Weights of Evidence Method for Landslide Susceptibility Mapping in Tandikek and Damar Bancah, West Sumatra, Indonesia

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Abstract: ***The September 30, 2009, Padang earthquake has induced huge landslide in Padang Pariaman district, West Sumatera, Indonesia. The goal of this paper is to assess the landslide susceptibility of Pariaman, using the weight of evidence statistical method. The method is based on the decision of which state is more likely to occur grounded on the presence or absence of a predictive variable and the occurrence of an event (e.g., landslide) within a pixel. This method can be used without requiring geotechnical, groundwater or failure depth data. However, the other factors to influence landslide occurrence, such as slope, curvature, peak ground acceleration, geological condition, lineaments/faults distance of landslide to the rivers and, land use can be known. This is quite impressive, based on AUC The highest factor controlling the landslide is lineament, than following with lithology, peak ground acceleration, slope and land use. Weights calculated individually for those themes were added to produce a probability estimate of the area. The predictive of the map was tested on the basis of 35% sample of landslides that were not used in the modeling process (test data). Analytical result verified by using test data of landslide shows AUC prediction rate is 0.849 and AUC success rate using all landslide data is 0.894 with difference 0.045. This condition to the allowed tolerance of 15%. This is showing good model of landslide susceptibility. The obtained landslide susceptibility map and landslide inventory data base can be used for landslide hazard prevention and mitigation, and proper planning for land use in the future.***

Keywords: Weights of evidence, landslide susceptibility map, area under curve.

1. Introduction

Landslides are a complex natural phenomenon that constitutes a serious natural hazard in many countries (Hutchinson, 1988; Cruden and Varnes, 1996). Nakano (2015) founds that the landslide at Padang Pariaman strongly controlled by geological factors as weathering of mixed layer at the base of pumice fall deposit, slope paralel to the pumice fall deposits, which had been cut at the foot slope and undercutting by river incision

Landslide susceptibility maps can be obtained through different methods: by empirical or heuristic, by qualitative or semi-quantitative combination of thematic layers, which are estimated as correlated with landslide occurrences (Rupke et al. 1988), or using deterministic and statistical techniques (descriptive, univariate, bivariate, or multivariate statistical analysis, Lee et al. 2002).

In spatial analysis, WOE was proposed by Agterberg and developed in the mineral and mining fields in late 1980s. WOE modeling for landslide susceptibility mapping, using the log-linear form of the Bayesian probability model, has been recently applied in geomorphologic risk assessments (van Westen 1993; van Westen 2002 ; van Westen et al. 2003, 2006; Lee et al.2002; Ranjan et al. 2008; Barbieri and Cambuli 2009). Bivariate statistical analysis methods such as WoE is one of the methods used to conduct landslide susceptibility mapping. This method utilizing historical data events to gain patterns geofactor or parameters that controlling and influence of the landslide occurrence (Sumaryono. 2013). GIS-based statistical methods have become very popular in landslide susceptibility assessment (van Westen et al. 2006), because of effective data management, simultaneous use, graphic and attribute crossing of these digital layers, and providing accurate output data and superior image quality. Advantages of this method are the accuracy that can be accounted and can be done quickly. Several statistical approaches that have been discussed and used in Van Westen, 2003, and is: "Information Value", "Frequency Ratio", "and Weight of Evidence".

2. Study Area

Pariaman regency located in West Sumatra Province, Indonesia (Figure 1). Landslide in this area triggered by West Sumatra Earthquake, 30 September 2009. Based on GIS analysis, West Sumatra Earthquake trigger 154 landslides. Extensive landslides occurred in Agam and Padang Pariaman Regency, West Sumatra Province, Indonesia, causing more than 250 peoples lost their live, and burying some villages. The landslides occurred during rainfall, and originated on mountains mantled with loose pumice. Translational slides and flowside are spread over the entire area on hornblende hypersthene pumiceous tuff. A lithological unit affected by translational slides is hornblende hypersthene pumiceous tuff underlying clay layer from the thepra alteration. From a geological point of view, shows the landslide occurred dominantly on hornblende hypersthene pumiceous tuff, a tephra deposit from Tandikat Volcano which consists of pumice lapilli, ranging from 2 – 10 cm in diameter, slightly consolidated (Qhpt). Landslide predominantly occurs in this rock type due to unconsolidated, very loose structure, easy collapse and eroded, pores are larger and have high permeability. Several landslide and rock fall occurred at andesite of Maninjau lake caldera. The elongated form of the caldera could indicate a prolonged period of eruption during right lateral displacement on the Great Sumatran Fault; also the pumice tuff seems to overlie all the Maninjau volcanic rock. Many landslides located at Manggur Gadang River, these rivers represented alignments of morphology. Susceptibility of landslide can be expressed by the spatial susceptibility of landslide which is controlled by geomorphology, geology, slope, land use/land cover, structure geology. Weights of evidence method can be used to develop landslide susceptibility mapping in this area.

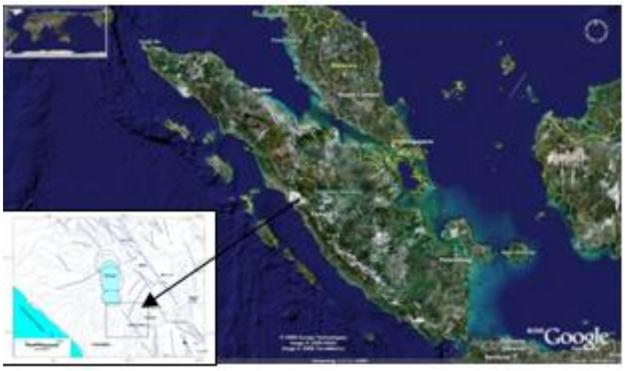


Figure 1: Study area

3. Research Methodology

A bivariate statistical analysis method such as WoE (Weight of Evidence) is one of the methods used to conduct landslide susceptibility mapping. This method utilizing historical data events to gain patterns parameters that controlling and influence of the landslide occurrence. Advantages of this method are the accuracy that can be accounted and can be done quickly and cheaply. To solve spatial-based problems such as geo-hazards (landslide, erosion, earthquakes) and site selection, GIS-based software have been used. Geo-factor Maps is some layer parameters containing the input parameters for a statistical approach. Each statistic methods are obtained from the relationship between geofactor of landslide and distribution of landslide. Bivariate statistical analysis using weight of evidence that a method based on the Bayes theorem is constructed but not for spatial analysis for diagnosis in the medical field since the '80s but found the application that can be used in earth science is the exploration of natural resources (Bonham-Carter et al, 1988) and also can be used in vulnerability assessment of ground movement (van Westen et al, 2003). Calculation of each particular predictive variable a positive weight (W+), when the event occurs and a negative weight (W-), when the event does not occur. The weights are measures of correlation between evidence (predictive variable) and event, facts that make them easy to interpret in relation to empirical observation. Formulation based on density functions.

$$W^{+} = \ln\left(\frac{\frac{Npix\ landslide\ area\ in\ class}{Npix\ total\ landslide\ area}}{\frac{Npix\ stable\ area\ in\ class}{Npix\ total\ stable\ area}}\right) \quad (1)$$

$$W^{-} = \ln\left(\frac{\frac{Npix\ landslide\ area\ outside\ class}{Npix\ total\ landslide\ area}}{\frac{Npix\ stable\ area\ outside\ class}{Npix\ total\ stable\ area}}\right) \quad (2)$$

Weights of each cell are determined by the equation;

$$W_i = \sum_{j=1}^{n} W_j^k \quad (3)$$

Where wj is a class parameter and wk describing positive and negative values of the weight. In this method factors controlling landslide can be mapped.

The weights can be used to produce a contrast value (C) for the particular susceptibility variable.

$$C = W^{+} - W^{-} \quad (4)$$

The obtained difference between weights (*C*) provides a measure of the strength of the correlation between the analyzed variable and landslides. In this method factors controlling landslide can be mapped by 5 parameters are: slope, curvature, lineament, geology, peak ground acceleration and distance of landslide to the river, land use, and rainfall. The research methodology for WoE (Figure 2.

Validation is a fundamental step in the development of susceptibility and prediction ability. The prediction of a landslide susceptibility model is usually estimated by using independent information. An alternative way to the above statistics is the area under the curve (AUC) (Van Westen et.al. 2009, Wahono, 2010, Pimiento, 2010). Formulation is defined as:

$$AUC = \sum_{i=0}^{n}(x_i - x_{i-1})y_i - \left[\frac{(x_i - x_{i-1})(y_i - y_{i-1})}{2}\right] \quad (5)$$

x_i; precentage area; y_i; precentage landslide area

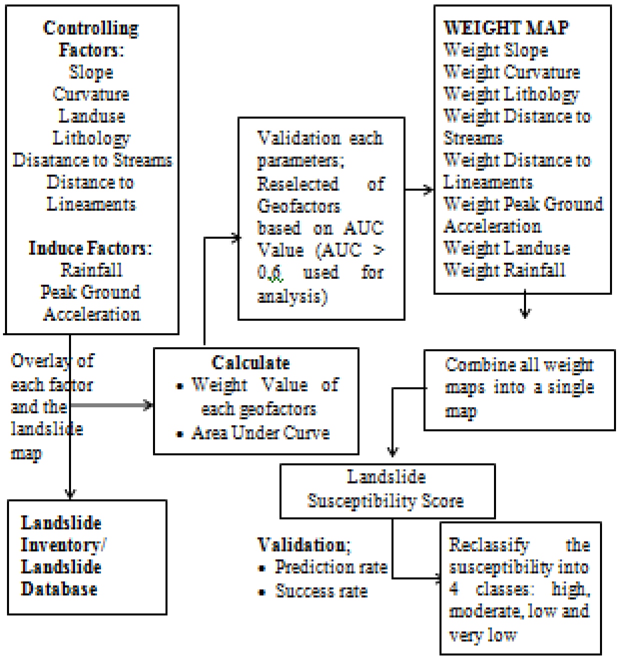


Figure 2: The methodological for WoE Method

4. Analysis and Results

4.1 Data basis and analysis

The initial step in the analysis was the preprocessing of the data (Fig. 2). The following basic maps were obtained from field mapping, interpretation of topographic maps and DEM:

- Landslide occurrence and inventory landslides were digitised from spot-5 and IFSAR
- Lithology
- Land use at 1/50,000;
- Digital elevation model (DEM) was developed for the area based on the IFSAR with 5 x 5 m resolution.
- Peak ground acceleration
- Rainfall intensity

Landslide inventory map is very essential for studying the relationship between the landslide distribution and the factors controlling the landslide. Landslide distribution and characteristic are important parameter for develop landslide susceptibility (Figure 3 and 4). To produce a detailed and reliable landslide inventory map, extensive field surveys and observations were performed in the study area. A total of 154 landslides were identified and mapped in the study area by evaluating Spot-5 and IFSAR. 65% of landslide data for analysis (training data), and 35% of landslide data used for prediction rate (test data). Figure 6 is the parameter for analysis landslide susceptibility.

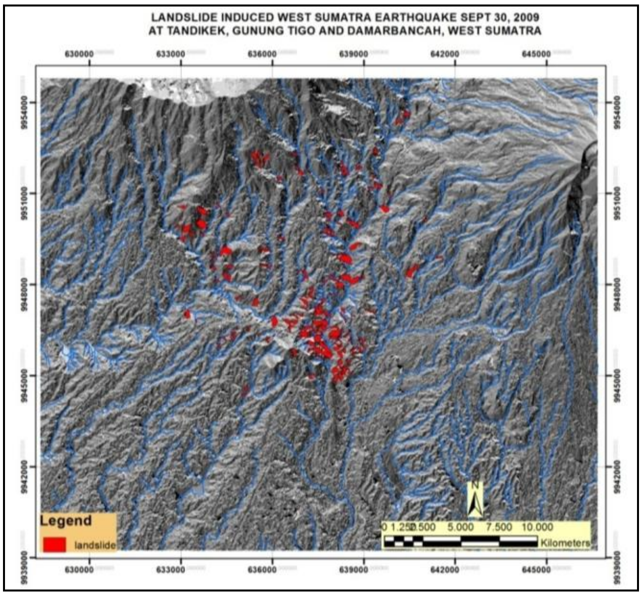


Figure 3: Landslide induced earthquake around Tandikek, Gunung Tigo, West Sumatra

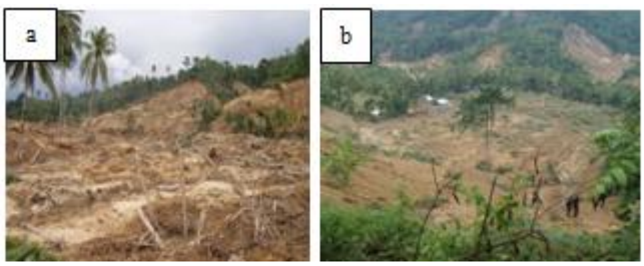


Figure 4: (a) Flowslide showing long travel distance (b) Morphology of landslide around Manggur Gadang River (c) scarp of the landslide with slope with 30^o slope

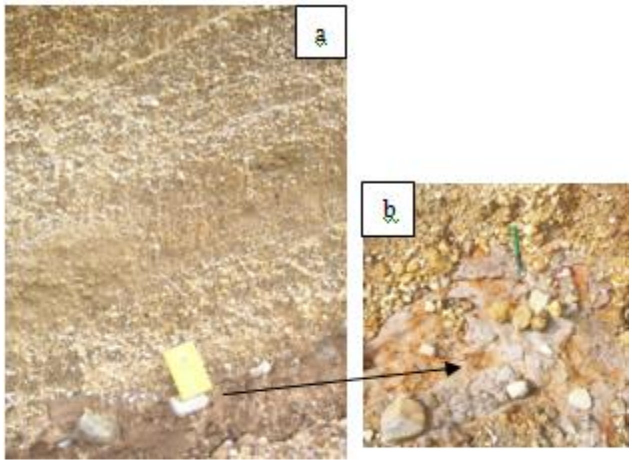
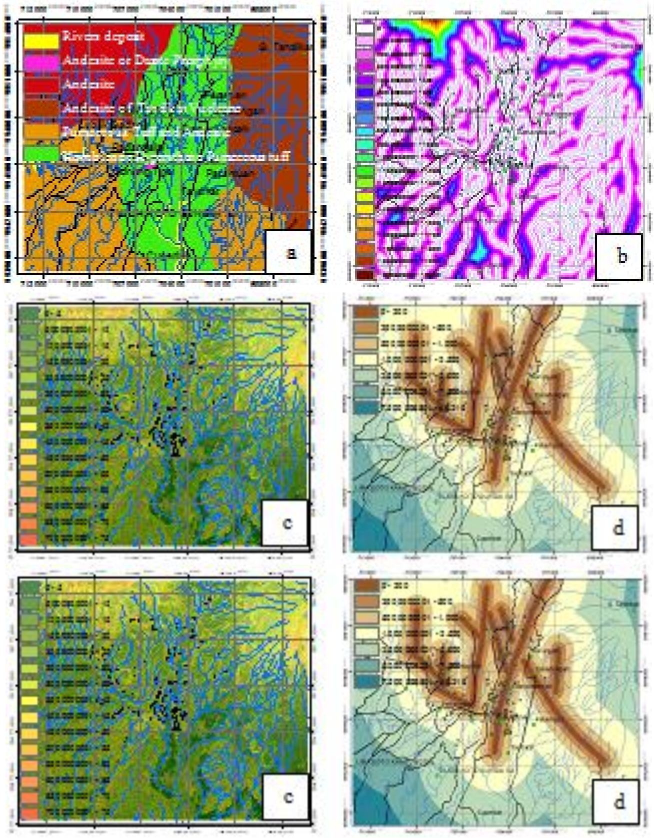


Figure 5: (a) stratigraphy of the sliding surface pumiceous tuff overlying clay layer (b) sliding surface of the landslide



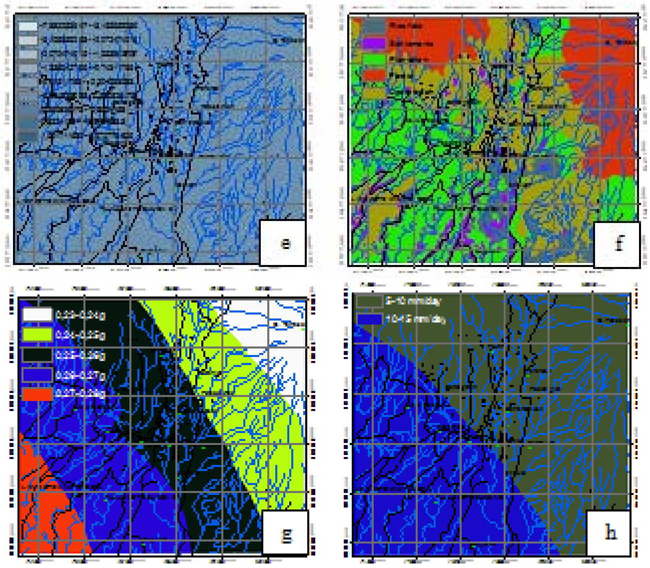


Figure 6: Parameters for Landslide Susceptibility Analysis (a) geological map, (b) distance to the stream, (c) slope (d) distance to the fault (e) slope curvature (f) land use (g) peak ground acceleration (h) rainfall intensity (mm/day)

4.2. Weight of Evidence Analysis

Area under curve test applied on the geofactor parameter, the selected predictive variables were as follows slope gradient, slope curvature, lithology, distance to lineament, distance to stream, peak ground acceleration, rainfall intensity and land use. The rainfall intensity and land use were not taken into account for the susceptibility analysis, because AUC indicates lower than 0.6. Based on WoE analysis, this fact indicates the lineament, lithology, slope, distance to the stream and slope curvature controlled the landslide occurrences.

As higher value for W+, as stronger is the positive correlation. High positive correlations to landslides are obtained for 20–40^o and 45-55^o slope angle class. This category has also a greater predictive power (C>1). When C is approximately 2, the correlation is very significant (Barbieri and Cambuli 2009). Area under curve 0,76 show that the slope is dominant factor controlling the landslide. In case of slope curvature, mostly landslides occurred on convex slope, even though some landslides occurrred on concave slope. This is because of on convex slope has more thickness hornblende – hypersthene pumiceous tuff. The area under curve 0.63 shows that slope curvature is slightly dominant. Distance the landslide to the lineament so us useful parameter. Based on area under curve the landslide distance to the lineament has highest factor compare which other (AUC 0,83). It's show that geological structure like fault has highest factor controlling the landslide in this area. Based on field investigation and morphology analysis by using IFSAR, it was identified that the existence of structural geology i.e. fault and lineament patterns was the important controlling factor for landslide, especially in creating the slope steepness (with 20^o to 50^o inclination) and jointed conditions in the andesitic and tuffaceous sandstone. Moreover, the existence of unstable and thick layer of hornblende hypersthene pumiceous tuff as the blanket covering the steep slope of andesitic or clay layer (Figure 5). Therefore, hornblende hypersthene pumiceous tuff was very sensitive to slide down slope, when it was triggered by the extreme rainfall or/and earthquake acceleration. This result confirmed with the landslide generally occurred close to the stream. Mostly landslide occurred on the range 0 – 400 m to the stream. This is clearly that lineament or fault has high contribute control the landslide occurrence beside the earthquake acceleration.

Based on the spatial analysis the landslides occourred mostly triggerring by earthquake acceleration, in fact that landslide occur during earthquake and rainfall. According to Faris, 2014 that the slope would fail due to earthquake shaking, even without pore pressure increase. However, because the Tandikat landslide occurred during rainfall and underwent flow mobility. He suggests that earthquake of smaller magnitude than the M7.6 2009.9.30 Padang earthquake can still lead to disaster if the required condition of sliding zone saturation due to rainfall is attained. This condition is similar with field investigation that after the rainfall the sliding surface easy to saturate (Figure. 7).

The result of WoE modeling is a probabilistic map based on evidence of landslides occurring adjusted given the data (Table.1). Weights calculated individually for the six parameters to produce estimated evidence. Weights between 0.1 and 0.5 are middle predictive, 0.5 and 1 are moderately predictive, 1 and 2 are strongly predictive, and greater than 2 are extremely predictive for the susceptibility analysis (Bonham-Carter et al. 1989).

Figure 7: Saturation of sliding surface during and after the rainfall

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Table 1: The weights, contrast values and AUC for each parameters

Classes	*Class area from total area (%)*	*Parameter Landslide-affected area in the parameter class (%)*	*Weight+*	*Weight-*	*Contrast value ©*	*AUC*
Controlling factors						
Slope (°)						
0-5	161,802	0,0334	-462,531	0,174978	-480,029	0,75
10-May	275,821	0,1546	-309,371	0,310254	-340,396	
15-Oct	216,669	23,472	-0,3733	0,082671	-0,45597	
15-20	143,243	49,331	0,369713	-0,077718	0,447417	
20-25	89,746	112,054	1,190,767	-0,25559	1,446,362	
25-30	51,866	109,877	1,171,133	-0,129714	1,300,846	
30-35	29,106	138,123	1,400,193	-0,095979	1,496,172	
35-40	15,183	6,637	0,666576	-0,014712	0,681287	
40-45	0,8008	0,0334	-462,531	0,007964	-46,333	
45-50	0,4525	74,189	0,778033	-0,005363	0,783396	
50-55	0,2226	150,484	1,486,034	-0,007649	1,493,682	
55-60	0,1233	0,0334	-462,531	0,00122	-462,653	
60-65	0,0488	0,0334	-462,531	0,000484	-462,579	
65-70	0,00702	0,0334	-462,531	6,95E-05	-462,538	
70-75	0,00134	0,0334	-462,531	1,32E-05	-462,532	
Curvature						
-7,882 –	0,598	0,056	0,50015	-0,00391	0,504062	0,63
-3,1556						
-3,1556 –	2,598	0,026	-0,26876	0,006268	-0,27503	
-2,0725						
-2,0725 -	6,340	0,048	0,337702	-0,02757	0,365268	
-1,334						
-1,334 -	11,475	0,012	-104,563	0,080738	-112,637	
-0,743						
-0,743 -	18,288	0,022	-0,42612	0,074795	-0,50091	
-0,2015						
-0,2015 - 0,291	20,664	0,038	0,096296	-0,02668	0,122976	
0,291 - 0,832	20,139	0,027	-0,23741	0,051925	-0,28934	
0,832 - 1,522	14,235	0,050	0,3759	-0,07874	0,454645	
1,522 - 4,6728	5,663	0,077	0,815992	-0,0787	0,894695	
Distance to lineament (m)						
0-200	70,719	0,109	1,163,381	-0,18313	13,465	**0,83**
200-500	96,059	0,1082	1,155,643	-0,26273	141,838	
500-1000	136,154	0,1034	1,110,594	-0,38665	14,973	
1000-2500	268,759	6,55E-03	-164,951	0,260077	-190,959	
2500-5000	299,533	3,34E-04	-462,531	0,353212	-49,785	
5000-7500	9,644	3,34E-04	-462,531	0,100503	-472,582	
7500-10217	32,335	3,34E-04	-462,531	0,032563	-465,787	
Geology						
Hornblende Hypersthene Pumiceous tuff	291,168	0,00095604	103,184	-1,352,099	2,383,933	**0,79**
Andesite	173,312	0,000254032	-0,2942	0,052060	-0,346265	
Pumiceous Tuff and Andesite	270,948	6.50E+00	-165,721	0,263054	-192,027	
Andesite of G. Singgalang and Tandikat	249,188	3.34E-01	-462,531	0,284266	-490,958	
Andesite or Dasite Phorphyry	0,1277	3.34E-01	-462,531	0,00127	-462,658	
River deposit	14,107	3.34E-01	-462,531	0,014074	-463,939	
Landuse						
Ricefield	4,483	0,015244	-0,80499	0,025625	-0,83062	**0,7**
Settlements	5,353	0,01282	-0,97818	0,034694	-101,288	
Plantation	34,689	0,017676	-0,65694	0,22781	-0,88475	
Forest	21,361	0,001899	-288,808	0,228418	-31,165	
Underbrush	34,113	0,076752	0,812011	-104,422	1,856,233	
Controlling factors						
Distance to stream (m)						
0-100	35,464	0,04651	0,310822	-0,22351	0,53433	0,65
100-200	22,754	0,035586	0,042972	-0,01302	0,055989	
200-300	17,796	0,020993	-0,48495	0,079921	-0,56487	
300-400	9,907	0,040817	0,180183	-0,02195	0,202131	
400-500	6,387	0,010799	-114,973	0,045576	-119,531	

500-600	3,290	0,030813	-0,1011	0,003265	-0,10436	
600-700	1,632	0,000334	-462,531	0,016296	-464,161	
700-800	0,793	0,000334	-462,531	0,007891	-46,332	
800-900	0,476	0,000334	-462,531	0,004729	-463,004	
900-1000	0,388	0,000334	-462,531	0,003851	-462,916	
1000-1100	0,288	0,000334	-462,531	0,002858	-462,817	
1100-1200	0,245	0,000334	-462,531	0,00243	-462,774	
1200-1300	0,149	0,000334	-462,531	0,001474	-462,678	
1300-1400	0,112	0,000334	-462,531	0,001106	-462,642	
1400-1500	0,096	0,000334	-462,531	0,000951	-462,626	
1500-1600	0,078	0,000334	-462,531	0,000775	-462,609	
1600-1700	0,065	0,000334	-462,531	0,000642	-462,595	
1700-1800	0,047	0,000334	-462,531	0,000464	-462,577	
1800-1900	0,027	0,000334	-462,531	0,000265	-462,558	
Land use						
Ricefield	4,483	0,015244	-0,80499	0,025625	-0,83062	0,7
Settlements	5,353	0,01282	-0,97818	0,034694	-101,288	
Plantation	34,689	0,017676	-0,65694	0,22781	-0,88475	
Forest	21,361	0,001899	-288,808	0,228418	-31,165	
Underbrush	34,113	0,076752	0,812011	-104,422	1,856,233	
]Induce factors						
Peak Ground Acceleration (g)						
0,23-0,24	7,371,696	0,000334	-462,531	0,075879	-470,119	0,75
0,24-0,25	2,397,832	0,010091	-12,176	0,200604	-141,821	
0,25-0,26	315,863	0,086039	0,926335	-121,625	2,142,583	
0,26-0,27	3,097,904	0,014359	-0,86481	0,231025	-109,584	
0,27-0,28	6,084,649	0,000334	-462,531	0,062201	-468,751	
Rainfall Intensity						
(mm/day)						
5 – 10	639,286	0,043203	0,237007	-0,64222	0,879226	0,59
10 – 15	360,714	0,017938	-0,64222	0,237007	-0,87923	

4.3 Validation

The main one is the validation made with the aim to determine the accuracy of the data, validation is divided into 2 (two); the success rate describes how well the model fits with past events and prediction rate describes how well the model predicts the occurrence of landslide occurrence in the future. The map was verified using test data (35 % landslide). The area under curve (AUC) of the model tested with test data (100% landslide) show success rate accuracy 0.894. The prediction curve, calculated by the method Chung (2003), prediction rate of the model tested with 35% landslide data (test data) is 0.849 (Figure 8). This condition is the allowed tolerance between success rate and prediction rate less than 15%. Moreover, it shows the good quality of model. From the modeling results obtained 4 (four) the susceptibility of landslide in Gunung Tigo, West Sumatra is high susceptibility values above 70%, while moderate susceptibility between 15% - 70%, with a low susceptibility value 5% - 15% and very with low susceptibility values 0-5%. From the modeling results in getting an area that has high susceptibility to landslide is in the middle part of research area (Figure 9).

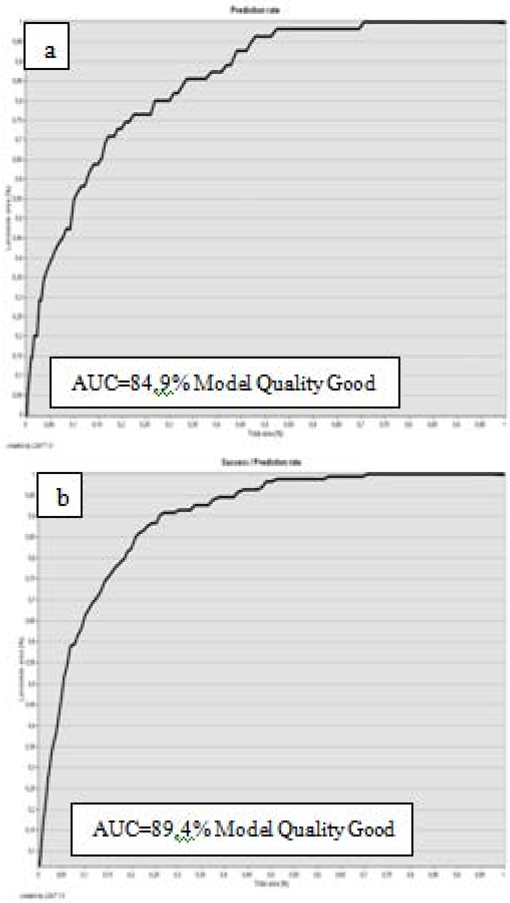

Figure 8: (a) Prediction rate curves of landslide hazard values calculated from 35 % were not used in the modeling

process (test data), (b) Success rate calculated from all data of landslide

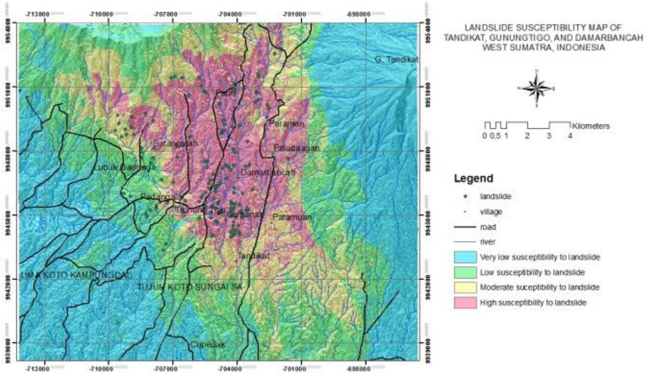

Figure 9: Landslide Susceptibility Map

5. Discussion and Conclusions

WoE model for landslide susceptibility assessments in this case illustrates that the morphological and geological conditions greatly contribute to the susceptibility to landslide. In this study, the positive and negative weights, contrast values, and final weight for each of parameters have been calculated: slope gradient, slope curvature, land use, lithology, distance to lineaments, and distance to the stream, peak ground acceleration, and rainfall intensity. Unfortunately, the resolution for each parameter is differences and spatial rainfall intensity based on TRRM, with a tendency to increase uncertainties. The crucial factors for landslide susceptibility in the study area are lineaments, slope, lithology, peak ground acceleration, and distance to the stream.

The highest contrast value for lineaments is 0 – 500 m, slope gradient is at 20–40, distance to the streams is 0 – 100 m, and lithologi is hornblende hypersthene pumiceous tuff. Land use is a most significant factor in morphodynamic evolution of slopes, and the grassland has highest contrast compare with other land use.

Classification and reclassification of results diminish through generalizing the accuracy of the final susceptibility map, the quality of end-results being dependent on the quality of input data, especially on the resolution of the digital elevation model. WoE proves to be a useful method to be applied for land use planning decisions in Indonesia. The obtained landslide susceptibility map and landslide inventory data base of Indonesia can be used for landslide hazard prevention and mitigation, and proper planning for land use and construction in the future. Continuously increasing landslide inventory further improves the result and easy and fast update.

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