Landslide Hazard GIS-based Mapping Using Mamdani Fuzzy Logic in Small Scale Mining Areas of Surigao del Norte, Philippines

Monalee A. dela Cerna and Elmer A. Maravillas

***Abstract* —Small Scale Mining (SSM) has been a long part of Surigaonon industry as many SSM operations exist around the province. SSM activities are not safe as it poses landslide hazards to small scale miners and the community. Mines and Geosciences Bureau (MGB) records show no landslide hazard map of Surigao del Norte. This study wants to address the gap by employing a fuzzy logic system that runs with multiple controllers to assess landslide hazard using eight causative landslide factors namely; slope gradient, vertical displacement, drainage density, weathering, lithology, ground stability, soil type and vegetation. Likewise, the study utilizes Geographic Information System to plot the identified landslide areas. The study reveals and pinpoints in the map ninety-nine landslide prone areas in different parts of Surigao del Norte. The researchers believe that the GIS hazard map as an output is relevant for local government planning and disaster prevention programs.**

***Index Terms*— fuzzy logic system, geographic information system, landslide hazard map, small-scale mining**

I. Introduction

LANDSLIDE is one of the primary natural disasters in the world. It causes extensive damage to property and results in loss of life [1], [2]. During the 21st century, many casualties were reported after heavy rains that resulted to flooding and landslides. However, landslides are not only naturally-caused. Most of the time, human activities could be blamed for causing landslides. In fact, one of the fundamental human causes of landslides around the world is mining [3] and as reported [4], Small Scale Mining (SSM) is one of the primary triggers of landslides in the Philippines.

The geographic location of the Philippines is very vulnerable to natural disasters particularly typhoons that could trigger flash floods and landslides [5]. In 2012, for example, flash floods and landslides because of unregulated SSM caused the damaged of 844 houses and 1,067 casualties in New Bataan and Moncayo, Compostela Valley, Davao region in Mindanao [3]. Hence, unregulated SSM poses risks not only to the workers depending in this dangerous livelihood but to the community as well.

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However, SSM activities are very difficult to regulate because people who are depending in this livelihood are poor, and their employment opportunities are very scarce [6].

Surigao, as a province, is not exempted to this predicament. Poverty and lack of opportunity forced many local residents to SSM. In fact, the presence of small-scale gold mining activities could attest, and these activities are even observed near at the Surigao Watershed Reserve Area [6].

Meanwhile, the application of Geographic Information System (GIS) has dramatically increased in the past few years [1], [7]. GIS is an excellent alternative conventional mapping technique used in monitoring, investigating, assessing and mapping geo-hazards areas [14]. Several researchers have utilized GIS for forecasting landslide hazard zones and applied probabilistic models. Some statistical models used are the logistic regression models [2], fuzzy logic [8], [9], [7], [10] and artificial neural network models [2] have also applied to landslide hazard. The use of Fuzzy Logic (FL) gives tremendous impact on the design of intelligent autonomous systems and becomes an essential method of solving problems. Fuzzy systems are very popular nowadays, being used in control, expert systems, prediction and decision making. The FL method concedes for more flexible combinations of weighted maps, and could readily implement with a GIS modeling language [11].

This paper developed a fuzzy logic controller to assess landslide hazard for small scale mining in areas of Surigao del Norte province adopting a Mamdani method with the integration of Geographic Information System application. The researchers believe that the GIS hazard map as an output is relevant for local government planning and disaster prevention programs.

II. Theoretical Framework

The study anchored on the ‘risk society' theory [12] which delves on the intellectual mapping of endemic potentially catastrophic risks. This ‘risk society’ paradigm calls for concerted efforts from various fields of discipline in mitigating the possible effects of risks to the most vulnerable sector of the society knowing that vulnerability towards risks is usually inseparable from the issue of poverty [2].

This theory has bearing on the present study since small-scale mining activities involve people in the margins and who are forced to work in this hazardous livelihood due to poverty. Any measure that could minimize the risk of the nature of their work is wanting hence this study is conducted.

The schema shows that the causative indicators are among the factors that contribute to the hazard of the small-scale mining areas. There are eight factors namely; slope gradient, vertical displacement, drainage density, the rate of weathering, lithology, ground stability, soil type and vegetation used as crisp inputs to feed into the controllers. The crisp input values are converted to the fuzzy values by the input membership function. The two-input single-output Mamdani fuzzy model is used in this study. Fuzzy Logic Controllers (FLC) 1, 2, 3, and 4 are the first primary controllers to fuzzify, and then defuzzify using Centroid Method. The crisp output of the four controllers used as input of controllers 5 and 6. The output of the last two FLCs is used again as crisp input for controller 7. The crisp output of FLC7 is the rate of landslide hazard within the area. The data stored in the geodatabase, and the landslide geo-hazard map created from GIS that could be used for planning and decision-making processes. Fig. 1 below shows the framework for landslide hazard assessment using the fuzzy logic controller.

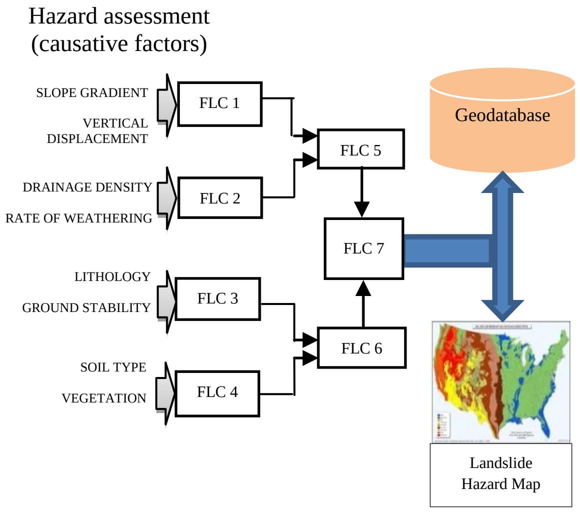

Fig 1. Framework for landslide hazard mapping

III. Methods

The study utilized Fuzzy logic algorithm employing Mamdani method to determine landslide hazard zonation with the integration of Geographic Information System (GIS) for mapping landslide hazards.

The researchers implemented the system in the .Net Framework using Microsoft Visual Studio 2010 as the integrated development environment (IDE) and running on Windows 8 Operating System. Visual C# used as the programming language for implementation. The data set used to test the algorithm stored in databases in the MySQL client version 5.0.51a and uses XAMPP control panel application. The output of the running system is also exported to Microsoft Excel and interpreted by the MapInfo and ArcGIS for mapping.

A. Study Area

Surigao del Norte province is located in the Northeastern part of Mindanao between 125º15' to 126º15' east longitude and 9º18' to 10º30' north latitude. It is bounded on the north and east by the Pacific Ocean. The province has abundant mineral reserves including gold, iron, manganese, silica, cobalt, copper, chromite, limestone, silver and among the world's largest nickel deposits [18]. The province falls under the tropical climate type and prone to brief afternoon downpours and thunderstorms. The soil in the region is clay and sandy loam type. In the mainland, the area is classified as loam soil characterized as permeable, moderately drained and highly suitable for agriculture. Fig. 2 shows the map of the Surigao del Norte province.

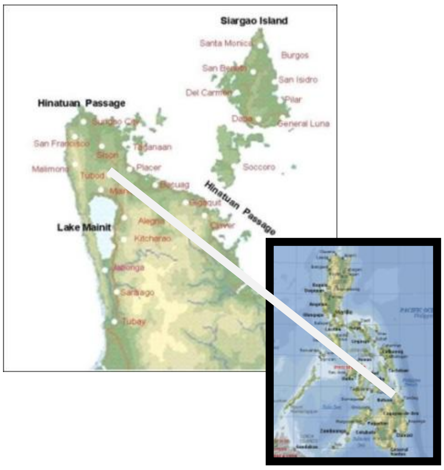

Fig 2. Location map of the study area

B. Indicators of Landslide Risk Areas

Published literatures about the indicators of landslide risk areas reveal eight causative factors of landslides [10], [19] such as slope gradient, vertical displacement, drainage density, rate of weathering, lithology, ground stability, soil type and vegetation. During the field surveys conducted by the researchers in order to gather baseline data for landslide inventory, September 2013 to February 2014 and December 2014 to January 2015 respectively, reveal the presence of eight causative factors of landslides in the research site.

These identified causative factors of the landslide are naturally occurring. One or two factors may be present in an area, but unregulated SSM activities can make their mining sites susceptible to landslides as the consequence of their activities. In fact, unregulated SSM activities can cause the presence of the eight causative factors of landslides. Table I shows the rate of landslide hazard parameter with their corresponding linguistic definitions. Further, the researchers conducted a geological investigation to prove areas of SSM. Fig. 3 presents some landslide photos.

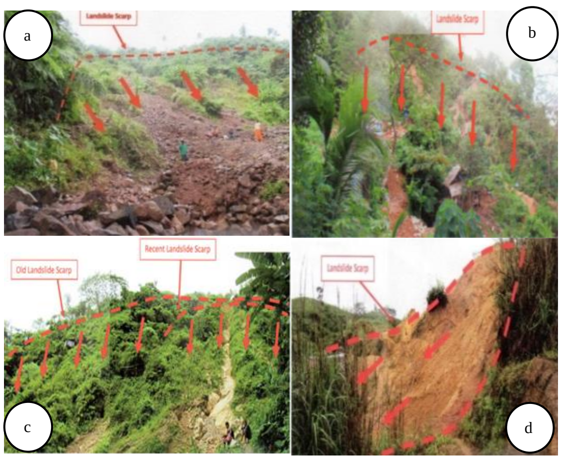

Fig 3. Panoramic view of some landslides (the arrow indicates the main scarp) (a) San Pedro, Alegria; (b) Cansayong, Malimono; (c) Masgad, Malimono; (d) Nabago, Surigao City

TABLE I
RATE OF LANDSLIDE HAZARD PARAMETER

VARIABLE		CLASSES	RATE
Slope Gradient	FU	▪ Flat and undulating (0° - < 8°)	1
	MS	▪ Moderately sloping (8° - < 18°)	3
	HS	▪ Hilly & Moderately steep (18° -< 26°)	6
	SP	▪ Steep (26° -<= 90°)	9
Vertical Displacement	SH	▪ Shallow (<2 m)	1
	MD	▪ Moderate (2-9 m)	3
	DP	▪ Deep (10-25 m)	6
	VD	▪ Very deep (>25 m)	9
Drainage Density	LD	▪ Low (0-1 drainage)	1
	MD	▪ Moderate (2-4 drainage)	3
	HD	▪ High (5-10 drainage)	6
	DD	▪ Very High (>10 drainages)	9
Weathering	SW	▪ Slightly weathered (stain along joints)	1
	MW	▪ Moderately weathered (less than half of decomposed rock material) [16].	3
	HW	▪ Highly weathered (discolored rock throughout; more than half of decomposed rock material)	6
	CW	▪ Completely weathered	9
Lithology	WF	▪ Weakly fractured/weathered (Andesite Porphyry; Diorite; Agglomerate; Hydrothermal Breccia)	1
	MF	▪ Moderately fractured/weathered (Andesite Porphyry; Diorite; Agglomerate; Siltstone; Hydrothermal Breccia)	3
	HF	▪ Alluvium; Highly weathered/ fractured and delighting structure (Siltstone; Andesite Porphyry; Ultramafic; Agglomerate; Hydrothermal Breccia)	6
	VF	▪ Highly weathered/Fractured Sandstone; Terrace Gravel; Highly fractured and highly weathered (Siltstone; Andesite Porphyry; Ultramafic; Agglomerate; Diorite; Hydrothermal Breccia) with tension cracks/or landslide scarp	9
Ground Stability	ST	▪ Stable with no identified landslide scars, it is either old, recent or active [17]	1
	SC	▪ Soil creep and other indications for possible landslide occurrence are present [17].	3
	IL	▪ Inactive landslides evident; tension cracks present[17]	6
	AL	▪ Active landslides are evident with tension cracks, bulges, terracettes, seepage present [17].	9
Soil Type	SG	▪ Silts and Clays (50% or more of material is smaller than No. 200 sieve size.) Liquid Limit 50% or greater [15].	1
	SL	▪ Silts and Clays (50% or more of material are smaller than No. 200 sieve size.) Liquid Limit is less than 50% [15].	3
	SD	▪ Sands (more than 50% of the material is larger than No. 200 sieve size), more than 50% of coarse fraction smaller than No. 4 sieve size. [15].	6
	GV	▪ Gravels (more than 50% of the material is larger than No. 200 sieve size), 50% more than of coarse fraction larger than No. 4 sieve size.) [15].	9
Vegetation	PG	▪ Primary Growth (Untouched, pristine forest that exists in its original condition/characterized by a full ceiling canopy and usually several layers of understory)	1
	SG	▪ Secondary Growth (rainforest that has been disturbed in some way, naturally or unnaturally/degraded forest recovering from selective logging to areas cleared by slash-and-burn agriculture that have been reclaimed by forest.)	5
	TG	▪ Tertiary Growth (Vegetation permanently cultivated land areas such as coconut trees, bananas, rice, corn, coffee, palm oil, rubber tree, tobacco, shrubs/ cogon grasses and fruit trees.)	9

C. Application of Fuzzy Logic Algorithm for Landslide Hazard

The theory of fuzzy logic was introduced to the world by Professor Lotfi A. Zadeh of the University of California at Berkeley in 1965. Fuzzy logic system (FLS) is a non-linear mapping of input data set to a scalar output data. In this study, the fuzzy logic algorithm is employed to determine landslide hazard zonation. Mamdani method, a fuzzy inference technique is used to assess landslide rate. The method performed in four steps: fuzzification of the input variables, rule evaluation (inference), aggregation of the rule outputs (composition) and defuzzification. The components and the general architecture of FLS shown in Fig. 4.

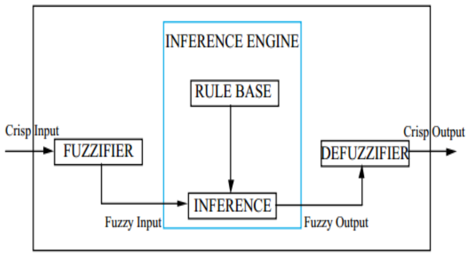

Fig 4. Fuzzy Logic System

Membership Functions

Membership functions are graphically representing a fuzzy set. The *x*-axis represents the universe of discourse, whereas the *y*-axis represents the degrees of membership (0, 1 interval). Triangular fuzzy numbers represent fuzzy sets and the firing level of the consequent computed as the product of firing levels from the antecedents. A triangular function is specified by three parameters (a, b, c) and defined as follows: *a* is a lower limit, *c* is an upper limit, and a value *b*, where a < b < c. Refer to (1) the computation of the degree of membership μ, with its crisp input *x*.

$$\mu A(x) = \begin{cases} 0, & x \leq a. \\ \frac{x-a}{b-a}, & a \leq x \leq b. \\ \frac{c-x}{c-b}, & b \leq x \leq c. \\ 0, & c \leq x. \end{cases} \quad (1)$$

The same crisp input ranges used for slope gradient, vertical displacement, drainage density, the rate of weathering, lithology, ground stability and soil type that starts from 0-2, 1.5-5, 4-8, and 7-10. For vegetation, there are only three hedges used (0-3, 2-7 and 6-10). Fig. 5 illustrates the sample of fuzzification method.

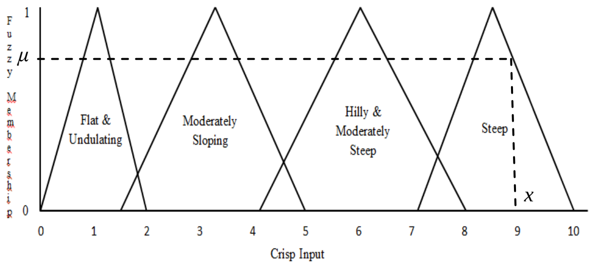

Fig 5. Fuzzy Membership Functions for Slope Gradient

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Fuzzy Rule Base

The fuzzy rule base describes the operation of the FLC to perform linguistic computations likewise a repository of the knowledge of the system. The rules take the form of IF-Then rules and can obtain from a human expert (heuristics) that infers the rules from the behavior of the system. Heuristics guidelines in determining the matrix are the following statements and their converses:

(1) When the Slope Gradient is Steep, and the Vertical Displacement is Deep, then Landslide Hazard Rating is Very High.
or IF **SG** IS **SP** AND **VD** IS **DP** THEN SET **FLC1** TO **VH**
(**SG** $\wedge$ **VD** $\rightarrow$ **VH)**

(2) When Slope Gradient is Flat and Undulating, and Vertical Displacement is Shallow, then Landslide Hazard Rating is Low.
or IF **SG** IS **FU** AND **VD** IS **SH** THEN SET **FLC1** TO **L**
(**SG** $\wedge$ **VD** $\rightarrow$ **L)**

(3) And so on…

The computation of the degrees of membership of the antecedent is performed using the fuzzy operator AND (T-Norm). The triangular membership function of the intersection defined in minimum criterion using this equation:

$$\mu A \cap B = \min(\mu A, \mu B) \qquad (2)$$

The matrix or rule base represents the antecedents and consequent. Hedges used for all FLCs to determine the landslide hazard were (**L**) for Low Hazard; (**M**) for Moderately Hazard; (**H**) for Highly Hazardous; and (**VH**) for Very Highly Hazard. Table II represents the sample fuzzy rule base.

TABLE II
FUZZY RULE BASE FOR FUZZY LOGIC CONTROLLER 7

		FLC6			
		L	**M**	**H**	**VH**
FLC5	**L**	L	L	L	VH
	M	L	M	VH	VH
	H	L	VH	VH	VH
	VH	VH	VH	VH	VH

The test is conducted for each rule base so as to validate the integrity of the system. Table III shows the result of system testing. It consists of running several simulations in which from time to time these functions changed. Results obtained from the simulations subjected to the statistical analysis that allowed us to perform a validation of simulation output data and real information taken from the landslide inventory.

D. Geographic Information System

The advent of geo-technologies has elevated the importance of geography to a level unprecedented in the history of the discipline [13]. Geographic Information System (GIS) lead a transformation in the meaning of technology. GIS is a powerful software technology that allows a virtually unlimited amount of information to link to a geographic location.

In this study, a detailed geohazard map in 1:10,000 scale is designed and constructed using GIS technology. Global Positioning System (GPS) used for getting the exact coordinates and Google Earth used for tracking the exact location of the study area. Map Source used to plot the waypoints. MapInfo Professional 2013 version 12.0, ArcGIS/Arc Map version 10.1 and Vertical Mapper used as GIS tools for mapping. Topographic map, Geologic Map and Mindanao Development Authority Map (MindaMap unpublished 2007) as based maps used for digitization and geo-referencing. WGS84 used as a geographic coordinate system.

Layers of information were overlaid on the base map such as the locations of potential landslide sites, drifting and sinking sites, ball mill, open-pit mines, drainage canal, tension cracks, and creeks. Fig. 6 illustrates digitize landslide scarp in some areas of SSM.

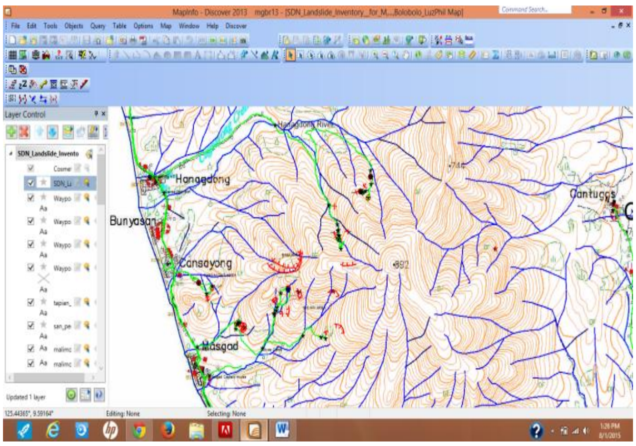

Fig. 6. Digitize landslide scarp using MapInfo in Malimono, Surigao del Norte

IV. Results and Discussion

This paper presented the running output of the landslide hazard fuzzy logic controller. The controller accepts data, and an image of a certain area is displayed (Fig. 7). The result is simulated and viewed in the fuzzy rule base environment (Fig. 8). The membership functions can make to overlap which is one of the great strengths of the FLC, as it gives certain robustness to the controller because for each possible observation at least one rule is completely fired. With this, the landslide hazard rate is used to feed data to the GIS to produce a geo-hazard map.

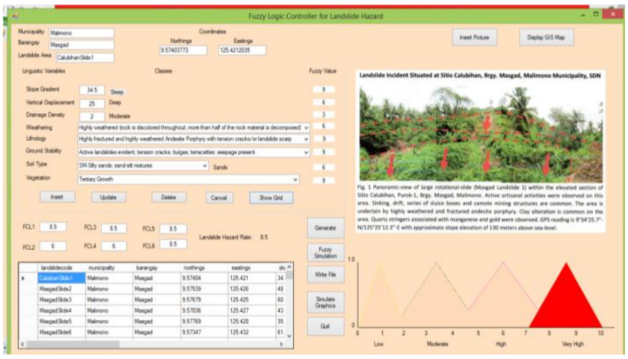

Fig. 7. IDE of the Landslide Hazard Controller

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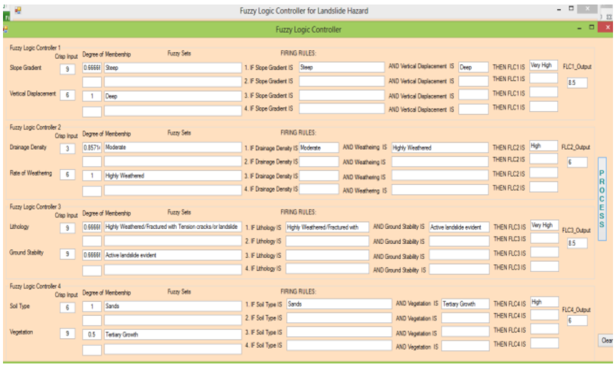

Fig. 8. Fuzzy rule base environment

The result of the landslide hazard analysis is verified using known landslide locations. Based on the results, there are 16 barangays within the six towns in the province of Surigao del Norte involved in the small-scale mining activities. Ninety-nine landslide areas observed during the comprehensive survey. They are all very highly prone to landslide based on the result of FLC7 (Table III). Fig. 9 shows the identified small-scale mining areas and landslide hazard map in scale 1:10,000.

TABLE III
LANDSLIDE DENSITY RESULT FROM FLCs

Hazard Zones	FLC 1	FLC 2	FLC 3	FLC 4	FLC 5	FLC 6	FLC 7
Low	-	8.08	-	18.18	-	-	-
Moderate	-	70.71	-	54.55	-	-	-
High	4.04	19.19	-	18.18	8.08	-	-
Very High	95.96	2.02	100	9.09	91.92	100	100

There are 31 classes for all eight causative factors and taken as variables for calculating the landslide hazard index. The landslide rate explains how well the model and factor predict the landslide. The rate illustrates the fact that more percentage of landslides occurs in the very high susceptible zone compared to the other areas.

Table III shows that 100% of the study area where very highly prone to landslide using eight causative factors namely; slope gradient, vertical displacement, drainage density, the rate of weathering, lithology, ground stability, soil type and vegetation. Based on the results, very high susceptible zones obtained 95.96% in FLC1, which consist of a steep slope and moderate vertical displacement. In FLC2, moderate hazard areas obtained 70.71% that means low drainage density and high rate of weathering. FLC3 obtained 100% prediction for very high hazard areas caused by lithology and ground stability variables. Lithology poses a hazard when it has highly fractured and highly weathered classes with tension cracks or landslide scarp. Moreover, when ground stability is affected by tension cracks, bulges, terracettes, and seepage would result to an active landslide. For FLC4, it only obtained 54.55% means moderate hazard zones since most of the areas have elastic silt, elastic silt with sand; and silt with sand soil types. Likewise, most small-scale mining areas are in tertiary growth vegetation.

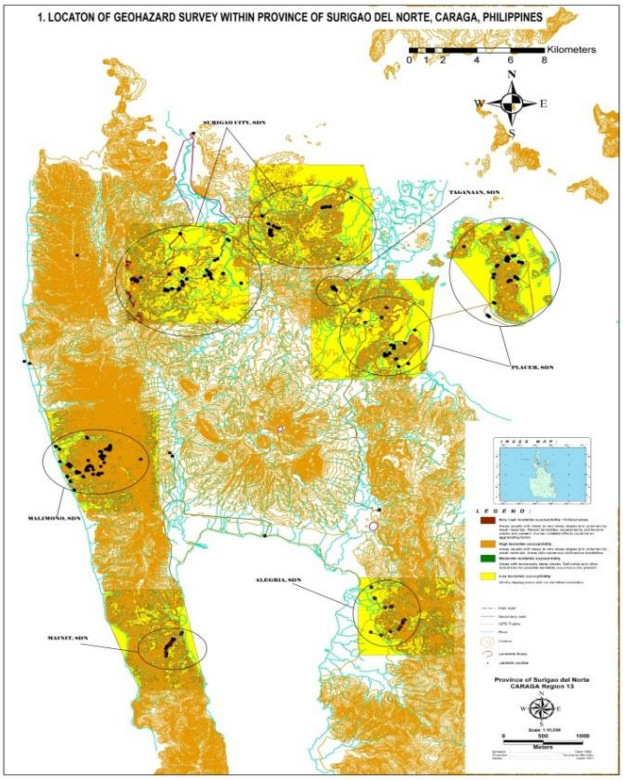

Fig. 9. Landslide Hazard Map using ArcGIS

Results from the survey reveal that the impact of SSM will not only cause soil erosion or landslides, but will also lead to forest destruction, agricultural lowlands, sedimentation or siltation of the water bodies, and flash floods and flooding in the neighboring places near small-scale mining areas due to poor mining practices.

V. Conclusion

In this paper, the landslide hazard mapping is developed using the fuzzy logic algorithm and GIS. The data was tested using the two-input single-output Mamdani-type fuzzy controller and the system simulated multiple controllers at the same time. The triangular function was successfully used for the computation of the degrees of membership of the antecedents. The fuzzy AND operator accurately defined the minimum criteria and the centroid method for defuzzification. The method gives accurate result simulating overlapping universe of discourse. Scalability of the system accurately calculates the landslide hazard rate. The result reveals that the system can predict the status of the emergence of danger to a landslide based on the test that showed resemblance to the heuristic prediction of the Mines and Geosciences Bureau. It can also show active landslide areas vulnerable to very high-risk landslide catastrophe. Moreover, small scale gold mining causes environmental destruction. The study further shows how geographic information system successfully investigates landslide hazard zones.

The FLC application for forecasting landslide hazard provides great advantage especially to the MGB personnel who conduct an investigation in mining activities.

The findings, therefore, are beneficial for the local government and non-government entities as their ultimate guide in their strategic planning in mitigating landslide risk.

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In the title, I changed the letter ‘u’ in ‘using’ from lowercase to uppercase, thus from ‘using’ to ‘Using’. In the Introduction, the word ‘landslide’ was misspelled so I corrected it. Also the word ‘Geographical’ was changed to ‘Geographic’. Lastly, under Results and Discussion for better emphasis of ideas sentences were rewritten observing improved grammar constructions.