The Spatio-temporal Analysis of b-value in the Banda Arc, Indonesia

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Abstract. Banda arc is a complex tectonic structure manifests by high seismicity due to the collision of a continent and an intra-oceanic island arc. Using the relocated earthquakes data from ISC-EHB and BMKG catalogues from the time period of 1960 to 2018, we have conducted a spatial and temporal variation of b-value using the Guttenberg-Richter formula in the area. Our results show that the spatial distribution of low b-values located in the south of Ambon Island and southeast of Buru Island. On the other hand, the temporal variation of b-value shows a decrease in the northern part of the Banda sea probably high potential to produce large earthquakes in the future. Therefore, further mitigation is needed to minimize the impact of earthquakes in the area.

1. Introduction
Banda arc is located in the triple junction of Pacific, Eurasia, and Indo-Australian plates. This region is formed from the convergence of three main plates, the Eurasian continent which is relatively stable, the Australian plate which is relatively moving towards the north, and the Pacific plate which is relatively moving towards the west [1].

Banda Arc is located in a complex tectonic structure and this area is still controversies for many scientists: how it acquired its shape, the origin, and the direction of subduction. During the formation process of the Banda Arc, there was a change in the proto-Banda oceanic crust with the Banda oceanic crust. During the formation of the Banda arc, the Banda Sea was expanded due to the rollback of the Keno-Tethys oceanic crust which subsequently triggered delamination and collision along the edges of the Banda continental crust, forming Timor trough, the Tanimbar trough, and the Seram trough [1]. The Banda Arc region has a frequency of large shallow and deep earthquakes [2,3].

Earthquakes are rapid shaking of the earth caused by the release of energy that occurs suddenly due to rock cracks that stretch beyond their elasticity limit [4]. Historical earthquakes of the Banda Sea show that this area has high seismicity, as shown in Figure 1. The earthquake and tsunami in Seram and Ambon on February 17, 1674, which killed 2322 victims [5]. Another tsunami event was caused by the earthquake that occurred on October 8, 1950, which struck Ambon (Hutumuri, Hative Kecil, and Galala) [5]. Therefore, one of the pieces of information that can be used to analyze the potential for earthquakes is the b-value from the Guttenberg-Richter formula [6]. The b-value will vary depending on the stress distribution [10] and material heterogeneity.

The previous study of spatial variations of b-value has been carried out in several areas. Ngadmanto [8] examined the b-value using the NEIC catalogue from 1973-2009 and stated that the
Banda Arc area where an earthquake with a magnitude 6.5 was around Flores, Alor, and in the west of Seram. The purpose of this study is to an analysis of spatial and temporal of b-value in the Banda arc and its surrounding area.

Figure 1. Seismicity of the Banda Arc region from the ISC-EHB and Indonesian Agency for Meteorology, Climatology, and Geophysics catalogue showing all hypocenters with magnitudes greater than 3 Mw between 1960 and 2018. The map shows a pattern of earthquakes that form a spoon-like shape with hypocenters that gets deeper at the inside of a curved Banda Arc.

2. Data and Method
In this study, we used catalogue data from International Seismological Center-Engdahl, van der Hilst, Buland (ISC-EHB) [2] and Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) [3] for a time period from 1960 to 2018, with a boundary area of 1.46° S–10.64° S and 124.13° E – 136.87° E, 0-680 km depth. The total number of earthquakes data is 6.779. We used the conversion magnitude formula [8] to converted of initial magnitude from the catalogues to Moment magnitude (Mw). We have 6.488 earthquakes after the declustering process using the Reasenberg method [9]. We used ZMAP [10] to calculate a-value, b-value, and magnitude of completeness (Mc) by plotting the frequency-magnitude distribution.

The seismicity parameters of a region can be calculated using the Gutenberg-Richter formula [6]:

\[
\log n(M) = a - bM
\]  

(1)

\( n \) = number of earthquakes
\( a \) = a constant which informed level of seismicity
\( b \) = the gradient of the cumulative number relative to the magnitude

b-value can be calculated using the Maximum Likelihood estimation [11] which use the equation:

\[
b = \frac{0.434}{M-M_{\text{min}}}
\]  

(2)

\( M \) = average magnitude
\( M_{\text{min}} \) = minimum magnitude
We used grids size of 0.2° x 0.2° with 150 km of a constant radius parameter and 50 minimum number of earthquakes for spatial analysis. Then, we calculated the variation of temporal b-value using the sliding time-window method. The time sliding-window method works by calculating the b-value of the number of earthquakes from the catalogue, then the window is shifted with a fixed number of earthquakes and the b-value for that number of earthquakes, the process is repeated until the last earthquake [8].

3. Result and Discussion

Distribution of b-values for all data from 0.36 to 1.61 (Fig. 2a). In the southern part of the Banda arc, shows a void of b-value, this is due to the low of seismicity in the area. Low b-values are seen in the northern and western parts of the study area (the North Banda Arc segment and the Banda Sea part). Further analysis is performed by dividing the event based on depth into three types, which are shallow (less than 60 km), medium (60-300 km), and deep (more than 300 km).

Distribution of b-value for depth less than 60 km range from 0.37 to 1.45 (Fig. 2b). This map shows that the b-value varies greatly, especially in the northern segment, meanwhile the southern segment tends to have a high b-value, especially around Banda Island. Besides that, there are also several earthquake events with Mw > 6.5 located in the southeast of Buru Island.

![Figure 2](image)

**Figure 2.** Map of b-value in the Banda Arc region based on the depth of hypocenter: a) Map of all dataset, b) for hypocenter less than 60 km, c) for hypocenter from 60 to 300 km, and d) for hypocenter more than 300 km. Red colour represents high b-value whereas blue colour represents low b-value. Red lines are fault [13]. The yellow stars depict earthquakes $M_w > 6.5$.

The variation of b-value for intermediate-depth (60 - 300 km) is shown in Figure 2c. The number of events at this depth is less than the shallow earthquakes, so the distribution of the b-value tends to
be less and local. The b-values range from 0.43 to 1.56. b-value tends to decrease for deeper earthquakes. The distribution of b-value tends to be distributed in the center of the Banda Arc. The difference in b-value is clear between the northern and southern parts of Banda Arc, the distribution of low b-values is located at 2° – 4° S and 126° - 132° E, while high b-values are spread over 4° - 9° E and 126° - 132° E. There are earthquake events with Mw > 6.5 which are located in areas with a high b-value distribution. Figure 1d. shows the distribution of b-values for depths more than 300 km. It shows that the distribution of b-values is centered on the center of the Banda Arc with a variation of the value that has a smaller range that is 0.49 - 1.34. There were also several earthquake events with Mw > 6.5 at depths more than 300 km.

3.1. Spatial Analysis

The distribution map of the b-value (Fig. 2) indirectly shows the seismic distribution of the Banda Arc. This map shows that as the depth of earthquakes increases, the seismicity starts to cover a smaller area and more concentrated in the inside of Banda Arc. Generally, the distribution of b-value concentration can describe the distribution of seismic activity that corresponds with the tectonic setting of the Banda arc. The slab reaches a depth of > 300 km in the western part of the study area and shallow to the east in the shape of a spoon [1].

The distribution of b-values at depths > 300 km are quite varied. A low b-value usually correlates with a high level of stress and its release can occur any time which causes a large earthquake [10]. However, at a depth of > 300 km, the b-value distribution shows a value > 1, it means that the area has relatively low stress. Based on the data in this study, large earthquakes at this depth only occurred in 1969 (Mw 7.2) and 1982 (Mw 7.5).

At a depth of 60-300 km, the b-value shows a pattern that forms a segmentation in the research area into northern and southern parts. The north shows a relatively low b-value, while the south shows the opposite. The contrast of b-value (between the northern and southern parts) tends to decrease towards the east, this phenomenon is presumed to be caused by the shape of the slab which resembles a spoon, and by the stress distribution which tends to be more uniform. However, this requires further research. At a depth of 60-300 km, several large earthquakes were recorded, mostly scattered in the Inner-Banda Arc area such as the 2009 event of Mw 7.2, and the 2012 event of Mw 7.5.

The potential for a large earthquake to occur at a depth of 60 - 300 km, especially in the northern part, is greater than that in the southern part because the stress level tends to be low as indicated by the high b-value. Based on the historical earthquakes, most of the major earthquakes occurred in the southern part. Thus, the stress in the south may have been accommodated by previous earthquake events. In contrast to the northern part, which has a relatively low b-value, no earthquakes with Mw > 6.5 are found.

Based on the distance of hypocenter from the surface, large earthquakes that occur at a depth of more than 60 km tend to experience energy absorption by the mantle and the earth's crust so this research focuses on depths less than 60 km. The distribution of b-values for shallow depths (< 60 km) shows varying values, especially in the north. Meanwhile, the southern part shows relatively low value. This variation of b-value in the northern part is thought to be related to the distribution of stress due to the presence of Seram Strike-slip and Fault Weight as an earthquake generator.

In the northern part of the Banda Arc, the distribution of low b-values is visible in the south of Ambon or southeast of Buru Island and Banda Island. It appears that there were large earthquakes concentrated in the Southeast of Buru Island. The low stress at this location is thought to be related to the existence of the South Buru Fault. Based on the catalogue data used, no earthquakes Mw> 7 were found, but there were several earthquakes above Mw> 6.5, including Mw 6.8 occurred in 2015 in the south of Seram Island, and Mw 6.5 occurred in 2001 in the Southeast of Buru Island.

3.2. Temporal Analysis

The temporal b-value analysis is only carried out for earthquakes with a depth of fewer than 60 km. Figure 3a. shows the distribution of b-value for the Northern Banda Arc, the highest value is 1.59 that
occurred in 1973 and the lowest is 0.6341 in 2012. Earthquakes with a magnitude greater than or equal to Mw 6.5 in the northern part of the Banda Arc usually occurred when the b-value decreases. Although an anomaly occurred in 1995 where an earthquake with Mw 6.8 occurred at the same time with a high b-value. Something similar happened in the southern part of the Banda Arc (Fig. 3b), it is shown that two of the three earthquakes that occurred with a magnitude greater than or equal to Mw 6.5 occurred simultaneously with decreasing b-value. The highest b-value for the southern part occurred in 1979 at 1.521 and the lowest b-value occurred in 2006 at 0.99.

Analysis of the b-value concerning time, generally shows that the occurrence of a large earthquake is associated with a low b-value, but it should be considered that there are generalizations of the b-value in a fairly wide area. This is what creates anomalies in the north (1995) and south (1991). The trend of changes in b-value over time shows that in 2018 there are differences between the northern and southern segments. The northern segment shows a decrease in the b-value, while the southern segment is relatively constant.

Figure 3. Temporal variation of b-value for the time period from 1960 to 2018 (depth less than 60 km) in (a) North Banda Arc, (b) South Banda Arc. Bold black lines show temporal variation of b-value, dotted black lines
represent the standard deviation of the b-value, the red arrow indicates earthquakes with a magnitude above Mw 6.5.

4. Conclusion
The spatial distribution of b-values using the ISC-EHB and BMKG earthquake catalogues from the time period from 1960 to 2018 at a depth of less than 60 km shows b-value variations with a range from 0.36 to 1.45. Low b-values are spread in the south of Ambon and Southeast of Buru Island. The temporal variation of the b-value shows a decrease in the North Banda Arc. Our results indicate that these areas have the potential to produce large earthquakes. The results of this study can be used as additional information in earthquake mitigation efforts.

Acknowledgements
We would like to thank ESC-EHB and BMKG for earthquake catalogue, QGIS for creating b-value map, and GMT for displaying the seismicity of Banda Arc.

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