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Application of Analytical Hierarchy Process (AHP) for Landslide Hazard Analysis (LHA) in Kota Kinabalu area, Sabah, Malaysia

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Abstract. A very good Landslide Hazard Analysis (LHA) model was developed using the Analytical Hierarchy Process (AHP) method for the area of Kota Kinabalu, Sabah. The AHP is defined as theory of measurement through pairwise comparisons and relies on the judgements of experts to derive priority scales that measure intangibles in relative terms. The derived priority scales are synthesised by multiplying them by the priority of their parent nodes and adding for all such nodes. Weighted value of different spatial factors from the best models calculated with the AHP method were derived. The results showed that the geology (27% variance), geodynamic features (14% variance), slope conditions (26% variance), hydrology/hydrogeology (14% variance), types of land use (3% variance), and engineering characteristics of soils (8% variance), and rocks (8% variance) play an important role in landslide susceptibility analysis. In terms of Landslide Hazard Map (LHM), the analyses resulted of Kota Kinabalu area suggests that 2.78% of the area can be categorised as Very Low Hazard, 14.14% as Low Hazard, 19.74% as Moderate Hazard, 51.63% as High Hazard, 11.34% as Very High Hazard and 0.37% as Extremely High Hazard. Model accuracy assessment of LHA was performed using consistency ratio (CR) equal to 0.0129 (< 0.1) (acceptable) and 93.50 % accuracy of the validation prediction. Thus, the newly developed method works satisfactory and high reliability; and is applicable to further research development in Kota Kinabalu, Sabah, and potentially to expand with different environmental settings.

1. Introduction

Kota Kinabalu, Sabah (Figure 1) has experienced various scales of landslides. Due to demands for increasing development and residential are taking places in hillslope areas, human activities such as deforestation or excavation of slopes for road cuts and building sites have become threat and hazards to residents [1-4]. The historical data gathered shows that landslide often occurred due to several causative factors. The main factors were identified as geomorphological factor, geological factor, hydrological



factor and anthropogenic factor. However, all the causal factors must be considered on the recurrence and intensity of triggering factors [5-10].

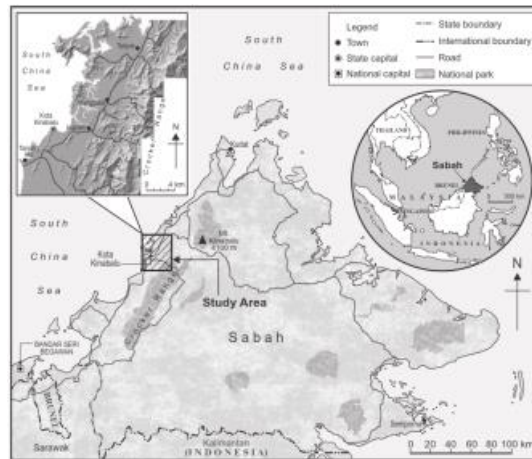


Figure1. Locality map of the studied area

2. Methodology

2.1 Landslide Hazard Identification (LHI)

Landslide Hazard Identification (LHI) involved three (3) main phases; namely desk studies, field studies and laboratory studies. The desk studies involved aerial photograph interpretation and satellite images analyses (Spot-5 dan QuickBird II), and extensive studies of literature review and secondary data collections. All of these sources were analysed and reclassified to get an idea or preliminary information about the landslide distribution and historical data (frequency) aspects in the study area. The product from the desk studies established a "Landslide Distribution Map" (LDM) (Figure 2).

The field studies in LHI involved sampling of rocks and soils, engineering geological mapping, observation of landslide hazard characterization information, such as lithology, soil types and land use; and extracting a digital elevation model. For the laboratory studies in LHI, all samples of rocks and soils obtained from the field were analyzed and evaluated for their engineering properties in accordance with the standards recommended by the ISRM [11, 12] and British Standard BS 1377 [13] such as the direct shear test for rock mechanic testing and the triaxial test (Consolidated isotropically undrained, CIU) for soil mechanic testing.

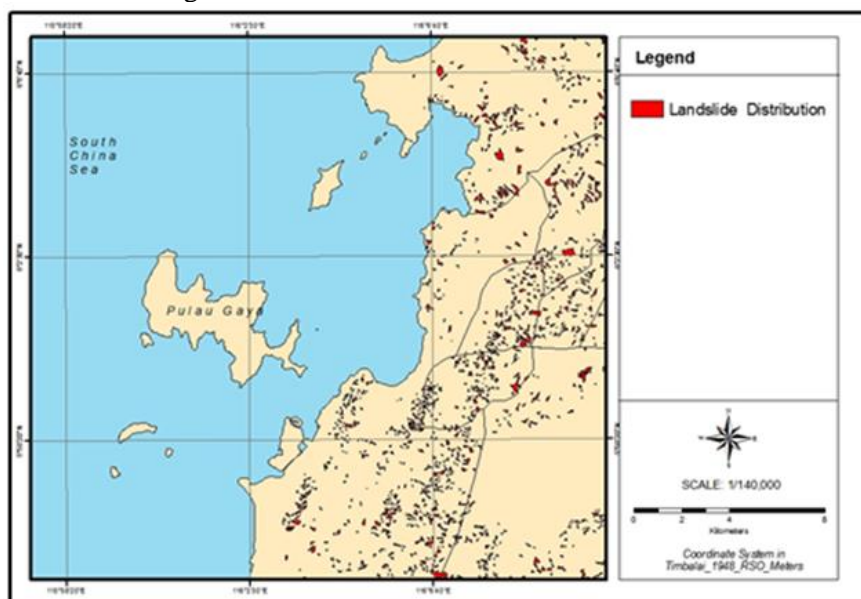


Figure 2. Landslide distribution map (LDM)

2.2 Production of the thematic data layers

With the combination of fieldwork (engineering geological mapping and observation information), laboratory studies and GIS extraction results, fifteen data layers were produced to represent the lithology, soil textures, lineament, weathering, magnitude, spreading distance, slope angle, slope height, rainfall, groundwater level, landuse, friction angle, cohesion, compressive strength and rock quality designation (RQD) (Figure 3).

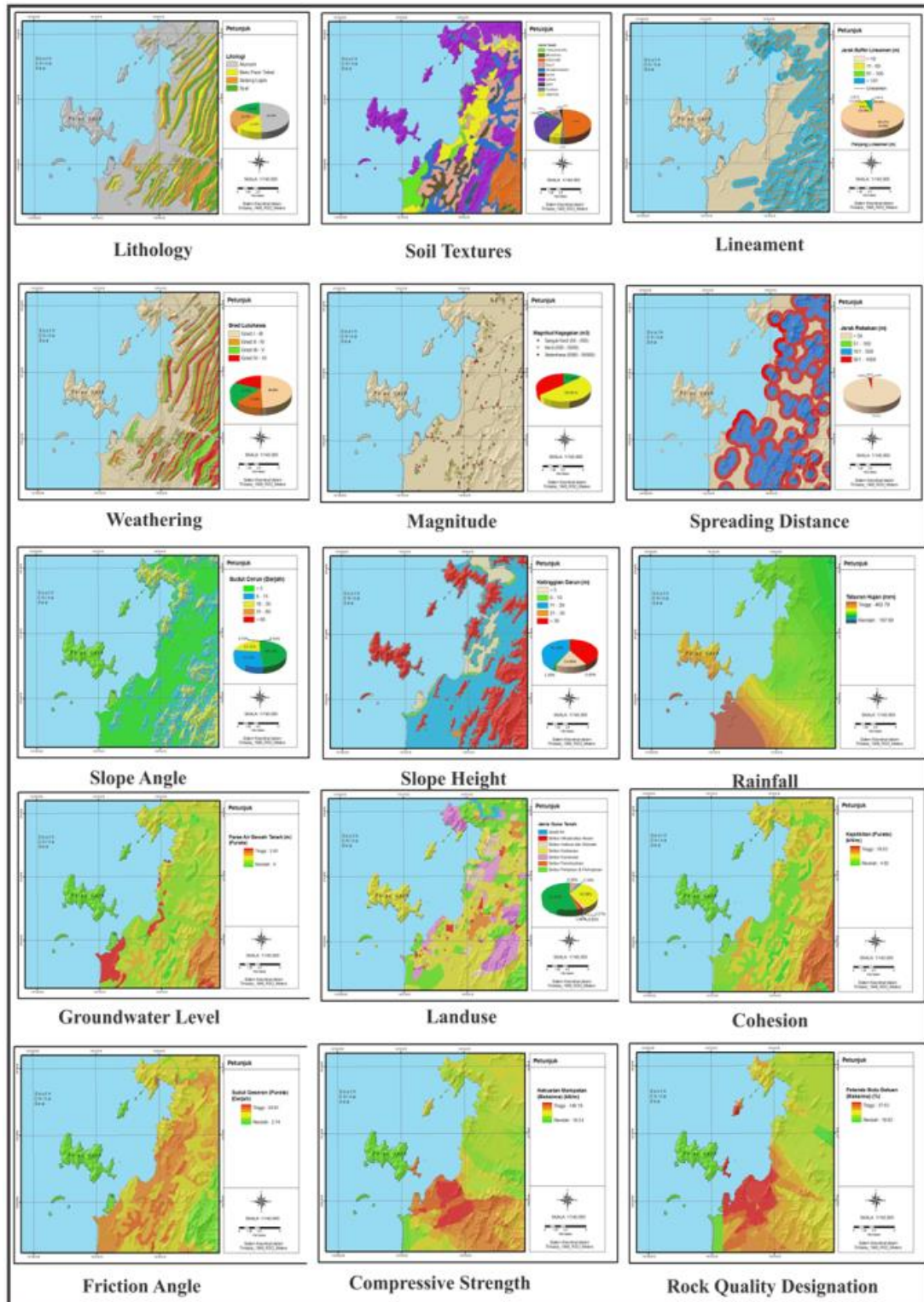


Figure 3. Thematic data layers for Landslide Susceptibility Analysis (LSA)

2.3 Application of Analytical Hierarchy Process (AHP)

Values ranging from 9 (extremely) to 1 (equally) and 1/9 (opposite extremely) are assigned by expert judgment to each pair of parameters yielding a square reciprocal matrix by rating rows relative to columns. The LSL map is established according to Eq. (1). The consistency of the weights and ratings are evaluated by taking the principal eigenvectors of each matrix and calculating the consistency index (CI) and consistency ratio (CR). The values are given in Table 1. It is found that all CR values are less than 0.1 (0.0129) and consequently this proves the preferences utilized to produce the comparison matrixes are consistent.

$$\sum [(8 \times \text{Lithology}) + (8 \times \text{Soil}) + (7 \times \text{Lineament}) + (6 \times \text{Weathering}) + (7 \times \text{Magnitude}) + (7 \times \text{Spreading}) + (13 \times \text{Slope}) + (13 \times \text{Height}) + (7 \times \text{Hydrology}) + (7 \times \text{Hydrogeology}) + (3 \times \text{Landuse}) + (4 \times \text{Cohesion}) + (4 \times \text{Friction}) + (4 \times \text{Compressive}) + (4 \times \text{RQD})] \tag{1}$$

2.4 Calculation and Evaluation of AHP

By generating a reciprocal square matrix with rows of proportional proportions to the spatial results, experts determine values from 9 (past), to 1 (equal to), and 1/9 (opposite past) for each pair of parameters. The weighting values obtained from the causal factor W_j and the weighting values W_{ij} from various classes in each layer factor are given in Table 1. The consistency of the weighting values is evaluated by considering the main eigenvectors for each matrix and calculating the CI values and values. The results of the calculations found that all CR values were less than 0.1 (0.0129) and this indicates that this experiment is acceptable and suitable to be used to produce a consistent comparison matrix.

Table 1. Evaluation of the consistency of the preferences used for rating the parameters and categories.

Total inverted row	0.0667
Normalized	Principal Eigen
Vector	
Lithology	0.08
Soil	0.08
Lineament	0.07
Weathering	0.06
Magnitude	0.07
Spreading	0.07
Slope	0.13
Height	0.11
Hydrology	0.07
Hydrogeology	0.07
Landuse	0.03
Cohesion	0.04
Friction	0.04
Compressive	0.04
RQD	0.04
Total	1.0000
	Principal Eigen value
Max lambda	15.2876
n	15
CI	0.0205
RI	1.59
CR	0.0129

3. Result and Discussion

A lithological map was produced to illustrate all the information about the rock units found in the study area (Figure 3). Different rock compositions and textures will affect the instability of the slope, affecting its strength, permeability, and resistance to weathering processes. There is a wide range of bedrock types in the study area, from Eocene to Miocene sandstones and shales from the Crocker Formation to young

Quaternary to recent alluvial sediments that are still being deposited [14]. This sandstone-mud-shale unit is defined as an interval unit of sandstone layers with shale found in the Crocker Formation. The thickness of this layered interval unit ranges from 2 cm to 130 cm. Sandstone is usually fine to very fine and easily broken while the shale layer is shear. Shale units consist of red shale and grey shale types, which represent almost 18.39% of the total rock units in the Crocker Formation. Quaternary sediments are mostly found in lowland areas and represent almost 49.29% of the total study area. It is an unconsolidated alluvial sediment on river terraces, floodplains, and coastal areas consisting of poor to good sand content, silt, and clay derived from the weathering process of the Crocker Formation rocks.

Information on soil types describes the diversity of physical characteristics of unconsolidated sediments. Based on the soil type map obtained from the Department of Agriculture (Sabah), land associations in the study area can be categorized into ten (10) types of associations, namely Weston association (very silty sand texture, BC) (5.47%), Tanjung Aru association (sand textured with slightly silty, SW) (2.98%), Tuaran association (highly silty sand texture, BC) (2.03%), Kinabatangan association (highly silty sand-textured, SC) (1.28%), Sapi association (peat -textured, Pt) (1.28%), Klias association (organically textured, O) (1.69%), Brantian association (clay -textured, C) (1.07%), Dalit association (highly clayey sand -textured, SC) (8.89%), Lokan association (sand-textured highly silty, BC) (26.23%), and the Crocker association (textured clayey sand, SC) (49.07%) (Figure 3).

Radbruch-Hall [15] noted that the lineament area zone is an area that frequently experiences landslides. Varnes [16] in turn concluded that the degree of cracking and shear play an important role in determining slope stability. Tectonic history contributes to slope instability through the presence of cracks, joints, faults, and other discontinuous structures [17]. The close relationship between tectonic zones and the process of landslide occurrence in the study area has been discussed in Rodeano et al. [14]. Thus, lineament density is also considered as a causal factor in the occurrence of landslides in the study area. The lineament distance maps were generated from the interpretation of aerial photographs and satellite images as well as lithological map evaluation as shown in figure 2 and the density was calculated using the "buffering" technique at total length distances of <10 m (88.27%), 11 m - 60 m (6.93 %), 61 m - 100 m (2.87%) and > 101 m (1.93%) (Figure 3).

Humidity from tropical climates had a significant impact on slope materials used in landslides. In addition to the rapid weathering process, the humid conditions have exacerbated the regolith cover conditions on the surface. Overall, the weathering process in the study area has a wide range of characteristics, including depth, texture, and shape of the Earth's surface as well as chemical-mineral compositions as well as geochemistry and origins. Many factors influence weathering, including climate (tropical monsoon climate), topography (mixed hills and weathering traces), and geology (existence of various geological structures). Mineral components, structures, and textures are typically found in each layer of the weathering zone and reflect the origin and conditions of the weathering zone. Weathering zones can be classified and named according to the chemical content, minerals, lithological components, as well as the texture structure of the weathering product according to the degree of weathering and its conditions. In the study area, weathering zones are classified according to the degree/grade of weathering that occurs on the rock body. Based on qualitative and quantitative evaluation, the weathering zone in the study area can be classified into four weathering zones, namely grade I (fresh rock) to grade III (moderate weathering rock) (49.29%), grade II (semi-fresh rock) to grade IV (rock high weathering) (12.58%), grade III to grade V (complete weathering rocks) (19.73%) and grade IV to grade VI (residual soil) (18.39%) (Figure 3).

The failure magnitude information approach is very useful for studying any physical changes to landslides. It quantifies all the information about a complex phenomenon. In this study, landslides were classified into various types depending on the materials involved, estimated volume, velocity of movement and degree of activity. Around 165 landslide locations have been identified through previous studies, aerial photo interpretation and field studies (Figure 2). The types of landslides are classified into several types: 20% of fall type, 30% of translation type, 20% of rotation type, 15% of flow type, and 15% of complex (combination of fall, slide, and/or flow). On the scale of landslide magnitude, the study area ranged from medium (5000 m^3 - 50000 m^3) (36.14%), small (500 m^3 - 5000 m^3) (50.82%) and very small (50 m^3 - 500 m^3) (13.04%).

Despite this, there isn't a lot of research on the relationship between landslides and distance. However, it is crucial in determining the extent of the damage or the number of lives lost. The close propagation distance combined with high velocity and magnitude increases the vulnerability of the risky elements even more. Based on a variety of case studies, the relationship between vulnerability and propagation distance has been established. A spread distance map was generated as shown in figure 7 and the density was calculated using the "buffering" technique in the total length of the long distance (501 m - 1000 m) (2.026%), medium (101 m-500 m) (0.001%), close (51 m-100 m) (0.462%) and very close (<50 m) (97.511%). Cruden & Varnes [18] identified two important things about the relationship between spread distance and velocity and magnitude of landslides, namely the first between "over speed" and "very fast" at five meters per second. Second, at 1.6 meters per year, which is the boundary between "slow" and "very slow", where some structures located on landslides remain intact and undamaged.

The terrain conditions in the study area are generally complex. The influence of elevation on landslides is often described as having a direct relationship. In the study area, weather factors play an important role in the process of landslide occurrence, which is closely related to altitude. At high altitudes, erosion is more likely to occur at weathering depths. Since the study area has a tropical monsoon climate, where erosion and weathering processes are intensive, it indirectly affects the influence of altitude on landslides [19-20]. A digital elevation model (DEM) for slope conditions was generated based on a raster data set of morphometric features (height, internal pattern, slope angle, aspect, longitudinal and transverse slope curvature, and slope roughness) and hydrological parameters (catchment area, drainage density, drainage network, channel length, etc.) which are automatically extracted from the DEM. In the DEM scale, the study areas ranged from 0 m-5 m (14.66%), 6 m-10 m (1.35%), 11m-20 m (41.84%), 21 m-30 m (0.45%) and > 30 m (41.69%) (Figure 3).

Slope steepness is important in relation to the initial process of landslide movement. In most landslide studies, slope steepness is considered as a major causal or trigger factor [21-23]. Moreover, slope steepness is also considered as an index of slope stability due to the existence of digital elevation models (DEM) evaluated numerically and described spatially [24-25]. In terms of slope steepness in the study area, the data obtained shows that 48.37% of the area can be categorized as 0° - 5° , 28.45% as 6° - 15° , 22.41% as 16° - 30° , 0.75% as 31° - 60° and 0.01% as exceeding 60° (Figure 3). Areas with a slope angle greater than 30° represent a very steep slope segment in the study area where the steeper the slope, the higher the degree of disaster.

Hydrology also plays an important role as a trigger for landslides. Among the hydrological processes involved are precipitation (spatial and temporal distribution of precipitation), absorption of water into the soil (potential for plateau flow), lateral and vertical movement within the regolith, evapotranspiration, and interception (interception). The spatial pattern of rainfall is closely related to the onset of landslide events [26-28] caused by the influence of pore water pressure on unstable slopes [29-32]. In the literature, most researchers usually refer to one of four types of rainfall, namely the amount of rainfall, short-term intensity, antecedent storm precipitation or storm period as the initiation factor of landslides. However, which type of rainfall has the best correlation with the occurrence of landslides has not been determined. Nevertheless, most researchers often use or assume that the short-term intensity of rainfall is the most important determinant [29,33]. While others [34-35] found that the correlation of rainfall amount over a long period of time played a role as a determinant of landslide incidence. In this research, the hydrological map produced is based on the condition of daily rainfall values (short-term rainfall intensity) for the study area (Figure 3). Based on some information obtained by the Malaysian Meteorological Department (JMM) and the Sabah Irrigation and Drainage Department, four (4) stations have been identified, namely Ulu Moyog station, Inanam station, Kota Kinabalu International Airport station (KKIA) and Tuaran station. Readings show that the daily flush data ranged from 197.69 mm to 462.79 mm.

The hydrogeological map shows the distribution and condition of groundwater levels in the study area (Figure 3). Based on the drill hole data, the groundwater level condition in the study area is relatively high where the depth ranges from 0.00 m to 2.93m. Pore water pressure is generally described as the transient (perched) formation of groundwater in the regolith responsible for the onset of landslides. Geomorphic hollows on landslides can occur because of transient formation of groundwater caused by

concentrated subsurface flow. Because the sub-surface flow process controls the movement of water infiltrating through the slope, it affects both the temporal and spatial characteristics of the pore water pressure distribution. The main currents for both characterizations are in soils [36-39] and in bedrock can provide primary control over the formation of pore pressures in steep slopes thus influencing the occurrence of landslides [40-41].

The land use type map shows several sector units, such as the residential sector, commercial sector, public infrastructure sector, industrial sector, higher education institutions and school sector, and agriculture, forestry, and other sectors (Figure 3). Based on the results of spatial GIS analysis that has been conducted, it was found that the agriculture, forestry, and other sectors cover the widest area in the study area (53.92%). This is followed by the residential sector (32.98%), the commercial sector (6.00%), water bodies (2.34%), institutions of higher learning and schools (2.27%), the industrial sector (1.68%), and the public infrastructure sector (0.82%). Judging from the progress of land use diversity, this means that the study area has been explored more than 70% for development or agricultural activities. Extensive exploration without control/enforcement of slope cutting activities can trigger the occurrence of landslide disasters.

Information on soil mechanical characterization describes a variety of types and physical as well as mechanical properties of unconsolidated sediments. The results of detailed analysis of soil samples are given in Figure 3. The physical and engineering properties of the soil from seventy-two (72) samples show that the soil materials in the study area are characterized as bad to good for clayey type soils to sandy, characterized by low to high plasticity properties, and have an attractiveness value (C) ranging from 4.92kPa to 18.03kPa and a friction angle (ϕ) ranging from 2.74° to 24.91° . The mechanical characterization of the rocks of seventy-two (72) samples showed that the rock material varied from very weak to very strong (coaxial compressive strength ranged from 18.24MPa to 148.19MPa). Meanwhile, the values for rock quality indicators ranged from 18.82% to 37.63% (very weak to moderate).

The thematic maps (Figure 3) that had been generated in the LHI phase were re-analysed with LDM based on equation (1) for estimation and classification of the degree of landslide hazard (Figure 4). Landslide Hazard Analysis (LHA) results for the Kota Kinabalu area suggest 2.78% of the total area is categorized as Very Low, 14.14% as Low, 19.74% as Medium, 51.63% as High, 11.34% as Very High and 0.37 % as an Extremely High (Figure 4).

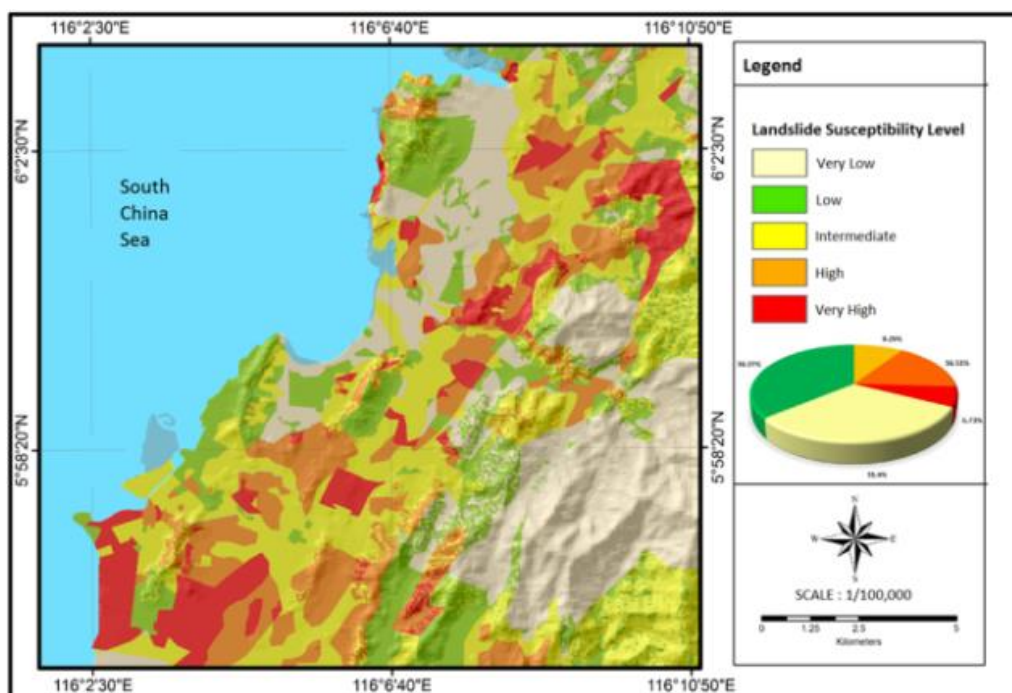


Figure 4. Landslide Hazard Analysis (LHA) map

4. Conclusion and Recommendation

In terms of the suitability of development area, the "very low" to "moderate" areas, which represent almost 36.66% of the total study area, refer to stable areas and no restrictions/constraints on development conditions are imposed. On the other hand, "high" to "very high" represent areas that are unstable and are basically not encouraged to be developed due to the constraints of geological, hydrological, and geotechnical factors. However, if there is no choice or the developer and/or local authority wants to develop the area, then some procedures must be followed. The "extreme" areas is found to be unsuitable for development and allocation for work-appropriate risk treatment work (structural and non-structural approaches) should be implemented, such as stabilization and mitigation measures (structural approaches) and regulatory measures, public awareness, disaster preparedness, behaviour modification (behavioural modification) and early warning systems (non-structural approach). The results of this LHA emphasize the importance of the potential impact of landslides on the study area, which can be considered representative of the entire district of Kota Kinabalu.

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