BAREKENG: Journal of Mathematics and Its Applications
September 2025 Volume 19 Issue 3 Page 2179-2190
P-ISSN: 1978-7227 E-ISSN: 2615-3017
https://doi.org/10.30598/barekengvol19iss3pp2179-2190

ANALYSIS OF EARTHQUAKE SEISMICITY IN MALUKU PROVINCE AND ITS SURROUNDING AREAS USING THE MAXIMUM LIKELIHOOD ESTIMATION METHOD

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Article History:

Received: 27th November 2024
Revised: 14th February 2025
Accepted: 16th April 2025
Published: 1st July 2025

Keywords:

Descriptive statistics;
Estimation Method;
Maluku Region;
Return period:
Seismicity Index;
Tectonic earthquakes.

ABSTRACT

Tectonic earthquakes are natural disasters that occur abruptly over a relatively short period, resulting from the movement of tectonic plates. The Maluku region is classified as prone to seismic activity due to its geographical location at the confluence of three tectonic plates: the Eurasian, Pacific, and Indo-Australian. This study aims to analyze the seismic activity of earthquakes in the Maluku region and its surrounding areas. The methodology employed is based on Descriptive Statistics and Maximum Likelihood Estimation. The data set was obtained from the International Seismological Centre (ISC) and comprises earthquakes occurring in the Maluku region and surrounding areas between 1970-2023. The earthquakes were selected based on the criteria of magnitude > 3.8 Mw and depth < 60 km. The research was facilitated by using various software applications, including Microsoft Excel, SPSS, Matlab, GMT, and Z-map. Descriptive statistics were employed to analyze the hypocenter and epicenter of the earthquake distribution. In contrast, the maximum likelihood method was employed to ascertain the seismicity value and earthquake return period. The findings indicate that the earthquake distribution is relatively dense, except in certain regions within the sea area. The results of the seismicity analysis demonstrate that Sub-region I exhibits the highest level of seismic activity. At the same time, the shortest return period is observed at a magnitude of 3.0 Mw, specifically within Sub-region I.

How to cite this article:

H. J. Wattimanela and A. Setiawan, "ANALYSIS OF EARTHQUAKE SEISMICITY IN MALUKU PROVINCE AND ITS SURROUNDING AREAS USING THE MAXIMUM LIKELIHOOD ESTIMATION METHOD," *BAREKENG: J. Math. & App.*, vol. 19, no. 3, pp. 2179-2190, September, 2025.

Journal homepage: *https://ojs3.unpatti.ac.id/index.php/barekeng/*
Journal e-mail: *barekeng.math@yahoo.com; barekeng.journal@mail.unpatti.ac.id*

Research Article • Open Access

1. INTRODUCTION

Indonesia is one of the countries most prone to seismic activity, as it sits at the convergence of three major tectonic plates: the Eurasian, Indo-Australian, and Pacific. Maluku Province and its surrounding areas are particularly prone to tectonic earthquakes [1], [2], [3], [4].

The earthquake and tsunami that occurred in Maluku Province and its surroundings was the Ambon earthquake on October 8, 1950. The earthquake had a magnitude of 7.3 Mw and a hypocenter depth of 20 km [5]. On September 11, 2008, a magnitude 7.2 earthquake struck Halmahera Island, North Maluku Province. The epicenter was located at coordinates 1.88 LU and 127.27 BT, with a depth of ±10 km due to fault activity in the East Maluku Sea. The earthquake was felt in several areas of North Sulawesi Province and as far away as the Philippines [6]. On July 7, 2019, an earthquake occurred on Halmahera Island, North Maluku Province. According to the Meteorology, Climatology and Geophysics Agency (BMKG) Jakarta, this earthquake had a magnitude of 7.0 Mw with a depth of 36 km. On September 26, 2019, a magnitude 6.6 Mw earthquake struck Ambon Island, causing casualties and infrastructure damage [7].

This vulnerability is a consequence of Maluku and its surroundings sitting on 3 major plates, resulting in the formation of a complicated geological order [8], [9]. Part of this region is the Eurasian plate, which moves relatively southeast and interacts with the Indo-Australian plate, which moves relatively north, and the Pacific plate, which moves relatively west. The convergence of the 3 tectonic plates gives rise to the formation of a trough, which is known as a subduction zone. The collision created faults in the Maluku Province and the surrounding areas in the west-east, northwest-southeast, north-south, and southwest-northeast directions. Faults linked to earthquake sources are active faults. Earthquakes whose sources are on land due to active faults, despite the relatively low amplitude, are highly probable to cause disasters—high-pressure faulting results in a high seismicity index [9].

Related to this, this research will focus on the characteristics and activation level of earthquakes in Maluku Province and its surroundings with the Descriptive Statistical Method approach [10], [11] and the Maximum Likelihood Method [12], [13], [14], [15].

2. RESEARCH METHODS

The research was conducted using two statistical methods: the Descriptive Statistics Method and the Maximum Likelihood Estimation Method. The research area was divided into three Sub-regions (SR). Observations were conducted on each SR. The Descriptive Statistics Method was employed to examine earthquake characteristics in each SR concerning earthquake distribution (epicenter) and depth (hypocenter). Additionally, earthquakes were classified into several magnitude and depth groups, which were then applied to each SR to determine the pattern of magnitude distribution and the predominant depth in each SR. Calculating seismicity value and earthquake return period utilized the maximum likelihood estimation method.

2.1 Descriptive Statistics

Descriptive statistics is a statistical method that aims to describe all research data by summarizing or presenting it without concluding. In descriptive statistics, data description can be achieved by examining various data set characteristics, including the total number of observations (N), the minimum and maximum values, the mean, the standard deviation, the kurtosis, the skewness, etc [16].

This study employs two variables: magnitude and depth. The number of earthquake data obtained was 9.447, with minimum and maximum values determined by examining the lowest and highest values within the data set. Furthermore, the mean value is calculated by summing up all data values and dividing them by the total data. The standard deviation represents the degree of variation in the data set [17].

Skewness is a deviation from the symmetry of a distribution. If the frequency curve is skewed to the right, it is called positive skewness (> 0). Meanwhile, if the curve slopes to the left, it is called a negative slope or negative skewness (<0) [18].

Kurtosis is the degree of height of a distribution. A curve is called normal (mesokurtic) if the graph is not too pointed and flat and has a value equal to 3. A curve is called leptokurtic if the shape of the peak of

the curve is pointed and has a value $K > 3$. At the same time, a curve is called platykurtic if the shape of the peak of the curve is flat and has a value *of* $K < 3$ [18].

2.2 The Momen Magnitude Scale

There are a number of different scales used to measure earthquake magnitude. This includes local magnitude (M_L), surface-wave (*Ms*), body-wave magnitude (*Mb*), and moment magnitude (*Mw*). The Mw scale is an earthquake magnitude measurement scale that produces reliable measurement results. This is because the Mw scale measurement does not experience saturation or the tendency of a saturated or constant magnitude calculation [19].

Earthquake data obtained in several different scales will be converted to the same scale before being applied to the research. In this research, the Mw scale will be utilized. Therefore, by referring to the rules of the National Earthquake Center (PuSGeN), the magnitude scale will be converted to the *Mw* scale through Equation (1), Equation (2), and Equation (3) [10].

a. Convert *Mb* to *Mw* ($3.7 \leq Mb \leq 8.2$)

$$Mw = 1.0107Mb + 0.0801 \tag{1}$$

b. Convert *Ms* to *Mw* ($2.8 \leq Ms \leq 6.1$)

$$Mw = 0.6016Ms + 2.476 \tag{2}$$

c. Convert *Ms* to *Mw* ($6.2 \leq Ms \leq 8.7$)

$$Mw = 0.9239\text{Ms} + 0.5671 \tag{3}$$

2.3 The a-*value* and b-*value*

Seismotectonic parameters can be known through Frequency Magnitude Distribution (FMD) based on the Gutenberg-Richer Equation through Equation (4) [20].

$$LogN(M) = a - bM \tag{4}$$

with $N(M)$ is the cumulative number of earthquakes, a describes the seismic parameter constant, and b is the slope that describes the parameter constant, and M is the magnitude value [20].

The $a-$value describes the level of seismic activity in the research area, with the amount of seismicity depending on the area and period of study. The larger $a-$value, the higher the seismic activity in the area. While $b-$value explaining the tectonics in an area whose value depends on the nature of the local rocks. It generally $b-$value has a value close to 1 which indicates the degree of brittleness of the rock. The larger $b-$value, the higher the brittleness of rock in the area. The magnitude can be estimated using the Maximum Likelihood Method through Equation (5) [20].

$$\hat{b} = \frac{\log e}{\bar{M} - M_0} \tag{5}$$

with $\bar{M}$ is the average magnitude, and M_0 is the smallest magnitude. While $\hat{a} - value$ it can be obtained using Equation (6) [20].

$$\hat{a} = logN + \log\left(\hat{b}\ln 10\right) + M_0\hat{b}, \tag{6}$$

2.4 The Seismicity Index and Earthquake Return Period

The seismicity index (SI) is a measure of the total number of earthquake events that occur within a one-year with a magnitude (M) greater than the minimum magnitude (M_0). By using the estimated values of $\hat{a} - value$ and $\hat{b} - value$, the SI can be calculated using Equation (7) [21].

$$N(M \geq M_0) = 10^{\hat{a} - \log(\hat{b}\ln 10) - \log\Delta t - \hat{b}M_0} \tag{7}$$

with t is the time of year of observation. Furthermore, the return period of an earthquake depends on its SI. The higher the SI, the lower the earthquake return period. The earthquake return period can be calculated using **Equation (8) [22]**.

$$\theta(M \geq M_0) = \frac{1}{N(M \geq M_0)} \tag{8}$$

3. RESULTS AND DISCUSSION

3.1 Research Location and Data

This research is located in the Maluku region and its surroundings, which are bounded by -2.62755°S - -8.61632°N and 124.86531°E – 135.09992°E. Then, the location of this research is divided into three SR, SR I, SR II, and SR III.

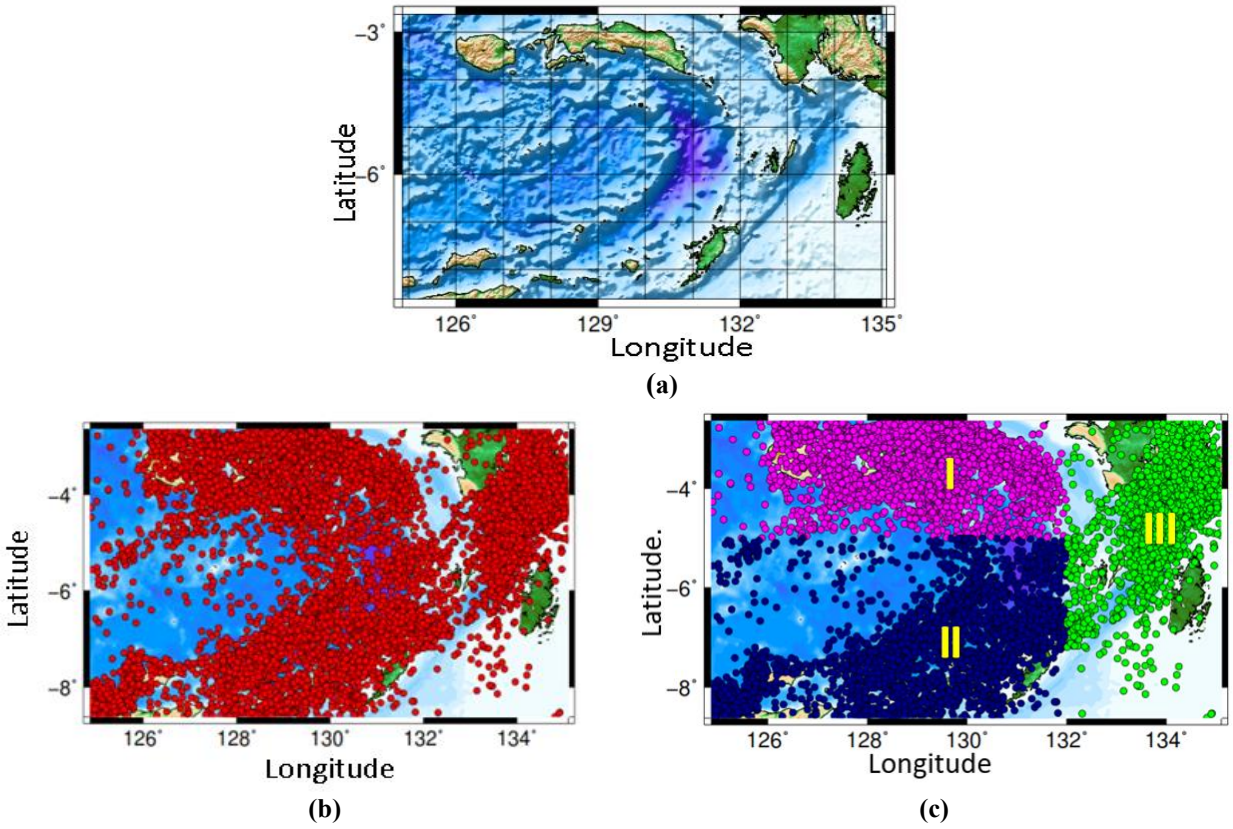


Figure 1. Map of the Location and Distribution of Earthquakes in the Maluku Region and Its Surroundings (a) Research Location Map, (b) Map of Earthquake Distribution in Maluku Province and Its Surroundings, (c) Distribution of Tectonic Earthquakes in 3 SR

The data used are tectonic earthquake data from 1970-2023 in Maluku Province and surrounding areas with magnitude $M > 3$ Mw and depth $D < 60$ km. This data is sourced from BMKG Indonesia and the International Seismological Center (ISC) catalog.

The research area is located in Maluku Province and its surroundings (**Figure 1** (a)). Earthquakes that occurred during 1970-2023 were detected at epicenter points within the research area (**Figure 1** (b)). Overall, the pattern of earthquake distribution in Maluku Province and its surroundings shows that the areas with the highest earthquake frequency are in the Central Maluku region, including Seram Island and its surroundings, Buru Island, North Maluku, especially in Halmahera Island, and the Banda Sea. The density of epicenters indicates a very high earthquake frequency. Furthermore, it can be seen that the distribution of infrequent earthquakes is in the Southeast Maluku region, Saumlaki, Aru Islands, and parts of the West Papua Region, especially the Fakfak area. However, seismic activity in the Fakfak and Aru Islands is relatively lower

(Figure 1 (b)). Furthermore, the earthquakes in the 3 SR show the most earthquake distribution in SR I, while the least earthquake distribution points are in SR III (Figure 1 (c)).

3.2 The Earthquake Characteristics

Based on earthquake events in Maluku Province and its surroundings in 1970-2023, it is known that 9,477 earthquakes occurred with magnitudes $M \geq 3.8$ Mw and depths $D < 60$ km. The following table shows the descriptive statistics of the depth and magnitude data for the entire SR (Table 1).

Table 1. Descriptive Statistics of Earthquake Data from 1970-2023 in 3 Maluku SR and Surrounding Areas with Criteria of Magnitude ≥ 3.8 Mw and Depth < 60 Km

Sub Region	N	Variable	Min	Max	Mean	SD	Skew	Kurt
I	4,278	Depth	0.2000	59.8000	28.8061	10.4149	-0.3720	-0.0570
		Magnitude	3.8000	6.7000	4.3880	0.4923	1.0370	0.7840
II	3,115	Depth	3.8000	59.9000	31.0136	12.7858	-0.2950	-0.5640
		Magnitude	3.8000	6.8000	4.4459	0.5234	0.9840	0.6730
III	2,054	Depth	6.4000	59.5000	25.6511	9.0349	-0.0560	-0.2820
		Magnitude	3.8000	6.9000	4.4138	0.5125	1.0910	1.1150

Earthquake depth data at SR II has a higher Standard Deviation (SD) than SR I and SR III, which is 12.7858 (Table 1). meaning the earthquake depth data in SR II shows a broader range of variance than SR I and SR III. Furthermore, the skewness value of earthquake depth data in SR I, SR II, and SR III shows a negative value ($S < 0$), indicating that the tail of the data distribution point is more skewed to the left. Then, the kurtosis value in SR I, SR II, and SR III is $K < 3$, indicating that the data distribution center has a flatter peak.

On the other hand, the earthquake magnitude data in SR II has a higher SD than SR I and SR III, which is 0.5125 (Table 1), meaning that the earthquake magnitude data in SR II has a wider range of variation compared to the magnitude data in SR I and SR II. Furthermore, the skewness of earthquake magnitude data in SR I, SR II, and SR III shows a positive value ($S > 0$), indicating that the tail of the data distribution point is more skewed to the right. Then, the kurtosis value in SR I, SR II, and SR III has a value *of* $K < 3$, indicating that the data distribution center has a flatter peak.

Furthermore, the frequency of earthquake occurrence based on magnitude in Maluku Province and its surroundings in 1970-2023 with magnitude $M \geq 3.8$ Mw and depth $D < 60$ km in 3 SR will be examined (Figure 2).

The pink, blue, and green diagrams show the frequency of earthquakes in SR I, SR II, and SR III, respectively (Figure 2). In SR I, the highest frequency of earthquakes occurred in the magnitude range of $4 \leq M < 5$ Mw, with a total of 2,831 events. Meanwhile, earthquakes with a magnitude of $M \geq 6$ Mw had the smallest number of 29 earthquake events. In SR II, the highest frequency of earthquakes occurred in the magnitude range of $4 \leq M < 5$ Mw, with a total of 2,050 events. Meanwhile, earthquakes with a magnitude $M \geq 6$ Mw had the smallest number, with 32 events. In SR III, the highest frequency of earthquakes occurred in the magnitude range of $4 \leq M < 5$ Mw, totaling 1,346 events. Meanwhile, earthquakes with magnitude $M \geq 6$ Mw had the smallest number of 21 events.

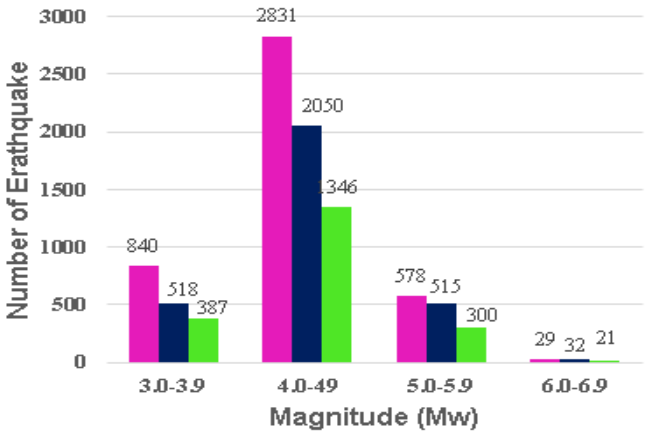


Figure 2. Number of Earthquake Events by Magnitude in Maluku and Surrounding Areas with Criteria of Magnitude $M \geq 3.8$ Mw and Depth $D < 60$ Km in SR I, II, and III

Furthermore, the frequency of earthquake occurrence based on depth in Maluku Province and its surroundings in 1970-2023 with magnitude $M \geq 3.8$ Mw and depth $D < 60$ km in 3 SR will be reviewed (Figure 3).

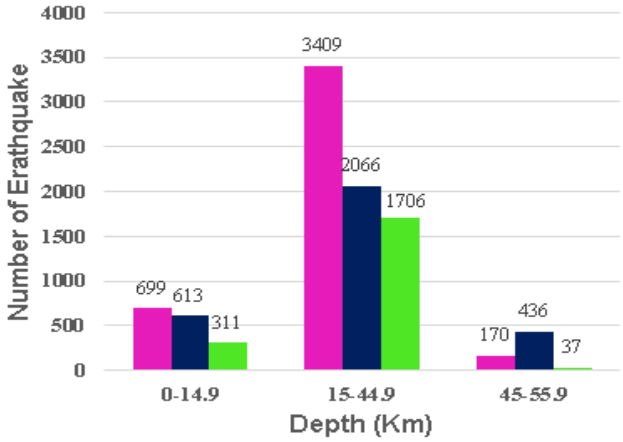


Figure 3. Number of Earthquake Events by Depth in Maluku and surrounding areas with criteria of Magnitude $M \geq 3.8$ Mw and Depth $D < 60$ Km in SR I, II, and III

The pink, blue, and green diagrams show the frequency of earthquakes in SR I, SR II, and SR III, respectively (Figure 3). SR I shows that the depth range of $15 \leq D < 45$ km has the highest frequency of earthquake events, totaling 3,409 earthquake events. Meanwhile, the km depth range has the least frequency of earthquake events, which is 170 events. SR II shows that the depth range of $15 \leq D < 45$ km has the highest frequency of earthquake events, totaling 2,066 earthquake events. Meanwhile, the $D \geq 45$ km depth range has the least frequency of earthquake events, which is 436 events. Furthermore, SR III shows that the depth range of $15 \leq D < 45$ km has the highest frequency of earthquake events, totaling 1,706 earthquake events. Meanwhile, the $D \geq 45$ km depth range has the least frequency of earthquake events, which is 37 events.

Furthermore, the characteristics of earthquakes in the Maluku region and its surroundings in 1970-2023 will be reviewed based on the depth of the earthquake hypocenter (Figure 4).

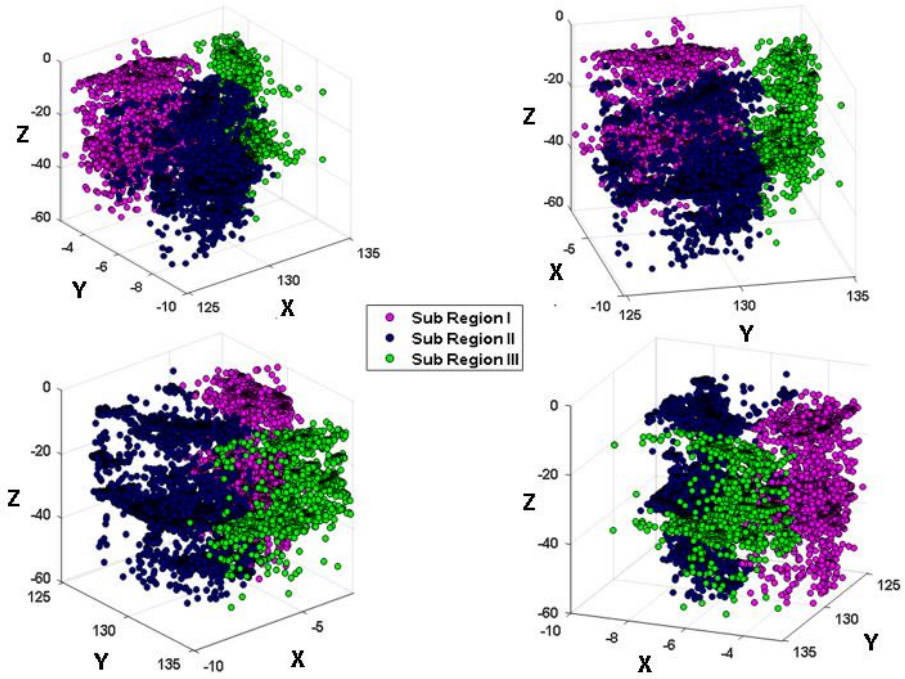


Figure 4. Distribution of Earthquakes in 3 SR by Depth

The graph of the distribution of earthquakes based on the depth of the earthquake hypocenter in the 3 SR shows that areas with a higher frequency of earthquake occurrence are found in the depth range of 10–55 km below sea level. Meanwhile, the depth range of 0–9 km and the depth range of 56–60 km are the areas with the least frequency of earthquake occurrence (Figure 4).

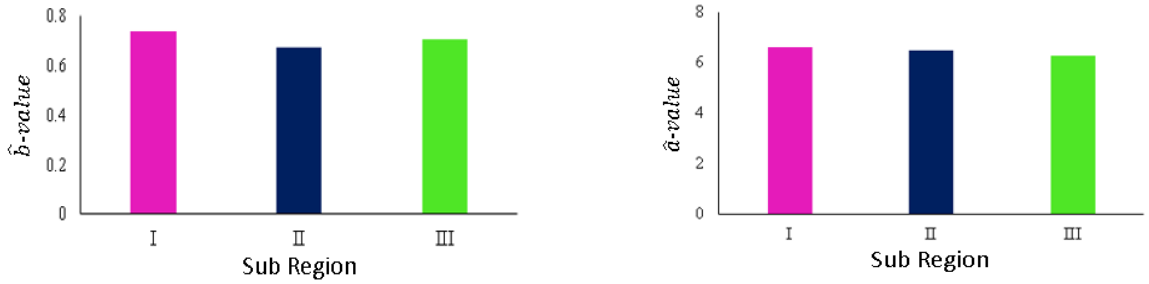
3.3 Calculation and Mapping Value of $\hat{a}$ and $\hat{b}$

Based on the data of earthquake events in Maluku Province and its surroundings from 1970 to 2023, using **Equation (5)** and **Equation (6)**, the values of $\hat{a}$ and $\hat{b}$ for the 3 SR are presented in **Table 2**.

Table 2. Parameter Value of $\hat{a}$-value and $\hat{b}$-value in 3 SR

Sub Region	Parameter/Value	
	$\hat{a}$	$\hat{b}$
I	6.6686	0.7386
II	6.2384	0.6724
III	6.2133	0.7076

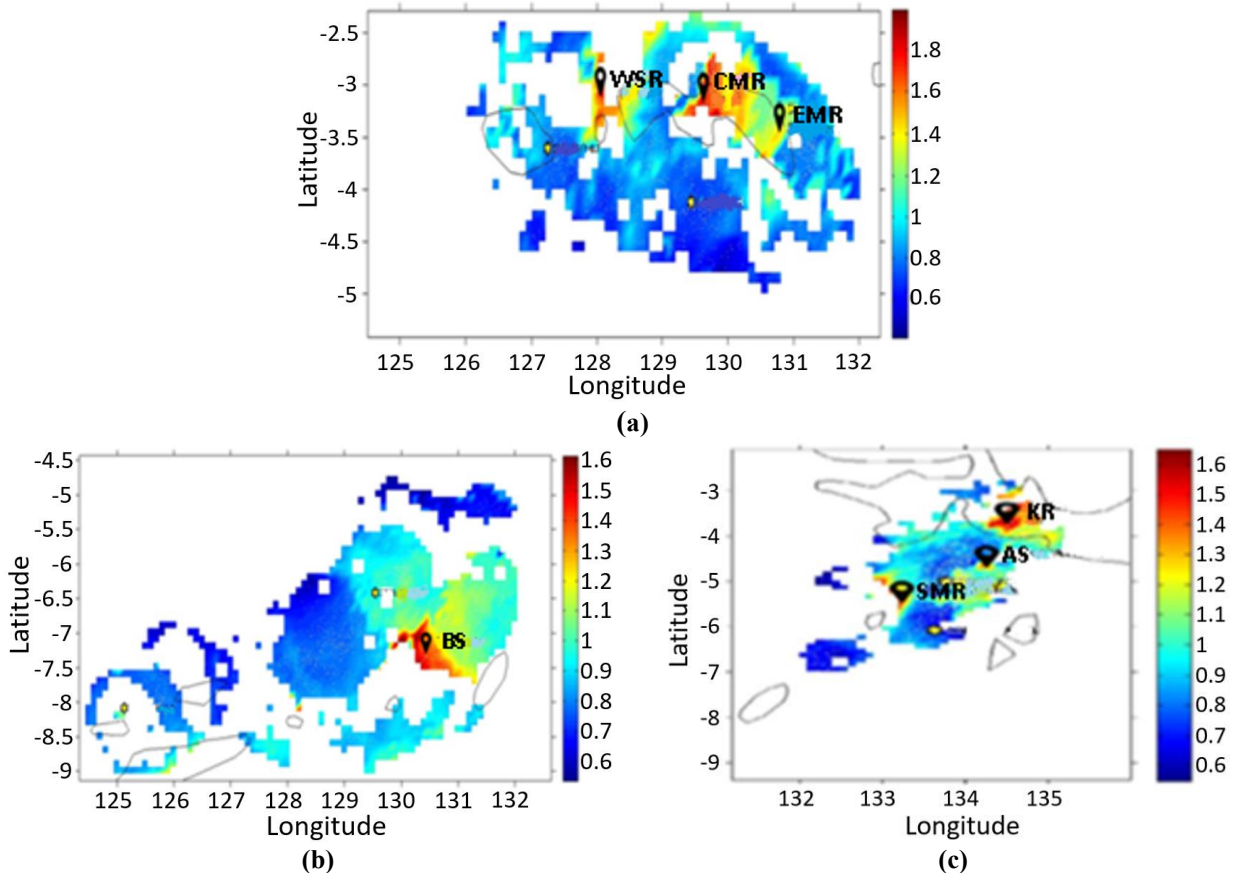
The values of $\hat{a}$-$value$ obtained are in the range of 6.2133 – 6.6686, with the maximum $\hat{a}$-$value$ being in SR I and the minimum being in SR III. The obtained $\hat{b}$-$value$ is in the range of 0.6724 – 0.7386, with the maximum being in SR I and the minimum being in SR II (**Table 2**). Based on the calculations in **Table 2**, the maximum and minimum value of $\hat{a}$ and $\hat{b}$ can be visualized through the graph (**Figure 5**).



(a) **(b)**

Figure 5. Graph Value in 3 SR of (a) $\hat{b}$ − value, (b) $\hat{a}$ − value

The $\hat{b}$-value mapping is done to identify areas with high rock fragility, while the $\hat{a}$-value mapping is done to identify areas with high seismic activity. To determine the areas with high rock fragility, mapping for $\hat{b}$-value was done with the help of Matlab and Zmap applications (**Figure 6**).



(a)

(b) **(c)**

Figure 6. Graph of $\hat{b}$ − value on (a) SR I, (b) SR II, (c) SR III

The $\hat{b}-$value on SR I, which ranges from 0.42 – 2.0, with the highest values located around West Seram Regency (WSR), Central Maluku Regency (CMR), and East Seram Regency (ESR) (**Figure 6** (a)). Furthermore, the $\hat{b}-$value on SR II which ranges from 0.54 – 1.62 with the highest values mostly in the Banda Sea (BS) area (**Figure 6** (b)). Meanwhile, the $\hat{b}-$value on SR III ranging from 0.55 – 1.65, with the highest values around Kaimana Regency (KR), Southeast Maluku Regency (SMR), and parts of the Arafura Sea (FS) area (**Figure 6** (c)).

Then, the areas with high levels of seismic activity, can be seen in the following $\hat{a}$-value map (**Figure 7**).

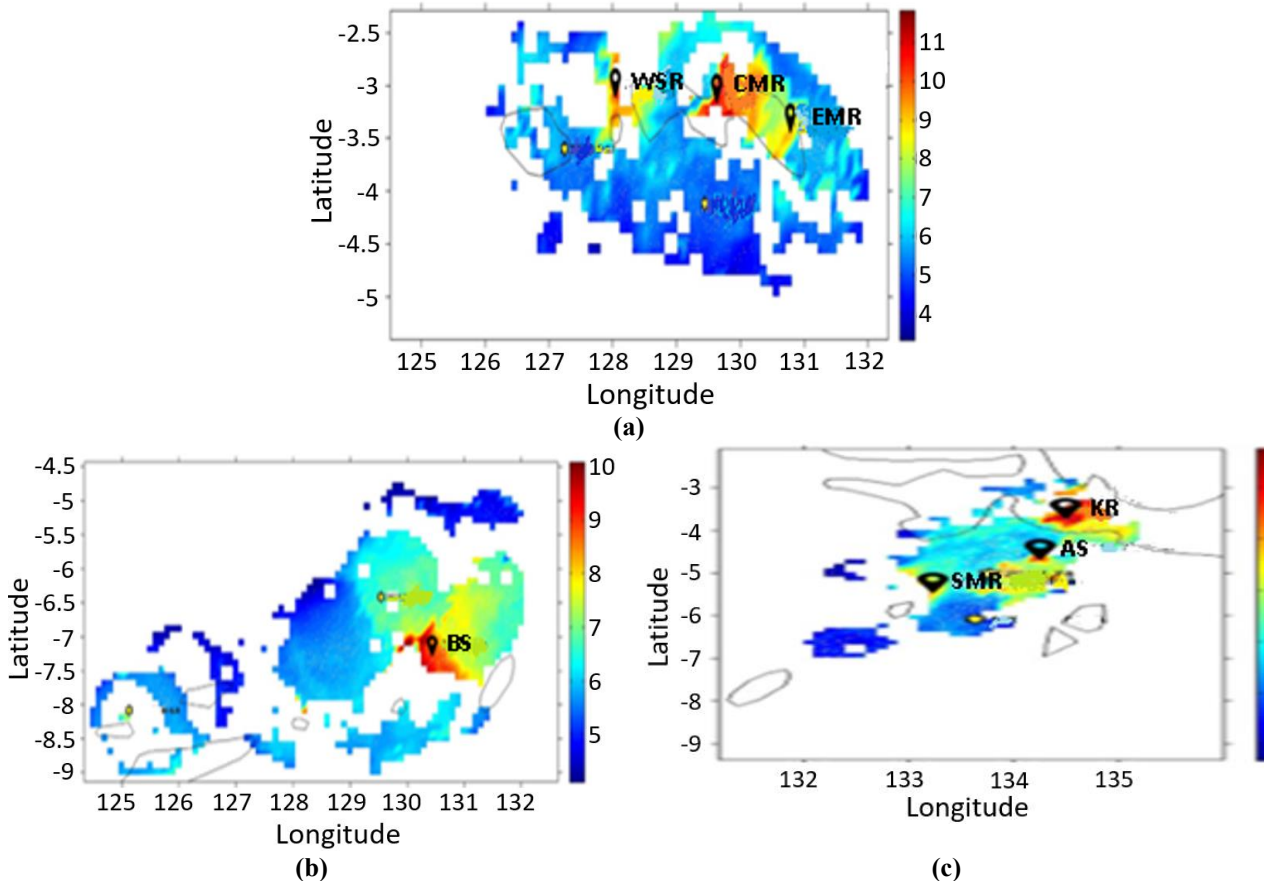


Figure 7. The Map of $\hat{a}-$value on (a) SR I, (b) SR II, (c) SR III

The $\hat{a}-$value on SR I which ranges from 3.4 – 11.8 with the highest values located around WSR, CMR, and ESR (**Figure 7** (a)). Furthermore, the $\hat{b}-$value on SR II which ranges from 4.1 - 10.1 with the highest values mostly in the BS area (**Figure 7** (b)). Meanwhile, the $\hat{b}-$value on Sub-region III which ranges from 3.7 – 9.7 with the highest values around KR (West Papua), SMR, and partly in the AS sea area (**Figure 7** (c)).

3.4 Analysis of Frequency-Magnitude Relationship

Frequency-magnitude relationship analysis helps in evaluating the level of seismic activity of a region by looking at the frequency distribution of earthquakes based on their magnitude. The frequency-magnitude relationship can be seen in the Magnitude of Completeness (Mc) value graph obtained with the help of Matlab and Zmap applications. Mc is the most frequent earthquake within a certain range of events in a region. The frequency-magnitude relationship can be seen in the graph of the Mc value (**Figure 8**).

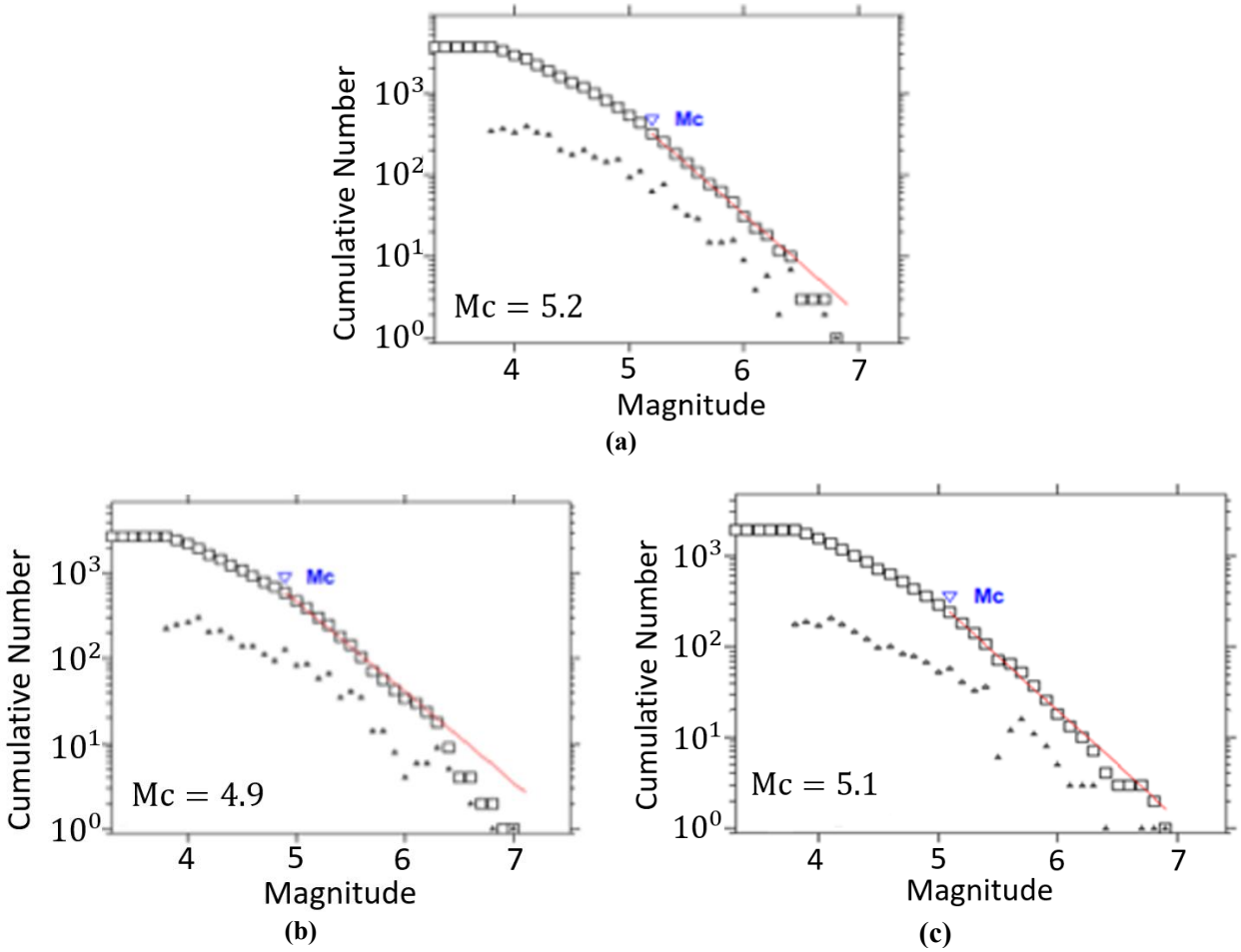


Figure 8. The Graph of *Mc* Value on (a) SR I, (b) SR II, (c) SR III

The Mc value graphs for SR I and II show that the relationship between the number of earthquake events and magnitude is inversely proportional, where the greater the earthquake magnitude, the smaller the number of earthquake events that occur (**Figure 8**). The Mc value in SR I is 5.2 Mw, which means that the number of earthquake events with a magnitude of $M > 5.2$ Mw will decrease (**Figure 8** (a)). In SR II, the Mc value is 4.9 Mw, which indicates that the occurrence of earthquakes with a magnitude of $M > 4.9$ Mw will decrease (**Figure 8** (b)). Meanwhile, the Mc value graph for SR III shows the relationship between the number of earthquake events and the magnitude, which is inversely proportional (**Figure 8** (c)). The Mc value in SR III is 5.1 Mw, which means that the occurrence of earthquakes with a magnitude of $M > 5.1$ Mw will decrease.

3.5 Calculation of Seismicity Index and Earthquake Return Period

By using the values of $\hat{a}$ and $\hat{b}$, and using **Equation (7)**, the seismicity index values for the 3 SR are obtained (**Table 3**).

Table 3. Seismicity Index Value in 3 SR

Sub Region	Seismicity Index			
	$M \geq 3,0$	$M \geq 4,0$	$M \geq 5,0$	$M \geq 6,0$
I	308.8385	56.3801	10.2925	1.8789
II	199.0583	42.3239	8.9989	1.9134
III	140.0407	27.4596	5.3844	1.0558

The seismicity index value in SR I with M ≥ 3.0 is 308.8385, which indicates that there is a possibility of an earthquake occurring 309 times, $M \geq 4.0$ as many as 56 times, $M \geq 5.0$ as many as 10 times, and $M \geq 6.0$ as many as 2 times (**Table 3**). In SR II with $M \geq 3.0$ as many as 199 times, $M \geq 4.0$ as many as 42 times, $M \geq 5.0$ as many as 9 times, and $M \geq 6.0$ as many as 2 times. In SR III with $M \geq 3.0$ as many as 140 times, $M \geq 4.0$ as many as 27 times, $M \geq 5.0$ as many as 5 times, and $M \geq 6.0$ as much as 1 (one) time.

Furthermore, the earthquake return period for each SR can be calculated using **Equation (8)** and obtained the earthquake return period time (**Table 4**).

Table 4. Earthquake Return Period Time in 3 SR

Sub Region	The return period of the Earthquake (Year)			
	$M \geq 3,0$	$M \geq 4,0$	$M \geq 5,0$	$M \geq 6,0$
I	0.0032	0.0177	0.0972	0.5322
II	0.0050	0.0236	0.1111	0.5226
III	0.0071	0.0364	0.1857	0.9472

The return period time in SR I with $M \geq 3.0$ is 0.0032 years or about 1 day, $M \geq 4.0$ about 6 days, $M \geq 5.0$ about 35 days, and $M \geq 6.0$ about 194 days (**Table 4**). In SR II with $M \geq 3.0$ about 2 days, $M \geq 4.0$ about 9 days, $M \geq 5.0$ about 41 days, and $M \geq 6.0$ about 191 days. In SR III with $M \geq 3.0$ about 3 days, $M \geq 4.0$ about 13 days, $M \geq 5.0$ about 68 days, and $M \geq 6.0$ about 346 days.

4. CONCLUSIONS

According to the results of the research and analysis, the conclusions of this research are: (1) The characteristics of earthquakes in Maluku Province and its surroundings based on magnitude for the whole region show that earthquakes occur more in the magnitude range of $4 \leq M < 5$ Mw, and the least frequent in the magnitude range of $M \geq 6$ Mw. Meanwhile, based on depth, earthquakes in Maluku Province and its surroundings more often occur at a depth of $30 \leq D < 45$ km, and the least frequent earthquakes occur in the depth range $D \geq 45$ km. Based on the 3 SR, earthquakes in Maluku Province based on magnitude and depth occur more frequently in SR I and least frequently in SR III. (2) The overall seismic activity level for Maluku Province and its surrounding areas is 0.7238. Meanwhile, the level of brittleness of rock is 6.9477. Based on 3 SR, the highest level of seismic activity is in SR I, and the lowest is in SR II, while the highest level of brittleness of rock is in SR I, and the lowest is in SR III. (3) The time of the earthquake return period in Maluku Province and its surroundings, the fastest return period at $M \geq 3.0$. At the same time, the most extended period is at $M \geq 6.0$. The earthquake return period is 3 SR, with the fastest return period time being in SR I and the longest return period time being in SR III.

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