



## Development of an Exposure Vulnerability Index Map Using GIS Modeling for Preliminary Seismic Risk Assessment in Sabah, Malaysia

Noor Suhaiza Sauti<sup>1,2\*</sup>, Mohd Effendi Daud<sup>1</sup>, Masiri Kaamin<sup>3</sup>, Suhaila Sahat<sup>3</sup>

<sup>1</sup> Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Batu Pahat, Johor, Malaysia

<sup>2</sup> Department of Polytechnic & Community College Education, Ministry of Education Malaysia, Putrajaya 62100, Malaysia

<sup>3</sup> Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Batu Pahat Johor, Malaysia

Corresponding Author Email: [gf180003@siswa.uthm.edu.my](mailto:gf180003@siswa.uthm.edu.my)

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### ABSTRACT

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*exposure, vulnerability, GIS modeling, seismic risk, indicators*

This research was conducted with a view to updating the management of earthquakes through an exposure vulnerability and potential seismic risk assessment, along with its application in Sabah (a state in East Malaysia). A set of indicators and methodologies has been proposed in this study with the goal of evaluating the level of exposure vulnerability and potential risk of certain locations to earthquake events at the local district scale. This study specifically involves the development of exposure vulnerability indicators; the statistical analysis method to standardize multivariate data together with a weight calculation of indicator variables; and a mathematical combination of different indicators for the development of the index map using the spatial analysis function of Geographical Information System (GIS) tools. Then, the derived exposure vulnerability index (EVI) map is overlaid with the seismic hazard in determining the geographical location of the most vulnerable areas and their exposure to seismic hazard events. As a result, and based on the available data, the exposure vulnerability index map shows that most districts in Sabah are at relatively low and moderate levels of risk except for a few districts, with several major cities in Sabah, such as Kota Kinabalu, Penampang, Sandakan and Tawau municipality, being situated at a high or very high exposure index. The combination of EVI maps and hazard maps indicate the dominance of the two factors influencing the potential level of earthquake risk. Studies reveal most of the southwest and central parts of the region are not at risk, as both exposure and hazard factors are at a low level. The proposed approach depicts an instrument for identifying cost-effective risk reduction initiatives by providing a scientific method for regional risk planning and management strategies. This research represents the first attempt to evaluate Sabah's vulnerability to this type of natural disaster by understanding the spatial relationship between exposure vulnerability and earthquake hazard, which undoubtedly could be improved in several aspects.

## 1. INTRODUCTION

In the past decade, uncontrolled development, rapid population growth and unmonitored infrastructure development have led to an ever-increasing number of people being exposed to natural disasters. A natural hazard could only become a disaster if it has a negative impact on the exposed and vulnerable human population [1]. Multiple groups have expressed different views on vulnerability by presenting several different definitions and conceptual frameworks according to their respective understanding [2-5]. Vulnerability is commonly referred to as the characteristics defined by social, economic, physical, and environmental influences or processes influencing the rate of destruction caused by earthquakes against the vulnerability of individuals, populations, properties, or structures [6-10]. In other words, vulnerability considers the elements at risk as referring to population and property (exposure); the resilience level of the elements at risk based on the ability to anticipate, adapt and recover effectively when such events occur; and the coping capacity or resistance measures that require the ability of the

community to apply the available skills and resources through continuous preparedness, resources stock and effective management in every phase of a disruptive event.

Implementation of earthquake disaster management in Malaysia (including Sabah) is still in its early stage [11] and there is an absence of research on seismic risks assessment [12]. The seismic risk assessment refers to the seismic hazard, vulnerability and response capacity assessment of an area against earthquake threats depending on the location, magnitude and intensity of an earthquake when it occurs. The impediment for developing countries such as Malaysia when implementing seismic vulnerability assessments is the lack of comprehensive data [13-16]. Most of the data required in assessing population and property vulnerability during disasters is the crucial statistical information from the census. This data rarely includes information on the buildings inventory or detailed social demographics, and is also usually presented at a geographical aggregation level that would cause difficulties for its efficient use in risk evaluation. Moreover, there would be constraining issues relating to access to the data

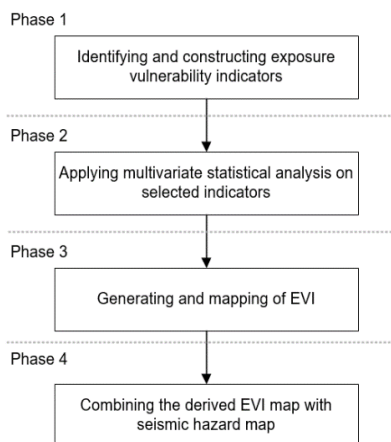
given its proprietary nature, confidentiality, reliability, consistency and lack of data transparency [17]. However, in recent years, various research has been conducted by local authorities and researchers to decrease seismic risks focusing on vulnerability assessment in Malaysia [12, 13, 18-21].

Vulnerability varies significantly within a community and over time [22]. In this context, the level of vulnerability of an area is defined as the outcome of an assessment of the index of exposure to natural hazards, as represented by data relating to population and infrastructure for the districts in Sabah. Exposure is the important element of risk in vulnerability that defines the extent of societies and properties which should be evaluated within the geographical context of a specific risk occurrence [3]. Evidence shows that the severity of the impact emanating from the disaster is highly dependent on the level of exposure and vulnerability in the affected area. This indirectly increases the level of global disaster risk due to increases in the exposure levels of people and assets to natural disasters [17]. Therefore, it is important to examine the extent of exposure levels for Sabah to earthquake disasters, especially in terms of its population and residential aspects, as preliminary information for disaster preparedness and planning.

In order to measure an exposure vulnerability level of the Sabah community that defines the relative state of the exposure, mathematical approaches combining several variables have been used to produce index maps [23]. A composite index allows for a direct comparison between the relative overall exposure of a district and the relative contributions of various factors to that overall exposure vulnerability [4].

In this study, the exposure vulnerability indicators were identified and constructed. Then, the statistical analysis method was performed to normalize multivariate data with different measurement units, together with a weight calculation of indicator variables. An exposure vulnerability index map was generated and mapped using the spatial analysis function of Geographical Information System (GIS) tools. Finally, the map was overlaid with the seismic hazard map to create a new data layer that displays the information and location of particular areas exposed to earthquake risk. Hence, this development of a new map through the combination of both existing maps provides the potential for a seismic risk assessment of the Sabah municipal district.

## 2. MATERIALS AND METHODOLOGY

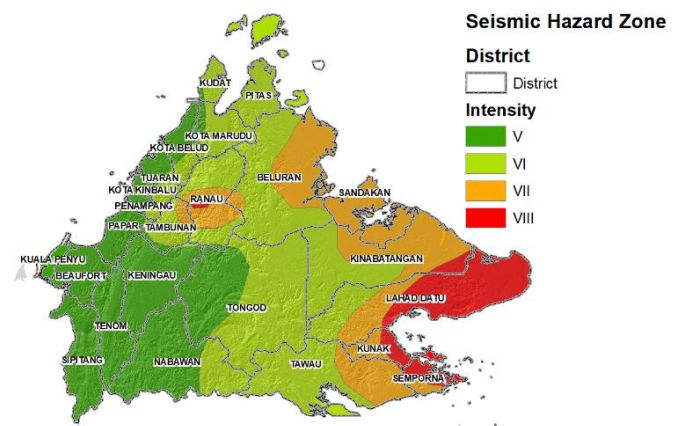


**Figure 1.** The methodological framework for assessing the EVI

In this study, the researchers applied the qualitative and quantitative approaches, including spatial analysis through the Geographic Information System (GIS) and statistical modeling on a local district scale. The methodological framework (Figure 1) for assessing the exposure vulnerability index (EVI) to seismic risk for Sabah comprised four main phases that were adapted based on the approaches of previous models [3, 24].

### 2.1 Study area

Geographically, Sabah is located in East Malaysia, approximately between longitude E115° and E119°, and latitude N4° and N7°, covering an area of 73,904km<sup>2</sup> and with an estimated population of 3.9 million [25]. It is considered to be at moderately active seismic risk through the existence of at least 13 active faults with 65 magnitude earthquakes (magnitude 3.3 to 6.5) having been recorded from 1923 to 2007 [11, 26]. The record of earthquake activity in Sabah is also monitored and updated continuously in the browser of the Incorporated Research Institutions for Seismology (IRIS) and the United States earthquake catalog website (USGS), as shown in Table 1. The active subduction zones of the Manila Trench, Negros Trench, Sulu Trench, Cotabato Trench and North Sulawesi Trench that surround Sabah have had an impact on past and current local and regional earthquakes [27, 28]. The geographical context of the Sabah region and its classification of seismic hazards [29] are shown in Figure 2. Classification is based on Table 2 [30].



**Figure 2.** Map of the study area and its seismic hazard classification

Seismic hazards refer to hazards related to a potential earthquake in a particular area, and a seismic hazards map displays the relative hazards according to a particular zone area [31]. The development of seismic maps incorporates consideration of fault lines, historical earthquakes, the mechanism of seismic waves during earthquakes and nearby site conditions at specific locations of interest. This type of map is usually beneficial for land-use planning, mitigation and emergency response.

In the Sabah region, Ranau and most of the south-east are the most hazardous territories (Zone VIII) with a high earthquake intensity recorded. Significant earthquake events that have caused considerable damage and fatalities are the Lahad Datu Earthquake (1976), the Ranau Earthquake (1991) and the Ranau Earthquake (2015) [32]. The impact of the Ranau Earthquake on 5 June 2015 on Malaysians, both local

residents and the authorities, was to increase efforts and raise awareness of the importance of management and disaster preparedness measures [33]. The majority of the areas lie within Zone V and VI with medium-low seismicity levels. The

remaining nearby area surrounds the dangerous area classified as Zone VII, with active seismicity concentrated in the Central North (Ranau) Zone, the Labuk Bay-Sandakan Basin Zone and the Dent-Semporna Peninsula Zone [29, 34].

**Table 1.** Earthquake catalog (2008 - 2018) in Sabah  
Sources: IRIS earthquake browser and USGS earthquake catalogue websites

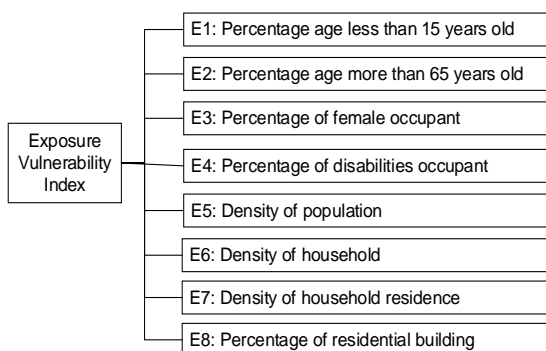
YEAR	MONTH	DAY	TIME UTC	MAGNITUDE	LATITUDE	LONGITUDE	DEPTH (KM)	PLACE
2018	3	8	13:06:13	5.2	06.037	116.6059	10	Ranau
2017	3	26	09:30:48	4.6	4.9334	118.7791	34	Lahad Datu
2016	3	4	00:43:35	4.1	4.9182	118.4359	35	Lahad Datu
2015	6	4	23:15:45	6.0	6.0439	116.6651	18.1	Ranau
2015	6	12	18:29:18	5.2	6.0674	116.6210	28.3	Ranau
2015	6	6	05:45:15	4.6	06.188	116.7836	10	Ranau
2015	6	23	09:32:33	4.5	6.0491	116.5472	35	Ranau
2015	6	12	18:25:39	4.4	06.039	116.5783	35	Ranau
2015	6	5	15:13:35	4.4	6.2153	116.8726	10	Ranau
2015	3	19	21:56:04	4.1	5.6182	118.6962	35	Sandakan
2014	2	1	11:35:10	4.6	6.1136	116.5807	15.6	Kota Belud
2014	9	5	01:15:53	4.3	4.5819	118.3607	10	Semporna
2012	5	28	16:44:14	4.8	4.8168	118.2948	40	Sabah
2010	8	21	19:43:33	4.2	5.1917	118.1427	35	Sabah
2008	5	18	06:26:46	5.0	04.598	118.1668	45.9	Sabah
2008	4	9	00:51:46	4.5	4.9453	118.7655	44	Sabah

**Table 2.** Comparison of Richter Scale Magnitude with Modified Mercalli Intensity (MMI) Scale

Magnitude	Maximum Modified Mercalli Intensity
1.0 – 3.0	I
3.0 – 3.9	II – III
4.0 – 4.9	IV – V
5.0 – 5.9	VI – VII
6.0 – 6.9	VII – IX
> 7.0	VIII and above

## 2.2 Identifying and constructing exposure vulnerability indicators

The first important phase in the methodology of this study was the identification and construction of the list and the number of exposure vulnerability indicator variables. This step involved a literature review and an expert consultation process. Once the assessment scope had been defined, secondary data and documents were gathered from related agencies. The Department of Statistics Malaysia (DOSM) is the crucial agency responsible for managing and providing the census data of Malaysia. Data is collected and organized based on the need to identify and construct exposure vulnerability indicators at the district level.



**Figure 3.** Structure of exposure vulnerability index (EVI) assessment

Theoretically, in a parameter study, the scale of seismic vulnerability research is directly proportional to the number of parameters or variables affecting it [35]. For example, on a small scale, the number of objects (e.g. buildings) increases rapidly. If too many factors are involved in the operation, not all the data could be obtained and modeled. However, a larger number of indicator variables would improve the accuracy of the calculation [36]. Most variables in this research were derived directly from census data and available data. Furthermore, the study was designed in the form of a structure for an EVI assessment, as shown in Figure 3. The following indicators were selected (Table 3) based on data availability, previous research and expert opinion.

**Table 3.** List and description of exposure indicator variables

Variable indicator	Descriptive analysis
Age structure (less than 15 years old)	In disaster events, children and older people are the most vulnerable groups as they affect the response activities during a disaster. Furthermore, affected day-care facilities would require time and financial support to take care of children. Sources: [23, 37, 38]
Age structure (more than 65 years old)	Most children, especially in younger age groups, could not protect themselves and cope effectively during a disaster due to a lack of tools, expertise or life experience. Sources: [39-41]
	Increased treatment burdens and a lack of resilience could occur among the elderly with mobility problems or mobility restrictions. Sources: [24, 38, 40, 41]
	Elderly people living alone are more inclined to be dependent and likely to be more vulnerable to disasters. Most older people have special needs and require the assistance of others, especially when facing disasters. Sources: [39]

Variable indicator	Descriptive analysis
Gender (female occupant)	Gender affects vulnerability, such that women would find it more difficult to recover than men, mostly due to sector-specific jobs, lower wages, and family care obligations. Sources: [24, 37, 38, 42]
Disabilities occupant	Most people of all ages with disabilities who have physical, sensory, or cognitive challenges need special help and assistance as they would be more vulnerable to disasters. Sources: [39, 43]
Population density	A population that is assigned to each zone based purely on census records is the crucial non-seismic and non-structural factor to assess vulnerability.  The rapid growth experienced by certain districts would lead to poor quality housing, and social service networks would insufficient time to adapt to expanding populations. New migrants who are unfamiliar with the local language and culture would make it difficult to deliver information on relief or disaster recovery, which would inadvertently increase vulnerability levels. A high population density affects any evacuation process. Sources: [24, 38-41, 44]
Household and household residence density	Family units with high birth rates, large families or single-parent households often have minimal outsourcing costs for dependent care. As a result, their durability and recovery during disasters are affected. Sources: [24, 42]
Building (residential) density	Most injuries or deaths during an earthquake have been caused by collapsing walls or large objects falling from buildings. The factor of building density affects vulnerability, though the incidence rate is low. Areas with low building density have low levels of vulnerability and vice versa. The density of buildings is measured by the number of physical buildings compared to the number of areas that are most likely to be affected by an earthquake. Sources: [38, 45]

### 2.3 Multivariate statistical analysis on exposure indicator

The second phase was the construction of an EVI that was developed through multivariate statistical analysis. The Iyengar and Sudarshan methods were applied to normalize and calculate the weight of each variable in this study, in accordance with the availability and feasibility of the required input data, and the conditions of the study area [36, 46]. All multivariate datasets were standardized with the normalization process, using linear min-max in Eq. (1). The value scores of each variable were scaled to a standard range between 0 and 1.

$$x_{ij} = \frac{(x_{ij} - \text{Min } x_{ij})}{(\text{Max } x_{ij} - \text{Min } x_{ij})}, (0 \leq x_{ij} \leq 1) \quad (1)$$

Based on the equation;

- $X_{ij}$  = normalized value of the indicator  $i$  of the component  $j$
- $x_{ij}$  = value of the indicator  $i$
- $\text{Max}(x_{ij})$  = the maximum values of the indicators  $i$  of the component  $j$  respectively

$\text{Min}(x_{ij})$  = the minimum values of the indicators  $i$  of the component  $j$  respectively

The next step was to calculate the linear sum of  $x_{ij}$  using Eq. (2), where:

$$\bar{y}_i = \sum_{j=1}^K w_j x_{ij} \quad (2)$$

- $M$  = region or districts
- $K$  = indicators of vulnerability
- $x_{ij}$  = normalized scores ( $i = 1, 2, \dots, M; j = 1, 2, \dots, K$ )
- $w_j$  = weight of indicator variable ( $0 < w_j < 1$ ) and  $\sum_{j=1}^K w_j = 1$

The weights were meant to differ inversely, as the difference between regions is the respective exposure measured. The contribution or weight ( $w_j$ ) of different indicator variables was determined by Eq. (3) and Eq. (4) where  $c$  represents the normalizing constant.

$$w_j = c / \sqrt{\text{var}(x_{ij})} \quad (3)$$

$$c = \left[ \sum_{i=1}^M \sum_{j=1}^K 1 / \sqrt{\text{var}(x_{ij})} \right]^{-1} \quad (4)$$

In this method, the selection of weights would ensure that the contribution of the remaining factors would not be excessively influenced by significant differences in any of the variables and would not mislead inter-regional comparisons. The calculated weight for the variable indicator is shown in Table 4.

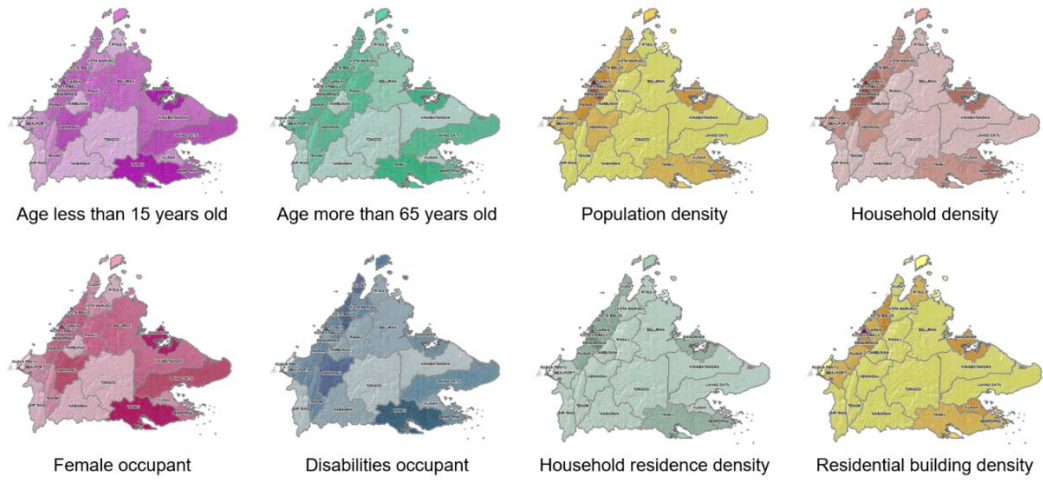
**Table 4.** Calculated weight for exposure indicator variables

Variable indicator	Abbreviation	Weight
Age structure (less than 15 years old)	E <sub>1</sub>	0.1059
Age structure (more than 65 years old)	E <sub>2</sub>	0.1043
Gender (female occupant)	E <sub>3</sub>	0.1101
Disabilities occupant	E <sub>4</sub>	0.1333
Population density	E <sub>5</sub>	0.1270
Household density	E <sub>6</sub>	0.1339
Household residence density	E <sub>7</sub>	0.1359
Building (residential) density	E <sub>8</sub>	0.1496

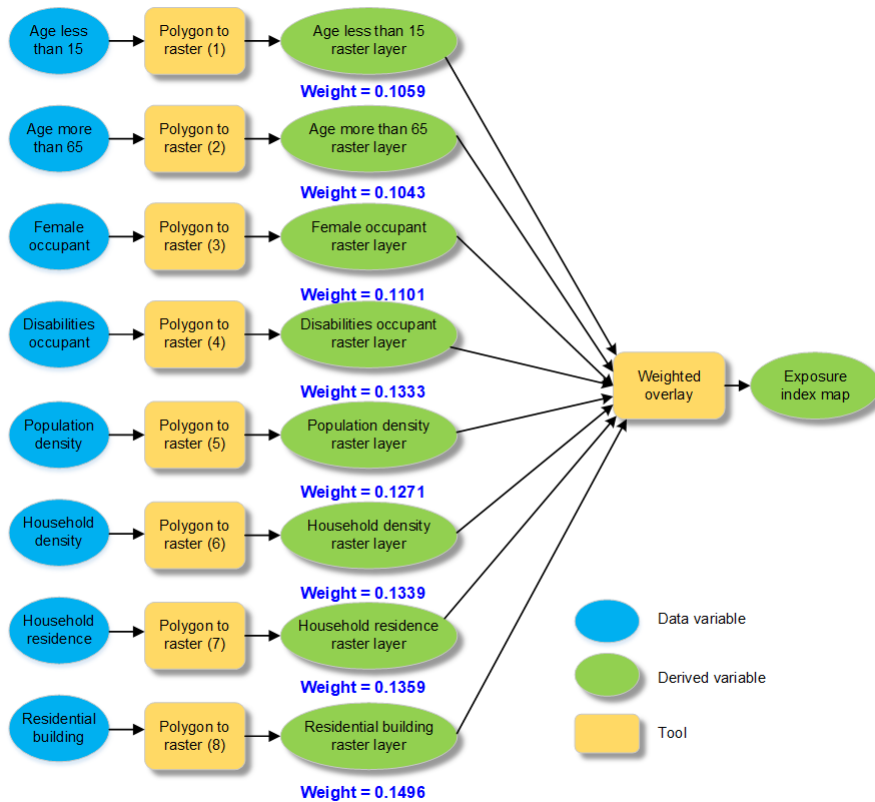
After the construction of the EVI, the third phase methodology involved spatial data analysis to generate and produce the exposure vulnerability index map.

### 2.4 Generating and mapping the exposure vulnerability index map

After generating the exposure criteria structure with the selection of indicators, normalization and weighting, composite index maps were generated using ArcGIS software. The data for each variable indicator was mapped to display its spatial distribution (Figure 4). The shifting of colors from light to dark on the map represents the increasing amount of data for the respective variable. In order to produce an EVI map, spatial analysis such as polygon to raster, reclassify and weighted sum were then performed. The ModelBuilder function in this software was used to model the spatial analysis workflows, as shown in Figure 5.



**Figure 4.** Spatial distribution of exposure indicators



**Figure 5.** GIS modeling for the exposure vulnerability index (EVI) map development

The derived maps were then classified based on the pixel values using the standard deviation method. The final map was classified according to the value of each category as follows: Low ( $< -0.5$  Std. Dev), Moderate ( $-0.5 < \text{Std. Dev} < 0.5$ ), High ( $0.5 < \text{Std. Dev} < 1.5$ ) and Very High ( $\text{Std. Dev} > 1.5$ ) [22, 40, 41].

### 2.5 Combining the exposure vulnerability index (EVI) map with a seismic hazard map

The final phase in the methodology was to overlay the exposure vulnerability index map ( $EVI_{\text{map}}$ ) (Figure 6) with the seismic hazard map ( $H_{\text{map}}$ ) (Figure 2) in order to produce a map with the potential for seismic risk assessment. Reclassified and weighted sum functions were applied to overlay those maps, multiplying each by their given weight

and summing them together, as shown in Eq. (5).

$$\text{Potential seismic risk map} = EVI_{\text{map}} \times Hazard_{\text{map}} \quad (5)$$

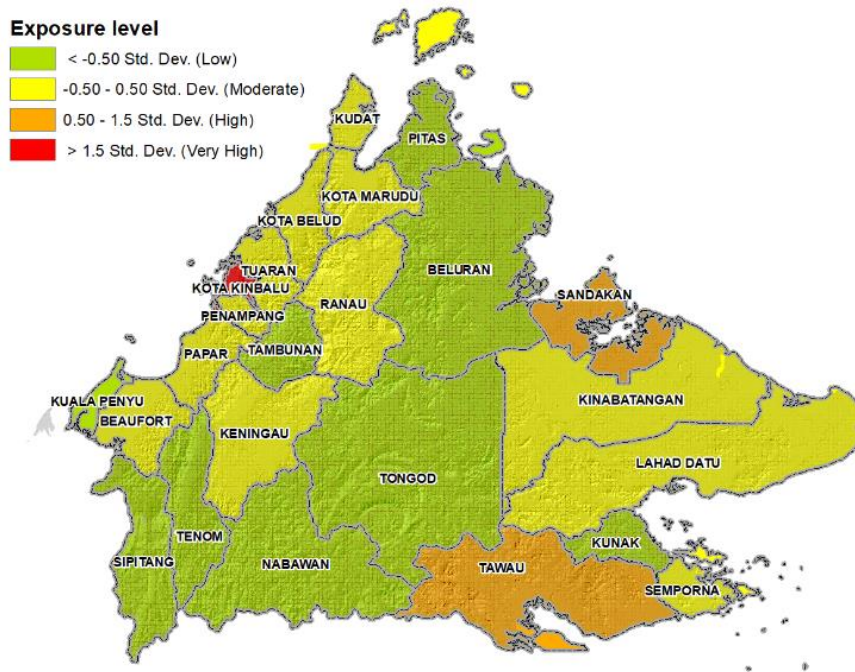
## 3. RESULTS AND DISCUSSION

The results and discussion following this research are explained in two sub-topics as follows:

### 3.1 Combining the exposure vulnerability index (EVI) map with a seismic hazard map

The outputs of the geospatial analysis of the EVI map are shown in Figure 6, together with the statistics of the exposure vulnerability index values distribution generated by GIS software.





**Figure 6.** Exposure vulnerability index map generated using ArcGIS software

Out of all the 25 districts in Sabah, the exposure vulnerability index map shows that most districts are seen to have relatively low and moderate levels with a small mean value. The mean value was 0.020 and the standard deviation was 0.023 (Figure 7) indicating a lower level of exposure index due to the low variance value. In contrast, the relatively greater standard deviation value indicates a higher variance value or a higher exposure level for a district.

Classification Statistics	
Count:	25
Minimum:	0.0020
Maximum:	0.11
Sum:	0.51
Mean:	0.020
Median:	0.013
Standard Deviation:	0.023

**Figure 7.** Classification statistics generated by GIS software

However, a few districts, especially the major cities in Sabah, are rated as high and very high in the exposure index. There is overall uniformity in the exposure levels throughout the region, with over 85% (21) of the districts in the range of less than +0.5 standard deviation (Figure 6). The minimal presence of vulnerable groups (i.e. children, elderly, female and disabled occupants) is the major contributory factor to the uniform exposure index across the region. Only 8% (2) of the districts located in the red zone show a standard deviation larger than 1.5, which are the Kota Kinabalu and Penampang areas. Correspondingly, only 8% (2) of the districts are in the high-level (orange) zone (Sandakan and Tawau municipalities) with a standard deviation between +0.5 and +1.5. The highest exposure index in the state was due to the highest percentage of children, elderly, female occupants and disabled occupants. In addition, the largest population density and residential building density reported in the district further exacerbated the higher level of exposure in the area. Based on the available

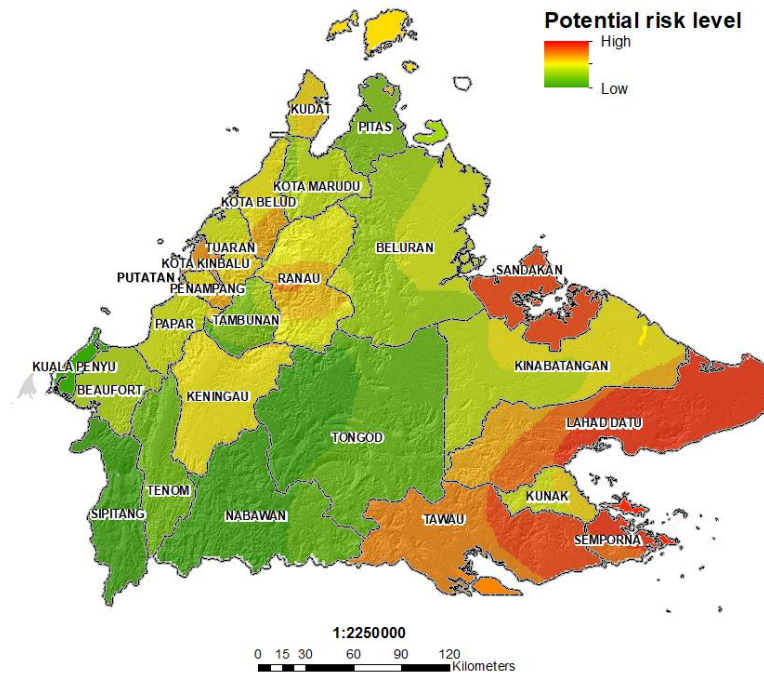
data, most districts have a moderate to low exposure level, indicating a moderate or low level of vulnerability.

### 3.2 Combination of exposure vulnerability index (EVI) map and seismic hazard map

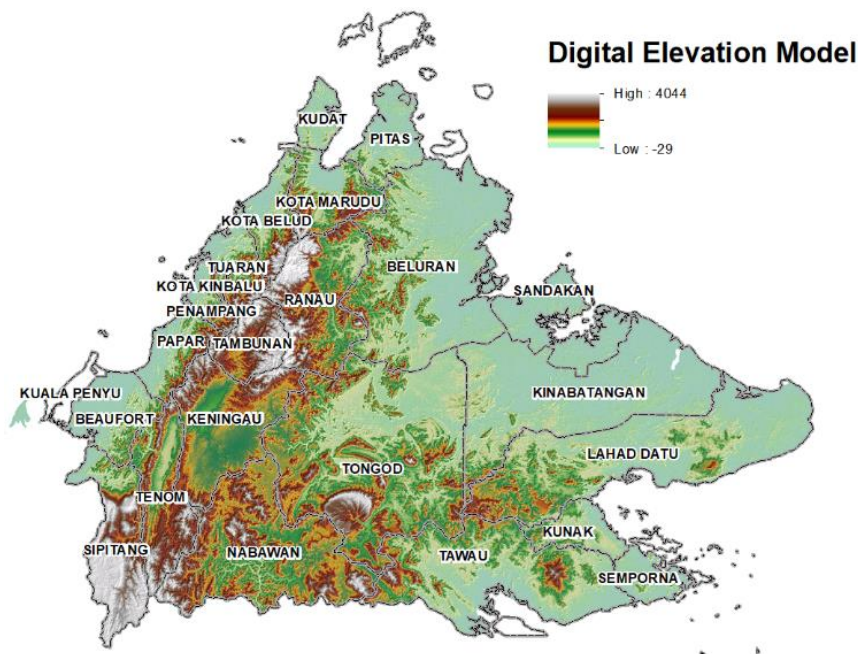
One of the primary findings derived from the EVI map was an assessment of combined risk scenarios by integrating the earthquake hazard with areas exposed to natural disasters, especially earthquake events. The potential seismic risk map derived from the combination of the exposure and seismic hazard maps is shown in Figure 8. The cumulative representation of these variables on a map is perhaps most useful as an instrument for determining with greater accuracy the geographic location of the most vulnerable and their exposure to seismic hazard events. Indirectly, these results are expected to assist policymakers and investors in developing risk-reduction strategies.

The southwest and central parts of the area are not at risk because they lay in Zone V, which does not include the possibility of an earthquake occurrence. In terms of exposure index, the population density here is lower than other parts of Sabah due to the limited accessibility of these mountainous and hilly morphological areas (Figure 9). Among the districts are Sipitang, Tenom, Nabawan, and Tongod. Additionally, the physical surface of the terrain also results in a low density of residential buildings.

In the northwest, apart from the Ranau district where earthquakes occur frequently despite a low probability of seismic hazard, researchers found some high-level exposure instances that would contribute to them being deemed 'at risk'. This includes Kota Kinabalu, Sabah's capital, which is surrounded by the Penampang and Putatan suburbs, considered part of the Greater Kota Kinabalu area. Those districts consistently recorded the highest number of every exposure indicator variable, resulted in their having the highest exposure index in Sabah. Furthermore, the location in Zone V had caused the area to be classified as 'at risk' of earthquakes.



**Figure 8.** Output for the EVI and seismic hazard maps combination



**Figure 9.** Digital Elevation Model (DEM) represents the Sabah terrain surface

The most at-risk part is the southeast zone, with high seismic hazards (Zone VIII). It also has a high level of exposure due to its large population of children (aged under 15 years old), the elderly (aged over 65 years old), female residents and disabled people, factors that lead to the increased impact of earthquakes. Furthermore, according to the exposure index, Sandakan and Tawau are among the major cities in Sabah with a high density of residential buildings.

Finally, the Sandakan, Lahad Datu, Semporna and Tawau areas are the most at-risk, because they all satisfied both assessment criteria, have high exposure indices, and are located within the most dangerous earthquake area (Zone VII and Zone VIII). Those districts deserve particular attention from the responsible agencies because they are the most

populated at-risk areas, with a high number of occupants and residential density.

#### 4. CONCLUSIONS

In this paper, the researchers proposed a methodology for establishing a technique that focuses on a socio-economic analysis of the population of Sabah and its residential areas, and which is capable of classifying areas into different capacities to respond to earthquake disasters. This provides a beneficial tool for measuring the exposure index, but a comprehensive understanding of the components is needed, as is a knowledge of how these variables interact and inevitably

lead to the vulnerability of a population on a regional scale. A significant selection of population and residential indicators for evaluating the exposure vulnerability index for Sabah are among the main findings in this study. In addition, multivariate statistical analysis serves as an instrument for standardizing and calculating the weight of each variable. Geostatistical methods were applied to evaluate the indicators spatially in producing cartographic representations showing the regional homogeneity and directional representation across the regions. The combination of the indicator maps produced the final exposure index map.

The visualization of the EVI map provides a relevant basis for the interpretation of spatial variability in Sabah's exposure vulnerability that could be used in the initial stage of district planning. The research also shows the significance of integrating the exposure vulnerability map with a seismic hazards map in producing a new qualitative potential seismic risk map.

Most exposure indicators derived from the census data that provide a good source of information on numerous aspects are particularly useful for generating the vulnerability index. However, the use of census data alone should be made with caution, as it only represents information at a household level without considering other aspects, such as the contribution of resilience and the capacity component to the vulnerability level. Therefore, future advancements are expected to determine the spatial relationship between all components of vulnerability, which include exposure, resilience, and capacity indicators, together with seismic hazards, and enable the production of a holistic seismic risk map through a GIS-based approach.

Finally, the findings from this study might assist in the provision of a strategic vision of seismic processes that could interfere with human populations. Thus, for those countries that are still in the early stages of implementing effective earthquake disaster management, the introduction of exposure risk components would be of great value due to their provision of preliminary information on disaster preparedness and planning. Moreover, the set of indicators and methodologies proposed in this study could be adopted for use with any region of Malaysia and is suitable for replication across various scales, dynamics and regional variations.

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