Seismic Hazard Identification in the North Banda Arc Region Using Gutenberg-Richter Law

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Abstract: The North Banda Arc region has a high risk of significant earthquakes due to its complex tectonic configuration. In order to assess seismic hazard potential of the North Banda Arc region, Gutenberg-Richter (G-R) Law is applied using earthquake catalogue from 1970 to 2023. The results are G-R parameters, including Mc, a, and b, where the spatial parameters (a and b values) and temporal parameter (b-value) are applied to investigate the seismic hazard in the North Banda Arc Region. The spatial results show that two regions with high risk to strong earthquakes occur are on eastern Seram Island and between eastern Buru and western Seram Island, including its smaller islands nearby. On the other side, temporal result shows a decreasing b-value, indicating an increasing effective stress that could lead to a strong earthquake.

Keywords: Earthquake; Gutenberg-Richter; seismic hazard assessment; spatiotemporal.

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I. INTRODUCTION

Indonesia is the worlds largest archipelago, comprising approximately 17,000 islands. However, Indonesia also faces a big challenge regarding its geographical location. The Banda Arc, located in eastern Indonesia, has a complex tectonic configuration since due its position at the convergence of several active plates, including the Eurasia Plate, the Australia Plate, and the Pacific Plate [1,2]. Initially, two main theories were proposed regarding the formation of the Banda Arc. The first theory explained that the Banda Arc was formed by a single slab subduction at Timor-Aru Through, while the second one was formed by two slabs subduction. Recent research conducted by Spakman and Hall [3], indicates that the Banda Arc was formed due to single slab subduction followed by rollback towards Southeast-South direction. These geological conditions make the Banda Arc as one of the most seismically active regions in Indonesia and has high risk of significant earthquakes. For instance, in 2019, an earthquake struck northeast Ambon City with Mw 6.5, causing fatalities and forcing many residents to evacuate [4,5].

Post-earthquake research has shown that the north Banda Arc has potential to generate earthquakes with Mw ranging from 6.4 to 7.6 [2]. However, seismic hazard research covering the northern Banda Arc remains limited, with most studies focusing on strong, notable earthquakes, such as the 2019 Ambon earthquake. Example of such studies include moment tensor inversion [6], geodetic observations [7], and stress drop variations [8]. To better assess seismic hazard potential in the northern Banda Arc, research on earthquake event histories, such as earthquake statistics, is necessary.

The Gutenberg-Richter (G-R) Law is a method demonstrates the relationship between earthquake frequency and magnitude. This law yields two main parameters a and b. Earthquake productivity is showed by the a-value, meanwhile frequency ratio between high-magnitude and low-magnitude earthquakes is represented by the b-value [9]. Spatial b-value calculations reveal the stress distribution within the study area, while temporal b-value calculations indicate changes in stress over time [10]. The G-R Law is widely used in seismotectonic and seismic hazard investigations. The G-R Law is able to provide spatial and temporal characteristics of the region, including fault characterisctics, volcanic activity, earthquake precursor, and earthquake recurrence [10,11]. Before determining the a and b values, the magnitude of completeness (Mc) must first be established. The Mc represents the lowest magnitude consistently recorded by the seismometer network and is typically obtained using the Maximum Curvature method, which identifies the highest frequency in a frequency-magnitude histogram [12]. This research applies the G-R Law to investigate seismic hazards in the northern Banda Arc, aiming to provide valuable information for hazard mitigation efforts.

II. METHODOLOGY

In this research, earthquake data were obtained from the ISC-EHB (https://www.isc.ac.uk/isc-ehb/search/catalogue/) and BMKG (https://repogempa.bmkg.go.id/) catalogs, recorded from 1970 to 2023 with latitude boundary -4.39°S to -2.06°S and longitude boundary 125.5°E to 131.9°E. The magnitudes in the event catalogs were converted into moment magnitudes Mw using empirical equations based on previous researchs [13,14]. Declustering was also applied to the earthquake catalogs to remove aftershock events and retain only mainshock event, using the Reasenberg method.

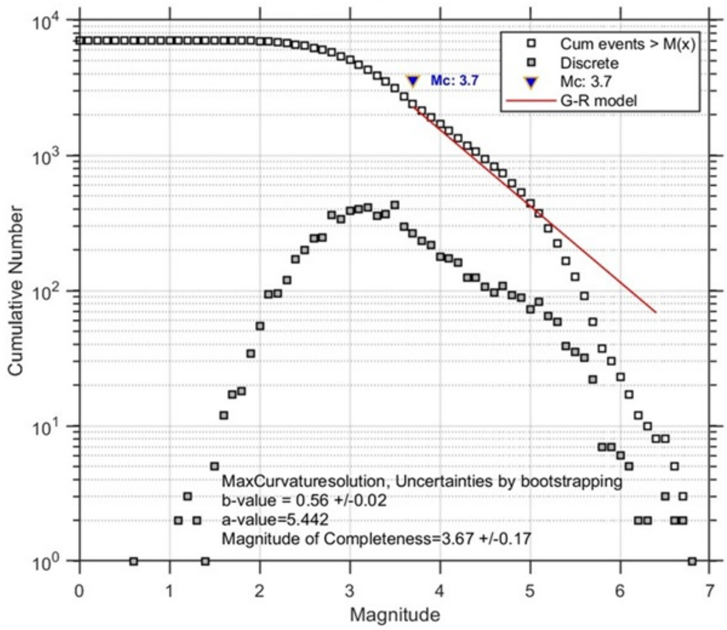

FIG. 1: Frequency-magnitude distribution of the northern Banda Arc region. Gray square represents frequency at a certain magnitude, white square represents cumulative frequency, and G-R model is showed by red line.

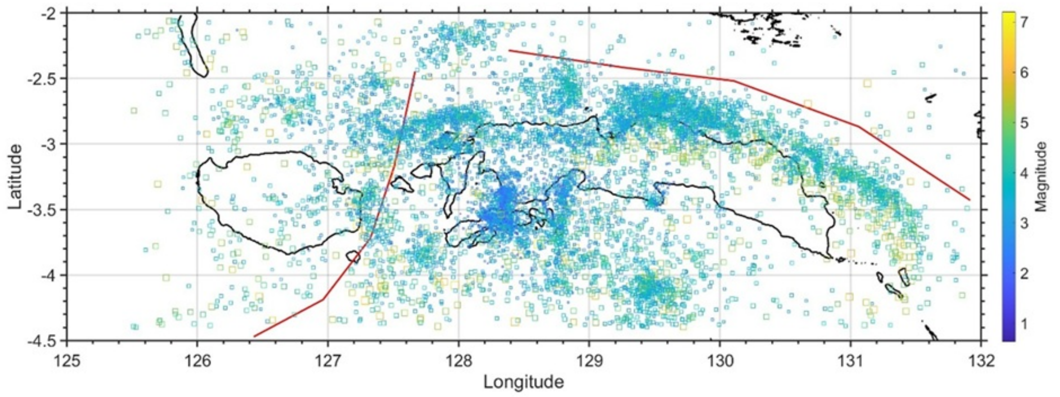

FIG. 2: Seismicity map of the northern Banda Arc region. Earthquake events are showed as square symbol and colors represent the magnitude of each event.

After declustering was done, G-R Law parameters could be calculated. G-R Law equation is defined as follows

$$logN(m) = a - bM \tag{1}$$

where N(M) represents earthquake frequency with magnitude $\geq$ M, and both a and b indicate G-R Law parameters.

Before G-R Law parameters are calculated, Mc value must be estimated. The magnitude of completeness (Mc) value was determined via the Maximum Curvature (MAXC) approach, and the b-value was calculated using Eq.(2)

$$b = \frac{log\ \ e}{M_{avg} - \left(Mc - \frac{\Delta M}{2}\right)} \tag{2}$$

where M_{avg} denotes magnitude average with M $>$ Mc and ΔM represents magnitude binning (ΔM = 0.1) [15].

In order to investigate seismic hazard potential, both spatial and temporal distribution of G-R Law parameters were evaluated. Spatial and temporal calculations were conducted to generate spatial Mc, a, and b-value maps and time-function b-value. The spatial calculations were performerd with a 0.05 $\times$ 0.05° grid size and 111 km constant radius. Temporal calculations were conducted using a 10% overlap and applied on undeclustered catalogue. The declustering and the calculation of G-R parameters, including spatial and temporal analysis, were performed using the ZMAP software [16].

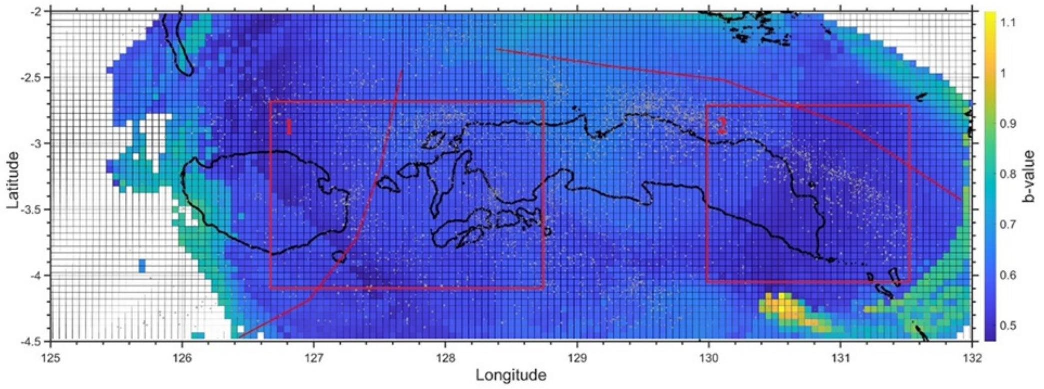

FIG. 3: Spatial b-value map of the northern Banda Arc region. Low b-value represented by red box number 1) between Buru Island and Seram Island, including smaller islands nearby; 2) eastern Seram Island.

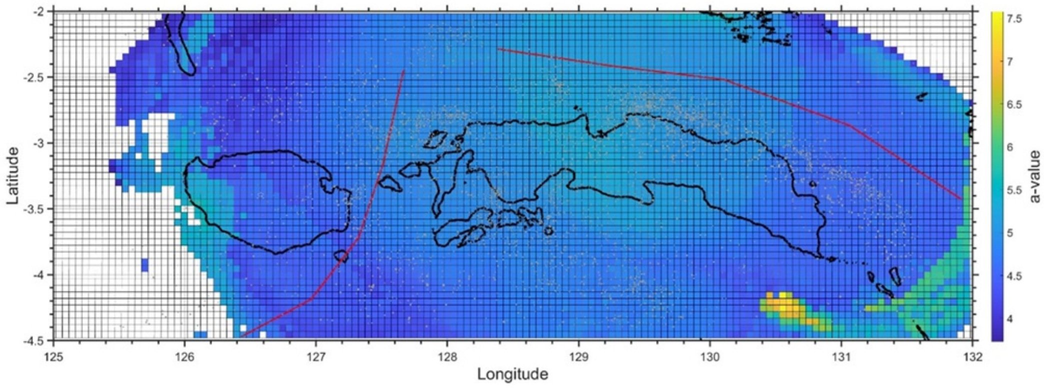

FIG. 4: Spatial a-value map of the northern Banda Arc region.

III. RESULT AND DISCUSSION

After earthquake catalogs declustered, seismicity map were generated by ZMAP software as in the Fig. 1. G-R Law parameters are calculated based on declustered earthquake catalogs as showed in the Fig. 2, including Mc, a, and b values. Bootstrapping is also applied to obtain the uncertainty on both Mc and b values. Mc value at 3.67 ± 0.17 implies that seismometers network has well-recorded start from the mentioned value. Since MAXC method tends to underestimate Mc, correction is added by 0.3 to overcome underestimate problem [17]. In order to acquire more detailed interpretations, spatial and temporal calculations are applied.

The spatial b-value map is represented by Fig. 3 with range value from 0.46 to 1.13. Fig. 3 shows that low b-value can be found in the two areas. The first one is between eastern Buru Island and western Seram Island, including smaller islands nearby. The second low b-value area locates on eastern Seram Island. Previous researchs showed that low b-value indicates high stress [10]. Mathematically, low b-value indicates low gradient on G-R model that high-magnitude earthquakes occurs more frequently than low-magnitude earthquakes. The northern Banda Arc also has numerous onshore active faults on its islands. These active faults contribute to northern Banda Arcs eastward convergence to Birds Head of Papua and high likely to produce strong earthquakes with minimum Mw at 6.4. On the other hand, Seram Through convergence on north-northeast direction also contributed to low b-value at Seram Island [2,14]. This indicates in the northern Banda Arc region has accumulating stress and potentially release the energy in strong earthquake.

Fig. 4 shows the spatial a-value in the northern Banda Arc region. The distribution of a-value is dominated in the range of 4 to 5.5, which are on intermediate level. The a-value represents seismic activity level; high a-value leads to high seismicity level, and vice versa. This means that the northern Banda Arc region has intermediate seismic activity level. Thus, based on the a and b-values, the northern Banda Arc region has middle-level seismic activity but tends to release stress in the form of high-magnitude earthquakes. In this research, the Mc value was also calculated in spatial variation to analyze the Mc value distribution in the northern Banda Arc region as in the Fig. 5. The figure indicates that the Mc value distribution is in the range of 3.2 to 5.1, with the lowest value locates around western Seram Island, including Ambon Island. The minimum magnitude of this region has well-recorded by seismometer network.

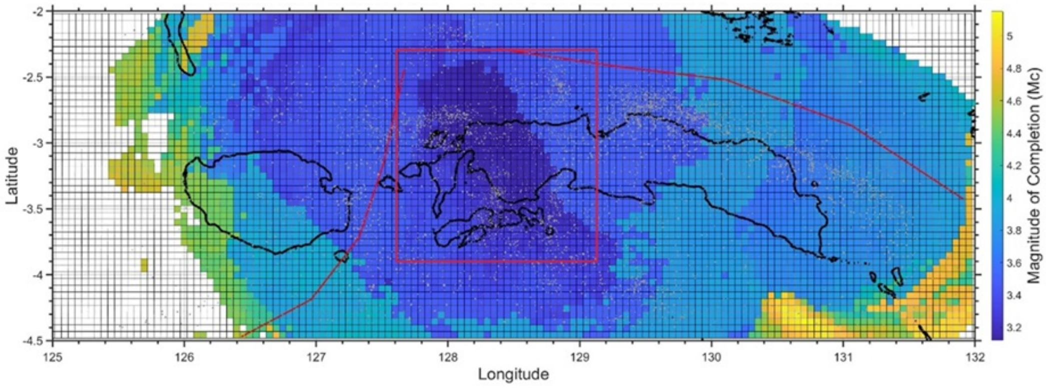

FIG. 5: Spatial Mc value map of the northern Banda Arc region. Low Mc value is showed by the red box on western side of Seram Island, including Ambon Island.

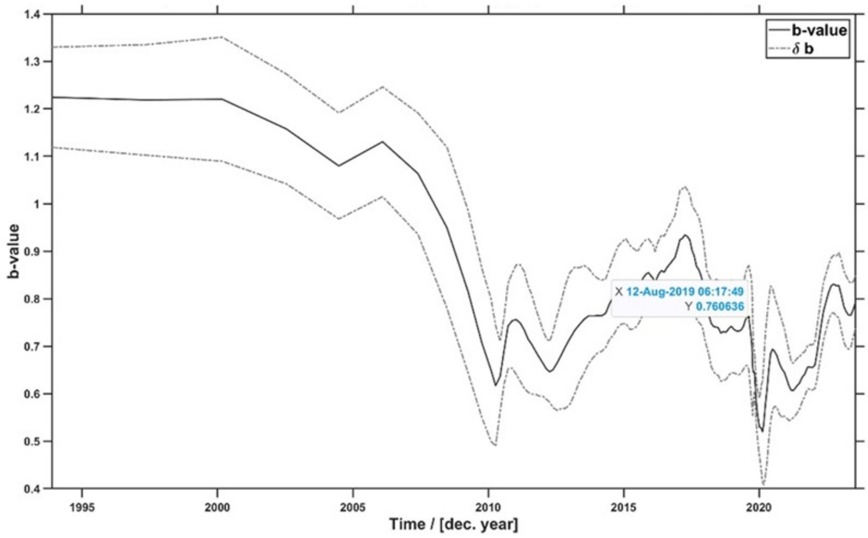

FIG. 6: Temporal map of b-value in the northern Banda Arc region.

The temporal calculation of the b-value is showed in Fig. 6. In this research, temporal b-value variation is observed before the Ambon 2019 earthquake occur on September 25, 2019 23:46:45 UTC time. Based on Fig. 6, b-value decreased approximately one month before the earthquake occurs. Some studies have shown decreasing b-value directs to effective stress increasing on a fault system and has been proved on some laboratory experiments [10]. This means that an earthquake in the northern Banda Arc may occur when the b-value decreasing.

IV. CONCLUSION

The G-R Law has been applied to investigate seismic hazard potential in the northern Banda Arc region. From the spatial calculations, there are two areas with high risk of strong earthquake which are between eastern Buru Island and western Seram Island, including its small islands nearby and eastern Seram Island. Based on the temporal calculation, the decreasing b-value in the northern Banda Arc region indicates an increasing effective stress that could lead to strong earthquake.

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