Mapping Landslide Vulnerability using Spatial Analysis of Weight of Evidence (WoE) in Central Mamuju, West Sulawesi Province, Indonesia

Ilham Alimuddin ([12*]), Muhammad Ichsan[1], Cahyadi Ramadhani[2]

[1]Disaster Study Center, LPPM Hasanuddin University

[2]Geological Engineering, Faculty of Engineering, Hasanuddin University

*ialimuddin@gmail.com (*Corresponding author's email only)

Abstract: *Mamuju Tengah Regency, West Sulawesi Province, is an area with a relatively high level of geological disaster risk, particularly landslides. Over the past five years, there have been several significant landslide incidents that have not only caused infrastructure damage but have also disrupted social and economic activities of the community. Spatial analysis to identify locations and map areas with high risk/hazard levels can be one of the efforts to assist in anticipating such disasters by serving as a basis for decision-making. The multivariate statistical method known as Weight of Evidences (WoE) can be used to evaluate the influence of each factor on landslide hazards by overlaying landslide distribution data and then comparing it separately with various thematic data layers from eleven factors, including slope direction, elevation, distance from roads, distance from the river, slope gradient, geology, peak ground acceleration, distance from geological structures, soil type, land type, and land cover. The validation results shown in The Central Mamuju area are presented in the form of attribute tables and prediction level graphs, namely AUC (Area under Curve), which is one type of accuracy statistic for prediction models (probability) in assessing/analyzing the level of landslide vulnerability in The Central Mamuju area, which is 0.9303 (Excellent Model). It is known that the three most influential parameters in landslide events in this area are slope gradient, slope direction, and land cover.*

Keywords: Landslide, Multivariate, AUC, Probability, Disaster

Introduction

District of Mamuju Tengah in West Sulawesi Province, it is an area which, in terms of its geographical location and geological perspective, is situated in the Palu Koro Fault zone, making this area with a relatively high level of geological disaster risk, particularly landslides. Landslide is a general term used to describe the downslope movement of soil, rock, and organic materials under the effects of gravity and the landform that result from such movement. The main factors that cause landslides are broadly divided into two main factors consisting of natural occurrences and human activities (U.S Department of the interior and U.S. Geological survey, 2008). Elevation, geology, peak ground acceleration (PGA), distance of structural geology, distance of river, and soil as natural occurrences factor. Slope direction, distance of road, slope, land type and land cover as human activities factors.

Over the past five years, there have been several significant landslide incidents that have not only caused infrastructure damage but have also disrupted social and economic activities of the community. Losses caused by landslides are more than not a huge loss both on a local and international scale. This is one of the triggers for researchers to conduct a study related to landslides in Mamuju Tengah. It is considered necessary to have a model to determine the distribution or level of danger/vulnerability of landslides in this area so that it can be considered so that level of loss can be anticipated. Spatial analysis to identify locations and map areas with high risk/hazard levels can be one of the efforts to assist in anticipating such disasters by serving as basis for decision-making.

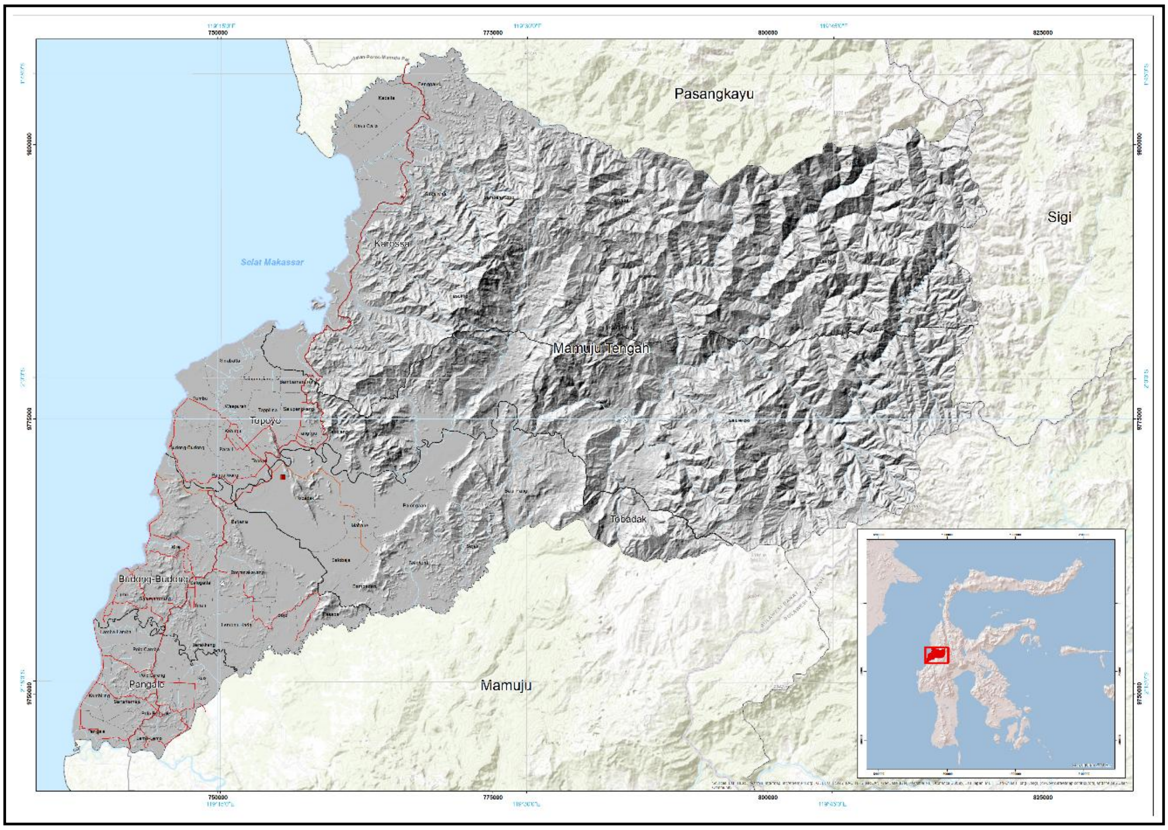


Figure 1: Research location map (Kabupaten Mamuju Tengah, Provinsi Sulawesi Barat)
Source: Esri-World Topographic Relief, RTRW Kab. Mamuju Tengah And FABDEM

Methodology

The multivariate statistical method (SNI 8921:2016) known as Weight of Evidence can be used to evaluate the influence of each factor on landslide hazards by overlaying landslide distribution data and then comparing it separately with various thematic data layers from eleven factors such as slope direction, elevation, distance from roads, distance from river, distance from structural geology, slope gradient, geology, peak ground acceleration, soil type, land type and land cover which is then overlaid by using ArcGIS software with data on landslide events in the last 10 years in Mamuju Tengah. In detail, the method used by the researcher is described in the following steps:

1. Preparation and collection of data required in the analysis

<table>
<tr><th>Category</th><th>Factor</th><th>Data Type</th><th>Source</th></tr>
<tr><td>Landslide</td><td>-</td><td>Vector</td><td>Database of PVMBG, Field survey, Image interpretation</td></tr>
<tr><td>Administrative boundary</td><td>-</td><td>Vector</td><td>RTRW Kab. Mamuju Tengah</td></tr>
<tr><td colspan="4">Landslide Control Factors</td></tr>
<tr><td rowspan="3">Topography</td><td>Slope</td><td rowspan="3">Raster</td><td rowspan="3">Forest And Building Removed Digital Elevation Model (FABDEM)</td></tr>
<tr><td>Slope gradient</td></tr>
<tr><td>Elevation</td></tr>
<tr><td rowspan="3">Distance of landslide</td><td>Road</td><td rowspan="3">Vector-Raster</td><td rowspan="2">RTRW Kab. Mamuju Tengah</td></tr>
<tr><td>River</td></tr>
<tr><td>Structural geology</td><td>Geological Map of The Pasangkayu Quadrangle, Sulawesi (PVMBG)</td></tr>
<tr><td>Peak ground acceleration (PGA)</td><td>Peak ground acceleration (PGA)</td><td>Raster</td><td>InaRisk BNPB</td></tr>
<tr><td>Geology</td><td>Lithology</td><td>Vector-Raster</td><td>Geological Map of The Pasangkayu Quadrangle, Sulawesi (PVMBG</td></tr>
<tr><td>Soil Type</td><td>-</td><td>Vector-Raster</td><td>RTRW Kab. Mamuju Tengah</td></tr>
<tr><td>Land Type</td><td>-</td><td>Vector-Raster</td><td>RTRW Kab. Mamuju Tengah</td></tr>
<tr><td>Land Cover</td><td>-</td><td>Vector-Raster</td><td>RTRW Kab. Mamuju Tengah</td></tr>
</table>

Table 1: Data used in Landslide Analysis

By using the method issued by National Disaster Mitigation Agency (BNPB), Landslide location data (Point) was divided into two datasets (70% for ground motion susceptibility as model (training set) and 30% to test the validity of geo factor linkages to ground motion). Each landslide control factor in vector format was converted into raster format using ArcGis software, each factor was then grouped according to the classification used. Tests were conducted on each parameter to determine the influence on ground motion. The test was conducted using ground motion (landslide training) to obtain the AUC (Area Under Curve) value.

$$(1)..\mathrm{n0Factor} = \frac{\mathrm{n0Bar}}{\sum \mathrm{Bar}}$$

$$(2)..\mathrm{n0TotLS} = \mathrm{n0Factor} + \mathrm{n0LS}$$

$$(3)..\mathrm{n0Class\ Density} = \frac{\mathrm{n0TotLS}}{\mathrm{n0Bar}}$$

$$(4)..\mathrm{Maps\ Density\ (n1 = n2 = n3.. = Etc)} = \frac{\sum \mathrm{Bar}}{\sum \mathrm{Factor}}$$

$$(5)..\mathrm{n0Frequency\ Ratio\ (FR)} = \frac{\mathrm{n0Class\ Density}}{\mathrm{Maps\ Density}}$$

$$(6)..\mathrm{n0IVM} = \mathrm{Natural\ Logaritma\ (LN)} \times \mathrm{n0FR}$$

$$(6)..\mathrm{n0W}+= \mathrm{LN}\left(\frac{\frac{\mathrm{n0TotLS}}{\sum \mathrm{TotLS}}}{\frac{\mathrm{n0Bar} - \mathrm{n0TotLS}}{\sum \mathrm{Factor} - \sum \mathrm{TotLS}}}\right)$$

$$(7)..\mathrm{n0W}-= \mathrm{LN}\left(\left(\frac{\frac{\sum \mathrm{TotLS} - \mathrm{n0TotLS}}{\sum \mathrm{TotLS}}}{\frac{\sum \mathrm{Factor} - \mathrm{n0Bar} - \sum \mathrm{TotLS} + \mathrm{n0TotLS}}{\sum \mathrm{Bar} - \sum \mathrm{TotLS}}}\right)\right)$$

$$(8)..\mathrm{n0C} = (\mathrm{n0W}+) - (\mathrm{n0W}-)$$

$$(9)..\mathrm{WeightWOE} = (\mathrm{n0W}+) - \left(\sum \mathrm{W}+\right) - (\mathrm{n0W}-)$$

Notes

• Bar: Area (number of pixels) of each parameter

• Factor: Small values used to manipulate landslide occurrences to prevent zero values.

• Ls (Landslide): Landslide occurrences after overlaying the distribution data per parameter.

• FR (Frequency Ration): Used to compare the results obtained for the FR and IVM methods.

• IVM (Information Value Ratio Method): An index used to indicate how well a variable can separate two data groups.

• W+: Probability in each class.

• W-: Impossibility in each class.

• C: Constant to simplify calculations.

• Weight WoE: Value/Weight for each class.

1. Use the TRUNC from Excel software to remove the fractional part the whole number part,X100 is used because ArcGIS raster cannot store decimal values, so the WOE value is ×1000 and the integer is taken.

2. Map the WoE values for each parameter. This stage is performed by overlaying the calculated WoE data with the previously used classification data. In this case, ArcGIS software uses the "Join" and "Lookup" tools to combine and eliminate data with similar values.

3. Validate the parameters from the mapped WoE values to obtain the AUC (Area Under Curve) value to test whether the parameter has a significant impact. Once all parameters have WoE and AUC values, overlay all the generated parameter data until it can be used to validate the model generated from the quantitative statistical modeling and prediction results. Without validation, the analysis results lack clear scientific validity.

$$\text{Tot Area} = \text{n1Bar} = \text{n1TotArea dan n2TotArea} = \text{n1TotArea} + \text{n2Bar}$$

$$\%\ \text{Total Area} = \frac{\text{nTotArea}}{\sum \text{Bar}}$$

$$\%\ \text{Total Landslide} = \frac{\text{nTotLandslide}}{\sum \text{Landslide}}$$

$$\text{n1AUC} = \frac{\text{nP\% Total Landslide} \times \text{n\% Total Area}}{2}$$

$$\mathbf{n2AUC} = \frac{(\mathbf{n1\%\ Tota\ Landslide} + (\mathbf{n1}+\mathbf{1})\%\ \mathbf{Total\ Landslide}) \times (\mathbf{n1})\%\ \mathbf{Total\ Area} + \mathbf{n1}+\mathbf{1})\%\mathbf{Total\ Area})}{\mathbf{2}}$$

2. The same formula is used to find the AUC values in subsequent classes, until the AUC values for each class are summed to obtain the AUC Parameter value, AUC Parameter = ∑AUC Each parameter class. The output from the overlay of each parameter will produce a landslide vulnerability area.
3. Landslide hazard assessment is carried out by identifying areas potentially affected by slope failure, calculating the probability of occurrence, n, and estimating the magnitude (area, volume, rate of movement) of the event (Petley, 2010 in the Landslide Disaster Technical Module - BNPB). Creating a "Landslide Hazard Index" based on the method used in the Landslide Disaster Risk Assessment by the National Disaster Management Agency (BNPB) is all done using ArcGIS Desktop software. Before the analysis process begins, it is recommended to first standardize the coordinate system for all data, namely by using the same coordinate system. The goal is to allow the mathematical analysis process to be carried out directly in meters. Figure 2: Flowchart methodology landslide Hazard Index

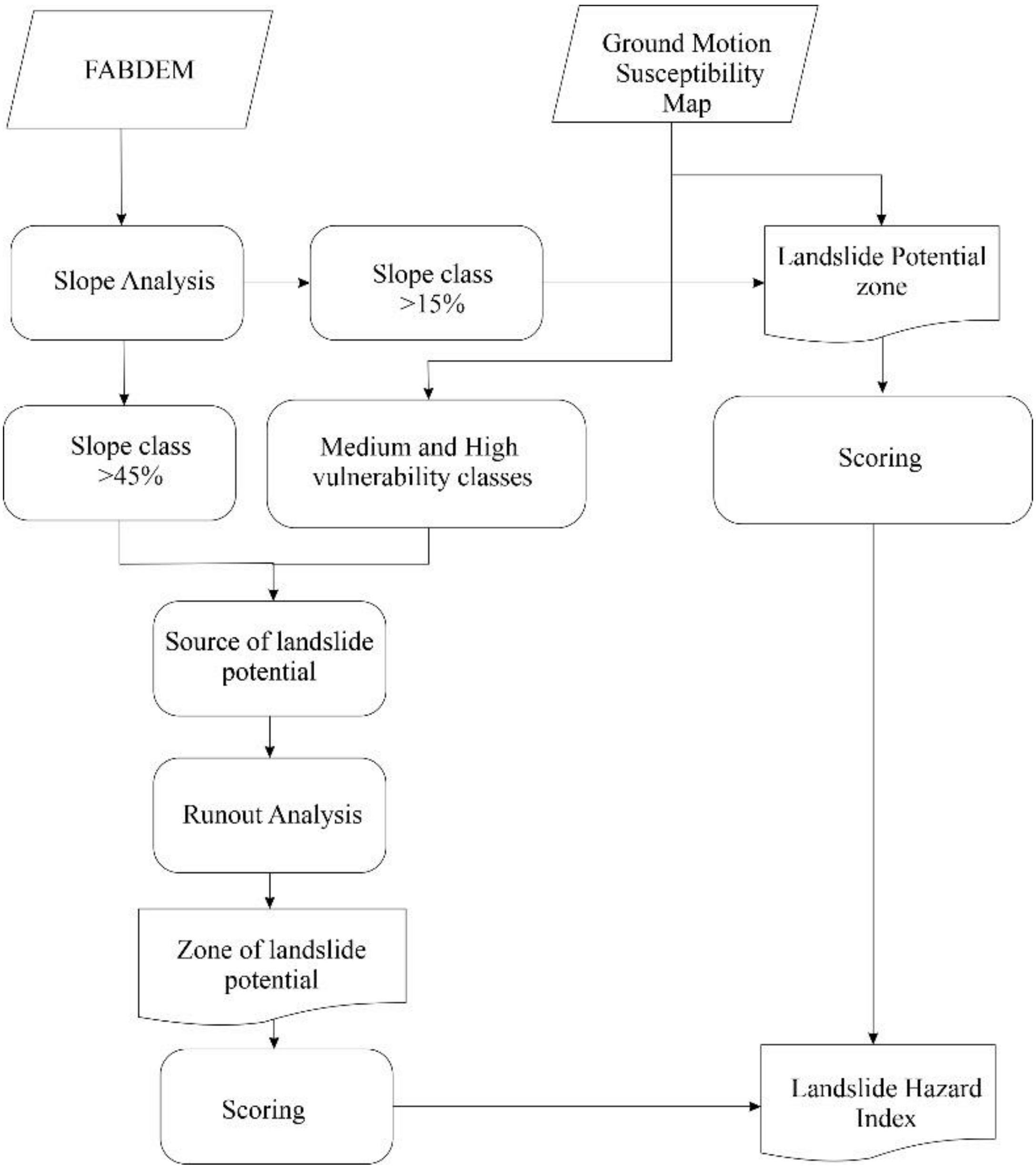


Figure 2: Flowchart methdology landslide Hazard Index

Results and Discussion

Based on disaster reports obtained from the Regional Disaster Management Agency (BPBD) of Central Mamuju, 18 landslide locations have been recorded over the past five years. This study used 13 (70%) of these locations to assess the model's suitability to previous events, and 5 (30%) to test the model's susceptibility to landslides. The spatial distribution of landslide locations in Central Mamuju is dominated by areas near roads, rivers, and areas with steep slopes. The topography of the study area varies from lowlands to highlands, with elevations ranging from 0 to 2,800 meters above sea level. The western part is a coastal area with lowland topography and elevations below 500 meters above sea level. The geology of the study area is dominated by rocks from the Latimojong Formation, a metamorphic rock (Central Mamuju Regional Development Plan 2025).

Using spatial analysis, we can identify the parameters that play a significant role or are most influential in causing landslides, based on the results of the spatial analysis using each parameter.

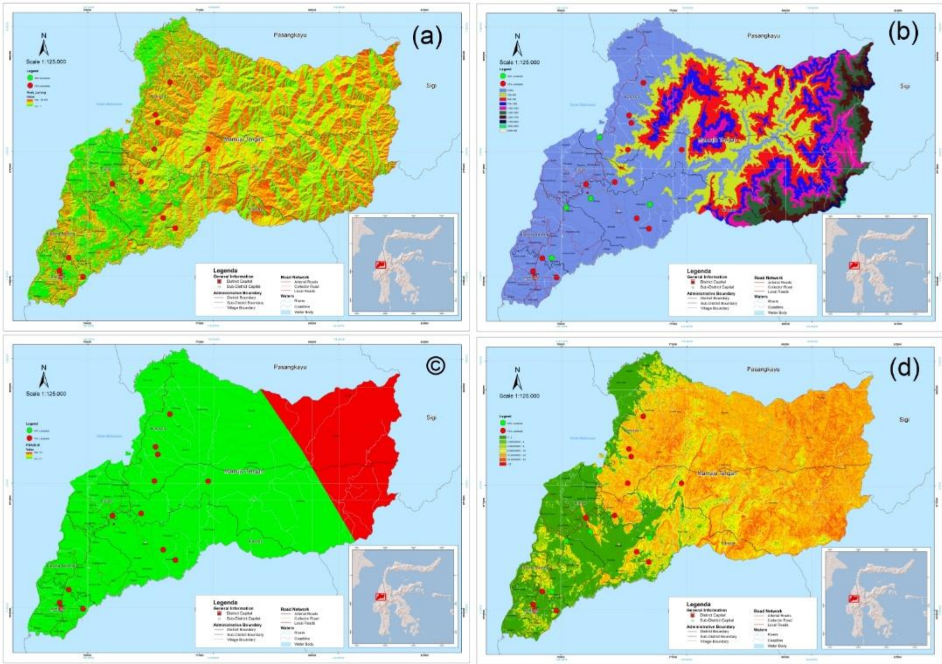


Figure 3: Overlay parameter (a)Slope Direction, (b)Elevation, (c)PGA, and (d)Slope

1. Slope Gradient

Based on spatial analysis using slope parameters, it can be seen that areas with slopes of 17º-24º have the highest likelihood of landslides, and four incidents have been recorded within this slope range. Slope gradient is one of the main factors controlling soil/rock stability. The steeper the slope, the greater the gravitational force acting on it, thus increasing the likelihood of landslides (Varnes, 1978).

Slope						
Class-Id	Slope	Bar	FR	W+	W-	Weight WoE
1	0-2	727150	0.076923	-2.56495	0.253181	-2.859591995
2	2-5 Derajat	144356	0.076923	-2.56495	0.044737	-2.651147238
3	5-8 Derajat	134551	1.824517	0.601319	-0.0387	0.598564479
4	8-17 Derajat	530246	1.40729	0.341667	-0.08935	0.389562704
5	17-24 Derajat	536198	1.831055	0.604896	-0.19454	0.757977542
6	24-33 Derajat	642507	0.442897	-0.81442	0.138247	-0.994125623
7	>33 Derajat	341819	2.140652	0.761115	-0.15503	0.874685168

Table 2: Analysis Weight of Evidence (WoE) on slope parameter

1. Elevation

Based on the analysis using elevation parameters, it was found that 11 landslides occurred in areas at elevations below 500 meters above sea level. Elevation is a contributing factor to landslides because it is a controlling factor affecting rainfall, weathering intensity, soil thickness, and slope conditions. (Cellek,2023)

Elevation						
Class-Id	Elevation	Bar	FR	W+	W-	Weight Woe
1	<500	1459839	1.855004	0.617891	-1.4975	1.050499549
2	500-1000	467399	0.581789	-0.54165	0.072483	-1.679023278
3	1000-1500	399430	0.076923	-2.56495	0.129434	-3.759278714
4	1500-2000	260501	0.076923	-2.56495	0.082189	-3.712033664
5	2000-2500	179543	0.076923	-2.56495	0.055798	-3.685643076
6	2500-3000	160097	0.076923	-2.56495	0.049577	-3.679422211
7	3000-3500	114674	0.076923	-2.56495	0.035219	-3.6650635
8	3500-4000	24622	0.076923	-2.56495	0.007441	-3.637285933
9	4000-4500	1536	0.076923	-2.56495	0.000462	-3.630307121
10	4500-5000	19	0.076923	-2.56495	5.72E-06	-3.62985052

Table 3: Analysis Weight of Evidence (WoE) in Elevation Parameter

2. Slope direction.

Based on the results of spatial analysis using slope direction as a parameter, it can be seen that the most dominant slope direction for landslides is the southeast, with three landslide incidents. Slopes facing the direction of incoming rain or moist winds receive more direct rainfall runoff or are more affected by humidity, resulting in faster soil saturation and greater susceptibility to landslides (Nakileza & Nedala, 2020).

Slope Aspect						
Class_ID	Aspect	Bar	FR	W+	W-	Weight WOE
1	Flat	574283	0.486305	-0.72092	0.112308	-0.862526201
2	North	276631	0.926796	-0.07602	0.007259	-0.112578216
3	Northeast	271424	0.076923	-2.56495	0.086147	-2.680397499
4	East	252138	1.941785	0.663611	-0.08848	0.722796666
5	SouthEast	220144	3.280752	1.188082	-0.19484	1.353623876
6	South	257260	0.076923	-2.56495	0.081432	-2.675683228
7	Southwest	293847	1.677084	0.517059	-0.07475	0.562509719
8	West	314309	1.572911	0.45293	-0.06793	0.491560238
9	NorthWest	317752	0.816812	-0.20235	0.021032	-0.252676773
10	North	278528	0.076923	-2.56495	0.088521	-2.682771632

Table 4: Analysis Weight of Evidence (WoE) pada parameter slope aspect

3. Peak Ground Acceleration (PGA)

Based on the results of spatial analysis with PGA parameters, it can be seen that in areas with a PGA value of 0.2, all landslide incident data recorded by BPBD occurred in this area. PGA is used as a parameter because it is used as a predictor of landslide occurrence because it can measure earthquake intensity.

Peak Ground Acceleration						
Class_ID	PGA	Bar	FR	W+	W-	Weight WOE
1	0.2	2421782	0.076923077	-2.564.953.269	1.495.642.334	-4.912.282.338
2	0.25	639482	0.076923077	-2.564.953.269	0.217624201	-3.634.264.205
3	0.3	6215	4.556.713.039	6.123.700.492	-2.564.953.269	7.836.967.028

Table 5: Analysis Weight of Evidence (WoE) on parameter of PGA

4. Distance from Rivers, Roads, and Geological Structures

Based on the results of spatial analysis using distance from rivers as a parameter, it can be seen that areas located <500 m from rivers, roads, and geological structures are more vulnerable. According to Cellek (2023), locations close to roads are more vulnerable due to slope undercutting and drainage changes, while proximity to rivers increases the risk of toe-slope erosion and soil saturation. Furthermore, areas around faults are more prone to landslides due to weak geological conditions and potential tectonic activity.Figure 4: Overlay parameter distance from (a)River,(b)Roads,(c)Structure geology.

Distance from River						
Class_ID	Distance	Area	FR	W+	W-	Weight WOE
1	500	608506	1.240230866	0.215298562	-0.061288981	0.242264746
2	500-1000	471475	1.578338357	0.456375072	-0.110971456	0.53302373
3	1000-1500	401382	0.664791798	-0.408282793	0.049233835	-0.491839425
4	1500-2000	346434	0.758033831	-0.277028287	0.030341435	-0.341692519
5	2000-2500	293284	1.686011354	0.522368501	-0.075288838	0.563334541
6	2500-3000	236865	0.076923077	-2.564953269	0.074405162	-2.673681229
7	3000-3500	184815	1.353658856	0.302812689	-0.022935082	0.291424974
8	3500-4000	139472	0.076923077	-2.564953269	0.043030585	-2.642306652
9	4000-4500	95714	0.076923077	-2.564953269	0.029297023	-2.62857309
10	4500-5000	71138	3.39385528	1.221976671	-0.05851323	1.246167104
11	>5000	218394	0.076923077	-2.564953269	0.06836675	-2.667642817

Table 6: Analysis Weight of Evidence (WoE) pada parameter distance from river

Distance from Road						
Class_ID	Distance	Bar	FR	W+	W-	Weight WOE
1	500	1190896	2.454560651	0.897953949	-2.564953269	1.58805903
2	500-1000	204514	0.076923077	-2.564953269	0.063856742	-4.5036582
3	1000-1500	91868	0.076923077	-2.564953269	0.028100348	-4.467901805
4	1500-2000	60152	0.076923077	-2.564953269	0.018294917	-4.458096375
5	2000-2500	48284	0.076923077	-2.564953269	0.014654325	-4.454455782
6	2500-3000	42086	0.076923077	-2.564953269	0.012759159	-4.452560617
7	3000-3500	38965	0.076923077	-2.564953269	0.01180643	-4.451607888
8	3500-4000	37948	0.076923077	-2.564953269	0.011496205	-4.451297662
9	4000-4500	37428	0.076923077	-2.564953269	0.011337627	-4.451139085
10	4500-5000	36777	0.076923077	-2.564953269	0.011139142	-4.4509406
11	>5000	1278561	0.076923077	-2.564953269	0.506660187	-4.946461645

Table 7: Analysis Weight of Evidence (WoE) on parameter of distance from road

Distance from Structural Geology						
ClassID	Distance	Bar	FR	W+	W-	WeightWOE
1	500	384043	0.691333242	-0.369134619	0.043227474	-0.412362093
2	500-1000	359662	0.076923077	-2.564953269	0.115653644	-2.680606913
3	1000-1500	298084	0.868511767	-0.140974702	0.014053589	-0.155028291
4	1500-2000	231623	1.095647137	0.091345587	-0.007842838	0.099188425
5	2000-2500	179689	1.390080382	0.329363228	-0.024571777	0.353935004
6	2500-3000	141974	0.076923077	-2.564953269	0.043822496	-2.608775765
7	3000-3500	113428	0.076923077	-2.564953269	0.03483027	-2.599783539
8	3500-4000	96633	0.076923077	-2.564953269	0.029583214	-2.594536484
9	4000-4500	79939	0.076923077	-2.564953269	0.02439921	-2.58935248
10	4500-5000	63.684	0	-3	0	-2.584334637
11	>5000	1.118.720	1.764279506	1	-1	1.14533337

Table 7: Analysis Weight of Evidence (WoE) on parameter distance from Structural Geology

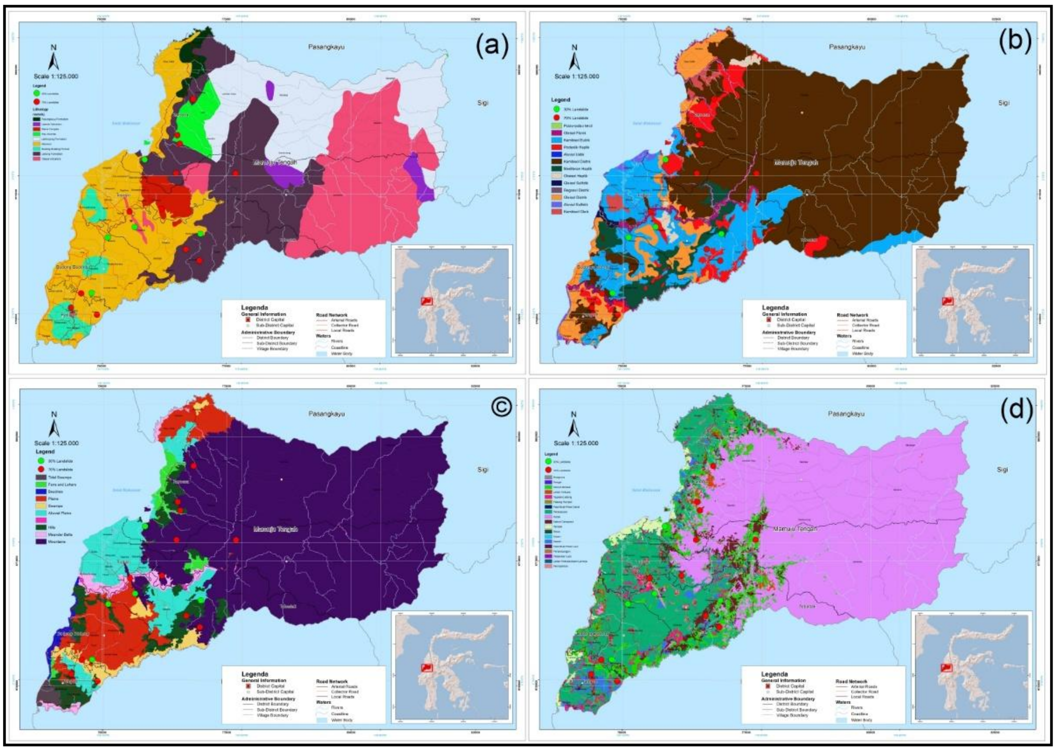


Figure 5: Overlay parameter (a)Lithology, (b)Soil,(c)Land Sistem, (d)Land Cover

4. Geology

Based on the results of spatial analysis with Geological parameters, it is known that landslides often occur in areas that include the Lariang formation, with 5 incidents recorded in this area, because this formation consists of fragile rocks such as sandstone and conglomerate so that it is easily eroded when it rains.

Geology						
Class_ID	Geology	Bar	FR	W+	W-	Weight WOE
1	Pasangkayu Formation	42987	0.077	-2.565	0.013	-2.614
2	Lamasi Volcanics	68161	0.077	-2.565	0.021	-2.622

3	Wana Complex	73425	3.291	1.191	-0.058	1.212
4	Palu Granite	84069	2.884	1.059	-0.055	1.077
5	Latimojong Formation	587437	0.077	-2.565	0.198	-2.799
6	Alluvium	711835	0.740	-0.301	0.076	-0.413
7	Budong-Budong Format	86319	5.544	1.713	-0.141	1.817
8	Lariang Formation	689408	1.788	0.581	-0.259	0.804
9	Talaya Volcanics	723838	0.403	-0.909	0.169	-1.115

Table 8: Analysis Weight of Evidence (WoE) on parameter Geology

5. Soil

Based on the results of spatial analysis with soil type parameters, Cambisol soil is the type of soil that most often experiences landslides. This is because this type of soil has clay characteristics, quickly saturates so that it increases the weight of the slope soil mass, reduces cohesion, easily expands and shrinks when humidity variability occurs. (Harry, Arif.2021)

Soil						
Class_Id	Soil	Bar	FR	W+	W-	Weight WOE
1	Pulau-pulau kecil	24981	0.077	-2.565	0.008	-2.526
2	Gleisol Fluvik	62459	3.855	1.349	-0.061	1.457
3	Kambisol Eutrik	459305	1.618	0.481	-0.115	0.643
4	Podsolik Haplik	153703	1.612	0.478	-0.033	0.557
5	Aluvial Ustik	384	0.077	-2.565	0.000	-2.518
6	Kambisol Distrik	1939903	0.928	-0.074	0.116	-0.144
7	Mediteran Haplik	129780	0.077	-2.565	0.040	-2.558
8	Oksisol Haplik	22811	0.077	-2.565	0.007	-2.525
9	Gleisol Sulfidik	6672	0.077	-2.565	0.002	-2.520
10	Regosol Distrik	3375	0.077	-2.565	0.001	-2.519
11	Gleisol Distrik	219627	0.077	-2.565	0.069	-2.587
12	Aluvial Sulfidik	17642	0.077	-2.565	0.005	-2.524
13	Kambisol Gleik	26837	0.077	-2.565	0.008	-2.526

Table 9: Analysis Weight of Evidence (WoE) pada parameter Soil

6. Landcover and Land System

Based on the results of spatial analysis using land cover and land system parameters, hilly areas with plantation and shrub cover that frequently experience landslides in the Central Mamuju area have been recorded several times. This change in land use significantly affects the mechanical behavior of the soil and that changes in land use such as deforestation, road construction, slope excavation can reduce slope stability. (Renata, dkk. 2022).

Land System						
Class_ID	Land System	Bar	FR	W+	W-	Weight WOE
1	Tidal Swamps	21529.000	0.077	-2.565	0.007	-2.471
2	Fans and Lahars	42976.000	0.077	-2.565	0.013	-2.478
3	Beaches	19769.000	0.077	-2.565	0.006	-2.471
4	Plains	289556.000	0.077	-2.565	0.092	-2.557
5	Swamps	73800.000	3.274	1.186	-0.058	1.344
6	Alluvial Plains	270648.000	0.077	-2.565	0.086	-2.550
7	Lower Hills	27759.000	0.077	-2.565	0.008	-2.473

8	Hills	177989.000	5.380	1.683	-0.314	2.097
9	Meander Belts	61589.000	0.077	-2.565	0.019	-2.484
10	Mountains	2081864.000	0.870	-0.139	0.242	-0.281

Table 10: Analysis Weight of Evidence (WoE) on parameter of land system

Land Cover						
Class_ID	Land Cover	Bar	FR	W+	W-	Weight WOE
1	Mangroves	6283	0.077	-2.565	0.002	-2.349
2	Rivers	24097	0.077	-2.565	0.007	-2.354
3	Shrublands	208944	3.465	1.243	-0.199	1.659
4	Open Land	24159	9.844	2.287	-0.073	2.578
5	Fields/Fields	75431	3.205	1.165	-0.057	1.440
6	Grasslands	4320	0.077	-2.565	0.001	-2.348
7	Inland Sand/Dunes	1139	0.077	-2.565	0.000	-2.347
8	Plantations	649064	1.168	0.155	-0.046	0.419
9	Forests	1837833	0.462	-0.772	0.590	-1.144
10	Mixed Gardens	117375	0.077	-2.565	0.036	-2.383
11	Fishponds	40637	0.077	-2.565	0.012	-2.359
12	Swamps	4096	0.077	-2.565	0.001	-2.348
13	Ponds	473	0.077	-2.565	0.000	-2.347
14	Ricefields	38623	0.077	-2.565	0.012	-2.359
15	Sea Sand/Dunes	178	0.077	-2.565	0.000	-2.347
16	Mining	46	0.077	-2.565	0.000	-2.347
17	Seaports	9	0.077	-2.565	0.000	-2.347
18	Other Natural Open Lands	73	0.077	-2.565	0.000	-2.347
19	Settlements	34699	6.877	1.928	-0.070	2.216

Table 11: Analysis Weight of Evidence (WoE) on parameter land cover

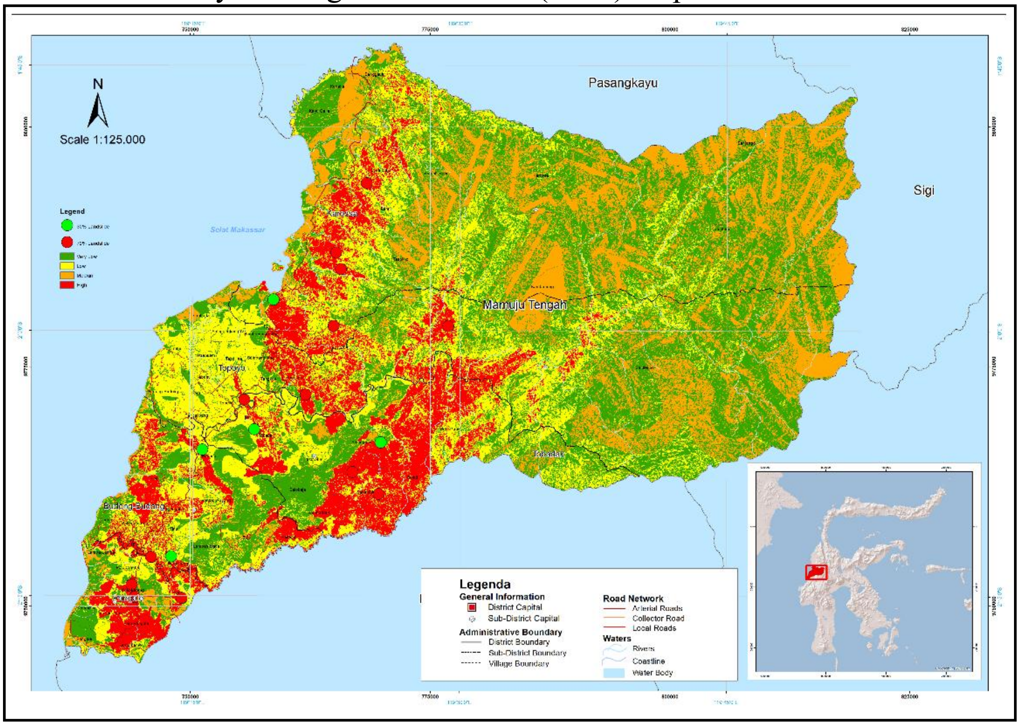


Figure 6: Land Movement Vulnerability Map of Mamuju Tengah From WoE Analysis result

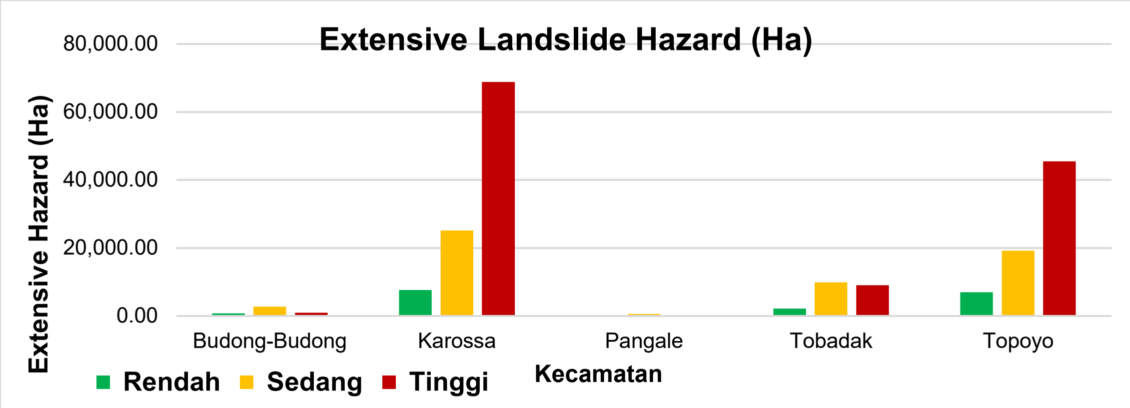
From the results of the WoE analysis to obtain landslide vulnerability zones, it can be seen that areas or zones classified as very low cover 36.1%, low 25.8%, medium 24%, and high 13.1% of the total analysis area, the resulting model is included in the very good category 0.9/1 based on the Yesilnacar, 2005 classification.

Landslides are the movement of rock, soil, or other materials that make up a slope, sliding down or off the slope due to the influence of gravity. This phenomenon occurs when the stability of the slope is disturbed, which is generally triggered by heavy rainfall, ground movement, or vibrations. Under these conditions, the Central Mamuju region, with its sloping topography, is at risk of landslides. To understand the level of threat, a study is required using several parameters described previously. Through analysis of these parameters, the level of landslide danger can be determined, including the extent of landslide-prone areas in each area within Central Mamuju Regency.

Kecamatan		Extensive Longsor (Ha)			Total Extensive (Ha)	Class
		Low	Medium	High		
01	Budong-Budong	734,89	2.712,94	937,10	4.384,93	High
02	Karossa	7.595,62	25.119,21	68.831,27	101.546,10	High
03	Pangale	4,32	554,22	25,29	583,83	Medium
04	Tobadak	2.160,63	9.922,68	9.016,20	21.099,51	High
05	Topoyo	6.964,38	19.252,53	45.494,55	71.711,46	High
Kabupaten Mamuju Tengah		**17.459,84**	**57.561,58**	**124.304,41**	**199.325,83**	**High**

Table 12: PotentiaL Hazard Map of Flood in Mamuju Tengah

The potential landslide hazard shown in the previous table illustrates the distribution of sub-districts in Central Mamuju Regency that are vulnerable to landslides based on the results of the study. The total landslide hazard area in this regency was obtained by accumulating the hazard area from all affected sub-districts, while the determination of the district's hazard class was determined based on the highest hazard category found in each sub-district. Overall, the potential landslide hazard in Central Mamuju Regency reaches 199,325.83 Ha with a high classification, the area is divided into three hazard classes, namely low class covering 17,459.84 Ha, medium class covering 57,561.58 Ha, and high class covering 124,304.41 Ha.



The graph shows the distribution of landslide-prone areas in Central Mamuju Regency in each potentially affected sub-district. Karossa Sub-district holds the highest position in the low hazard class with an area of 7,595.62 hectares, while also recording the largest area in the medium hazard class at 25,119.21 hectares. In the high hazard category, Karossa dominates with an area reaching 68,831.27 hectares. Overall, the highest level of landslide vulnerability is found in Karossa and Topoyo Sub-districts, so these two areas require special attention through more serious and planned management measures.

Conclusion and Recommendation

This study successfully identified the dominant factors influencing landslide vulnerability in Central Mamuju Regency using a multivariate Weight of Evidence (WoE) approach. The analysis showed that slope, elevation, and land cover were the most influential factors affecting landslide occurrence. Model validation yielded an AUC value of 0.93, which is considered a very good model, making this method reliable for predicting landslide hazard potential in the study area. Spatially, the high landslide vulnerability zone covers 13.1% of the total study area, with the main concentration in the Karossa and Topoyo Districts. The total landslide hazard potential reaches 199,325.83 hectares, classified as high, with 17,459.84 hectares classified as low, 57,561.58 hectares classified as medium, and 124,304.41 hectares classified as high.

Recommendations based on the research findings are:

1. Structural and Non-Structural Mitigation

2. Land Use Control

3. Integration into regional planning

4. Monitoring and further research

References

Badan Nasional Penanggulangan Bencana. (2019). *Modul teknis penyusunan kajian risiko bencana tanah longsor* (Versi 1.0). Direktorat Pengurangan Risiko Bencana, BNPB.

Çellek, S. (2023). Morphological parameters causing landslides: A case study of elevation, slope, aspect, plan, and profile *curvature. Arabian Journal of Geosciences, 16(*2), 176. https://doi.org/10.1007/s12517-022-11178-7

Harmandar, E. (2012). A method for spatial estimation of peak ground acceleration in the Marmara region using regression models. *Geophysical Journal International, 191*(3), 1272–1284. https://doi.org/10.1111/j.1365-246X.2012.05694.x

Kristie, H. J., & Budiman, A. (2021). Karakteristik sifat fisis tanah daerah potensi longsor di Jalan Raya Sumbar–Riau Nagari Koto Alam, Sumatera Barat. *Jurnal Fisika Unand, 10*(1), 123–129. https://doi.org/10.25077/jfu.10.1.123-129.2021

Nakileza, B. R., & Nedala, S. (2020). Topographic influence on landslides characteristics and implication for risk management in upper Manafwa catchment, Mt Elgon Uganda. *Geoenvironmental Disasters, 7*(27), 1–17. https://doi.org/10.1186/s40677-020-00160-0

Pusat Vulkanologi dan Mitigasi Bencana Geologi. (n.d.). *Pedoman teknis Analysis peta kerentanan gerakan tanah menggunakan metode statistik bivariate Weight of Evidence: Studi kasus Bopunjur*. Kementerian Energi dan Sumber Daya Mineral, Badan Geologi.