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Analysis of Landslide Disaster Vulnerability in North Tapanuli Regency Using a Grid-Based Geographic Information System Approach

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ABSTRACT

Landslides are natural disasters that cause material losses, casualties, and environmental damage. North Tapanuli Regency has a hilly and valley-filled topography that makes it prone to landslides. Data from the Regional Disaster Management Agency (BPBD) shows a high intensity of landslides, indicating the need for a study to identify the level of vulnerability. This study aims to map landslide vulnerability in North Tapanuli Regency using a Grid Base Geographic Information System (GIS) approach. This study uses a quantitative descriptive method with a spatial approach. The results of the study show that most of the area is classified as having a very high (52.13%) and high (42.31%) level of vulnerability, while the moderate, low, and very low levels of vulnerability only cover a small part of the area. These findings confirm that North Tapanuli Regency is highly prone to landslides, requiring serious attention from the government in disaster mitigation efforts.

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INTRODUCTION

Landslides are natural disasters that cause material losses, casualties, and environmental damage. North Tapanuli Regency has a hilly and valley-filled topography that makes it prone to landslides. Data from the Regional Disaster Management Agency (BPBD) shows a high intensity of landslides, indicating the need for a study to identify the level of vulnerability. This study aims to map landslide vulnerability in North Tapanuli Regency using a Grid Base Geographic Information System (GIS) approach. This study uses a quantitative descriptive method with a spatial approach. The results of the study show that most of the area is classified as having a very high (52.13%) and high (42.31%) level of vulnerability, while the moderate, low, and very low levels of vulnerability only cover a small part of the area. These findings confirm that North Tapanuli Regency is highly prone to landslides, requiring serious attention from the government in disaster mitigation efforts.

North Tapanuli Regency has a hilly and valley-filled topography, which makes it prone to landslides. Based on data from the North Tapanuli Regency Disaster Management Agency (BPBD), there were 139 landslide incidents in 2018, 120 in 2019, 52 in 2020, 104 in 2021, and 181 in 2022. Landslides in North Tapanuli Regency occur due to the hilly terrain and usually happen in settlements located on hillsides and along roads that pass through hilly areas.

Based on these events, it is necessary to conduct a study on the vulnerability of landslides in the region. According to Agustina et al. (2020), the results of the study in the form of maps can facilitate decision-making. Therefore, this study aims to map the level of landslide disaster vulnerability in North Tapanuli Regency using a Grid-Based Geographic Information System (GIS) approach as a reference for disaster mitigation and prevention.

THEORETICAL REVIEW

Landslide Vulnerability Factors

According to Nugroho, J.A et al. (2009), several parameters consisting of factors causing landslides include climate (rainfall), topography (slope gradient), vegetation (land cover), soil (soil type), conservation factors (land management), and other factors (geomorphology/landform, soil texture, soil moisture, and geology).

1. Slope Gradient

Slopes with high degrees of inclination are more prone to landslides. Slope gradient can also be expressed in percentages (%), with 0^o equivalent to 0% and 45^o equivalent to 100% (Agustina et al., 2020).

2. Rainfall

Rain increases the load on a slope, and the presence of water in pores without a retaining structure can cause slope instability. This is what causes landslides. The higher the rainfall, the higher the potential for landslides in the area (Agustina et al., 2020).

3. Soil Type

Soil stability is influenced by soil type in terms of its water retention capacity and properties that affect soil structure stability. The number of landslides increases during the rainy season. The absence of vegetation to bind the soil and absorb water causes the soil to reach saturation point, and the reduced strength of the rocks/soil that make up the slope causes the slope to become unstable along the slip plane (Agustina et al., 2020)

4. Rocks Type

Classification based on formation, parent rock, estimated hardness, and rock compaction to assess resistance to weathering. This classification is intended to group parent rocks based on their resistance to erosion and weathering into soil. Parent rock that is not resistant tends to cause landslides compared to rock that is more resistant (Mangga et al., 1993).

5. Land Cover

The presence of objects on the ground surface is a factor that needs to be taken into account when assessing areas prone to landslides. Natural conditions with deep root systems are better able to maintain soil stability than vegetation with shallow roots. Human presence for various production and residential purposes worsens slope stability, as do deforestation activities and areas left without vegetation cover (Agustina et al., 2020).

Utilization of Geographic Information Systems (GIS) in Disaster Mapping

Geographic Information Systems (GIS) are a very effective tool for analyzing disaster vulnerability because they are capable of integrating various spatial and non-spatial data. With GIS, various parameters such as topography, rainfall, soil type, geology, and land use can be mapped and analyzed in an integrated manner. The advantage of GIS is its ability to perform spatial analysis such as overlay, buffering, interpolation, and classification, which enables the identification of areas prone to landslides with a high degree of accuracy. A number of studies show that GIS can produce vulnerability maps that can be used as a reference in decision-making related to mitigation and spatial planning.

Grid-Based Approach in Vulnerability Analysis

The grid-based approach is a spatial analysis method that divides the study area into grid-shaped units of a certain size. Each grid is assigned a value according to the parameters being analyzed, resulting in more detailed and consistent mapping results. The grid approach is more flexible in accommodating data with high spatial variation. In addition, grid-based analysis allows for more accurate spatial statistical calculations and minimizes bias due to differences in polygon shapes. This method has been widely used in landslide vulnerability mapping because it is able to represent field conditions more realistically, especially in areas with complex topography such as North Tapanuli Regency.

METHODOLOGY

The type of research used in this study is quantitative descriptive with a spatial approach. The research methods used are weighted overlay and grid-based. The weighted overlay method is a method used for decision making using spatial criteria that are scored and weighted. Spatial data analysis in the weighted overlay method uses parameter maps that influence landslides (Khusnawati &

Kusuma, 2020). The grid-based method is a data format used to store raster data and summarize vector data that represents geographical space as an arrangement of cells of equal size arranged in rows and columns, with each cell storing a value that represents the geography of that spatial unit (Koerniawan, 2022). The size of each grid is determined and set by the user according to the purpose, scale, or available format. In this study, a 1000 x 1000 meters grid was used. Grid-based analysis was used to identify locations prone to landslides based on factors that influence the level of landslide vulnerability, which became parameters and were used as the basis for grid assessment.

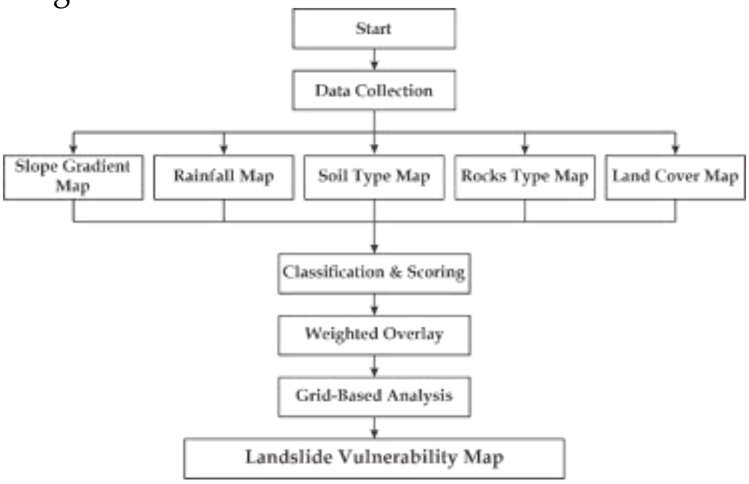

Figure 1. Research Flow Chart

Classification of each parameter used with a score is then multiplied by its weight using a model from the Center for Soil and Agroclimate Research (2004) with the following formula:

Total Score = 0,3FCH+ 0,2FJB+0,2FKL+0,2FPL+0,1FJT…………… (1)
Description:
FCH = Rainfall Factor
FJB = Rocks Type Factor
FKL = Slope Gradient Factors
FPL = Land Cover Factor
FJT = Soil Type Factor

The parameters used to measure the level of landslide vulnerability according to the Center for Soil and Agroclimate Research (2004) are presented in Table 1.

Table 1. Weight and score of landslide disaster parameters

Parameters	Indicator	Score	Weight	Source
Slope gradient (%) (FKL)	> 45	5	20%	DEMNAS
	30-45	4		
	15-30	3		
	8-15	2		
	<8	1		

Parameters	Indicator	Score	Weight	Source
Rainfall (mm/year) (FCH)	>3000	5	30%	CHIPS
	2501-3000	4		
	2001-2500	3		
	1501-2000	2		
	<1500	1		
Soil Type (FJT)	Oxisol	5	10%	Puslittanak
	Andosol	4		
	Ultisol	3		
	Inceptisol	2		
	Unclassified	1		
Rocks Type (FJB)	Extrusive Igneous Rocks	3	20%	ESDM
	Metamorphic Rocks	3		
	Sedimentary Rocks	2		
	Intrusive Igneous Rocks	1		
	Unclassified	1		
Land Cover (FPL)	Rice fields, Dry fields	5	20%	Ina-Geoportal
	Bushes	4		
	Forest, Plantation	3		
	Settlement	2		
	Water	1		

The final stage in determining the vulnerability level was conducted using grid-based analysis based on the model from the Ministry of Environment and Forestry's DDLTH Determination Guidelines (2019) using the following formula::

$$Total\ Grid\ Index = \frac{Polygon\ Area}{Total\ Grid\ Area}\ x\ Index\ Polugon \ldots\ldots\ldots\ldots\ (1)$$

This formula is used to obtain the proportional distribution of the vulnerability parameter score index for each polygon. After that, the vulnerability parameter score index for each polygon in a grid is added up to obtain the final total vulnerability score index for each grid.

RESULTS AND DISCUSSION

North Tapanuli Regency is one of the regencies in North Sumatra Province, located in a highland area. Geographically, North Tapanuli Regency is flanked or directly borders five regencies, namely: to the north, it borders Toba Regency and Samosir Regency; to the east, it borders North Labuhanbatu Regency; to the south, it borders South Tapanuli Regency; and to the west, it borders Humbang Hasundutan Regency and Central Tapanuli Regency. Astronomically, North Tapanuli Regency is located at 1°20'-2°41' North Latitude and 98°05'-99°16' East Longitude. The area of North Tapanuli Regency is 3,800.31 km2, consisting of 3,793.71 km2 of land and 6.60 km2 of Lake Toba.

Parameters of Landslide-Prone Areas

1. Slope Gradient Map

The slope gradient in North Tapanuli Regency varies greatly, ranging from flat to very steep. The classification of slope inclination is as follows: very steep slope inclination is >45%, steep slope inclination is 30–45%, moderately steep slope inclination is 15–30%, gentle slope inclination is 8–15%, and very gentle slope inclination is <8%. According to Lestari et al. (2022), the greater the slope gradient, the greater the area of landslides. This is related to the amount of water present on the slope due to seepage, which causes a reduction in the shear strength of the soil.

Table 2. Weighting and scoring of slope parameters

Slope Gradient (%)	Total Score	Area (Ha)	Percentage (%)
> 45%	1	47,55	0,01
30 - 45%	0,8	6.102,90	1,57
15 - 30%	0,6	62.869,93	16,15
8 - 15%	0,4	82.844,78	21,28
< 8%	0,2	237.387,82	60,99
Total		**389.252,99**	**100,00**

Based on Table 2, the slope gradient is very steep >45%, covering an area of 47.55 ha with a percentage of 0.01%. steep slopes of 30–45% cover an area of 6,102.90 ha with a percentage of 1.57%, moderately steep slopes cover an area of 62,869.93 ha with a percentage of 16.15%, for gentle slopes covering an area of 82,844.78 hectares with a percentage of 21.28%, and for flat slopes covering an area of 237,387.82 hectares with a percentage of 60.99%. Therefore, it can be concluded that most of the area in North Tapanuli Regency has a flat to fairly steep slope, due to the morphological shape of the area in the form of hills and topographical intervals that are not much different.

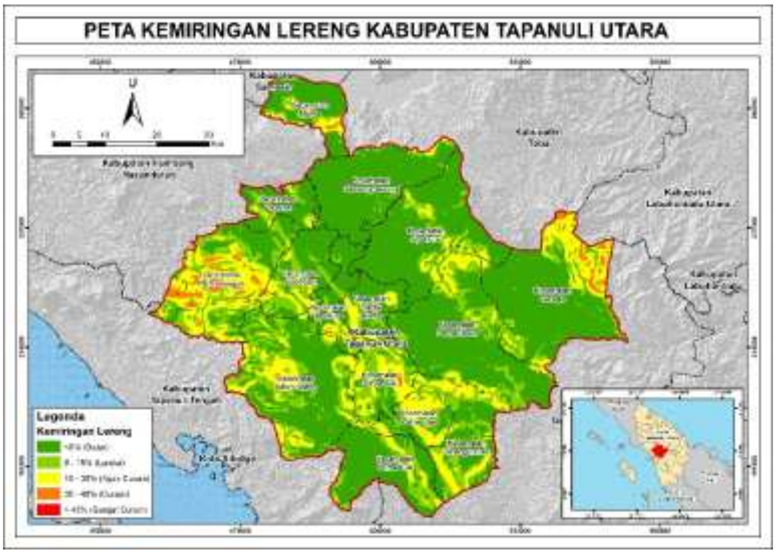

Figure 2. Slope Gradient Map

2. Rainfall Map

Rainfall in North Tapanuli Regency has three intensities: very high intensity (>3000 mm), high intensity (2501-3000 mm), and moderate intensity (2000-2500 mm). High rainfall is influenced by the undulating to hilly and mountainous geomorphological conditions.

Table 3. Weighting and scoring of rainfall parameters

Rainfall (mm/year)	Total Score	Area (Ha)	Percentage (%)
>3000	1,5	47.173,13	12,12
2501-3000	1,3	115.055,57	29,56
2001-2500	0,9	227.024,28	58,32
Total		**389.252,99**	**100,00**

As one of the main parameters in determining areas prone to landslides, the likelihood of landslides occurring is largely determined by the intensity of rainfall in the study area and the distribution of rainfall. Based on Table 3, rainfall with very high intensity (>3000 mm/year) covers an area of 47,173.13 Ha with a percentage of 12.12%, high intensity rainfall of 2501-3000 mm/year covers an area of 115,055.57 ha with a percentage of 29.56%, and moderate intensity rainfall of 2001-2500 mm/year covers an area of 227,024.28 ha with a percentage of 58%. Therefore, it can be concluded that most of the area in North Tapanuli Regency has moderate rainfall intensity, while there are several areas with high to very high rainfall intensity, namely in Adian Koting District and Purba Tua District.

Figure 3. Rainfall Map

3. Soil Type Map

The aspect used to map landslides is soil sensitivity to erosion. Soil sensitivity to erosion is closely related to soil permeability (Mujib et al. 2021). The types of soil found in North Tapanuli Regency consist of Oxisol, Andosol, Ultisol, and Inceptisol, with soil type classification using the Soil Taxonomy Equivalents according to the National Soil Classification (Agricultural Research and Development Agency, 2014).

Table 4. Weighting and scoring of soil type parameters

Soil Type	Total Score	Area (Ha)	Percentage (%)
Oxisol	0,5	9.605,34	2,47
Andosol	0,4	209.967,25	53,94
Ultisol	0,3	24.603,31	6,32
Inceptisol	0,2	133.784,58	34,37
Unclassified	0,1	11.292,51	2,90
Total		**389.252,99**	**100,00**

Based on Table 4, the soil types that are highly susceptible to erosion are oxisols, covering an area of 9,605.34 ha with a percentage of 2.47%; andosols, covering an area of 209,967.25 ha with a percentage of 53.94%; ultisols, covering an area of 24,603. 31 hectares with a percentage of 6.32%, for inceptisols covering an area of 133,784.58 hectares with a percentage of 34.37%, and for unclassified soils, which are water bodies in the form of rivers and Lake Toba, covering an area of 11,292.51 hectares with a percentage of 2.90%. Therefore, it can be concluded that most of the area in North Tapanuli Regency has andosol and inceptisol soil types. There are andosol soil types in all subdistricts in North Tapanuli Regency, indicating that the soil in this area is quite sensitive to erosion, which can trigger landslides.

Figure 4. Soil Type Map

4. Rocks Type Map

In general, rocks are influenced by texture, structure, hardness, mineral content, weather, and sedimentation. Extrusive igneous rocks are prone to weathering, which can weaken their structural and rock properties, making them susceptible to landslides (Madani et al., 2023). The types of rocks found in North Tapanuli Regency are divided into four types, namely extrusive igneous rocks, metamorphic rocks, sedimentary rocks, and intrusive igneous rocks.

Table 5. Weighting and scoring of soil type parameters

Rocks Type	Total Score	Area (Ha)	Percentage (%)
Extrusive Igneous Rocks	0,6	286.819,78	73,68
Metamorphic Rocks	0,6	37.510,27	9,64
Sedimentary Rocks	0,4	10.035,75	2,58
Intrusive Igneous Rocks	0,2	44.367,92	11,40
Unclassified	0,2	10.519,26	2,70
Total		**389.252,99**	**100,00**

Based on Table 5, the types of rock most prone to landslides are extrusive igneous rock and metamorphic rock, covering areas of 286,819.78 Ha and 37,510.27 Ha, respectively, with percentages of 73.68% and 9.64%. sedimentary rocks cover an area of 10,035.75 hectares with a percentage of 2.58%, intrusive igneous rocks cover an area of 44,367.92 hectares with a percentage of 11.40%, and unclassified areas, which are water bodies in the form of rivers and Lake Toba, cover an area of 10,519.26 hectares with a percentage of 2.70%. Therefore, it can be concluded that around 70% of the area in North Tapanuli Regency has extrusive igneous rock resulting from magma solidification, making it prone to landslides.

Figure 5. Rock Type Map

5. Land Cover Map

Land use can be used as a reference for the strength of the soil in resisting erosion. Land cover in North Tapanuli Regency consists of rice fields, dry fields, shrubs, forests, plantations, settlements, and waterways.

Table 6. Weighting and scoring of land cover parameters

Land Cover	Total Score	Area (Ha)	Percentage (%)
Rice fields	1	242.868,23	62,39
Dry fields	1	9.598,33	2,47
Bushes	0,8	20.683,11	5,31
Forest	0,6	3.086,52	0,79
Plantation	0,6	18.608,66	4,78
Settlement	0,4	22.738,51	5,84
Water	0,2	71.669,64	18,41
Total		**389.252,99**	**100,00**

Based on Table 6, rice fields and dry fields have the highest potential for landslides because their roots are not strong enough to hold the slope mass that will cause landslides. Rice fields and dry fields cover areas of 242,868.23 Ha and 9,598.33 Ha, respectively, with percentages of 62.39% and 2.47%. Shrubs cover an area of 20,683.11 Ha with a percentage of 5.31%. forests cover an area of 3,086.52 hectares with a percentage of 0.79, plantations cover an area of 18,608.66 hectares with a percentage of 4.78%, settlements cover an area of 22,738.51 ha with a percentage of 5.84%, and water bodies cover an area of 71,669.64 ha with a percentage of 18.41%. It can therefore be concluded that rice fields dominate the land cover, accounting for 62.39% of the total area.

Figure 6. Land Cover Map

Grid Map of Landslide-Prone Areas in North Tapanuli Regency

Based on the five parameters of landslide disasters, landslide-prone areas can be determined. The results of the analysis of all these parameters are then classified based on scores, which are then weighted according to their respective contributions and then analyzed using grid analysis. This results in five criteria for landslide vulnerability, namely very high, high, moderate, low, and very low.

Table 7. Classification and Analysis of Landslide Vulnerability Grid

Vulnerability Level	Total Grid	Percentage (%)
Very High	1.854	52,13
High	1.881	42,31
Medium	179	3,02
Low	207	2,33
Very Low	38	0,21
Total	**4159**	**100,00**

Based on Table 7, it can be seen that of the total 4,159 grid units, there are 1,854 grid units with a percentage of 52.13% representing areas with a very high level of vulnerability spread across all subdistricts in North Tapanuli Regency. However, several subdistricts are particularly dominant: Pangaribuan Subdistrict with 325 grid units, Garoga Subdistrict with 312 grid units, and Purba Tua Subdistrict with 196 grid units. For the high vulnerability level, there are 1,881 grid units with a percentage of 42.31%, which are dominated by several sub-districts, namely Adian Koting Sub-district with 335 grid units, Siborong-Borong Sub-district with 246 grid units, and Parmonangan Sub-district with 233 grid units. For the medium vulnerability level, there are 179 grid units with a percentage of 3.02%, which are dominated by several subdistricts, namely Muara Subdistrict with 93 grid units, Garoga Subdistrict with 24 grid units, and Adian

Koting Subdistrict with 15 grid units. For the low vulnerability level, there are 207 grid units with a percentage of 2.33%, which are dominated by several subdistricts, namely Garoga Subdistrict with 37 grid units, Muara Subdistrict with 33 grid units, and Parmonangan Subdistrict with 28 grid units. For the very low vulnerability level, there are 28 grid units with a percentage of 0.21%, which are dominated by several subdistricts, namely Purba Tua Subdistrict with 7 grid units, Muara Subdistrict with 6 grid units, and Adian Koting Subdistrict with 6 grid units.

Based on Table 7, it can be concluded that most areas in North Tapanuli Regency have a high to very high level of vulnerability, as evidenced by the percentage of grid units classified as such, which are 52.13% and 42.31%, respectively. The landslide vulnerability map can be seen in Figure 7.

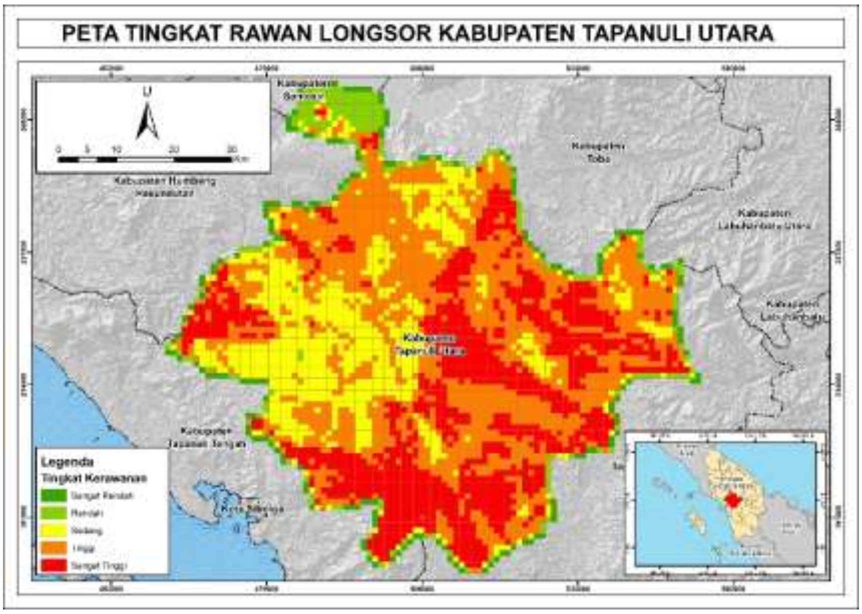

Figure 7. Landslide Vulnerability Map

This study not only contributes to the creation of a landslide hazard map in North Tapanuli Regency, but also emphasizes academic aspects. First, this study reinforces the argument that a grid-based approach in GIS is capable of representing spatial variations, thereby providing a stronger methodological basis for disaster vulnerability studies. Second, the analysis results show that rainfall is a dominant factor in determining the level of vulnerability in tropical regions with mountainous and hilly topography, thus providing empirical contributions to the development of landslide vulnerability theory in similar areas. Third, the analysis model used in this study can be seen as a development of a vulnerability assessment framework that integrates biophysical factors in grid units, so that it can be applied to similar studies in other regions. Thus, this study is not only useful in practical terms for disaster mitigation, but also enriches the academic literature in the field of geographic information systems and disaster risk management.

CONCLUSIONS AND RECOMMENDATIONS

Mapping the level of landslide vulnerability can be calculated based on the spatial integration of parameters that influence and trigger landslides. The use of the Weighted Overlay method and Grid analysis in this study contributed significantly to revealing the potential for landslides in North Tapanuli Regency because the technique was carried out by inputting data based on importance levels, where each data point had a different weight according to its influence, and the grid analysis in this study provided a more structured picture of the distribution of potential landslide vulnerability. By dividing the study area into grid units, each influential parameter can be analyzed in more detail according to its level of importance. The mapping results show that the grid method is able to clearly display spatial variations in vulnerability levels, thereby facilitating the identification of very high, high, medium, low, and very low vulnerability levels.

The results of the study show that areas in North Tapanuli Regency have a very high vulnerability level (52.13%), high vulnerability (42.31%), moderate vulnerability (3.02%), low vulnerability (2.33%), and very low vulnerability (0.21%). Almost all areas in North Tapanuli Regency fall into the very high and high vulnerability categories. This needs to be taken into consideration by village, sub-district, and regency governments in planning landslide mitigation and decision-making by relevant parties.

FURTHER STUDY

This study still has limitations, particularly in the use of parameters and data resolution. Therefore, further research is recommended to integrate high-resolution data, add parameters such as hydrology, and develop more detailed grid analysis to produce varied and more accurate outputs.

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