit, sandy clay deposit, marl sandstone, limestone, andesite intrusion, andesite breccia, and sandy marl and Table 2 shows this parameter's FR Value.

Table 2 shows that limestone has the highest FR value of 4.27, way above others rock type. In terms of characteristics, limestone has specific properties which makes it prone to weathering upon exposure to water. Also, the presence of fractures due to geological structure may further weaken it, especially in high-rainfall area (H. Rahardjo *et al.*, 2010). Andesite intrusion, as the second-highest lithology with an FR value of 1.74, shows that it is not as prone as limestone but still more prone compared to other lithology. Andesite intrusion is usually expected to have low susceptibility, but its high FR value tells otherwise. It is probably because of fractures which can weaken the rock and increase the weathering process (Sisay *et al.*, 2024). This also matches what Cruden & Varnes (1993) stated that discontinuities and groundwater can make slopes more unstable, especially in regions with high seismic activity and heavy rainfall.

4.2 Lineament density and land use

Lineament density is one parameter that always present when creating landslide susceptibility map. It is because lineament density can be associated with geological structures, which can decrease rock strength that led to lowering slope stability. Previous studies have shown a correlation in which area with high lineament density usually more prone to landslides (Sisay *et al.*, 2024). In this study, calculation of lineament density was being done per km^2. Figure 4A shows the lineament density generated in the study area, while Table 3 shows FR values of lineament density.

Table 3 shows FR values of lineament density which gradually increase and at its peak at class of 2.461 – 3.076 per km^2 with FR value of 3,47. After that, it follows a normal distribution in which the FR value is decreasing. An anomaly occurred in >4.921 – 5.537 per km^2 class in which FR value rises again to 1, 10 but decrease again on the higher class. This distribution shows that lineament density does not always correlate with landslide susceptibility. Increase in FR value might be caused by local parameters such as geological conditions, land cover, or other parameters (Thapa *et al.*, 2023).

Figure 4B. shows the land use in the study area. Land use parameter influences landslide susceptibility as different land use would have different effects on the land, such as weight, slope stability, or rain infiltration (Li *et al.*, 2024). Land use that was found in the research area were lakes, grasslands, plantations, settlements, paddy fields, rain-fed paddy fields, shrubs, and crop field. This classification was following the classification of Geospatial Information Agency of Republic of Indonesia. Frequency ratio values of land use are shown on Table 4.

Table 4 shows that plantation has the highest FR value of 1.35. This happened might be because a plantation usually only have shallow-rooted crops in which diminished root reinforcement on soil (Lv *et al.*, 2024). It is also noted that locals said that most plantation in the area was a forest that suffered landslides. Without the loss of large trees, the locals find it easier to change use the land. The second highest FR value was settlements with FR value of 1.07. This might be happening because most settlements involve modification of natural slopes and vegetation removal. Both things led to increase in erosion and possibility of decreasing rock strength. Additionally, studies also shows that change in land use to settlements would

TABLE 2. Frequency ratio value of lithology.

Classes	Area of Landslide (m^2)	Area of each class (m^2)	Total area of landslide (m^2)	Total Study Area (m^2)	Frequency Ratio Value
Limestone	7,105	15,282,712	12,835	117,779,716	4.27
Marl Sandstone	397	5,608,216	12,835	117,779,716	0.65
Andesite Breccia	4,347	71,598,567	12,835	117,779,716	0.56
Sandy Clay Deposit	9	4,446,343	12,835	117,779,716	0.02
Gravely Sand Deposit	126	15,682,767	12,835	117,779,716	0.07
Andesite Intrusion	846	4,457,082	12,835	117,779,716	1.74
Sandy Marl	5	704,028	12,835	117,779,716	0.07

TABLE 3. Frequency ratio value of lineament density.

Classes (Lineament/km^2)	Area of Landslide (m^2)	Area of each class (m^2)	Total area of landslide (m^2)	Total Study Area (m^2)	Frequency Ratio Value
0 – 0.615	9	7,125,782	12,835	117,779,716	0.01
>0.615 – 1.230	138	7,171,973	12,835	117,779,716	0.18
>1.230 – 1.846	560	7,564,460	12,835	117,779,716	0.68
>1.846 – 2.461	794	10,769,202	12,835	117,779,716	0.68
>2.461 – 3.076	6,061	16,025,494	12,835	117,779,716	3.47
>3.076 – 3.691	2,581	22,809,143	12,835	117,779,716	1.04
>3.691 – 4.306	879	20,862,294	12,835	117,779,716	0.39
>4.306 – 4.921	874	16,775,553	12,835	117,779,716	0.48
>4.921 – 5.537	879	7,300,800	12,835	117,779,716	1.1
>5.537 – 6.152	61	1,374,862	12,835	117,779,716	0.41

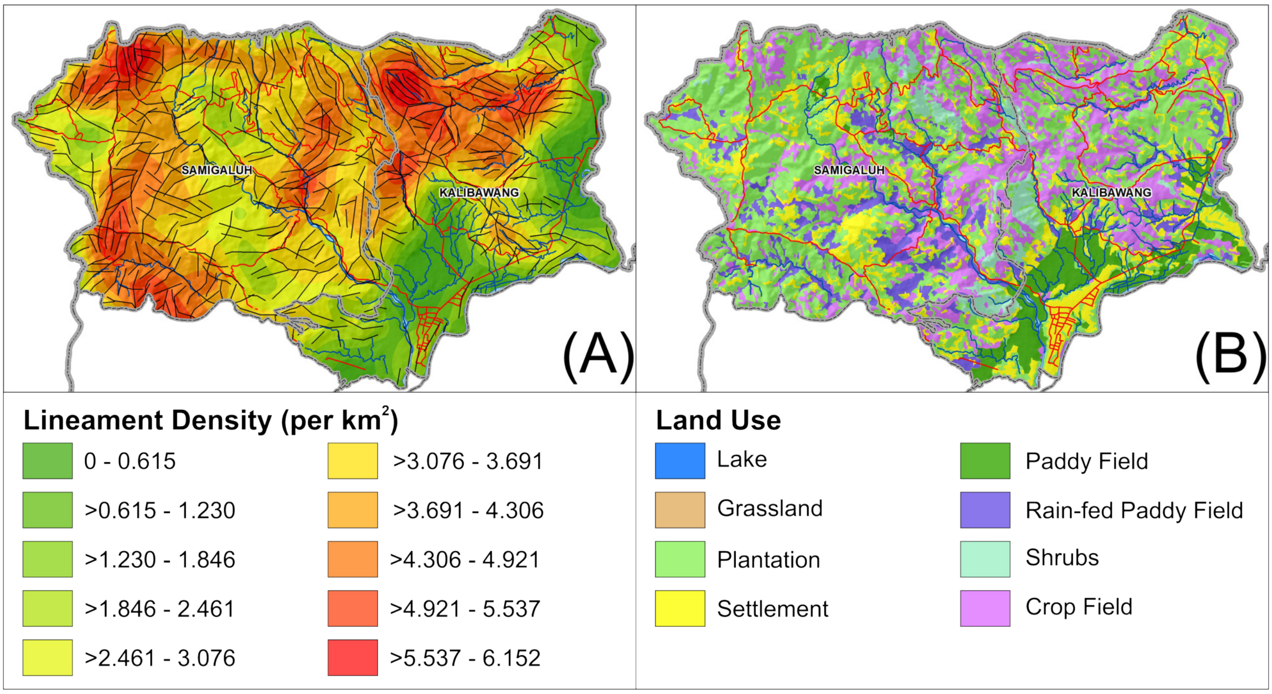

FIGURE 4. (A) Lineament density map based topography data (Geospatial Information Agency of Republic of Indonesia, 2018) and method proposed by Avinash & Ashamanjari, 2010; (B) Updated land use map.

increase landslide susceptibility (Rabby *et al.*, 2022).

4.3 Soil thickness and groundwater depth

Soil thickness is one of vital parameter in creating landslide susceptibility map as it correlates with slope stability and groundwater occurrences. Thicker soil layer can store more wa-

TABLE 4. Frequency ratio value of land use.

Classes	Area of Landslide (m^2)	Area of each class (m^2)	Total area of landslide (m^2)	Total Study Area (m^2)	Frequency Ratio Value
Grassland	-	101,438	12,835	117,779,716	0
Plantation	7,214	49,110,949	12,835	117,779,716	1.35
Settlement	2,070	17,732,144	12,835	117,779,716	1.07
Paddy Field	106	7,721,612	12,835	117,779,716	0.13
Rain-fed Paddy Field	787	9,644,534	12,835	117,779,716	0.75
Shrub	74	3,851,396	12,835	117,779,716	0.18
Lake	-	7,961	12,835	117,779,716	0
River	-	1,390,953	12,835	117,779,716	0

ter which in turn reduce soil cohesion. Slope stability has high degree of change in thickness less than 2 meters (Brayfield, 2013; Ray *et al.*, 2010). As such, in this study, classification of soil layer is divided into 3 which is 0 – 1 meter, more than 1 – 2 meters, and more than 2 meters. Field mapping result of soil thickness is showed in Figure 5A and the result of frequency analysis are shown in Table 5.

Table 5 shows that soil thickness of 1 – 2 meters has the highest FR value of 1.47. On the other hand, the other classification has less than 1 FR values. This shows that moderate soil thickness is the most hazardous. A shallow soil thickness might be too little for landslide to happen while a deeper soil more stable as its being supported by its own total weight.

Groundwater depth is rarely used as landslide susceptibility parameters because not every area has groundwater (Neuhäuser & Terhorst, 2007). But if found, it became one of the most crucial parameters as groundwater would decrease soil or rock strength and even accelerates weathering process (Ganvir & Guhey, 2023). By using normal distribution, the groundwater depth was classified into 3 class which is 0 to 4 meters, more than 4 to 8 meters, and more than 8 meters. Groundwater depth map is showed in Figure 5B while Table 6 shows its frequency ratio analysis score.

Table 6 shows groundwater depth less than 4 meters has the highest FR Value of 1,78 while the others less than 1 FR Value. Shallow groundwater means the soil is saturated for prolonged time which causes the materials relatively loose with less cohesion (Batumalai *et al.*, 2023). Another special trait of groundwater FR value is when compared to other parameters that's using ordinal as the data, groundwater depth is the only one that the FR value is not normally distributed. As such, its predicted groundwater might have significant effect toward landslide susceptibility accuracy.

4.4 Landslide susceptibility index

LSI values of landslide susceptibility maps created without groundwater depth parameters ranged from 1,312 to 12,954 as shown in Figure 6A, while those with groundwater depth parameters ranged from 1,808 to 14,736 as shown in shown in Figure 6B, while Figure 7 shows the AUC Graph.

An increase in accuracy of the susceptibility map was made by adding groundwater depth parameter (Figure 7). Susceptibility map without groundwater depth parameter has an accuracy of 67.02%. Susceptibility map by calculating the groundwater depth parameter in this study has an accuracy of 89.31%. This shows that the addition of groundwater depth parameter can increase map accuracy by 22.29%.

In this research, increase of accuracy showed that groundwater parameter has a significant role in determining the level of landslide susceptibility, which also in line with previous study conducted by (Ganvir & Guhey, 2023). More water content in a rock mass or soil will result in the decreasing of cohesion forces between particles. If the water content exceeded the threshold, it will cause a landslide. The main problem found is people always gather around water sources as human activities need water. When a river is not possible, groundwater becomes the choice. According to data, most groundwater can be found on settlements and plantations (). Both settlement and plantation on the other hand also inhibit the highest FR

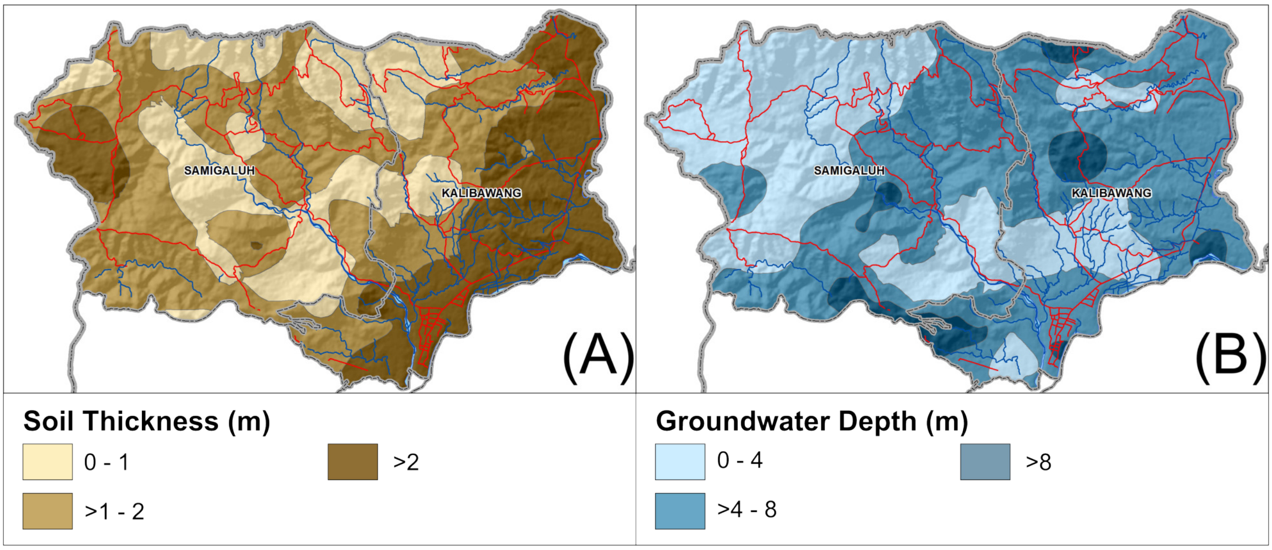

FIGURE 5. (A) Soil thickness map; (B) Groundwater depth map.

TABLE 5. Frequency ratio value of soil thickness.

Classes (m)	Area of Landslide (m^2)	Area of each class (m^2)	Total area of landslide (m^2)	Total Study Area (m^2)	Frequency Ratio Value
0 – 1	1,665	31,181,052	12,835	117,779,716	0.49
>1 – 2	9,890	61,826,132	12,835	117,779,716	1.47
>2	1,279	24,772,532	12,835	117,779,716	0.47

TABLE 6. Frequency ratio value of soil thickness.

Classes (m)	Area of Landslide (m^2)	Area of each class (m^2)	Total area of landslide (m^2)	Total Study Area (m^2)	Frequency Ratio Value
0 – 4	9,020	46,450,525	12,835	117,779,716	1.78
>4 – 8	3,408	64,179,030	12,835	117,779,716	0.49
>8	407	7,150,296	12,835	117,779,716	0.52

value. As such, indirectly, people are coming and living in the landslide prone area.

A further thing to discuss is groundwater depth data acquisition method. In this survey, groundwater depth data are being gathered by using field survey method which is not cost and time effective. Previous study shows not many remote sensing methods that can be used for groundwater exploration, as most of it is affected by atmospheric conditions and can only estimate shallow groundwater (Ibrahim *et al.*, 2024). Further research related to deeper groundwater depth using remote sensing needs to be developed.

5 CONCLUSION

The research shown susceptibility map created without groundwater depth parameter has an accuracy of 67.02%, while susceptibility map that created with groundwater depth parameter has an accuracy of 89.31%. It means, that groundwater depth parameter managed to increase landslide susceptibility map accuracy by 22.29%. Looking at groundwater classification, area with groundwater depth less than 4 meters has the highest FR value which is 1.78. That value is 3 times higher than area with groundwater depth more than 4 to 8 meters with 0.49 FR value and area with groundwater depth more than 8 meters with 0,52 FR value. To support sustainable living of people in mountainous and hilly areas that are prone to landslides, groundwater depth parameters should be prioritized when it present.

Groundwater depth data in this study were obtained by field surveys which are Labor-

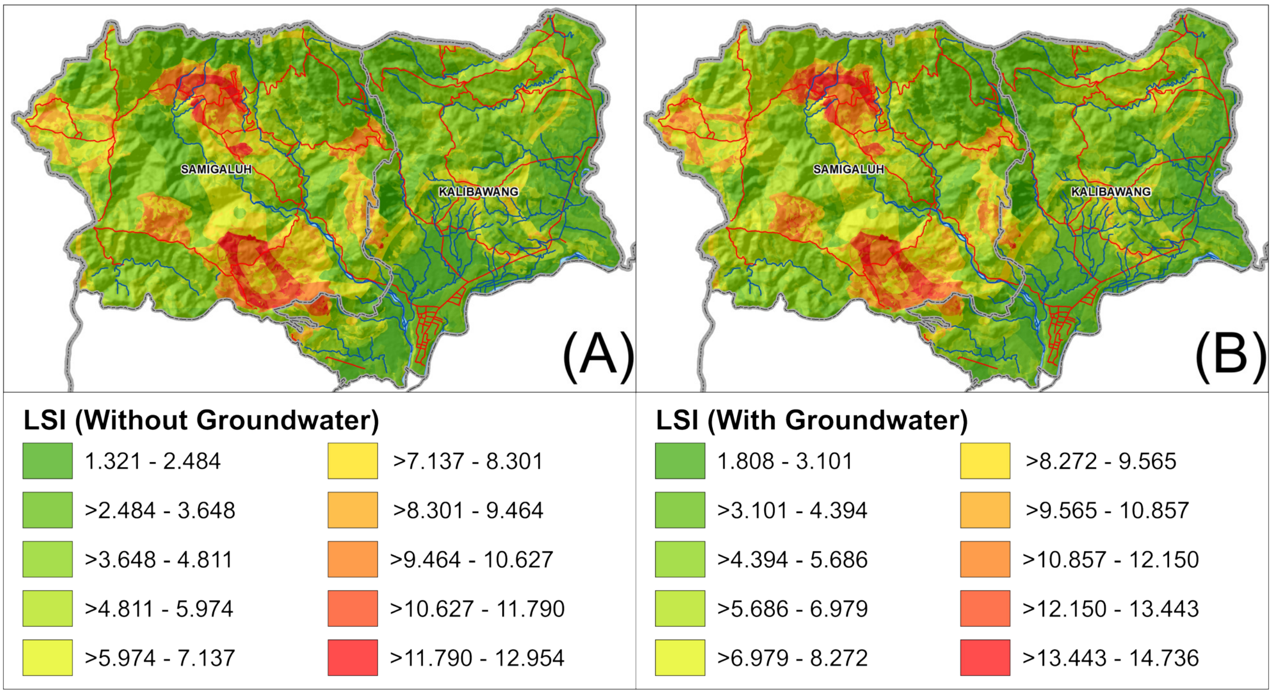

FIGURE 6. LSI map without groundwater parameter; (B). LSI map with groundwater parameter.

TABLE 7. Groundwater sources location and land use FR value.

Land Use	Groundwater Depth (m)			Total	Land Use FR Value
	0 – 4	>4 – 8	>8		
Grassland	0	0	0	0	0
Plantation	29	8	3	40	1.35
Settlement	21	21	22	64	1.07
Paddy Field	3	1	0	4	0.13
Rain-fed Paddy Field	7	4	0	11	0.75
Shrubs	0	0	1	1	0.18
Crop Field	3	5	3	11	0.8

intensive and expensive. Most remote sensing only manages to locate shallow groundwater or springs. Further research related to deeper groundwater depth using remote sensing need to be developed to support accurate detailed scale mapping of landslide susceptibility.

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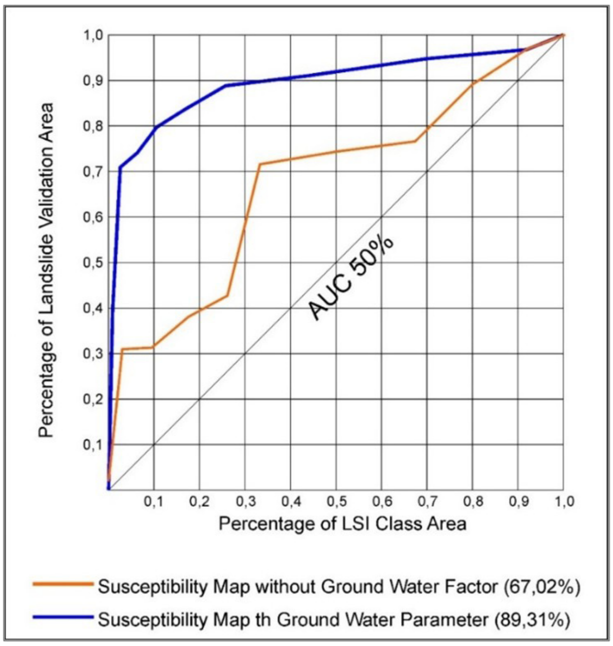

Figure 7. Accuracy comparison of landslide susceptibility.

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