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Landslide Susceptibility Mapping in a Geologically Complex Terrane: A Case Study From Northwest Mindoro, Philippines

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ABSTRACT

Northwest Mindoro is underlain by inherently weak materials that are the product of arc-continent collision involving the Philippine Mobile Belt and the Palawan Microcontinental Block. Consequent to having an arc-continent collision setting, the frequent exposure to precipitation and the human-induced pressure on the environment is the occurrence of landslides in the island. Because of the complicated tectonic makeup of the area and the complex controls to slope failures, a variety of approaches to landslide susceptibility assessment was used and compared. Using a geographic information system-based platform and the weighted overlay method, three different grading techniques were investigated for their reliability in quantifying landslide susceptibility in northwest Mindoro. The first set of overlay analysis involved the assignment of weights to the different factors based on subjective, expert knowledge. Application of the analytic hierarchy process (AHP) was utilized in the generation of two other susceptibility models in which different sets of factor weights were assigned. Parameters that influence slope failure such as lithology, slope gradient, elevation, distance from faults and lineaments, land cover, distance from historical earthquakes, and slope aspect were assigned susceptibility ratings using two methods: One set assumed progressive increases in landslide susceptibility equivalent to increases with typical value scales (e.g., steepest and highest slopes are most susceptible to slope failure), and the other set utilized expert knowledge based on field observations of active and inactive landslides. Generated landslide susceptibility maps generally show zones of highest susceptibility to landslides coinciding with areas that are underlain by old and highly weathered sedimentary sequences (i.e., Lasala Formation), while geomorphological constraints such as slope gradient and slope aspect appear to have minimal contribution to slope failure. Results further reveal the importance of expert opinion, especially for lithological factors, in the generation of the most appropriate landslide susceptibility map for a particular region. A comparison of three susceptibility models shows that the combination of the AHP method with factor ratings derived from expert knowledge produced a susceptibility map that closely approximates the actual distribution of landslide occurrences observed. The usefulness of these landslide susceptibility maps, particularly for science-directed land use planning, may be validated with continued monitoring and inventory of landslides in northwest Mindoro Island.

Keywords: landslide susceptibility, Geographic Information System (GIS), Palawan Continental Block, northwest Mindoro, Philippines

INTRODUCTION

The western part of central Philippines is an interesting region for investigating features associated with the arc-continent collision involving the seismically active Philippine Mobile Belt (PMB) and the relatively aseismic Palawan Continental Block (PCB) (Fig. 1). Within this geologically complex region is Mindoro Island, where ancient collision zone markers such as accretionary complexes bounded by thrust faults are well-preserved. At the northwestern tip of the island, the geologic setting is further affected by subduction along the southern terminus of the Manila Trench and faulting along Lubang and Aglubang River faults (Yumul et al., 2003). Moreover, deformation brought about by collision and subduction processes in northwest Mindoro resulted in lineaments and faults that generally strike NNW (Fig. 2).

Consequent to having an arc-continent collision setting, combined with the frequent exposure to precipitation and the human-induced pressure on the environment, is the occurrence of landslides in Mindoro Island. The Philippine archipelago's geographic setting exposes the island, particularly the northwestern region, and the rest of the country to constant or prolonged and even extreme rainfall that further weakens materials on the shallow surface. It is worth noting that most landslide occurrences in the Philippines are triggered by heavy and/or prolonged rainfall, with slopes often characterized by materials that are heavily weathered, poorly indurated, and highly fractured (Fig. 1). In August 2011, rainfall-induced landslides in the municipality of Mamburao in northwestern Mindoro led to significant damage to properties and evacuation of some residents (PAGASA–DOST, 2012).

Although past slope failures in northwest Mindoro have not resulted in significant casualties, it is deemed necessary to conduct landslide susceptibility mapping in the area due to geomorphologic features (e.g., old and recent landslide scarps) that are indicative of unstable slopes. The relatively weak conditions of the slope affected by landslides are a direct consequence of the arc-continent collision in the island, with the accretion of inherently weak materials (e.g., metamorphic rocks within the tectonic mélange) and the formation of faults and fractures among others.

With the increasing population and development in northwestern Mindoro, landslide susceptibility assessment all the more becomes important. Furthermore, with the geologic setting of northwest Mindoro being within a tectonic collision zone, the changing rainfall pattern of the Philippines with more intense rains recorded and the expanding population requiring more lands to be utilized, this kind of information for the country, in general, and northwest Mindoro, in particular, becomes an important decision-making tool.

This study aims to evaluate the physical factors that contribute to landslide occurrences in northwest Mindoro using combined field observation and analytical hierarchy process (AHP) procedures. AHP, developed by Saaty (1980), is an easily understandable way for quantifying decisions (Yalcin, 2008) and is suited for regional studies (Sorters & van Westen, 1996). Ultimately, the goals of this study are to provide fundamental information on the physical factors contributing to landslide occurrences in the region and to introduce an effective science-based tool for land use planners in identifying suitable areas for future developments and expansion plans. The information generated in this study can be used as critical inputs into the development of other areas with similar geologically complex settings worldwide.

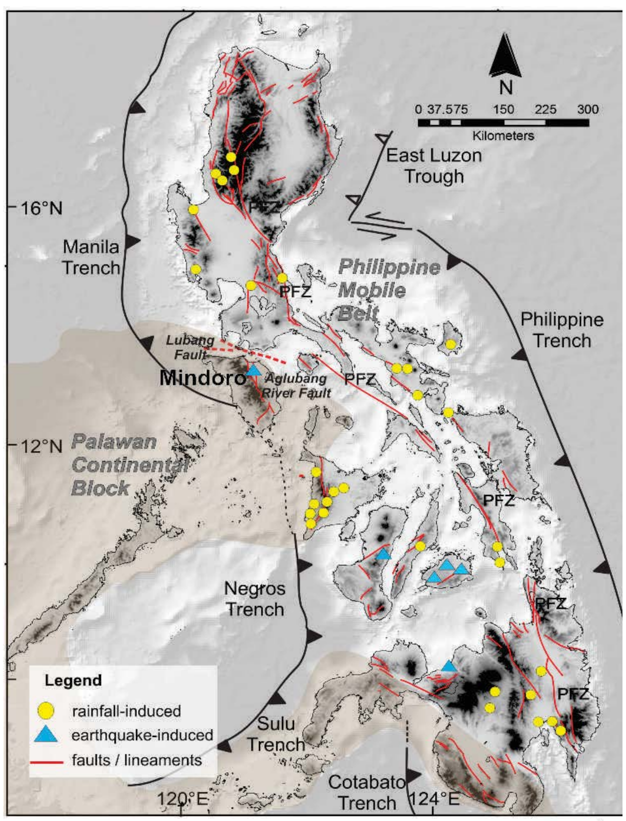

Figure 1. Earthquake- and rainfall-induced landslides in the Philippines (2002 to 2012) with reported casualties (NDRRMC, 2012; 2013). Topographic data are from the Shuttle Radar Topography Mission (SRTM; Farr et al., 2007), while faults and lineaments are from the Philippine Institute of Volcanology and Seismology (PHIVOLCS, 2002). PFZ: Philippine Fault Zone.

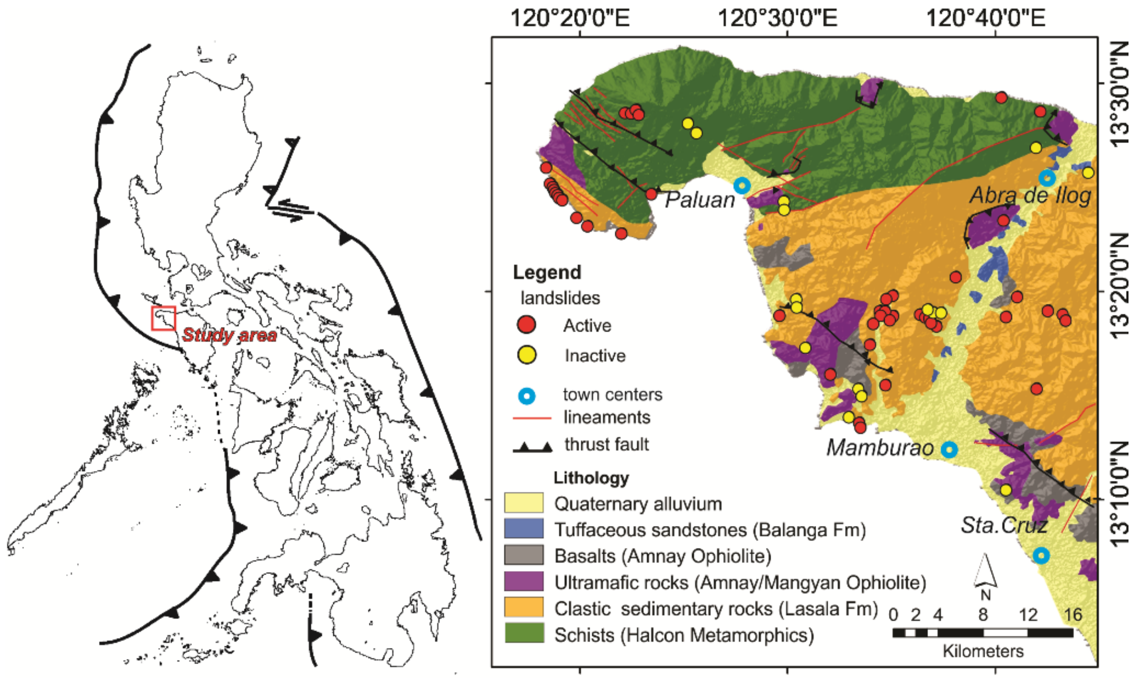

Figure 2. Tectonic and geologic setting of the study area. (Left) Map shows the location of northwest Mindoro. (Right) Map shows the distribution of rock formations consisting of ophiolitic and metamorphic complexes overlain by sedimentary sequences (modified from Concepcion et al., 2012). Lineaments and thrust faults observed in the field are shown as solid and toothed lines, respectively.

MATERIALS AND METHODS

Test Site Description

Mindoro Island is a geologically complex region where ancient collision zone markers such as accretionary complexes bounded by thrust faults are well-preserved. Apart from the thrust faults within the island, the region is at the southern terminus of the Manila Trench and the Lubang Fault considered as a splay of the Philippine Fault. Subduction along the Manila Trench in the southern segment is characterized by an almost vertical, east-dipping lithosphere associated with the South China Sea (Bautista et al., 2001). Shallow- to moderate-depth (0 to 150 km) earthquakes of magnitudes 5 and 6 generally characterize northwest Mindoro while approximately 20 intermediate-depth to deep (more than 150 m) earthquakes have been recorded in the past (Ramos et al., 2005). In 1994, a magnitude 7.1 earthquake along the Aglubang River Fault resulted to ground shaking and rupture, a tsunami with average run-up heights of 3 to 4 m in severely damaged areas, liquefaction, lateral spreading, and minor landslides (Punongbayan et al., 1994; Imamura et al., 1995).

Northwest Mindoro is underlain by a tectonic mélange composed of Mesozoic metamorphic rocks and ophiolitic blocks that are thrust onto Cenozoic sedimentary sequences (Canto et al., 2012; Fig. 2). The basement unit, Halcon Metamorphics, is composed of varieties of metamorphic rocks with protoliths that are igneous and sedimentary in origin (Caagusan, 1966; Canto et al., 2012). It also encloses moderately to highly serpentinized megablocks of ultramafic rocks that represent portions of the oceanic-upper mantle sequence of the Izanagi Plate thrust onto and incorporated into the accretionary complex prior to the metamorphism of the Halcon Metamorphics protoliths (Canto et al., 2012). The overlying sedimentary sequence of the Lasala Formation, composed of gray sandstones interbedded with dark gray shales with minor conglomerates, mudstones, limestones, and basalt flows, is distributed in the central and northeastern portion of the study area (Concepcion et al., 2012). In the southwest, an Oligocene ophiolite sequence of the South China Sea crust was emplaced over the Halcon Metamorphic and Lasala Formation. This formation consists of a complete suite of moderately to highly serpentinized upper mantle and crustal rocks. Subhorizontal interbeds of tuffaceous and fossiliferous sandstones and siltstones, minor conglomerates, and limestones of the Plio-Pleistocene Balanga Formation are observed along the NNE trending narrow depression from Abra de Ilog to Mamburao (Canto et al., 2012).

Earthquakes and climate-related events, specifically heavy rainfall, are often the triggering mechanisms of devastating landslides in the Philippines. The changing rainfall pattern in the country, with observed precipitation becoming more intense over the years, further increases the susceptibility of mountainous areas to slope failure. With recent observations on extreme weather conditions, understanding the rainfall distribution of an area is important in landslide hazards assessment.

Western Mindoro Island experiences two pronounced seasons based on the Modified Coronas Classification: dry from November to April and wet during the rest of the year with maximum rain periods from June to September (Coronas, 1920; PAGASA-DOST 2011). Based on the 30-year monthly rainfall data from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) station in San Jose, Occidental Mindoro, the highest amount of monthly precipitation was recorded in July 2004 (1240.6 mm). Extreme rainfall events in the past few years that resulted in massive flooding in Metro Manila and Cagayan de Oro (NDRRMC, 2012), however, did not affect Mindoro Island. Over the last decade, monthly rainfall data at the San Jose station in Occidental Mindoro show minimal deviation from the climatological norm (PAGASA–DOST, 2011; NDRRMC, 2012).

Data

Field reconnaissance surveys were conducted in northwest Mindoro using 1:50,000-scale topographic maps published by the National Mapping and Resource Information Authority (NAMRIA). Geological and geomorphological data were digitized into thematic layers and later georeferenced to the WGS84 geographical coordinate system to create a common digital base map. Other thematic maps (e.g., slope factors) were also generated and derived from the 30-m resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model Version 2 (ASTER GDEM V2; ERSDAC, 2011). The geologic map of the study area was adapted from Concepcion et al. (2012). Distance to lineaments and thrust faults and the effect of earthquakes of magnitude 5 were also evaluated. All thematic maps were digitized and processed using ArcGIS (Fig. 3).

The relationship of geologic and geomorphologic factors with landslide frequency was also evaluated from field observations of landslide occurrences; rock type, structures present (e.g., joints or fractures), slope, degree of weathering, ground stability (i.e., if landslide scars are present), among others, were all noted (Table 1, Fig. 4).

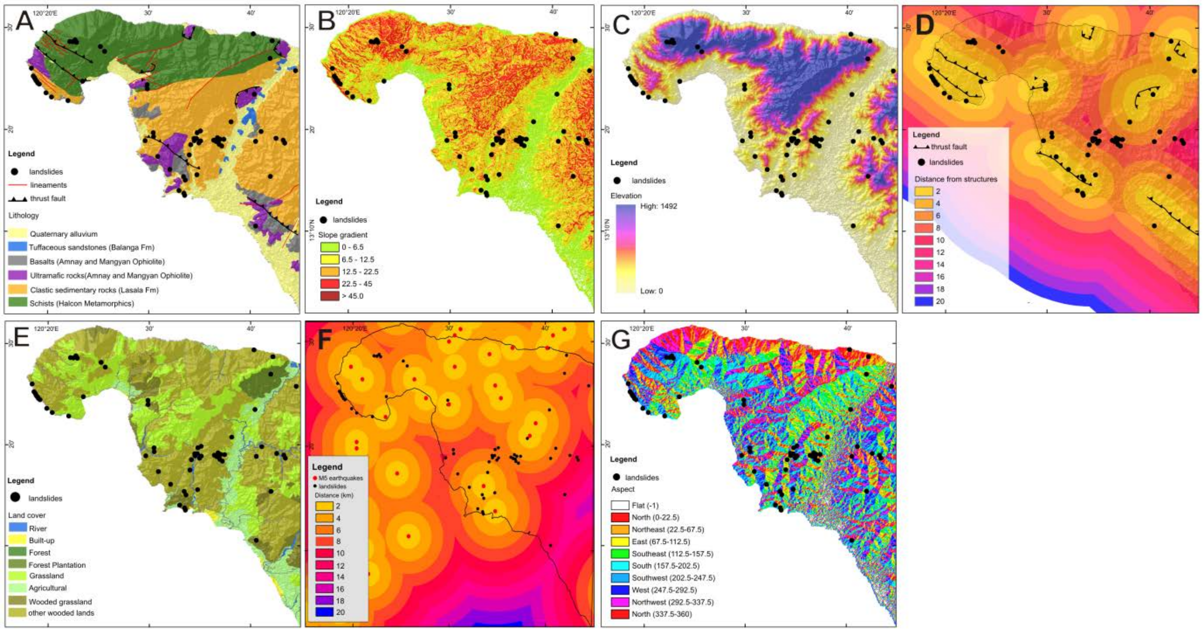

Figure 3. Thematic maps of physical parameters or factors that influence slope failure: (A) lithology, (B) slope gradient, (C) elevation, (D) distance from faults and lineaments, (E) land cover, (F) distance from magnitude 5 earthquakes, and (G) slope aspect.

Table 1. Sample Landslide Data Collected in Northwest Mindoro Showing Geologic and Geomorphic Characteristics Evaluated

	Location (Degree decimal)		**Relief**		**Soil Cover and Geology**				
	Northing	*Easting*	*Slope gradient*		*Soil cover thickness*	*Soil over consistency*	*Compactness*	*Toughness of granular soil*	*Bedrock lithology*
1	13.3158	120.7141	12.5–22.5	moderate	5–10 m	medium stiff	slightly loose	friable	Interbedded sandstone and shale
2	13.3304	120.6801	22.5–45	steep	10–20 m	medium stiff	slightly loose	friable	
3	13.3150	120.7310	45–90	very steep	10–20 m	medium stiff	slightly loose	friable	
4	13.3024	120.4985	22.5–45	steep	<5 m	stiff	slightly loose	firm	

	Rock Mass Strength		
	Weathering	*Degree of fracturing*	*Coherence*
1	completely weathered		
2	completely weathered		moderate
3	completely weathered		moderate

Table 1 continued...

4	slightly weathered	jointed	high

	Mass Movement							
	Type	*Material*	*Subtype*	*Activity*	*Width area*	*Depth*	*Total length*	*Other evidence of slope instability*
1	slide	fine earth	rotational	active	>25 m			tension cracks
2	slide	fine earth	rotational	active	2–10 m	2–10 m	1.0–50 m	--
3	slide	fine earth	rotational	reactivated	>25 m	10–25 m	1.0–50 m	tension cracks
4	slide	rock	translational	active	2–10 m	<2 m	1.0–50 m	tilted trees

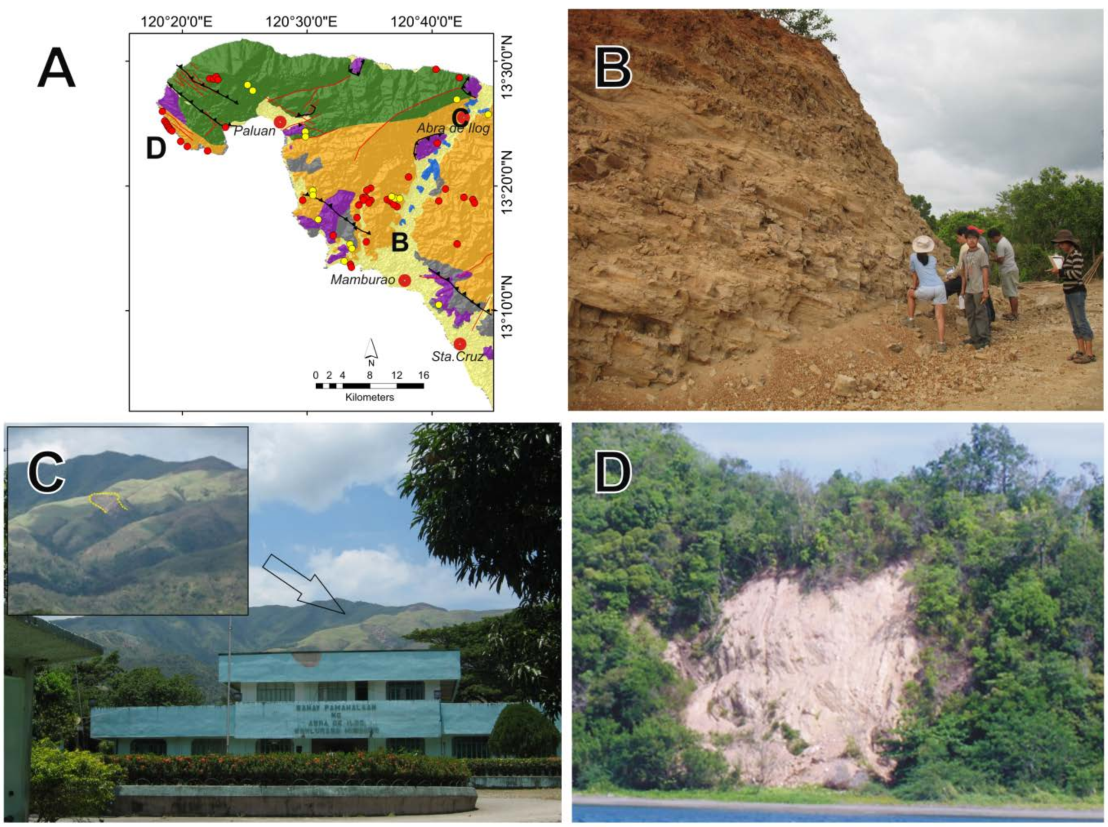

Figure 4. Graphs showing the relationship of landslide frequency with geological and geomorphological factors.

Factor Selection

The stability of slopes is a direct function of numerous factors including the type of terrain, the presence of discontinuity features, morphology of the slope, hydrogeological conditions, and type of vegetative cover or land use. Triggers to mass movements can either be internal or external forcing that includes intensive rainfall and earthquakes. Anthropogenic activities such as deforestation and changes in land use are additional factors that can increase the chances for mass wasting to occur (Crozier, 1984), which, in turn, risks landslides. In this study, physical factors such as lithology, topographic features (i.e., slope gradient, elevation, and slope aspect), distance from faults and lineaments, land cover, and distance from historical earthquakes with magnitudes of 5 and greater were considered to influence slope failure (Fig. 4). The rainfall intensity factor was not included since the nearest PAGASA station is located in the southern part of the study area; thus, the data may not represent actual rainfall in northwest Mindoro. Distance to drainage was also not included since only few landslides were observed near the drainage network. Additionally, the number of factors being considered could affect the final susceptibility map. Dou et al. (2015) and Pradhan and Lee (2010) concluded that using 6 and 7 factors resulted to better predicting accuracy.

The influence of bedrock lithology and structure on slope failure widely varies based on inherent rock characteristics. For example, sedimentary rocks tend to be easier to erode compared with fresh, unfractured igneous rocks due to the varied processes that formed these two rock types. Furthermore, structural features such as faults, bedding planes, folds, fractures, joints, and shear zones decrease the strength, induration, and cohesion of slope materials (Sidle & Ochiai, 2006). In most instances, especially along road cut exposures, bedding planes that daylight the slope (i.e., sliding planes facing the slope) are prone to rock slides. Intense weathering and dense fracturing of slope materials also tend to increase the probability of slope failure.

Lithologic units of the Halcon Metamorphics are characterized by foliations that develop into weak planes when weathered. Quartz mica schists along the western coast of Paluan exhibit foliations oriented to the northwest with low angle plunges while chlorite schists along northern coast near Abra de Ilog generally have northeast foliations (Canto et al., 2012). Rotational slides were observed to occur mostly on the lithologies of the Lasala Formation, which is characterized by intense weathering and weak bedding planes. In areas underlain by ultramafic rocks, the few slope failures noted were often associated with highly sheared rock materials. Peridotites are highly weathered and densely fractured. Basalts of Amnay Ophiolite are also highly weathered, mostly exhibiting spheroidal weathering. Interbedded sedimentary rocks of the Balanga Formation are often friable and highly weathered.

The role of topographic factors in landslide occurrence is represented by elevation, slope aspect, and gradient (Sidle & Ochiai, 2006). In rainfall-induced landslides, higher elevations are taken to affect mass movement due to strong orographic effects (Daly et al., 2003; Lepore et al., 2012). Slope aspect and gradient may also influence erosion in the event of slope failure. Aspect shows the direction of slopes and may indicate zones with high landslide probability when paired with slope gradient, which refers to the rate of maximum change in z values (Oh & Lee, 2011). Slope aspect has been demonstrated to affect landslide susceptibility, in which different slope directions may dictate the threshold of slope failure depending on wind direction and rainfall; that is, windward slopes receive more rainfall than the leeward side (Liu & Shih, 2013). Slope angle may have an effect in unconsolidated materials; however, an increase in slope angle does not necessarily result in an increase in landslide occurrence (e.g., Yamagishi & Iwahashi, 2007). Landslides commonly occur in areas with the same slope aspect and foliation direction (e.g., Lee et al., 2002). In northwest Mindoro, however, no direct correlation was observed between slope aspect and landslide frequency although the foliation direction of metamorphic rocks was noted to coincide with aspect direction.

In the study area, high mountain ranges (up to 1760 masl) are underlain by metamorphic rocks while moderately sloping hills are underlain by sedimentary rocks.

Steeply dipping foliated metamorphic rocks comprise the highlands in the northern and central portions. In Sta. Cruz, steep slopes are underlain by amphibolites while peridotite hills are characterized by gentle slopes. A gently rolling terrain is also exhibited by ultramafic rocks exposed in low lying areas while younger sedimentary sequences are located in the NNE-trending synclinal basin extending from Abra de Ilog to Mamburao (Fig. 4A). A contrasting relationship between topography and landslide occurrence is observed in the area; hillslopes at lower elevations appear to have more landslides than slopes at higher elevations. Thus, field observations reveal that the influence of topography on slope failure is varied and is less significant compared to lithological characteristics. Furthermore, landslide assessments reveal that the majority of slope failures occurred on relatively gentle slope gradients (i.e., between 6.5° and 22.5°; see Fig. 3B), contrary to the general assumption that steeper slopes are more prone to landslides. In northwest Mindoro, weathered and poorly indurated sedimentary rocks of the Lasala Formation characterize the slopes with gentle gradients while steeper slopes are underlain by metamorphic rocks (Figs. 3A and 3B).

Many of the reported landslide occurrences in the Philippine archipelago are located in areas proximal to mapped active faults (NDRRMC, 2012). Ground shaking that results from earthquakes may significantly affect the landslide susceptibility of a region if the underlying rocks are heavily weathered and densely fractured. Faults and lineaments, often resulting from fractured and weakened rocks, were used to assess the influence of tectonic structures to slope failure. Areas in an active tectonic setting are often characterized by rocks that are highly weathered, altered, and fractured, consequently promoting slope instability (Sidle & Ochiai, 2006). Several assessments of the 2006 landslide in St. Bernard, Leyte, reveal that slope failure was attributed to the altered and fractured lithological units traversed by a segment of the Philippine Fault Zone (e.g., Lagmay et al., 2006). Moreover, six reported landslides in the Philippines (i.e., the July 16, 1990, earthquake in Luzon; March 5, 2002, earthquake in Mindanao; October 8, 2004, earthquake in Mindoro; February 6, 2012, earthquake in Negros Oriental; March 2012 earthquake in Dinagat Island; and June 3, 2013, earthquake in North Cotabato) were triggered by earthquakes with magnitudes ranging from 5.7 to 7.8 (Punongbayan et al., 1994; NDRRMC, 2012; PHIVOLCS–DOST, 2012). Known earthquake generators proximal to the study area include offshore and onshore faults (e.g., Lubang, Sibuyan Sea, Aglubang River, Central Mindoro, and Southern Mindoro faults; PHIVOLCS–DOST, 2000) and the subduction zone along the southernmost Manila Trench (Fig. 2).

Land use may either help improve the condition of the slope or degrade it. Vegetation cover, especially woody vegetation, tends to influence slope stability (Sidle & Ochiai, 2006). Changes in land use and land cover by human activities such as deforestation, forest logging, road construction, and slash-and-burn cultivation on steep slopes contribute to an increased rate of weathering of rock units and, consequently, the probability of slope failures. Note that slash-and-burn farming is continuously being done in the Philippines. The current land cover of northwestern Mindoro is generally agricultural and built-up areas while patches of forest, plantation forest, grassland, wooded grassland, and other wooded lands are also identified (Fig. 3E, modified from NAMRIA, 2003). Grasslands and other wooded lands comprise areas northwest of Abra de Ilog, which coincide with the exposures of metamorphic rocks. Some bare land patches were observed to have resulted from slash-and-burn farming practices of the residents. Development activities in the community such as road constructions further lead to exposure of rock units. A few slope failures observed at lower elevations were caused by road cuts exposing bedded sequences that daylight the slope, as seen in Paluan and the newly constructed Abra de Ilog–Puerto Galera road. Few slope failures were observed along Pagbahan and Tuguilan rivers, which drain towards Mamburao.

Factor Analyses and GIS Analysis

Factors and subfactor classes (Table 2) were derived and reclassified in ArcGIS. Gradations were assigned relative weights depending on their degree of influence to landslide susceptibility. Rankings are assigned from 1 to 5, with 1 having the lowest and 5 having the highest contribution to slope failure. Two modes of analysis for the different physical factors and subfactors were done to compare susceptibility assessments derived from idealized and field-based weighing. The first mode, herein designated as Mode A, employs idealized or generalized weights by assuming that progressive increases within a subfactor class will translate to a higher or lower probability of slope failure. For example, slopes with steeper gradients (Pradhan & Lee, 2009) or higher elevations tend to be prone to landslides. Mode B, on the other hand, utilizes field observations that provided constraints on the geological and geomorphological factors contributing to slope failures in the area. Table 2 compares the weights assigned for the different factors and subfactors considered in this study.

Table 2. Geological and Geomorphological Parameters and Subclasses Rated on a Scale of 1 to 5 Based on Their Contribution to Slope Failure

Table 2 continued...

Parameters	Rating	
	Mode A	Mode B
Lithology		
Mica schist$_{Halcon\ Metamorphics}$	4	4
Chlorite schist$_{Halcon\ Metamorphics}$	4	4
Sandstones$_{Lasala\ Formation}$	5	5
Conglomerates$_{Lasala\ Formation}$	3	3
Ultramafics$_{Amnay/Mangyan\ Ophiolite}$	2	2
Basalts$_{Amnay/Mangyan\ Ophiolite}$	2	2
Limestones$_{Balanga\ Formation}$	3	3
Sandstones$_{Balanga\ Formation}$	4	4
Quaternary alluvium	3	3
Slope Gradient (°)		
0–6.5	1	2
6.5–12.5	2	5
12.5–22.5	3	4
22.5–45	4	3
>45	5	1
Elevation (km)		
0–176	1	2
176–352	1	3
352–528	2	4
528–704	2	5
704–880	3	4
880–1056	3	3
1056–1232	4	2
1232–1408	4	1
1408–1584	5	1
1584–1760	5	1
Distance to Structure (km)		
2	4	4
4	4	4
6	3	3
8	3	3
10	2	2
12	2	2
14	1	1
16	1	1
18	1	1
20	1	1

Table 2 continued...

Parameters	Rating	
	Mode A	Mode B
Land cover		
Agricultural	1	1
Built-up	2	2
Forest plantation	3	3
Forest	3	3
Grassland	5	4
Other wooded land	4	5
Wooded grassland	3	2
Distance to M5 historical earthquakes (km)		
2	4	3
4	4	4
6	3	5
8	3	3
10	2	2
12	2	2
14	1	1
16	1	1
18	1	1
20	1	1
Slope aspect		
Flat	1	1
North	1	1
Northeast	1	1
East	2	2
Southeast	2	2
South	3	3
Southwest	4	4
West	2	2
Northwest	1	1

Note. The parameter characteristic with the least or most likely contribution to slope failure is designated a rating of 1 or 5, respectively.

The analytic hierarchy process (AHP) is a semiquantitative method of evaluating quantifiable and intangible factors that influence the occurrence of a phenomenon (Saaty, 1980; Saaty & Vargas, 2001). The AHP is a multiobjective, multicriteria decision-making approach that enables the generation of a scale of preference drawn from a set of alternatives and thus has been applied to various problems including decision theory and conflict resolution (e.g., Vargas, 1990; Yalcin, 2008). Ercanoglu et al. (2008) concluded that the results of the AHP method vis-à-vis that of artificial neural networks (statistical method) are comparable and show general agreement. In the AHP method, each contributory factor is compared with other factors based on their levels of importance; each factor is rated against every other factor by assigning a relative dominant value between 1 and 9. A value of 1 indicates that the factors being compared are of equal importance, and a rating of 9 means that one factor is of extreme importance over the other (Table 3; Yalcin, 2008). From numerical pair-wise comparisons of the factors, relative weights are derived and are used to assess the relative importance of the landslide hazard factors considered. From an expert opinion-based AHP analysis of the seven physical factors influencing slope failures in northwest Mindoro, lithology is evaluated as the most important contributory factor, followed by slope gradient, elevation, distance from structures, land cover, distance from historical earthquakes of magnitude 5 and higher, and, lastly, aspect (Table 4). The consistency index (CI) and consistency ratio (CR) were calculated to check for inconsistencies in the pair-wise comparison (see Saaty, 1980). If the CR, which is the CI compared to the value of the random consistency index for a given matrix (in this case 7 matrix or factors being considered has 1.32 random consistency index), is less than 10% (0.10), the pair-wise comparison is acceptable. If the CR value is greater than 10%, the pair-wise comparison should be improved (Saaty, 1980).

Table 3. Rating Scale Adapted from Saaty (1980)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgment slightly favor one over the other.
5	Much more important	Experience and judgment strongly favor one over the other.
7	Very much more important	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favoring one over the other is of the highest possible validity.
2, 4, 6, 8	Intermediate values	When compromise is needed

Table 4. Pair-Wise Comparison Matrix of the Seven Factors Used for Landslide Susceptibility Assessment in Northwest Mindoro Shows Relative Ratings and Derived Weights (Saaty, 1980)

Parameters	**Lithology**	**Slope**	**Elevation**	**Distance to Structure**	**Land Cover**	Distance to M5	Aspect
Lithology	1	3	3	3	3	7	9
Slope	1/3	1	3	3	3	5	7
Elevation	1/3	1/3	1	3	3	5	7
Distance to structure	1/3	1/3	1/3	1	3	5	7
Land cover	1/3	1/3	1/3	1/3	1	5	7
Distance to M5	1/7	1/5	1/5	1/5	1/5	1	3
Aspect	1/9	1/7	1/7	1/7	1/7	1/3	1
Total	2.59	5.34	8.01	10.68	13.34	28.33	41.00
Derived weights	0.33	0.22	0.17	0.13	0.1	0.04	0.02
					Consistency index		0.13
					Consistency ratio		0.09

Different approaches in landslide susceptibility studies are currently being utilized, such as deterministic, nondeterministic (e.g., heuristic analysis, bivariate statistics based), and quantitative (e.g., fuzzy logic, artificial neural networks, conditional probability) methods. The advantages and disadvantages of each method are discussed in Varnes (1984), Aleotti and Chowdhury (1999), and van Westen et al. (2006), among others. Several studies compare the different landslide susceptibility mapping methods and the various multicriteria decision analysis approaches (Feizizadeh & Blaschke, 2014; Eker et al., 2015).

This study employs the heuristic analysis approach (expert-judgement method) using AHP (e.g., Muthu & Petrou, 2007; Yalcin, 2008; Wati et al., 2010; Pourghasemi et al., 2012; Kayastha et al., 2013) coupled with weighted overlay analysis in a GIS platform. Heuristic analysis is a type of deterministic approach that is based on the knowledge and experience of the decision makers (Van Westen, 2000). In order to establish the most appropriate landslide susceptibility assessment and analysis for northwest Mindoro, three variations of overlay analyses were employed and compared.

Analysis 1 (Mode B, non-AHP): Based on expert opinion and field observations, each factor was assigned a weight percent commensurate to its perceived contribution to landslide occurrence at a given location. Elevation, slope, slope aspect, and land cover were each assigned 15%, distance from structures and historical earthquakes, 10%, and lithology, 20%.

Analysis 2 (Mode A, AHP): The weight of each contributory factor was derived using AHP combined with Mode A.

Analysis 3 (Mode B, AHP): The weight of each contributory factor was derived using AHP combined with Mode B.

Subclass ratings (from Mode A and Mode B) were added for each factor with a 30-×-30-m resolution that corresponds to the resolution of the ASTER GDEM map. Consequently, weights derived from the pair-wise comparison matrix were multiplied to the subclass rating to get the susceptibility value. For example, a mica schist type of lithology has a rating of 4 using Mode B (see Table 2) and the lithology parameter has a 0.33% weight (see Table 4). So for areas with mica schist lithology, the susceptibility value is 0.6. This value will be added to the susceptibility values of the remaining parameters to get the final susceptibility value, which is reflected in the landslide susceptibility map.

Field and Remote Observations

To evaluate the landslide susceptibility of northwest Mindoro, lithologic characteristics (e.g., fracturing, weathering), slope morphology of recent landslides and historical landslide scars, and human-initiated activities along road cuts were noted (Fig. 5). This study assumes that the frequency of landslides in the past and at present time may increase the probability of occurrence in the future (e.g., Varnes, 1984; Dai & Lee, 2002). In Longmenshan Town, China, for example, the catastrophic landslides triggered by the 2008 Wenchuan earthquake occurred on old landslide deposits (Wang et al., 2009).

A total of 60 landslides were identified and were categorized as active or inactive based on the classification of Crozier (1984; Fig. 2). The landslide inventory was done at a reconnaissance level by visual observation of hillslope characteristics. Table 4 shows representative landslide data collected in the study area. Active landslides were identified based on the presence of recent talus or rock/soil materials at the foot of the slope, while inactive landslides are characterized by relatively “old” geomorphic features such as “amphitheater” features and landslide scars. Though most of the inactive slides have already been covered by vegetation, these geomorphic features indicating past landslide events may still be recognized.

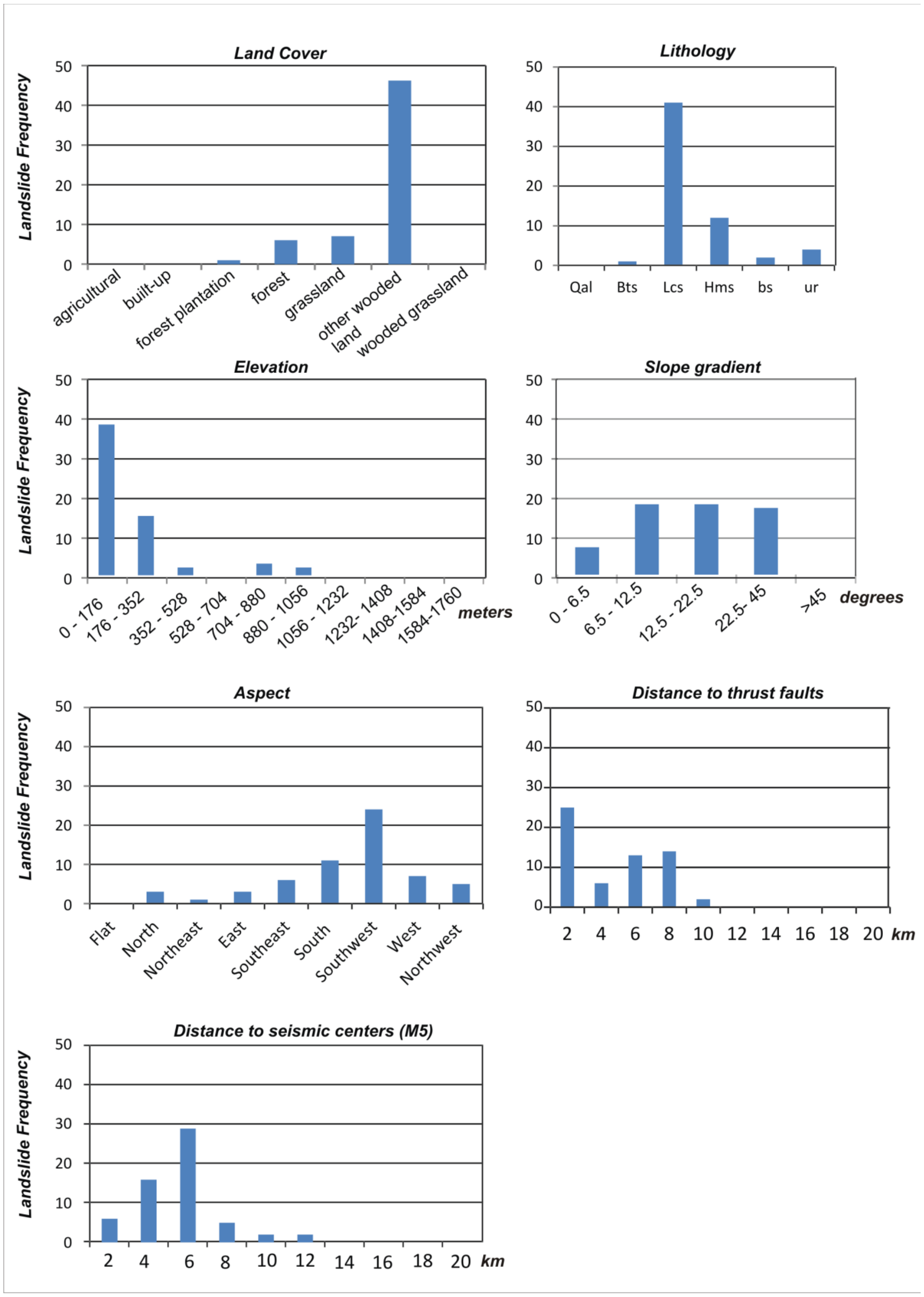

Figure 5. Map and representative photos of slope failures in northwest Mindoro. A) Inset map showing the location of slope failures observed. B) Road cut along Mamburao shows sedimentary structures (i.e., beds) that daylight the slope; these highly weathered tuffaceous sandstones comprise the Plio-Pleistocene Balanga Formation. C) Inactive landslide scar behind Abra de Ilog municipal hall. D) A fresh landslide scar observed along the southwestern coast of Paluan exposes highly weathered and poorly indurated rocks.

Rotational and translational slides generally characterize the slope failures in northwest Mindoro. Active landslides appear more frequent along hillslopes underlain by the clastic sequences of the Lasala Formation while inactive landslides were observed on the schists and phyllites underlying the rugged terrain (Fig. 2); inactive landslides were identified through the presence of slow-growing vegetation on slide surfaces.

RESULTS AND DISCUSSION

The frequency of landslides occurrences and the factors being considered were analyzed (Fig. 5). The frequency of landslides is highest in the areas characterized by other wooded land type of land cover underlain by sedimentary rocks of the Lasala Formation (Fig. 5). Most landslides also occur in the lowest elevation (<176 masl), southwest aspect, within a 2-km distance from thrust faults and within a 5- to 6-km distance from historical seismic centers with >5 magnitude. The landslide frequency is mostly similar for slope gradients with 6.5° to <45°. Those with steep slopes (>45°) are mostly characterized by hard rock or outcropping bedrock; some might be associated with rock fall, but were found to be not associated with landslides in the study area (also see Pradhan & Lee, 2009).

For the AHP-derived weights based on expert judgements, lithology has the highest derived weight (0.33) and is considered to be the most important factor in the occurrence of landslide in northwest Mindoro. On the other hand, aspect has the least derived weight (0.02). The CR value, 0.09, for the seven parameters being considered denotes that the weights assigned for each parameter are acceptable.

Three GIS-based landslide susceptibility maps were generated to evaluate varied approaches in establishing the most appropriate landslide susceptibility assessment for northwest Mindoro (Fig. 6). In the maps generated, landslide susceptibility zonations are categorized as low, moderate, and high using the equal interval method with minimum landslide susceptibility index value at 1.99 and maximum value at 4.79. Breaks between the different susceptibility values are at 2.92 and 3.86. Three variations of weighted overlay analysis were carried out using subjective and semiquantitative or numerical assignment of factor and subfactor weights.

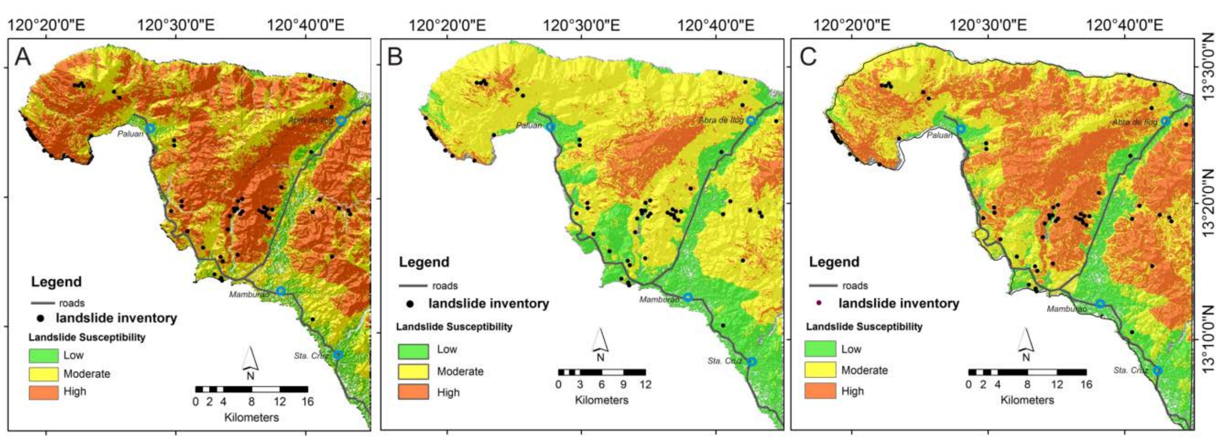

Figure 6. Maps showing landslide susceptibility zonations as low, moderate, and high based on the assessment of seven physical parameters that may contribute to landslide occurrences. Note that the town centers of Mamburao, Abra de Ilog, and Paluan have low susceptibility to landslides; however, hillslopes surrounding Abra de Ilog are highly susceptible. A) Landslide susceptibility map using Mode B analysis. B) Landslide susceptibility map using Mode A analysis and AHP-derived weights. C) Landslide susceptibility map using Mode B analysis and AHP-derived weights.

Analysis 1 (Mode B, non-AHP): The resulting GIS-based landslide susceptibility map shows that a significant area of northwest Mindoro has high susceptibility to slope failure (i.e., 53%) while zones having low to moderate susceptibility comprise 8% and 39% of the study area, respectively. Zones that are categorized as highly susceptible to landslides are underlain by the rock units of the Lasala Formation. Zones that have low susceptibility to landslides are often coastal lowlands and wide gullies and fluvial channels bounded by relatively gentle slopes. Very few landslides were noted in the zones of moderate susceptibility. Comparison of the generated map with the landslide inventory of active and inactive landslides in the study area shows that 13% of the landslides fall within the moderate susceptibility zones while 87% coincide with the high susceptibility zones.

Analysis 2 (Mode A, AHP): The generated landslide susceptibility map shows that most of the mapped landslides fall within the moderate susceptibility zone (63%) while the high susceptibility and low susceptibility zones comprise 12% and 25%, respectively, of the study area. Correlating these percentages with observed slope failures, the high susceptibility zones coincide with only 37% of the field data while moderate susceptibility zones coincide with 63% of mapped landslides. Low susceptibility zones coincide with 25% of mapped landslides. Hence, this method appears to overestimate the areas that fall within the high susceptibility zones and suggests that Mode A analysis (i.e., idealized or generally assumed weights) is not appropriate in landslide hazards susceptibility assessment and mapping. Differences in Mode A and Mode B ratings were assigned for factors such as slope gradient, elevation, land cover, and distance to >5 magnitude historical earthquakes (see Table 2). When compared with their AHP assigned weights (0.22, 0.17, 0.1, and 0.04, respectively), the Mode A ranking shows low accuracy for landslide predictability. In the case of Analysis 2, the idealized ranking based on the general progressive increase in geomorphologic factors subclasses is different from what is observed in the study area. In this case, the expert-base assessment mimics the function of quantitative type of landslide susceptibility assessment (e.g., conditional probability), albeit its subjective nature.

Analysis 3 (Mode B, AHP): The generated landslide susceptibility map shows zones of high (44%), moderate (39%), and low (17%) susceptibilities. Areas categorized as highly susceptible to slope failure coincide with 77% of the landslide inventory while moderate and low susceptibility zones coincide with only 20% and 3% of the observed landslides, respectively. Results from this analysis show that field-based data is integral in the generation of appropriate landslide hazard maps.

CONCLUSIONS

The rugged terrain and steep-sided hillslopes reflect the arc-continent collision processes that shaped the lithologic, structural, and geomorphological characteristics of northwest Mindoro. Lithologic characteristics are considered to be among the most significant of the physical factors contributing to slope failure, in which landslides are observed to be more frequent in areas underlain by clastic rocks of the Lasala Formation.

Field observations also show that slope failures do not necessarily occur along slopes of steep gradients or at areas of high elevation. Assessment of active and inactive landslides reveals that slope failures are strongly influenced by the characteristics of underlying rock units and soil cover, regardless of slope gradient and elevation. At relatively lower elevations and gentler slope gradients (i.e., 6.5° to 22.5°), numerous slope failures occur along intensely weathered and bedded sedimentary sequences that daylight the slope while a few occurrences are associated with the metamorphic terrane, which underlies the rugged and steep topography at higher elevations. Land cover may also be a significant factor since several landslides were noted on wooded lands. While distance to tectonic structures and historical earthquakes seem to have a minimal effect on landslide occurrence, proximity to these contributory factors is still important since fracturing and ground shaking affect the physical conditions of the bedrock soil cover and other slope materials.

Varied subjective and semiquantitative approaches were employed to generate the most appropriate landslide susceptibility map for northwest Mindoro. A combination of expert opinion, AHP, and weighted overlay analysis in GIS were used to assess the relationship of landslide susceptibility with predisposing factors such as lithology, slope gradient, elevation, distance from tectonic structures and historical earthquakes, land cover, and slope aspect. The GIS-based landslide susceptibility maps categorize northwest Mindoro into zones of low, moderate, and high susceptibility to landslides.

Landslide occurrences observed in the field correlate well with GIS-based maps that utilized factor and subfactor weights derived from field observations (i.e., Mode B analysis). In contrast, idealized or assumed weights assigned to contributory physical factors and subfactor classes resulted to a susceptibility map that did not correlate well with field data. The extent of highly susceptible zones was also notably overestimated in Mode A analysis without AHP. Results show that for northwest Mindoro, the best method to employ in landslide susceptibility studies is the combination of field-based and AHP-derived ratings. This further suggests that the combined use of field observations, expert opinion, AHP, and GIS is indispensable input for generating landslide susceptibility maps, which can be most useful for land use planning and development.

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