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SPATIAL AND TEMPORAL B-VALUE ANALYSIS OF THE YOGYAKARTA REGION USING EARTHQUAKE DATA 1960– 2024

ANALISIS B-VALUE SECARA SPASIAL DAN TEMPORAL PADA WILAYAH YOGYAKARTA MENGGUNAKAN DATA GEMPABUMI 1960-2024

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Abstract. Yogyakarta is one of the areas in Indonesia with a high risk of earthquakes due to its proximity to the subduction zone of the Indo-Australian Plate and Eurasian Plate and the presence of active fault activity, namely the Opak Fault, which generates shallow earthquakes. A total of 13 destructive earthquakes were recorded in Yogyakarta and surrounding areas from 1840 to 2023, with the most destructive earthquake occurring in 2006 in Bantul. A total of 417 earthquakes were felt in the Yogyakarta area between May 2006 and March 2016. The high earthquake activity after the 26 May 2006 earthquake indicates a stress field on the active fault segment that has not been fully released. This study aims to analyze the seismotectonic parameter b-value spatially and temporally to determine the accumulation of tectonic stress in Yogyakarta. The method used is a frequency-magnitude distribution with Gutenberg-Richter relation and Maximum Likelihood approach. Earthquake data were obtained from ISC and BMKG catalogs, with a total of 205 events. The results show that spatially, the b-value of the Yogyakarta region is generally low with a range of values of 0.35 - 0.75 using a grid of 1.5 x 1.5 km and a radius of 15 km with low values around the Opak Fault and Ngalang Fault, meaning that the area still holds a high accumulation of stress energy and has the potential for large earthquakes to occur again in the future. Temporal analysis of the b-value shows a tendency for the b-value to decrease before a large earthquake and increase afterwards, reflecting the accumulation and release of stress in the rock.

Abstrak. *Yogyakarta merupakan salah satu daerah di Indonesia yang berisiko tinggi mengalami gempa bumi karena letaknya berdekatan dengan zona subduksi penunjaman Lempeng Indo-Australia dan Lempeng Eurasia serta adanya aktivitas sesar aktif yaitu Sesar Opak yang menjadi pembangkit gempa* *bumi dangkal. Tercatat sebanyak 13 kejadian gempa bumi merusak di wilayah Yogyakarta dan sekitarnya dari tahun 1840 hingga 2023, dengan gempa paling merusak terjadi pada tahun 2006 di Bantul. Sebanyak 417 gempa dirasakan di wilayah Yogyakarta periode Mei 2006 – Maret 2016. Tingginya aktivitas gempa bumi setelah gempa bumi 26 Mei 2006 mengindikasikan adanya medan tegangan pada segmen sesar aktif yang belum sepenuhnya terlepas. Penelitian ini bertujuan untuk menganalisis parameter seismotektonik yaitu b-value secara spasial dan temporal untuk mengetahui akumulasi stress tektonik Yogyakarta. Metode yang digunakan yaitu distribusi frekuensi-magnitudo dengan relasi Gutenberg-Richter dan pendekatan Maximum Likelihood. Data gempa diperoleh dari katalog ISC dan BMKG, dengan total 205 kejadian gempa. Hasil penelitian menunjukkan secara spasial, b-value wilayah Yogyakarta secara umum termasuk rendah dengan rentang nilai 0.35 – 0.75 menggunakan grid 1.5 x 1.5 km dan radius 15 km dengan nilai rendah di sekitar Sesar Opak dan Sesar Ngalang artinya wilayah tersebut masih menyimpan akumulasi energi stress yang tinggi dan berpotensi terjadi kembali gempa besar di masa depan. Analisis temporal b-value menunjukkan adanya kecenderungan penurunan b-value sebelum gempa besar dan kenaikan setelahnya, mencerminkan terdapat akumulasi dan pelepasan stress pada batuan.*

1. INTRODUCTION

The Yogyakarta region is adjacent to the subduction zone of the Indo-Australian Plate which moves northward to strike the stationary Eurasian plate, causing the Indo-Australian plate to subduct beneath the Eurasian plate and generating rock movements, making Java a tectonically active region with a high rate of earthquakes and volcanoes (Hamilton, 1988). In addition, the lateral force of the Indo-Australian plate subducting beneath the Eurasian plate triggered fault systems in Java, including the Opak Fault in Yogyakarta, which becomes very active and has the potential to produce shallow earthquakes (BMKG, 2016).

As many as 13 destructive earthquakes were recorded in the Yogyakarta and surrounding areas from 1840 to 2023 with a magnitude range of 6.0-8.1. Destructive earthquakes are earthquakes that cause significant damage to infrastructure, buildings and the environment, and have the potential to cause loss of life. One of the destructive earthquakes occurred on May 26, 2006, 22:54:01 (UTC) with a magnitude of 6.3 Mw at a depth of 33 km with an impact area in Bantul, Klaten, Yogyakarta, Prambanan and Central Java as many as 5,782 people died, 36,299 people were injured, and 390,077 houses were damaged (BMKG, 2018). The total loss caused by this earthquake reached Rp 29.1 trillion (BAPPENAS, 2006). This earthquake was caused by a shift of the Opak Fault with sinistral or left-lateral frictional movement.

In the last ten years after the Yogyakarta earthquake on May 26, 2006, earthquake activity in Yogyakarta and surrounding areas has remained high. Based on BMKG data from May 2006 to March 2016, there were 417 earthquakes that were strong enough to be felt in Yogyakarta (BMKG, 2016). The high earthquake activity after the May 26, 2006 earthquake indicates the presence of stress fields on active fault segments that had not been fully released during the 2006 earthquake. Therefore, it is necessary to analyze seismotectonic parameters, namely b-value spatially and temporally.

Seismotectonic parameters are quantities used to explain the relationship between seismic activity (earthquakes) and the tectonic conditions of a region obtained through frequency-magnitude distribution using the

Gutenberg-Richter relation (Lay & Wallace, 1995). The b-value analysis is conducted to determine the level of accumulation of tectonic stress in a region with a value of about 1, which means that every one unit increase in magnitude, the number of earthquakes decreases about 10 times (Prawirodikromo, 2012), based on the logarithmic relationship between b-value and number of earthquake occurrences. For example, if b-value is equal to 1: earthquakes with magnitude more than 8 occurs once, and earthquakes with magnitude more than 7 occurs 10^1 or 10 times in certain period. Regions with a low b-value have a high level of stress accumulation that can be used as a precursor to large earthquakes (Nuannin, 2006).

While the a-value describes the level of seismic activity of a region. A larger a-value indicates that a region has high seismic activity. Previous studies have analyzed the spatial and temporal distribution of the b-value to identify areas with easily fractured rock fragility and the potential for large earthquakes. The results show that a decrease in b-value before an earthquake can be a potential occurrence of a large earthquake in the future (Nuannin, 2006; Prananda et al., 2022; Rohadi, 2009; Wiemer & Wyss, 2002). Spatial analysis is done through the spatial distribution of b-value, while temporal analysis is done by looking at the graph of b-value changes against time during the seismicity data period (Zakhra et al., 2023; Hanafi et al., 2024).

The results of this study are expected to make an important contribution to earthquake disaster mitigation efforts in the Yogyakarta region to minimize damage and casualties if earthquakes occur again in the future. In addition, this research can also make an academic contribution to the development of seismology and geophysics, especially in understanding the dynamics of seismic activity in earthquake-prone areas.

2. LITERATURE REVIEW

2.1. Geological Map of the Study Area

The geological map of Yogyakarta (**Figure 1**) shows some of the main geological features in the area, including the various rock formations and faults that influence the geology of the area. The rock formations in the study area are dominated by sedimentary and volcanic rocks such as Quaternary volcanic cover, early Miocene volcaniclastics, Oligo- Miocene volcanics, Plio-Plistocene diorite, Mid Mio-Pliocene limestone, Eocene siliciclastic, and Pre-Tertiary metamorphic.

In addition, there are also several faults such as the Opak Fault, Ngalang Fault, Oyo Fault and Nglipar Fault. The Opak Fault is a strike-slip fault that extends in the SW-NE direction (Southwest-Northeast), meaning that the relative movement between two rock blocks occurs horizontally parallel to the fault itself. The Ngalang Fault is also a strike-slip fault with a direction almost parallel to the Opak Fault, namely SW-NE (Southwest-Northeast).

This fault is located to the east of the Opak Fault. The study by Librian et al. (2024) showed that the main earthquake on May 26, 2006 M6.3 occurred on the Ngalang Fault about 10 km east of the Opak Fault at a depth of 9 km (red star), and the southern part of this fault is connected to the Opak Fault through the Oyo Fault. The Oyo Fault is a fault that connects the Opak Fault and the Ngalang Fault. This fault has a NW-SE (Northwest-Southeast) orientation. The Nglipar Fault is a SW-NE (Southwest-Northeast) oriented left-lateral strike-slip fault located to the Northeast of the Opak-Ngalang fault. The fault cuts Early Miocene volcanic rocks and Miocene limestone deposits (Zulkifli et al., 2024).

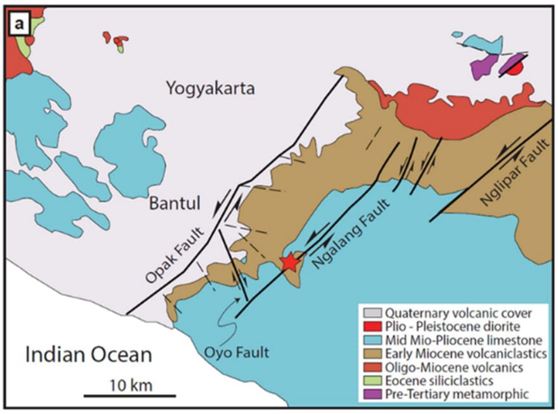


Figure 1. Geological Map of the Opak Fault Vicinity (Librian et al. (2024), modified from Surono et al. (1998). The star symbol is the hypocenter location of Yogyakarta earthquake 27 May 2006.

2.2. a-value and b-value

a-value and *b*-value are seismotectonic parameters obtained through the Gutenberg-Richter relation with the equation:

$$\log N = a - bM \quad (1)$$

N is the number of earthquakes, M is the magnitude, a and b are constants.

The a-value represents the level of seismic activity in a region based on the number of events in a given time period. Mathematically, the a-value is the intercept of the regression line of log N against M (**Figure 2**). Larger a-value indicates more active seismic activity in that area. Conversely, if the a-value in an area is small, the seismic activity is also small. The a-value depends on several factors: the observation period, observation area, and seismicity of the observation area.

Meanwhile, the b-value parameter describes the level of tectonic stress and the degree of brittleness of the subsurface rocks in an area, usually close to 1 (Godano et al., 2014). Mathematically, the b-value is the gradient of the regression line (Figure 2). b-value of about 1 means that for every one unit increase in magnitude, the number of earthquakes decreases about 10 times, for example, it is known that there are 10 earthquakes with magnitude 7.0 so that it can be predicted that there are 100 earthquakes with magnitude 6.0 and so on (Prawirodikromo, 2012). The degree of rock fragility indicates the ability of the rock to withstand the stress received from endogenous forces within the earth's layers. The more fragile the rock, the easier it is to fracture and produce earthquakes.

The main parameter that influences the b-value is the accumulated stress acting on the rock. A low b-value indicates high stress accumulation. This means that the rock is more prone to fracture and is often associated with the final stage of energy accumulation in the medium resulting in large earthquakes with less frequency. A high b-value indicates low stress accumulation. This means that the rocks are more resistant to stress, resulting in small earthquakes with a higher frequency and thus an active seismicity level in the region.

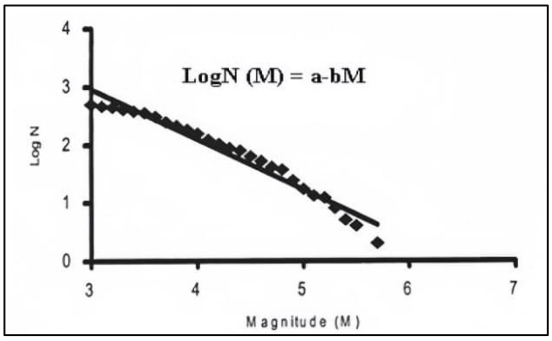


Figure 2. Gutenberg-Richter Relation Showing the Logarithmic Relationship of Number of Earthquakes and Magnitude (Rohadi, 2009).

Both seismotectonic parameters are obtained through maximum likelihood estimation which is used to calculate the spatial mapping of b-value and a-value. The maximum likelihood estimate of the b-value is:

$$b = \frac{\log e}{\bar{M} + M_0} \quad (2)$$

Log e value is 0.4343, $\bar{M}$ is the average magnitude, and M_0 is the minimum magnitude in the catalog.

The maximum likelihood estimate of the a-value is as follows:

$$a = \log N(M \geq M_0) + b\,(ln10) + bM_0 \quad (3)$$

N is the number of earthquake data with magnitude ≥ M_0 and M_0 is the minimum magnitude in the catalog.

Statistically, b-value variations can be seen in various stress regimes such as in slab subduction zones along fault areas and in regions with volcanic activity (Wiemer & Wyss, 2000). Variations in b-value can be mapped spatially and temporally. This mapping provides important information, namely that large magnitude earthquakes generally occur in regions with low b-values (Nuannin, 2006). Based on tectonic studies in Indonesia, the b-value in the Indonesian region ranges from 0.6 to 1.8, while the a-value ranges from 4.0 to 12.1 (Rohadi et al., 2007).

3. METHODS

This study uses earthquake catalog data for the Yogyakarta area with boundaries of 7.75°-8.25°LS and 110.25°-110.75°BT. The data were obtained from the International Seismological Center (ISC) in the period January 1, 1960 - May 31, 2024 and the Earthquake Repository of the Meteorology, Climatology, and Geophysics Agency (BMKG) in the period January 1, 2024 - May 31, 2024. We used 205 open-access data: 5 events from the BMKG Earthquake Repository and 200 events from the ISC catalog, as shown by **Figure 3**.

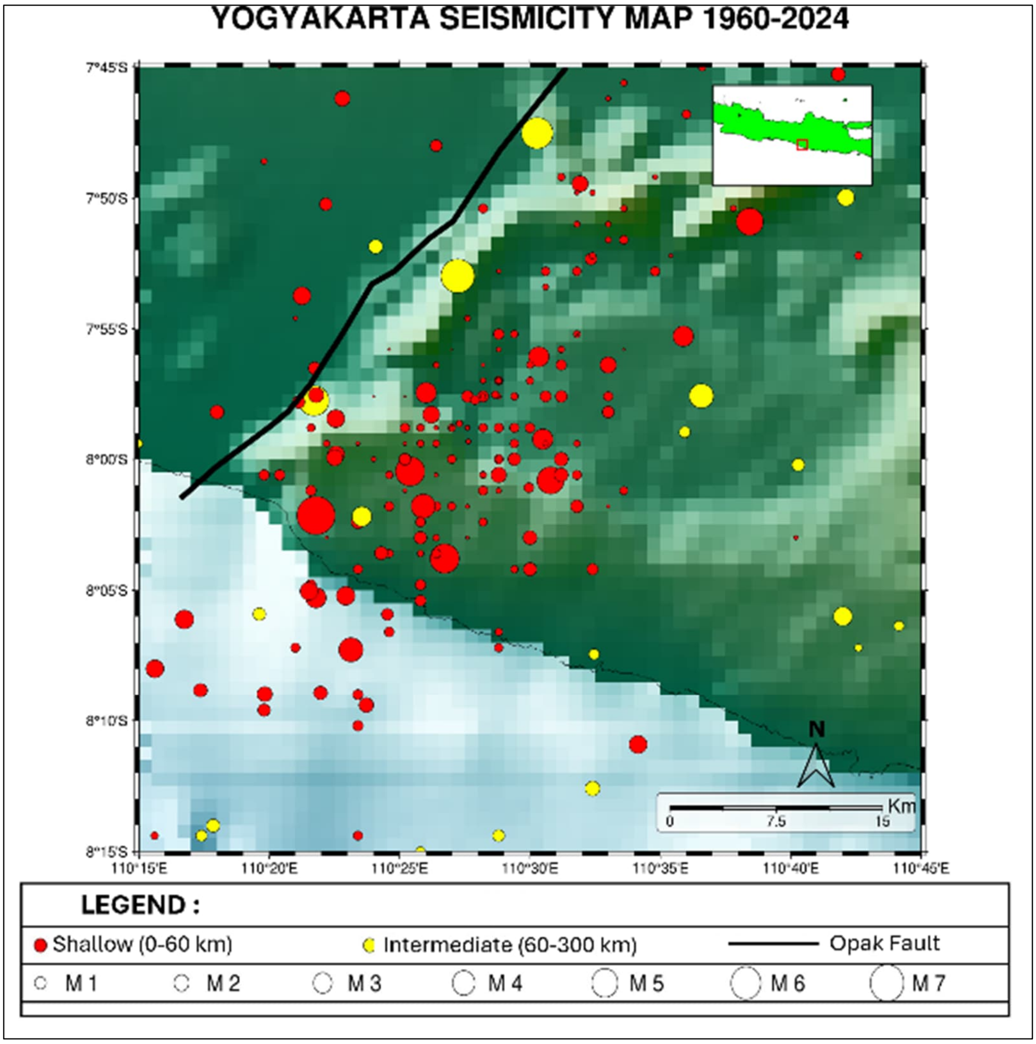


Figure 3. The distribution of earthquakes in Yogyakarta 1960 -2024 (ISC Catalog).

3.1. Workflow

To perform data processing in this research, several software such as ZMAP7 program and Generic Mapping Tools GMT). ZMAP7 is used for b-value analysis to obtain earthquake distribution patterns both spatially and temporally, and GMT is used to plot or visualize the maps.

The research phase began by preparing the input data in a format consisting of longitude, latitude, year, month, date, magnitude, depth, hour, minute, and second, which were then saved in .DAT format. However, because the data obtained from the ISC earthquake catalog and BMKG Earthquake Repo consists of several types of magnitudes such as Body Magnitude (mb), Local Magnitude (ML), the magnitude scale used by the Japanese Meteorological Agency (Mjma), and Vertical Local Magnitude (MLv). All magnitude types were being homogenized to be MLv type.

MLv (Vertical Local Magnitude) is a measure of earthquake strength calculated based on the maximum amplitude of seismic waves in the vertical component of the seismogram. MLv has the largest amount of data in the study and is suitable for use throughout the world including in areas with complex geological conditions. This is the same as the results of research by Taruna et al. (2021) who conducted a suitability test between the summary magnitude that is widely used by BMKG and other types of magnitude such as MLv.

The linear regression equations of several magnitude types are shown in **Table 1**. Data processing was carried out using ZMAP7 starting with data input, then determining the grid, minimum number of earthquakes, radius, and Frequency-Magnitude Distribution (FMD) parameters.

Table 1. Magnitude Homogenization Regression Equation

Category	Value
mb	MLv = 1.1014(mb) − 0.2068
ML	MLv = 1.0947(ML) + 0.0905
Mjma	MLv = 0.9733(Mjma) − 0.5074

To obtain the b-value temporally, calculations are performed using the sliding time-window method that takes into account parameters such as sample window size (N events) to calculate the b-value, with minimum number of earthquakes above the Mc value per window (n events), and the number of earthquakes allowed to overlap (m events). The workflow of research is shown by **Figure 4**.

4. RESULTS AND DISCUSSION

The total number of events in the study area is 205 data with magnitude 1.4≤MLv≤ 6.6 at a depth of 0-242 km (**Figure 5a**). Yellow colored hexagons are earthquake event data with magnitude ≥5.

In this study, there are 2 cross-sections that are oriented Northeast-Southwest (A-A') and Southeast-Northwest (B-B') (**Figure 5b**) is the cross-section result for cross-sections A-A' and B-B' which have a width of 8 km, meaning that the cross-section is mapped with a width of 8 km on the left and 8 km on the right. Both cross-sections show the results of a fixed depth at a depth of 10 km and the dominant earthquake hypocenter is at a shallow depth of 0-20 km, indicating that the earthquake in the study area was caused by active fault activity, namely the Opak Fault. These shallow earthquakes are located around the fault area, and it is more convincing to relate the earthquakes with Opak Fault rather than other sources such as volcano or subduction zone.

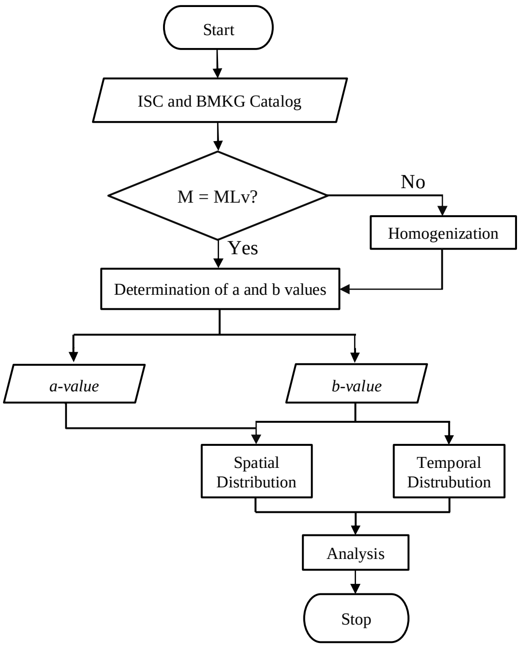
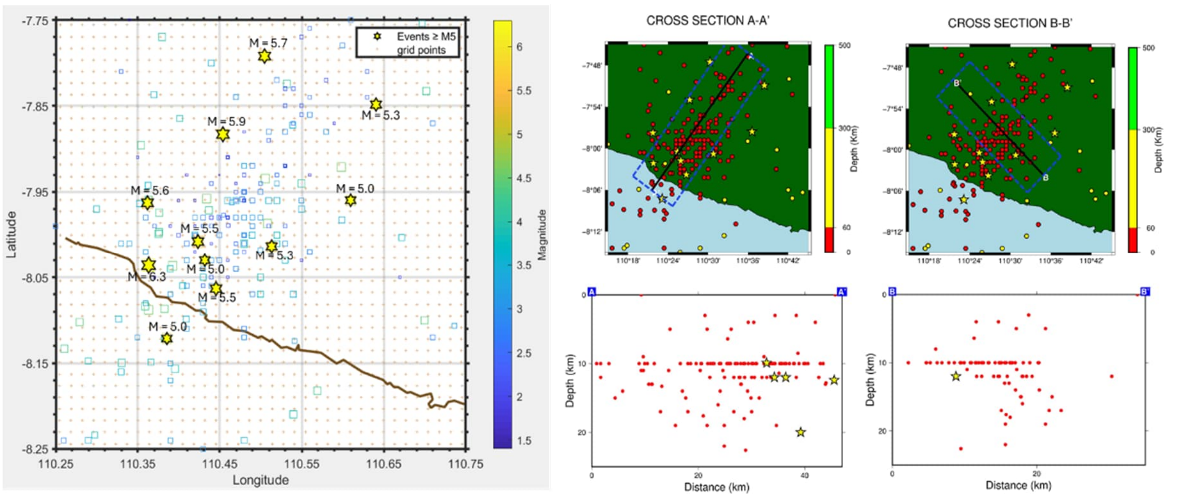


Figure 4. The research workflow.

The fixed depth at 10 km appears when the earthquake signal recorded by the system produces an inaccurate estimate. However, the a-value and b-value estimation is not affected by the earthquake depth, unless we want to obtain the value distribution in the depth domain (section).

In cross-section A-A', there are 5 earthquakes with magnitude ≥ 5 located at a depth of 10-20 km. The distribution of earthquake hypocenters in cross-section A-A' is more than that in cross-section B-B' because it is located parallel and adjacent to the Opak Fault, which is the cause of shallow earthquakes in the study area. While cross-section B-B' is located perpendicular or intersects with the Opak Fault, there is 1 earthquake that has a magnitude ≥ 5 with a depth of 12 km.



(a) (b)

Figure 5. (a) Distribution of Earthquakes in Yogyakarta Area; (b) Cross-Section Map.

Figure **6a** is a histogram of magnitude against the number of events with an interval of 0.5. Based on the histogram, the dominant earthquakes that occurred were in the magnitude range of 2.0-4.0. Earthquakes with a magnitude of 3.0-3.5 occurred most frequently with a total of 50 events. **Figure 6b** is the distribution of magnitude against time.

From this distribution, there were 3 major earthquakes that occurred in the study area, namely the earthquake that occurred on April 2, 1969 with a magnitude of 5.9, the earthquake that occurred on July 7, 1999 with a magnitude of 5.9, and the earthquake that occurred on May 26, 2006 with a magnitude of 6.6.

Figure 6c is a histogram of depth versus the number of events at 5 km intervals. Based on the histogram, the dominant earthquakes that occurred were in the depth range of 0-20 km. The most frequent earthquakes in the study area have a depth of 10-15 km with a total of 132 events and are considered shallow earthquakes. There were several earthquakes that occurred at depths between 20-100 kilometers. While earthquakes with a depth of ≥100 km only occur occasionally.

Figure 6d represents the cumulative rate curve of earthquakes. The seismic activity that occurred in the Yogyakarta area in the period 1960-2024 was quite high, with 11 earthquakes with magnitude ≥5 marked by yellow hexagons. The curve shows a significant increase in the occurrence of large earthquakes such as in 2006, 2010, and 2022, indicating an increase in seismic activity in the study area. However, the 1960-2005 period shows a constant curve as there were only 13 earthquakes during this period.

Figure 7 is a frequency-magnitude distribution (FMD) plot that shows the relationship between frequency (number of earthquakes) and magnitude (size of earthquakes). The slope of the FMD plot has a gentle gradient with b-value is equal to 0.56. The gradient or slope represent the b-value, if the gradient is steep, the b-value is large and close to 1. The b-value is quite low (0.56) which means that the frequency of earthquakes with small magnitudes is low, which causes seismic energy (stress) to accumulate so that when the energy is released once it is released in the form of a large earthquake.

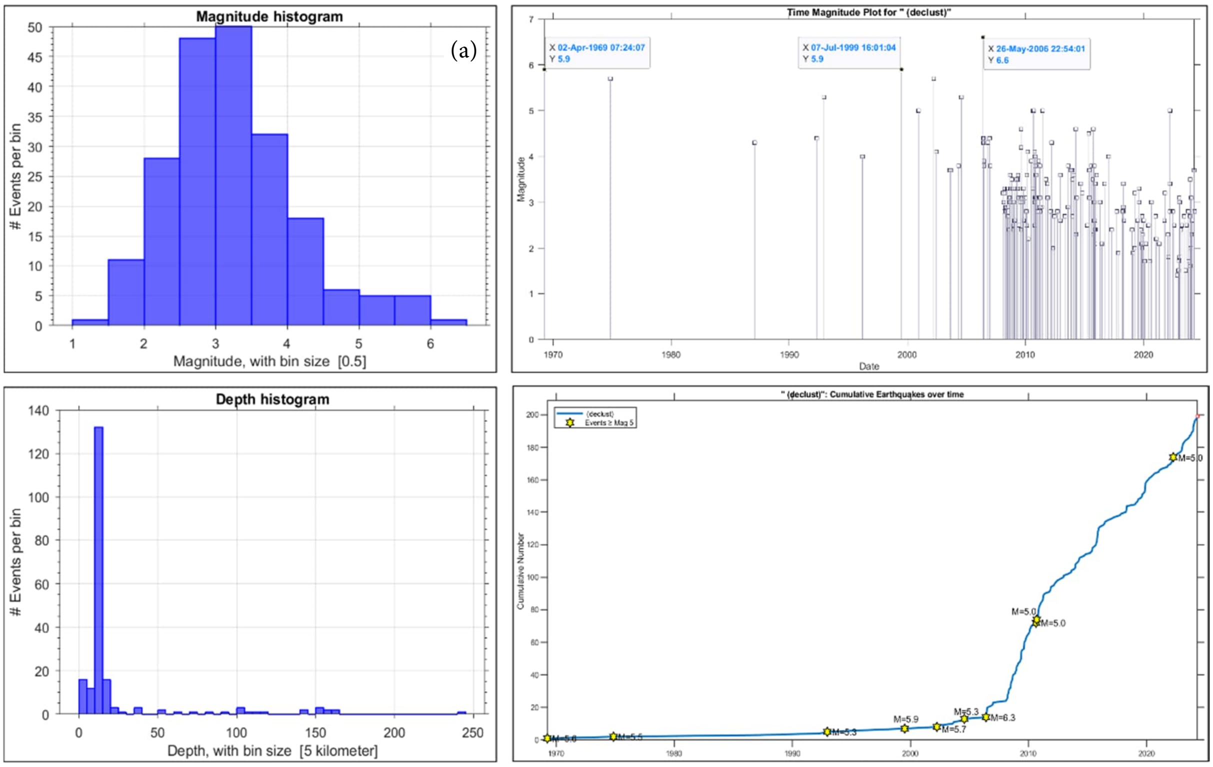


Figure 6. (a) Magnitude Histogram; (b) Depth Histogram; (c) Magnitude versus Time Distribution; (d) Earthquake Cumulative Rate Curve.

The results of the FMD plot obtained a magnitude of completeness (Mc) of 3.10, a b-value of 0.56 (with a measurement uncertainty of 0.05), and an a-value of 3.757. Based on the b-value classification by Wiemer and Wyss (1997), the study area is considered to have a low b-value, which means that there is a high accumulation of stress and there is a possibility of a large earthquake occurring again in the future. The Mc value of 3.10 is the smallest magnitude at which all earthquakes occurring in the study area in the period 1960 - 2024 can certainly be detected and recorded perfectly by earthquake stations (Rydelek & Sacks, 1989).

From the known b-value and a-value, the Gutenberg and Richter equation is obtained, namely $\log N\ (M) = 3.757 - 0.56M$.

Spatial variations of b-value and a-value were mapped using a 1.5 km x 1.5 km grid with a constant radius of 15 km and a 3 x 3 km grid with a constant radius of 45 km as well as a minimum number of earthquakes greater than Mc, namely 8. In this study, two different grid sizes were used to compare which grid is more suitable for the study area. The grid size used has been tested for resolution with varying grid sizes, with the result that both grid sizes have good results among other grid sizes. The selected grid size and radius resulted in a balance between spatial resolution and sufficient earthquake data for spatial analysis. If the grid is too small or the radius too narrow, there may not be enough earthquakes in each grid to calculate the a-value and b-value with sufficient statistical accuracy. The same is true if the grid is too large. The red star is the location of the May 26, 2006 earthquake based on USGS data which is located on the Ngalang Fault.

Figure 8a is the distribution of the b-value of the Yogyakarta region with a grid of 1.5 km x 1.5 km and a constant radius of 15 km. The distribution of b-value is in the range of 0.35 - 0.75 with low b-value marked in dark blue and high b-value marked in yellow. Low b-value is found in the southwest (0.32-0.55) and northeast (0.5-0.58) of Opak Fault and Ngalang Fault marked with red oval lines. Meanwhile, relatively high b-values are located in the southern part of Yogyakarta and a small part in the eastern part of the Ngalang Fault (0.65-0.75).

Figure 8b is the distribution of the b-value in the Yogyakarta area with a 3 km x 3 km grid and a constant radius of 45 km. The distribution of b-value is in the range of 0.52-0.62 with low b-value marked in dark blue and high b-value marked in yellow. The low b-value is located in the northeast part of Opak Fault and Ngalang Fault (0.53-0.55). While the relatively high b-value is in the Southwest and a small part of Southeast Yogyakarta (0.59-0.62).

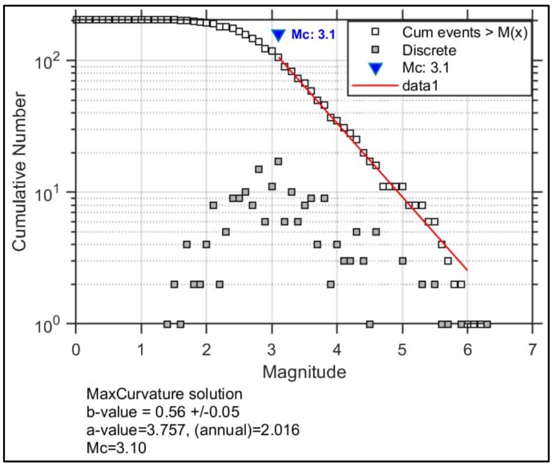


Figure 7. Frequency - Magnitude Distribution (FMD).

Based on the distribution of b-values obtained, according to the classification of Wiemer and Wyss (1997), in general, the Yogyakarta area has a low b-value (0.35-0.75). However, the lowest is in Bantul and Gunung Kidul regencies, precisely in the southwest part of the Opak and Ngalang faults or about 1 - 10 km east of the Opak Fault (0.37-0.55). It is also found in the northeastern part of the Opak and Ngalang Faults (0.5-0.58). Areas with a low b-value mean that the area still holds a high accumulation of energy (stress) that can be released in the form of a large earthquake, moreover in the northeastern part of the Opak Fault and Ngalang Fault about 2-10 km to the east of the Opak Fault there has been no history of large earthquakes so that the area has the potential for large earthquakes in the future.

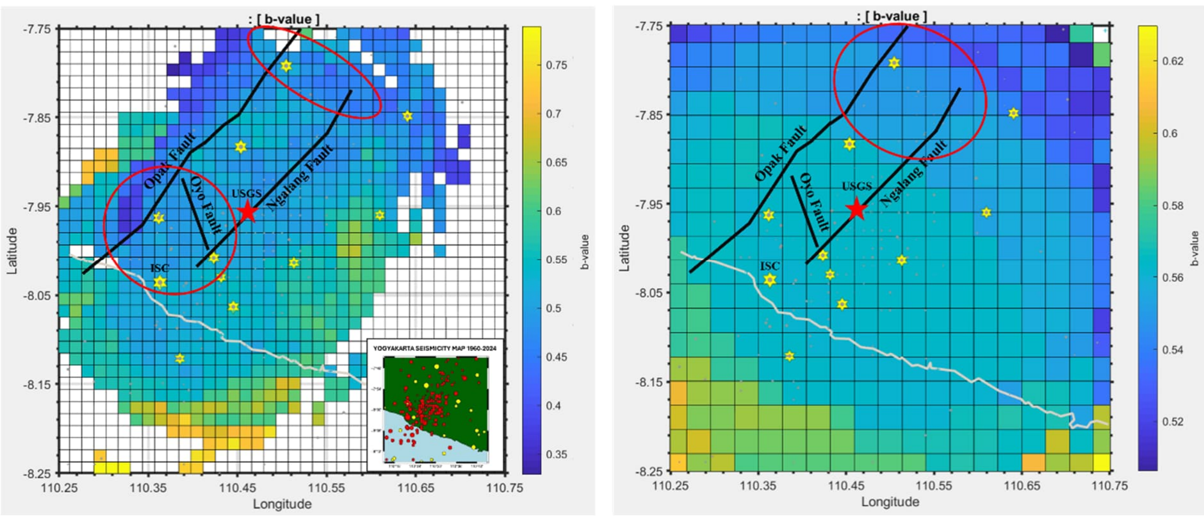
In addition, a low b-value generally indicates rocks with high elasticity where stress energy is not immediately released during the deformation but stored first until it reaches the limit of rock elasticity. This results in the occurrence of earthquakes with larger magnitudes, but with less frequency compared to areas with high b-values. This is evidenced by the occurrence of several large earthquakes in the vicinity of the Opak Fault, namely the May 26, 2006 M6.3, the July 7, 1999 M5.9, the March 29, 2002 M 5.7 and the April 2, 1969 M5.6.

A high b-value is interpreted as the region having a low level of rock stress and a higher frequency of small earthquakes, which may be due to the release of energy more frequently but with a smaller magnitude. This is because in the southern part of Yogyakarta there is a subduction zone of the Indo-Australian Plate subducting beneath the Eurasian Plate and also the activity of the Opak Fault, resulting in quite a lot of earthquake activity in the region.

When comparing the results of the b-value distribution in the Yogyakarta area using a 1.5 km x 1.5 km grid with a constant radius of 15 km and a 3 km x 3 km grid with a constant radius of 45 km, the results are not much different because although the color scale is different, the b-value around the Opak Fault and Ngalang Fault is similar. The range of b-values obtained with the 1.5 km x 1.5 km grid is larger (0.35-0.75) compared to the 3 km x 3 km grid results (0.52-0.62). The smaller grid also gives better resolution.

This is due to the use of the radius used where if a wider radius (45 km) is used, the 3 km x 3 km grid will cover a wider area and each grid includes more earthquake data, meaning that even though one grid has inactive seismic activity, because the radius is large, earthquakes that occur around the Opak Fault are also taken in the calculation of the b-value of each grid. Whereas the smaller grid (1.5 km x 1.5 km) with a smaller constant radius (15 km) will cover a smaller area with fewer events analyzed per grid, meaning that only events within a closer radius are taken into account, so that outliers or extreme events can have a greater influence on the b-value.

We recommend using a 1.5 km x 1.5 km grid with a constant radius of 15 km because it has a higher resolution, allowing for more accurate identification of areas with active seismic activity in mapping b-value variations in the Yogyakarta region. Due to the high resolution, the b-value calculation for each grid is more specific so that some grids that are relatively seismically inactive have empty b-values because they do not have enough earthquake data recorded within a 15 km radius. This is due to the lack of events in the region and the limited network of seismometers available to record data.



(a) (b)

Figure 8. Distribution of b-value (a) With 1.5 x 1.5 km Grid and 15 km Radius; (b) With 3 x 3 km Grid and 45 km Radius.

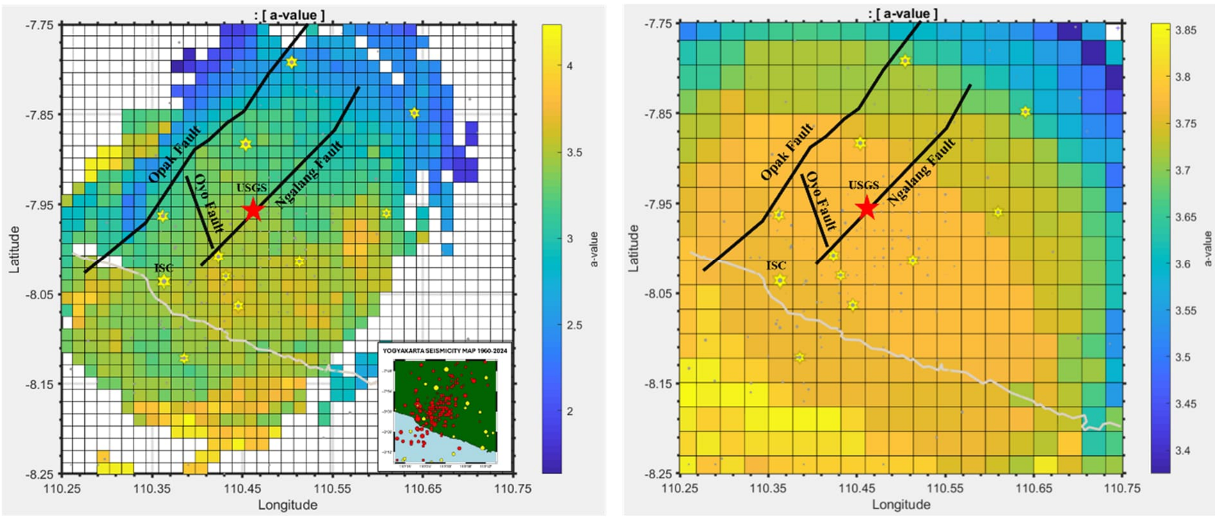
Figure 9a shows the distribution of a-value in the Yogyakarta area with a grid of 1.5 km x 1.5 km and a constant radius of 15 km. The distribution of a-value is in the range of 2-4 with low a-value marked in dark blue and high a-value marked in yellow. High a-value is found in the East of Opak Fault and the South of Yogyakarta (3.6-4). Low a-values are found in the northeast and west of the Opak Fault (2.2-2.8).

Figure 9b shows the distribution of a-values in the Yogyakarta area with a 3 km x 3 km grid and a constant radius of 45 km. The distribution of a-value is in the range of 3.4-3.85 with low a-value marked in dark blue and high a-value marked in yellow. High a-value is found in the West and East of Opak Fault, as well as in the South of Yogyakarta (3.75-3.85). Meanwhile, low a-values are found in the northeastern part of the Opak Fault (3.4-3.63).

The spatial variation of a-value is not much different from the variation of b-value, this is in accordance with previous research (Rohadi, 2009) which showed a corres-pondence between the distribution patterns of b-value and a-value. High a-values indicate high seismic activity in the region, which is caused by more frequent release of seismic energy due to active fault activity, namely the Opak Fault and subduction activity in the southern part of Yogyakarta.

The temporal variation of b-value is obtained by calculation using the sliding time-window methods which take into account the sample window size parameter of 7 events with a window overlap of 4, which means that the window is shifted by 7 events with the addition of 4 from the number of events in the previous window and the minimum number of earthquakes per window of 2 events.

Figure 10 is a graph of the temporal variation of the b-value against time connected to the curve of the cumulative rate of earthquakes. The red line is the link between the occurrence of large earthquakes and the temporal variation of the b-value. The yellow hexagon is a large earthquake with a magnitude ≥5. While the dashed red line is a sign that the temporal analysis of the b-value is not good before 2006 because in the period 1960-2005 there were only 13 events.



(a) (b)

Figure 9. Distribution of a-value **(a)** With 1.5 x 1.5 km Grid and 15 km Radius; **(b)** With 3 x 3 km Grid and 45 km Radius.

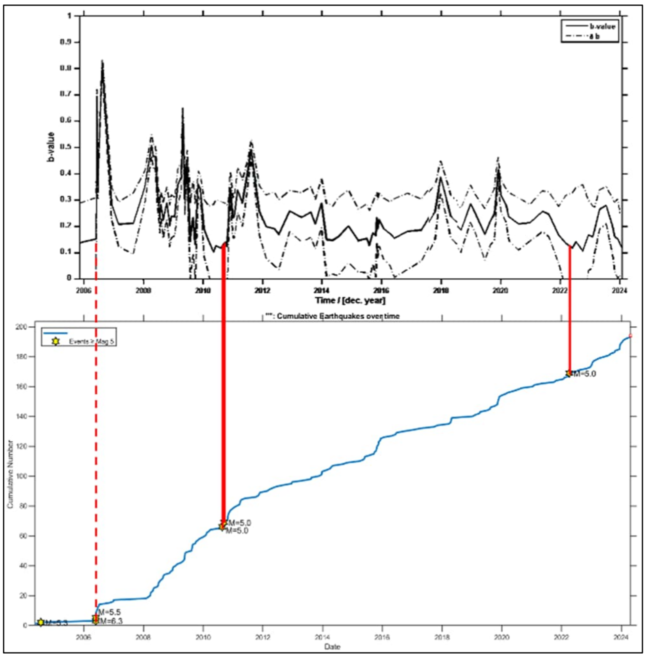


Figure 10. b-value temporal variation of Yogyakarta earthquakes 1960-2024 (ISC Catalog).

In the period 1960-2005, the temporal analysis gives poor results because there were only 13 earthquakes in that period. The temporal variation curve of b-value shows the range of 0.15 - 0.8, which indicates fluctuations throughout the period with some sharp decreases followed by significant earthquakes. From the graph, there is a tendency for the b-value to decrease before major earthquakes (M ≥5.0) such as in 2010 and 2022 and then increase again after the earthquake. The decrease in b-value indicates an increase in stress accumulation in the rock. When this stress reaches a limit where the elasticity of the rock can no longer withstand it, the accumulated energy will be released suddenly through a large earthquake. We also suspect there were numerous earthquakes between 2016-2020 due to the decreasing b-value, but they were not included in the analysis because we only focus on earthquakes with magnitude ≥5.

5. CONCLUSION

Spatially, the b-value distribution in the Yogyakarta area is low with a range of 0.35-0.75 using a grid of 1.5 x 1.5 km and a radius of 15 km. In general, the b-value in the eastern part of the Opak Fault is low, which means that there is a high accumulation of stress. The low b-value is found in Bantul and Gunung Kidul regencies, especially in the southwestern part of the Ngalang Fault and around the Oyo Fault or about 1-10 km to the east of the Opak Fault (0.37-0.55). In addition, low b-values are also found in the northeastern part of the Opak Fault and Ngalang Fault about 2-10 km to the east of the Opak Fault (0.5-0.58). The accumulation of higher seismic energy in areas with low b-value could potentially lead to large earthquakes in the future. Temporally, the b-value in the Yogyakarta region shows fluctuations throughout the period with some sharp decreases followed by significant earthquakes. The tendency of the b-value to decrease before a major earthquake (M≥5.0) such as in 2010 and 2022 indicates that there is a high accumulation of stress that has the potential to cause a major earthquake in the future. The decreasing b-value can be related to the probability of major earthquake. But if the fault activity releases low tectonic stress frequently, the probability of major earthquake occurrence can be lowered. However, temporal analysis could not be conducted in the period before 2006 due to lack of data (from 1960-2005 there were only 13 earthquake data).

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