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Analysis of *Weight of Evidence* (WOE) and *Weighted Overlay* (WO) Methods for Mapping Landslide Potential in East Lombok Regency, West Nusa Tenggara Province

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ABSTRACT

East Lombok Regency, West Nusa Tenggara Province, is an area with a high level of landslide susceptibility due to geological conditions, extreme rainfall, and complex land use. An accurate delineation of landslide susceptibility zones is essential to support disaster mitigation and spatial planning. This study aims to analyze the reliability of the Weight of Evidence (WoE) and Weighted Overlay (WO) methods in assessing landslide susceptibility in the region. The research data include physical parameters such as rainfall, soil type, land cover, slope gradient, lithology, and landslide inventory records collected from relevant agencies, as well as satellite image interpretation results. Data processing was conducted using Geographic Information System (GIS) tools, applying the WoE and WO methods, while model validation was performed using the Receiver Operating Characteristic (ROC) curve technique and Area Under the Curve (AUC) calculation. The results of the study produced a landslide susceptibility map categorized into four classes: very low, low, medium, and high. In the WO method, the distribution of landslide occurrences is 0.05% in the very low class, 2.76% low, 55.95% medium, and 41.24% high. Meanwhile, using the WoE method, the distribution is 5.68% (very low), 9.30% (low), 15.08% (medium), and 69.95% (high). The implications of this study indicate that the WoE method is more accurate in identifying high-susceptibility zones, making it a suitable main reference for disaster mitigation planning, spatial planning policies, and disaster risk reduction programs in East Lombok.

INTRODUCTION

Landslides are frequent geological disasters and can cause significant losses in the economic, infrastructure, environmental, and fatalities (Gariano & Guzzetti, 2016; Wang et al., 2021). The main causes of landslides are complex interactions between dynamic factors (such as rainfall and earthquakes), soil conditions (slope slope, geology, and soil type), and anthropogenic disturbances (such as deforestation and road cutting). Other causative factors include precipitation, slope, and human activity (Grahn & Jaldell, 2017).

Indonesia, located at the confluence of three large tectonic plates (Indo-Australian, Eurasian, and Pacific), has geological conditions that make it vulnerable to landslide disasters. High rainfall and intensive rock weathering also exacerbate its vulnerability, making Indonesia one of the countries with a high risk of landslides. East Lombok Regency, which is at the foot of Mount Rinjani, is an area with a high landslide risk index (Darmawan et al., 2018; Febriarta et al., 2022; Hasan & Sutriyono, 2021; Irjaya & Pamungkas, 2014; Utomo et al., 2016).

Analysis of landslide potential currently often uses Geographic Information System (GIS) technology, especially ArcGIS software with the Weight of Evidence (WoE) method (Ferawati & Agustawijaya, 2023; Linkov et al., 2015; Pamela et al., 2018). The WoE method is based on quantitative data and has been widely used to analyze disaster risks, including landslides (Kurowksa et al., 2021; Li et al., 2024; Lü et al., 2019; Tseng et al., 2022). However, there has been no research that applies the WoE method specifically for landslide analysis in East Lombok Regency (Ozdemir, 2011a).

Relevant previous research includes a Weight of Evidence (WoE) model used for mapping landslide vulnerability in tropical regions such as Cameron Highlands, Malaysia. Pradhan et al., (2010) showed that WoE, considering factors such as slope, lithology, and land cover, was able to generate vulnerability maps that showed high accuracy (AUC up to 0.97) through field data validation. Meanwhile, Kristiawan et al. (2022) applied WoE to Mamuju Regency post-earthquake in West Sulawesi with complete physical parameters, resulting in an AUC value of around 0.80—indicating that WoE is suitable for application in dynamic conditions after natural changes. However, the two studies did not specifically evaluate landslide susceptibility conditions in East Lombok Regency, where the combination of volcanic geology, high rainfall, and anthropogenic activity creates unique challenges.

This study aims to compare the accuracy and reliability of WoE and WO methods in mapping landslide potential in East Lombok, while providing valid and contextual vulnerability maps. The practical benefits include support for more targeted disaster mitigation planning, evidence-based mitigation policy making, and strengthening the spatial planning capacity of landslide-prone areas in Indonesia.

METHOD

Theoretical basis:

Landslide

Landslides generally involve the movement of slope-forming material, such as rocks, debris, soil, or other materials moving down or away from a slope. Geologically, a landslide is a geological phenomenon involving the movement of land, such as the fall of rocks or large clumps of soil (Nandi, 2007). Classification of landslide causes according to Nandi (2007) is explained **in Table 1**

Table 1. Common causes of landslides

Causal Factor Group	Source of Cause
1. Geological Factors	1. Weak and sensitive rock layers; 2. Rock weathering; 3. Rock shift; 4. Cracks or junctions of rock layers; 5. Differences in permeability of soil layers; 6. Differences in rock strength (rigid, dense,

Causal Factor Group	Source of Cause
	plastic).
2. Morphological Factors	1. Tectonic or volcanic uplift; 2. Ice sheet; 3. Erosion; 4. Changes in the position of the load on the slope; 5. Damage to protective plants on slopes.
3. Physical Factors	1. Very high rainfall; 2. Ice melting; 3. Very long rain; 4. Changes in groundwater levels; 5. Earthquake; 6. Volcanic eruption; 7. Flower – shrinkage due to soil weathering.
4. Human Factors	1. Slope excavation; 2. Deforestation; 3. Mining; 4. Artificial vibrations, such as nuclear tests.
	Source: Landslides (Nandi, 2007)

The following is a classification of types of soil/rock movement based on classification Varnes (1984).

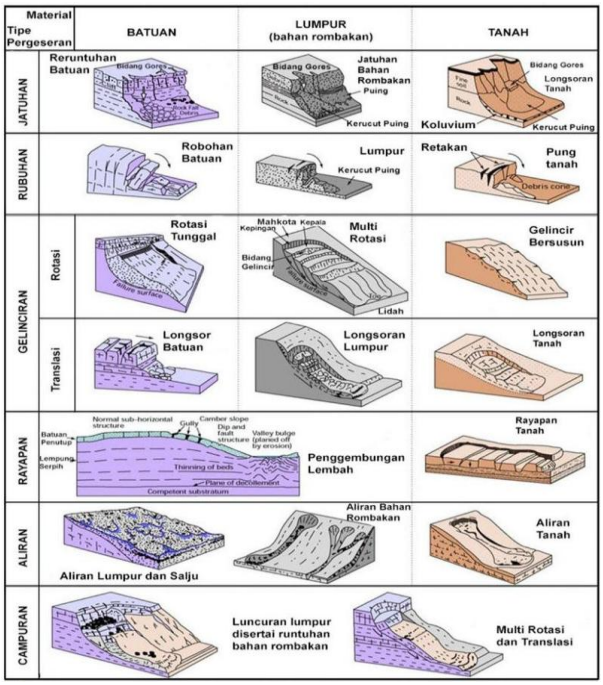


Figure 1. Classification of Types of Soil/Rock Movement (Varnes, 1984)

Spatial Data Model

A data model in GIS can be defined as a picture or representation of real objects on the earth's

surface and a depiction of the geographic relationships between these objects. Two types of data models currently used in GIS are vector and raster models. In the early stages of GIS development, hardware and software only used one data model (vector or raster only), but with current technological developments, many systems now use both types of models, namely the so-called "hybrid" model, where both types of data models can be transformed into each other (Santoso, 2021).

Bivariate Statistical Method (Weight of Evidance/WoE)

The WoE method uses a Bayesian probability model in log-linear form, and each factor can be linearly stacked in GIS data processing. Furthermore, the WoE method is based on the independent characteristics of each variable in each landslide controlling factor, allowing the influence of each controlling factor to be calculated independently. This distinguishes the WoE method from other statistical methods, preventing the possibility of correlation factors that could lead to poor calculation results.

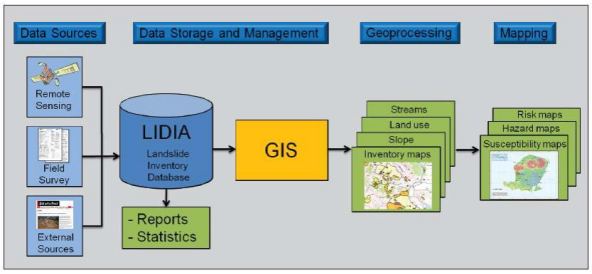


Figure 2. Illustration of weighting class calculation using the *Weight of Evidence* (WoE) method

The WoE formulation is as follows (Bonham-Carter 1994):

$$W_i{}^{+} = In\left|\frac{P(Fi|S)}{P(Ei|S)}\right| = In\left|\frac{\frac{P(N_j \cap S)}{P(S)}}{\frac{P(N_j \cap S)}{P(S)}}\right| = In\left|\frac{\frac{Npix\ Landsslide\ in\ class}{NPix\ total\ lansslide\ area}}{\frac{Npix\ stable\ in\ class}{NPix\ total\ stable\ area}}\right|$$

$$W_i{}^{-} = In\left|\frac{P(\bar{N}_j|S)}{P(\bar{N}_j|\bar{S})}\right| = In\left|\frac{\frac{P(\bar{N}_j \cap S)}{P(S)}}{\frac{P(\bar{N}_j \cap \bar{S})}{P(\bar{S})}}\right| = In\left|\frac{\frac{Npix\ Landsslide\ outside\ class}{NPix\ total\ lansslide\ area}}{\frac{Npix\ stable\ area\ outside\ class}{NPix\ total\ stable\ area}}\right|$$

With:

W^{+} =the probability weight of landslides in a geofactor class (positive weight).

W^{-} =the weight of the impossibility of land movement in a geofactor class (negative weight)

Nj =Number of pixels in the parameter class

S =The total number of pixels containing ground motion over the entire area.

P = Valueprobability

The parameter C is introduced as the sum of W^{+} and W^{-} considering the influence of the i-th class of the causal factor E, as well as the impact of the absence of other causal factors on the sub-classes, which will be used for the identification of the overall weights assigned to the raster units, as described in Equation:

$$C = W_i{}^{+} + \left[\sum_{j=1}^{n} W_j{}^{-}\right] - W_i{}^{-}$$

With:

C =The total value or combined score of a unit (e.g., a raster cell or sub-class in a vulnerability map);

W_i^+ =Positive weight for the factor i, showing a positive contribution from the factor i to the incident;

W_j^- =Negative weight for the factor j, indicating a negative (risk-reducing) contribution from the factor j;

$\sum_{j=1}^{n} W_j$ = Sum of all negative weights of all factors j (from 1 to$n$)

W_i^- =Negative weight of the factor i, which is subtracted at the end to neutralize the calculation from the previous step (because of the factor$i$may have been counted in the total amount Wj).

One of the important steps in quantitative statistical modeling is the evaluation (validation) of the model and the resulting prediction map. Without validation, the analysis results lack clear scientific weight. To evaluate the magnitude of the parameter's influence on ground motion, a threshold-independent method is used, in the form of a receiver operating characteristic (ROC) curve. The basis for evaluating this ROC curve is plotting the results of different accuracy values against the inferred threshold value (Chung & Fabbri, 2003).

The AUC calculation formula (Pimiento, 2010) is:

$$AUC = \sum_{i=0}^{n} (x_i - x_{i-1}) y_i - \frac{(x_i - x_{i-1}) - (y_i - y_{i-1})}{2}$$

With:

x_i= Percentage of area

y_i = Percentage of landslide area

Validation results are presented in the form of an attribute table and a prediction level graph. The area under the curve (AUC) is a type of accuracy statistic for prediction (probability) models in natural disaster assessment/analysis. AUC is a graph of index numbers that vary, usually between a maximum value of 1 (100%) and 0.5 (50%).

Table 2. AUC Threshold Values

AUC value	Information
0.9 – 1.0	Highly Accurate Model
0.8 – 0.9	Very Good Model
0.7 – 0.8	Good Model
0.6 – 0.7	Moderate/Good Enough Model
0.5 – 0.6	Weak Model

Source: Shallow Landslide Susceptibility Modeling and Validation (Pimiento, 2010)

The classification of landslide vulnerability zones using statistical methods is divided into four based on SNI 8291, 2016 that is:

1. The high landslide vulnerability zone is an area that has a proportion of landslide events greater than 25% of the total population of events;
2. The medium landslide vulnerability zone is an area that has a proportion of landslide events greater than 10% to 25% of the total population of events;
3. The low landslide vulnerability zone is an area that has a proportion of landslide events greater than 5% to 10% of the total population of events;

4. The very low landslide vulnerability zone is an area that has a landslide occurrence proportion of 0% to 5% of the total occurrence population.

Weighted Overlay Method

Weighted overlay is "spatial analysis using overlay techniques of several maps related to factors that influence vulnerability assessments (Adininggar et al., 2016). *Weighted overlay*is one of the facilities in ArcGIS software that combines various inputs in grid form with weighting factors from AHP expert.

According to Reppi et al. (2021), disaster analysis involves the following stages: "base maps are required, including maps of slope gradient, rainfall, soil type, and land use. After overlaying these maps, landslide susceptibility class intervals are created, which aim to differentiate landslide susceptibility classes from low to high using the following formula:

$$Ki = \frac{\mathrm{Xt-Xr}}{\mathrm{K}}$$

With:

Ki =Interval Class
Xt = Datahighest
Xr = Datalowest
K =Desired number of classes

Landslide Incident Data

Landslide event data can be obtained from the Regional Government (Regional Disaster Management Agency) and through remote sensing interpretation. This landslide event data is then collected in a digital spatial format represented as points (geo-referenced points). The landslide event data is divided into two data sets: the first set to create a landslide vulnerability map (*training set*), and the second set to test the validity/reliability of the relationship between geofactors and landslide events (*test set*) (Ozdemir, 2011b).

Research Steps

Research Location

The research location, namely East Lombok Regency, is shown in the following **Figure 3**.

East Lombok Regency is a regency located at the eastern tip of Lombok Island with an astronomical location between 116°46'-117°20' East Longitude and 8°-9° South Latitude. The area of East Lombok Regency is 2,684,097 km² consisting of land covering 1,609,767 km² (59.91 percent) and sea covering 1,074.33 km² (percent). The land area of East Lombok Regency covers 33.88 percent of the area of Lombok Island or 7.97 percent of the land area of West Nusa Tenggara Province (East Lombok Regency in figures, 2024).

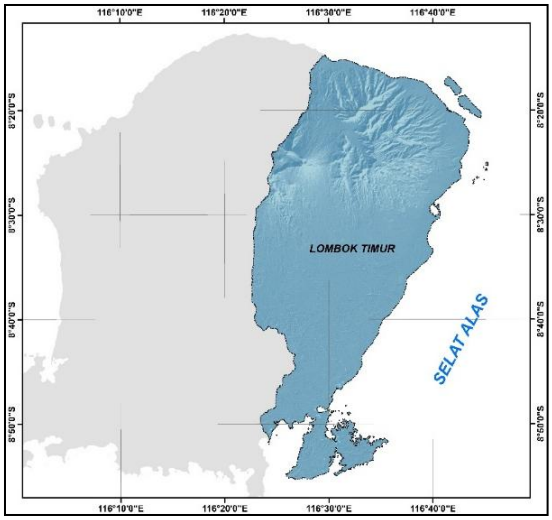


Figure 3. Research Location

Data Preparation

The data to be processed must have the same format and form to ensure proper processing. The following are the requirements for data to be processed and analyzed:

1. Parameter Data must be in raster/grid format;
2. Each parameter data must have the same coverage, resolution (size) and number of pixels; and

The parameter data has the same projected coordinate system, and for East Lombok Regency the UTM 50S coordinate system is used.The data used in landslide mapping using the Weight of Evidence (WoE) method is as follows:

Table 3. Types and Sources of Data

No	Data	Source
1	Administration	BIG
2	Landslide	BPBD of NTB Province and BPBD of East Lombok Regency
3	Slope Gradient	Aster GDEM
4	Slope Direction	Aster GDEM
5	Land Cover	Ministry of Environment and Forestry
6	Geology	NTB Provincial ESDM Service
7	Rainfall	*https://www.chc.ucsb.edu/data/chirps*
8	Soil Type	BAPPEDA of NTB Province

Data processing

The steps used in data processing can be seen in the following flowchart:

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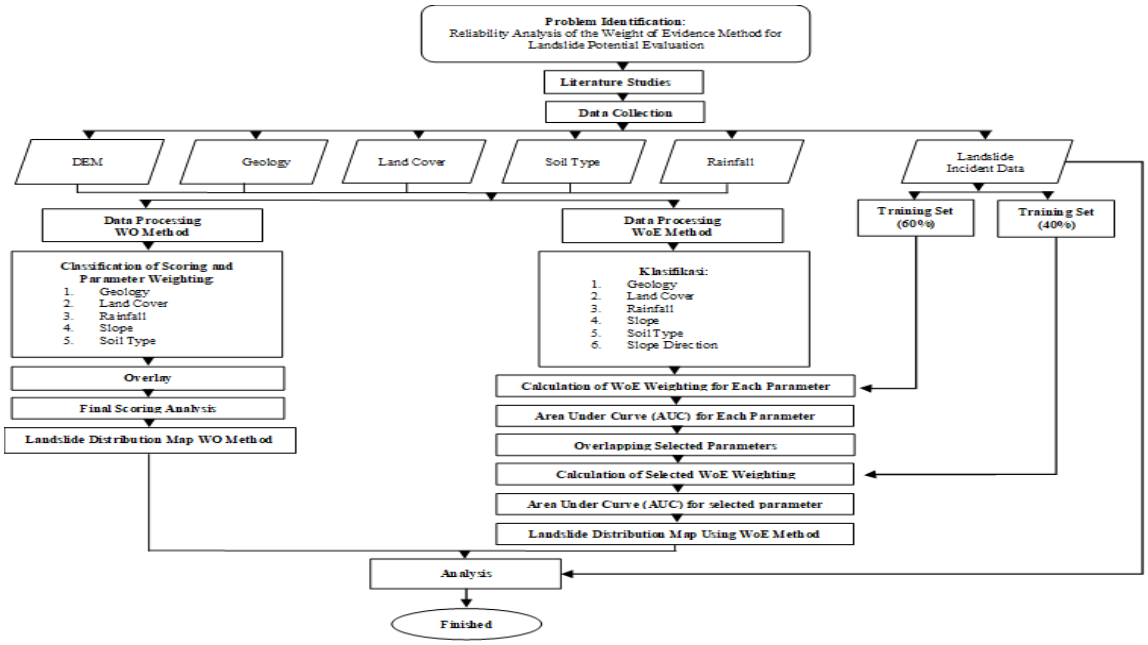


Figure 4. research flowchart

RESULTS AND DISCUSSION

Weight of Evidence/WoE

Landslide data obtained from the BPBD of West Nusa Tenggara Province and East Lombok Regency as well as the results of analysis in Google Earth were divided into 2 (The division was done randomly using the Subset Features tool in ArcGIS.), (Training set (60%) – for WoE calculation and Test set (40%) – for model validation).

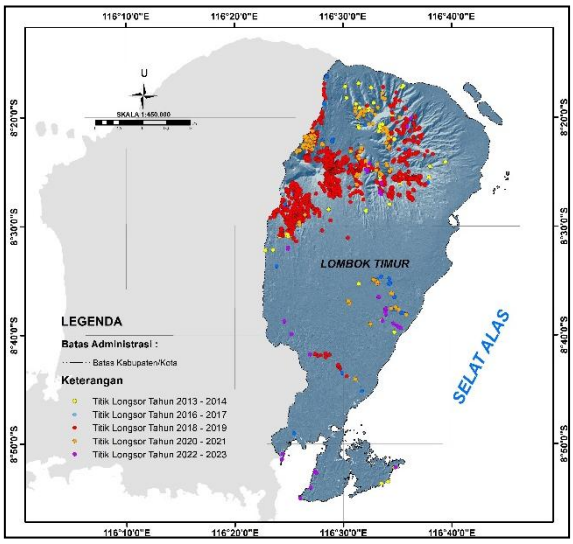


Figure 5. Landslide Points from 2013-2023

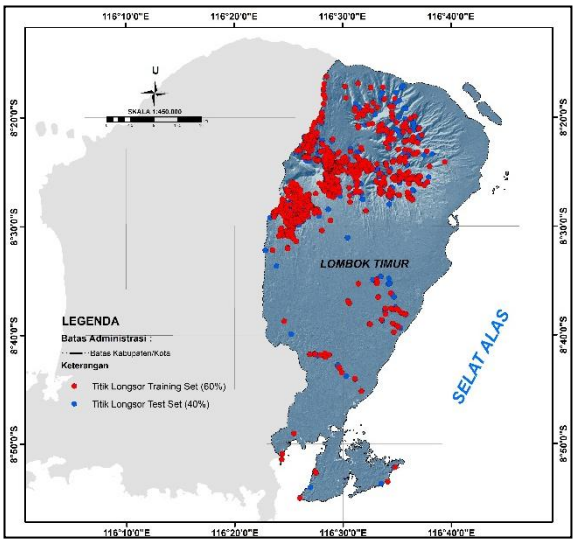


Figure 6. Division of training set and test set

The next step is Classify parameters into several classes and convert them to raster. DEM data will be processed into slope and slope direction data using the slope and slope tools.

classified into several classes (in percentages) using the equal interval function. After the slope gradient and slope direction data are obtained, the next step is to overlay the landslide points (training set) against the six parameters used.

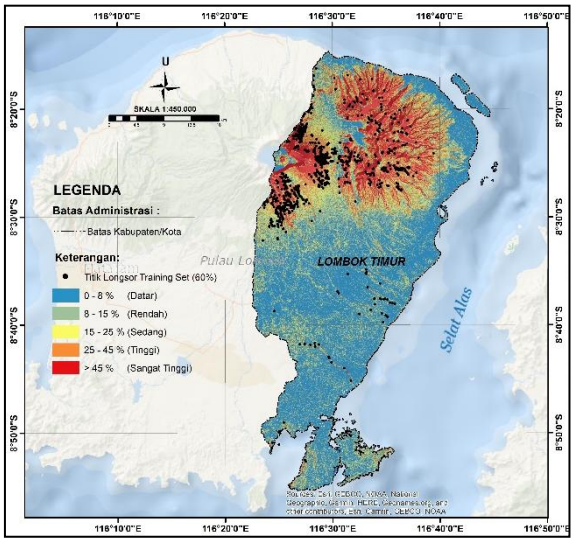


Figure 7. Slope Gradient Parameter Map

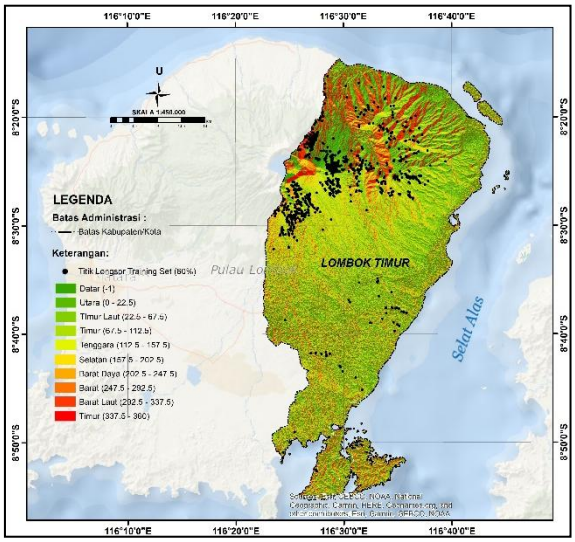


Figure 8. Slope Direction Parameter Map

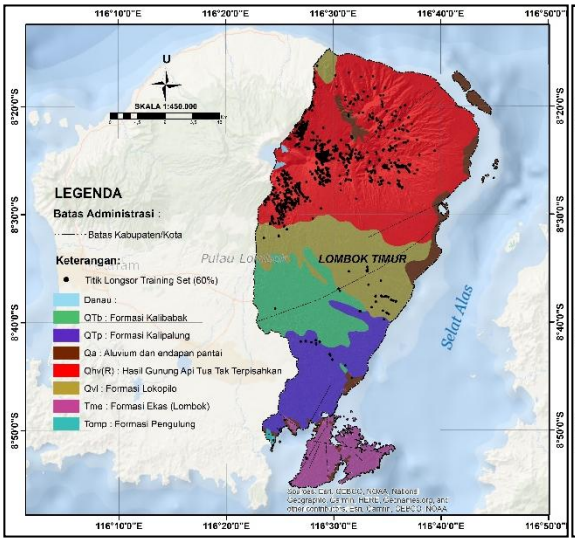


Figure 9. Geological Parameter Map

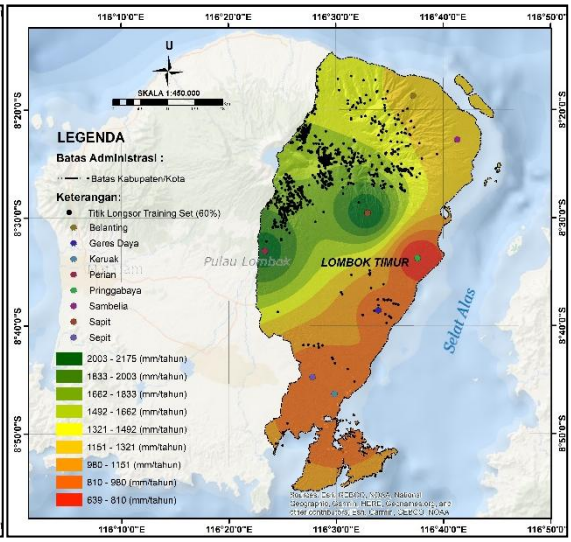


Figure 10. Rainfall Parameter Map

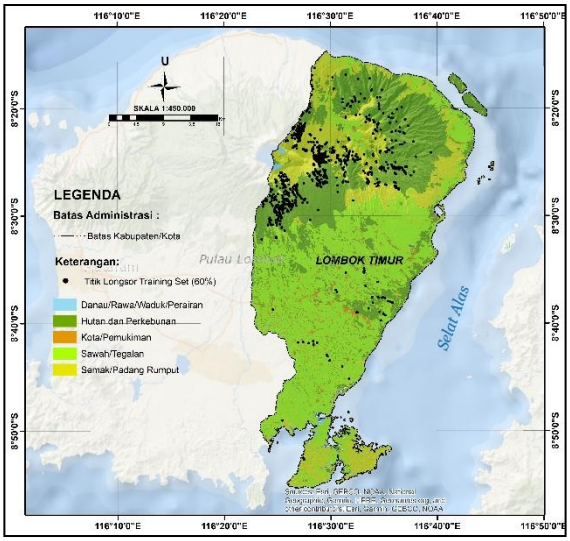


Figure 11. Land Cover Map

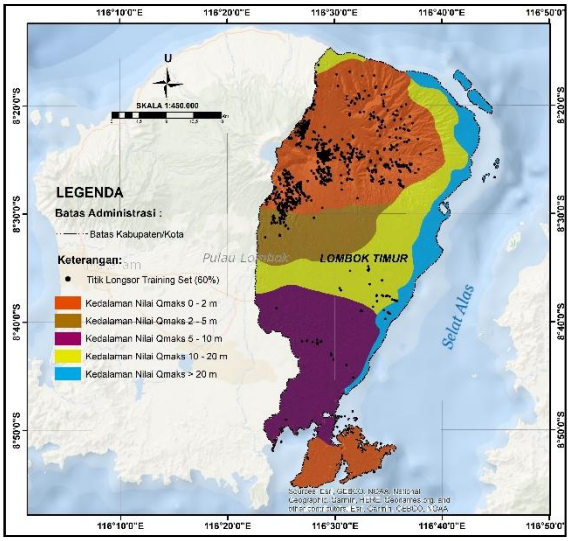


Figure 12. Soil Layer Parameter Map

In the Weight of Evidence method, the next step is to calculate the WoE value and measure the level of influence on landslides by calculating the Area Under Curve (AUC) value.

Table 4. *Area Under Curve (AUC)* Value of Each Parameter

No	Parameter	Area Under Curve (AUC) Value
1.	Geology	0.734
2.	Slope	0.842
3.	Rainfall	0.824
4.	Land Cover	0.753
5.	Soil Layers	0.766
6.	Slope Direction	0.604

The table above shows that the Slope parameter has the highest AUC value of 0.842, while the slope direction parameter has the lowest AUC value of 0.604. The AUC values of each parameter indicate the level of influence they have on landslide occurrences.

The next step is to calculate the total WoE of the selected parameters with an AUC value > 0.6. The total WoE calculation is performed by summing the selected parameters. Summing the selected parameters is done by statistically overlaying the selected parameters or using statistical assistance in ArcGIS using the raster calculator tool.

Based on the total *Weight of Evidence* (WoE) calculation data, the next step is to test/validate the level of influence on landslide occurrence. The level of influence testing is carried out by validating the total WoE with the landslide data from the test set, calculated to obtain the AUC value. This model validation process is the same as the parameter verification process. This validation is carried out to ensure the landslide susceptibility model (parameter selection and landslide occurrence) can be accounted for its accuracy. The results of the WoE calculation on the level of influence on landslides at the research location obtained an AUC value of 0.883.

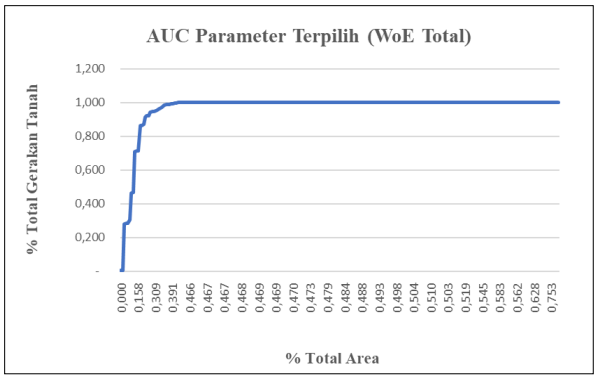


Figure 13. *Area Under Curve* (AUC) values of selected parameters

Next, landslide classification is carried out and a map is created with the total WoE value in percentage according to the landslide vulnerability zone according to SNI 8291:2016 and overlaying all the landslides that occurred.

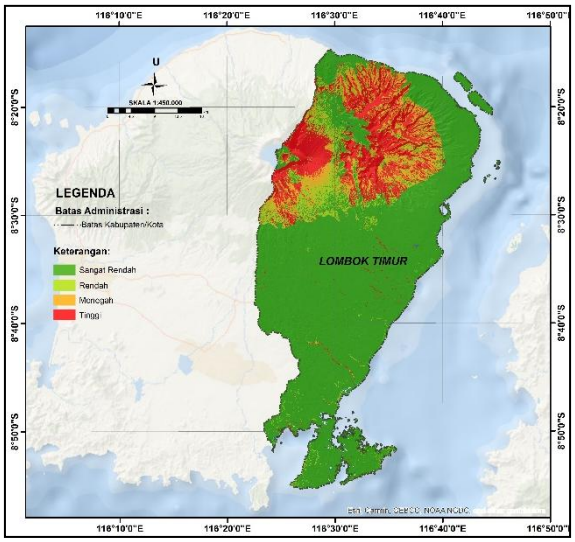


Figure 14. Landslide vulnerability level map using the weight of evidence method

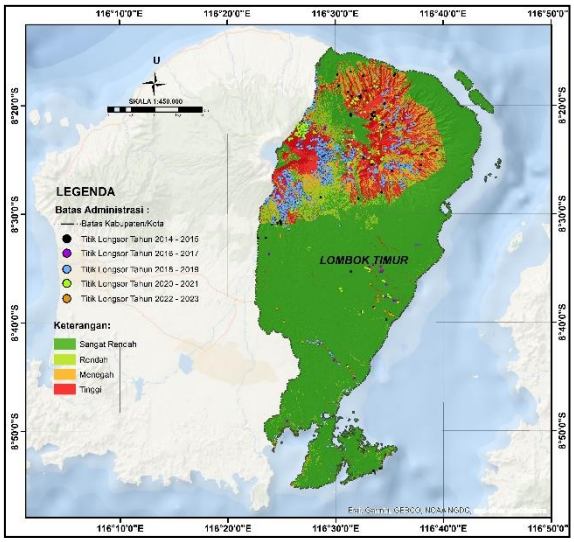


Figure 15. Landslide point distribution map using the weight of evidence method

Table 5. Results of overlaying landslide points using the *Weight of Evidence* (WoE) method

No	Vulnerability Level	WoE Method	
		Distribution Area (Km²)	Number of Landslide Points
1	Very Low	1,119,617	105
2	Low	126,375	172
3	Intermediate	108,767	279
4	Tall	255,008	1,294
	Amount	**1,609,767**	**1,850**

Weighted Overlay

The data used as parameters in data processing uses the Weight of Evidence method based on the classification of the Bogor Research Center (2004) in Rahmad R, et al. (2018), namely

1. Geological Data/Rock Type;
2. Slope Gradient Data;
3. Rainfall Data;
4. Land Use Data;
5. Soil Type Data;

The following is the weighting and score values issued byBogor Research Center (2004) in Rahmad R, et al (2018).

Table 6. weighting and score values

Parameter	Class	Weighting	Score
Rainfall (mm/year)	Very wet (>3000)	30%	5
	Wet (2501-2300)		4
	Medium (2001-2500)		3
	Dry (1501-2000)		2
	Very dry (<1500)		1
Types of Rocks	Volcanic rocks	20%	3
	Sedimentary rocks		2
	Alluvial rocks		1
Slope Gradient (%)	>45	20%	5
	30-45		4
	15-30		3
	8-15		2
	<8		1
Land Cover	Dry fields, rice fields	20%	5
	Shrubs		4
	Forests and plantations		3
	City/settlement		2
	Ponds, reservoirs, waters		1
Soil Type	Regosol	10%	5
	Andosol, podzolic		4
	Brown Lotosol		3
	Yellowish brown latosol association		2
	Alluvial		1

Source: Rahmad et al., (2018)

The scoring technique used in this study was to assign scores and weights to five parameters/variables/criteria: slope gradient, soil type, geology, rainfall, and land cover. The scoring technique used to determine the criteria for landslide triggers in East Lombok Regency was based on expert perceptions and the weighting of each landslide-causing criterion, which refers to the 2004 Puslitanak classification.Rahmad et al., (2018) that is:

Total Score = 0.3FCH + 0.2FBD + 0.2FKL + 0.2FPL + 0.1FJT

With:

FCH =rainfall factor
FBD =rock type factor
FKL =slope factor lSlope
FPL =land cover factors
FJT =soil type factor
0.3;0.2;0.1= Value weight

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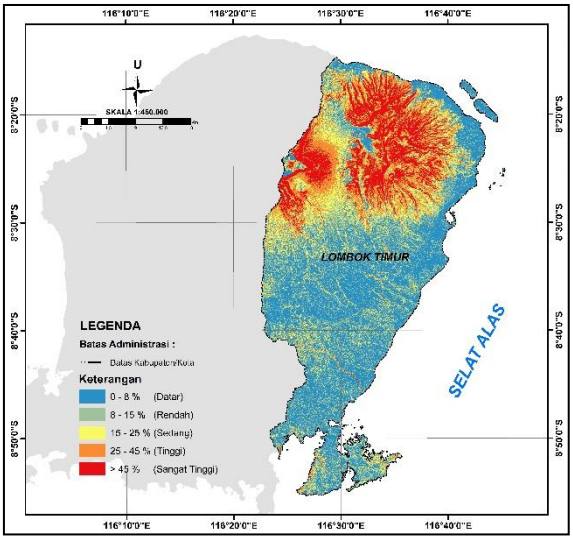


Figure 16. Slope Gradient Parameter Map

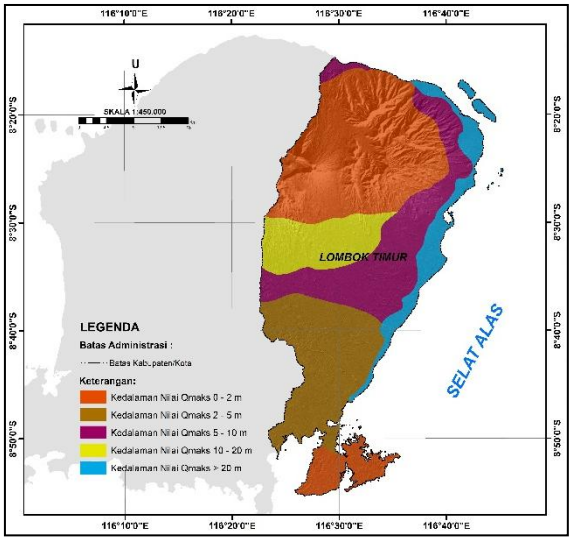


Figure 17. Soil Layer Map

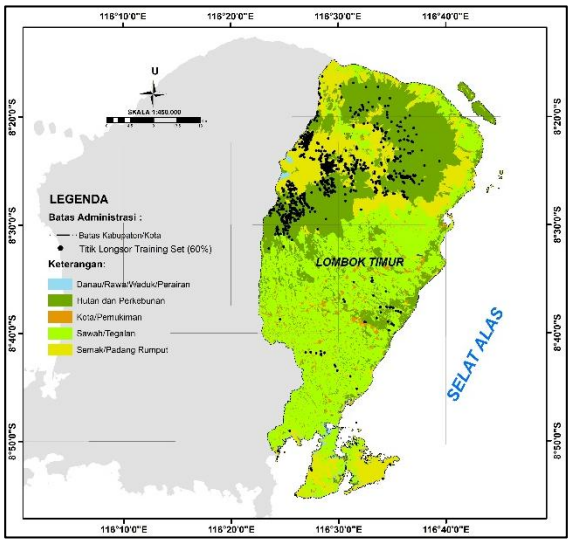


Figure 18. Land Use Parameter Map

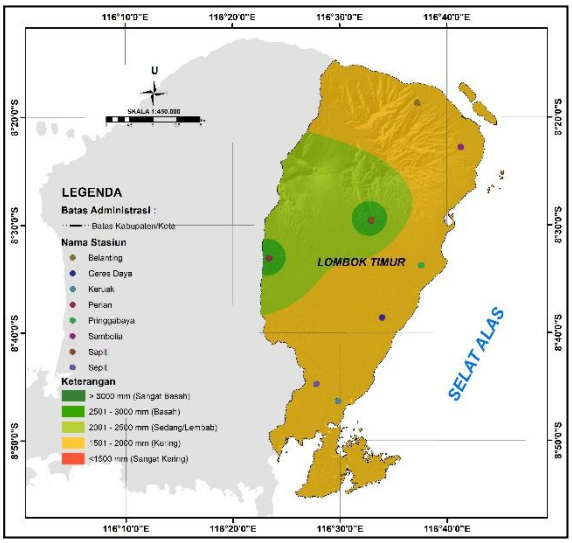


Figure 19. Rainfall Parameter Map

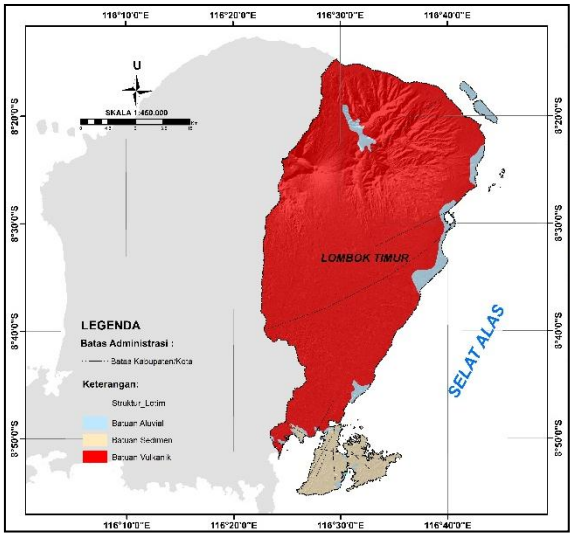


Figure 20. Rock Parameter Map

The next step is to carry out the overlay process on the map that has been scored and weighted; Determination of class intervals.

Table 7. Weights and scores of landslide vulnerability parameters

Parameter	Minimum Score	Maximum Score	Weight	Weight x Minimum Score	Weight x Maximum Score
Rainfall	1	4	30%	0.3	1.2
Types of Rocks	1	3	20%	0.2	0.6
Slope Gradient	1	5	20%	0.2	1
Land Cover	1	5	20%	0.2	1
Soil Type	1	5	10%	0.1	0.5
Amount				1	4.3

$$\text{Interval Class} = \frac{\text{highest data} - \text{lowest data}}{\text{number of classes desired}}$$

$$\text{Interval Class} = \frac{4{,}3 - 1}{4} = 0{,}83$$

Based on the calculation results above, the class interval for the landslide vulnerability map of East Lombok Regency used is 0.83 and there are four class intervals.

Table 8. Landslide vulnerability level interval classes

No	Vulnerability Level	Interval Value (0.83)
1	Very Low	1 – 1.83
2	Low	1.83 – 2.65
3	Intermediate	2.65 – 3.48
4	Tall	3.48 – 4.3

Create a landslide vulnerability map based on the level of landslide vulnerability resulting from class interval calculations and conducting distribution analysis.

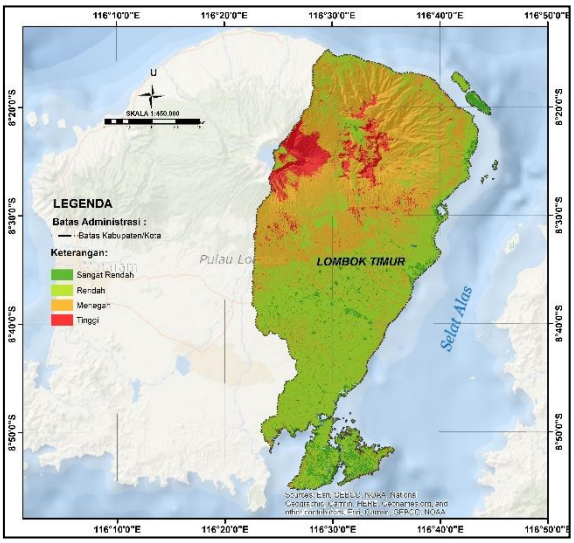


Figure 21. *Weighted Overlay* (WO) method of landslide vulnerability zone

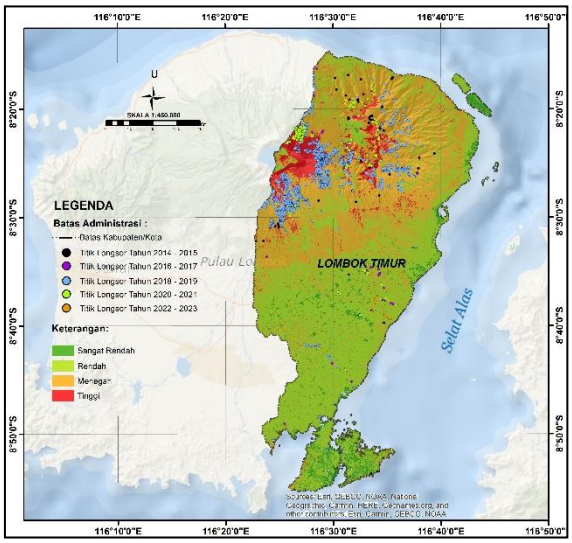


Figure 22. Results of overlaying landslide points using the *Weighted Overlay* (WO) method

Table 9. Results of overlaying landslide points using the *Weighted Overlay* (WO) method

No	Vulnerability Level	WoE Method	
		Distribution Area (Km²)	Number of Landslide Points
1	Very Low	68,932	1
2	Low	735,544	51
3	Intermediate	701,200	1,035
4	Tall	104,091	763
	Amount	**1,609,767**	**1,850**

CONCLUSION

The primary factors contributing to landslides, identified using the Weight of Evidence (WoE) method, are rainfall and slope (both with an AUC of 0.849), followed by soil type (AUC 0.766), land cover (AUC 0.753), and geology (AUC 0.734). The landslide susceptibility mapping based on WoE shows that most landslide occurrences (69.95%) fall within the high susceptibility class, with smaller proportions in medium (15.08%), low (9.30%), and very low (5.68%) classes. In contrast, the Weighted Overlay (WO) method distributes landslide points differently, with 41.24% in the high vulnerability class, 55.95% medium, 2.76% low, and only 0.05% very low. These results suggest that the WoE method provides a more distinct differentiation of high-risk areas. Future research should consider integrating additional dynamic factors such as land-use change and rainfall intensity trends to enhance the predictive accuracy of landslide susceptibility models in East Lombok Regency.

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