Study of Earthquake Damage Potential Based on b-Value Variation in The Special Region of Yogyakarta

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ABSTRACT

Indonesia is a region prone to various natural disasters, including earthquakes. It is located at the convergence of three major tectonic plates: the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate. The collision of these three plates causes earthquakes. The Special Region of Yogyakarta is one of the areas that has been impacted multiple times by damaging earthquakes due to its proximity to the meeting point of the Eurasian and Indo-Australian Plates. This study was conducted to examine earthquake statistics in the Special Region of Yogyakarta based on analyses of a-value and b-value in this area, thereby identifying potential earthquake recurrence. Secondary data from the IRIS (Incorporated Research Institutions for Seismology) earthquake catalog from 2006 to 2020 were used for this seismic analysis. The data processing results showed that a-values ranged between 3.5 and 7, with an average value across the entire region of 5.17; meanwhile, b-values ranged between 0.7 and 1.2, with an average value across all areas being 0.775. The area requiring caution is the southern sea region of Special Region Yogyakarta, which has potential for earthquakes with magnitudes up to 6 occurring within intervals of every 5–10 years.

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1. INTRODUCTION

Tectonic plates are formed from the continental crust, oceanic crust, and the uppermost layer of the Earth's mantle. The boundary regions between several tectonic plates are areas of active tectonics that lead to the formation of volcanoes, highlands, and earthquake events [1]. Indonesia is a region prone to earthquakes because it lies at the intersection of three tectonic plates: the Pacific Plate, the Indo-Australian Plate to the south, and the Eurasian Plate [2] [3]. The Indo-Australian Plate moves northward and collides with the Eurasian Plate, while the Pacific Plate moves westward [4] [5]. he movement of continental and oceanic plates is sometimes interconnected, causing energy accumulation until rocks in these tectonic plates can no longer withstand this energy. This accumulated energy is then suddenly released as an earthquake [2] [6]. Earthquakes are not only caused by plate movements but also by active faults. Based on reviews of various destructive earthquakes, their causes are predominantly due to movements along active faults known as fault planes or fault zones [7] [8] [9]. Tectonically speaking, Java Island frequently experiences earthquakes due to collision activities between tectonic plates and various fault activities on land; therefore, Java Island is considered an earthquake-prone area [10] [11] [12] [13].

This study is an extension of previous research conducted by [14] and [15]with a broader scope covering the Special Region of Yogyakarta Province. The main difference lies in the data sources and the earthquake catalog years used. The data source for this study is based on the IRIS (Incorporated Research Institutions for Seismology) earthquake catalog, covering the period from 2006 to 2020. This research analyzes seismic activity using earthquake data from the IRIS catalog by employing b-value analysis over the years 2006 to 2020. The b-value is useful for understanding local stress conditions in rocks within the study area, namely the Special Region of Yogyakarta, which requires careful monitoring [16] [17]. In this study, variations in b-values are used to identify areass with potential damaging earthquakes within the Special Region of Yogyakarta.

2. METHODS

This study requires supporting tools and data. The tools used include Microsoft Excel, Notepad, MATLAB, and ZMAP. The data utilized in this research is sourced from the IRIS (Incorporated Research Institutions for Seismology) earthquake catalog covering the period from 2006 to 2020. The dataset components consist of earthquake epicenter coordinates, date of occurrence, earthquake magnitude (M), depth (h), and origin time.

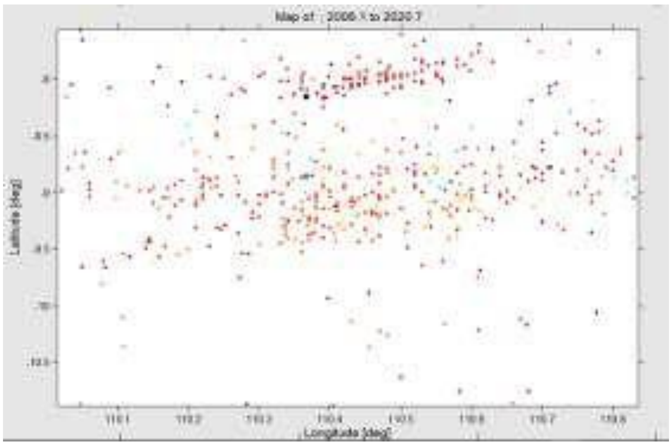

Figure 1. Data Distribution on the Seismicity Map

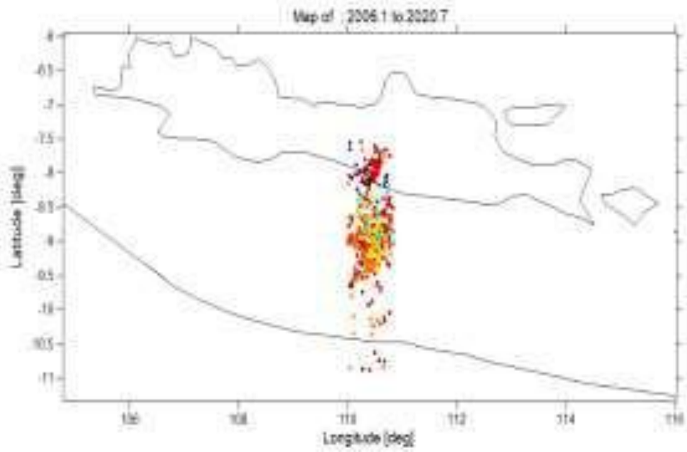

Figure 2. Distribution of Earthquake Data Along with Their Locations

The first step in data processing is to input data containing the earthquake epicenter coordinates, the date of the earthquake (year, month, day), earthquake magnitude, depth, and time of occurrence (hour, minute). Next, the data is saved as a tab-delimited file (.txt) and then opened with Notepad. After that, the file is re-saved in .dat format. Subsequently, MATLAB software is launched to open the ZMAP tool. The .dat file is then loaded into ZMAP to display the distribution of earthquake data on a seismicity map.

Afterward, the earthquake data distribution map is overlaid with coastline maps and fault zones to accurately identify the actual locations of the data points. Then, a declustering process is performed to remove foreshocks and aftershocks, resulting in a dataset of mainshocks. Subsequently, a time-domain analysis is conducted, producing a graph that shows the relationship between the cumulative number of earthquake events and time.

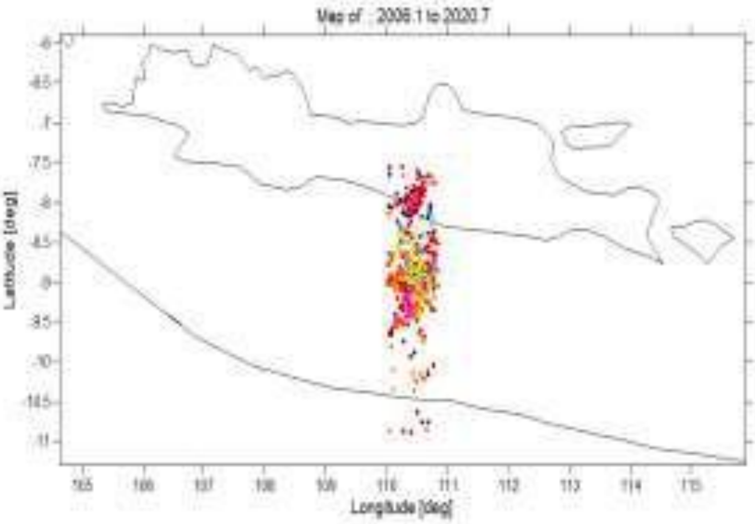

Figure 3. Distribution of Earthquake Data After the Declustering Process

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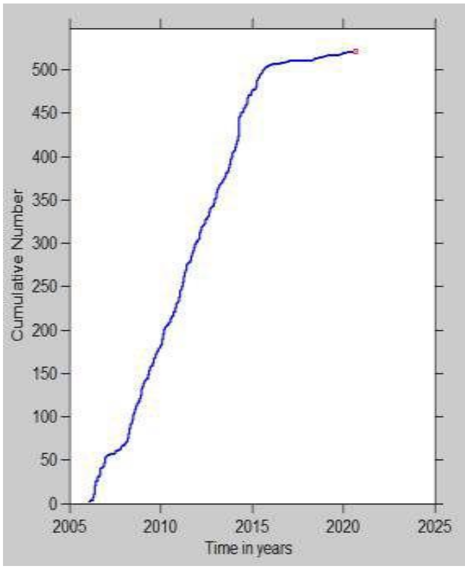

Figure 4. Graph of the Relationship Between the Cumulative Number of Earthquake Events and Time

The graph of the frequency-magnitude distribution resulting from the automatic estimation of the magnitude of completeness and b-value is displayed using the ZMAP tool, employing the maximum likelihood method to determine the b-value. Subsequently, mapping processes for a-value, b-value, earthquake density, and earthquake recurrence are carried out by inputting appropriate grid parameters. After obtaining the mapping results, an interpolated shading process is applied to smoothen the visual appearance of the images.

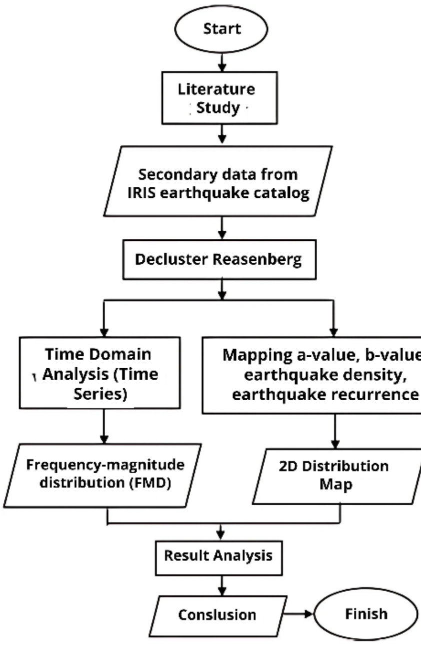

Figure 5. Research Flowchart

2.1. Gutenberg-Ritcher Relation

The Gutenberg-Richter relation, or Frequency-Magnitude Distribution (FMD), is one method used to investigate seismic activity in a region, formulated as:

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

where N is the cumulative number of earthquakes with magnitude greater than or equal to M within a certain period, a is the seismic activity, b is the tectonic parameter, and M is the earthquake magnitude.

Equation (1) above is the Gutenberg-Richter relation used to understand the distribution pattern of seismic activity or the distribution of various zones with active seismicity. The analysis of the frequency-magnitude relationship is obtained by mapping the distribution of various seismicity parameters and their recurrence intervals, as well as classifying one area relative to another based on the seismic mapping results in the region [17].

2.2. a-Value

The a-value represents the parameter of seismic activity. Seismic activity can be influenced by the degree of rock brittleness. The magnitude of the a-value can be affected by:

1. Observation period
2. Area of observation
3. Seismicity in the observation area

If the a-value in a region increases, it indicates a higher level of seismic activity; conversely, if the a-value decreases, the seismic activity is lower [18].

The a-value parameter can be formulated by the equation:

$$a = \log N + \log(b \ln 10) + M_c b \quad (2)$$

Where a is a-value, N is the cumulative number of earthquakes with magnitude greater than or equal to M within a certain period, M_c is the magnitude of completeness, and b is b-value [19].

2.3. b-Value

The b-value represents the gradient of the linear equation relating frequency and magnitude. The b-value can also reveal the degree of rock brittleness; the higher the b-value, the greater the rock brittleness. The b-value also depends on the rock structure condition; a higher b-value indicates a more heterogeneous rock structure. Areas with high temperatures, such as magma chambers and geothermal sources, exhibit high b-values [17]. Most experts agree that the b-value varies depending on the region and earthquake depth, as well as the heterogeneity and spatial distribution of stress within the rock volume that is the earthquake source. The classification of b-values according to the Gutenberg-Richter theory is as follows:

1. 2.0 – 2.7: rock structure is very brittle
2. 1.0 – 2.0: rock structure is heterogeneous
3. 0.3 – 1.0: rock structure is homogeneous

The b-value is a tectonic parameter representing the relationship from small to large earthquakes, usually with a value close to 1 [20] .

The b-value can be estimated using statistical methods, one of which is the Maximum Likelihood Estimation (MLE) method, formulated as:

$$b = \frac{1}{MM_{min}} log_{10^e} \quad (3)$$

$$b = \frac{1}{MM_{min}} \quad (4)$$

where M is the average magnitude and Mmin is the minimum magnitude.

2.4. Maximum Likelihood Method

The maximum likelihood method is a statistical approach that is highly suitable for solving various problems in seismology.

$$b = \frac{\log e}{M - M_0} \quad (5)$$

where *M* is the average magnitude, M_0 is the minimum magnitudo value, and *log e* is 0,4343.
Equation 1 above is the formula of the maximum likelihood method used in estimating the b-value [1].

3. RESULTS AND DISCUSSION

3.1 Data Distribution

The image below shows the earthquake data distribution map in the Special Region of Yogyakarta, covering both land and sea areas during the period 2006–2020. The colors of the earthquake points are differentiated based on depth and magnitude, where red indicates the shallowest earthquakes with depths less than 50 km, while blue represents the deepest earthquakes at approximately 150 km. Earthquake magnitudes are represented by circle sizes; larger circles correspond to higher magnitudes. Based on this image, it is observed that the average depth of earthquake sources is less than 47.6 km. The smallest detected earthquake occurred in Nglipar, Gunung Kidul Regency with a magnitude of 2, while the largest was detected in the southern sea region of Java with a magnitude of 6.4.

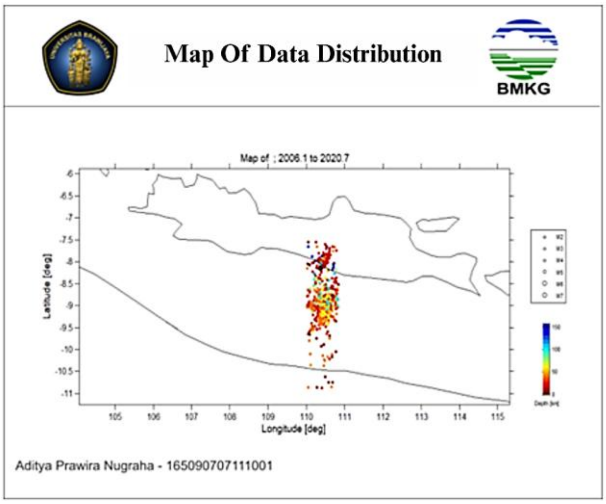

Figure 6. Earthquake data distribution map in the Special Region of Yogyakarta

3.2 Magnitudo Distribution

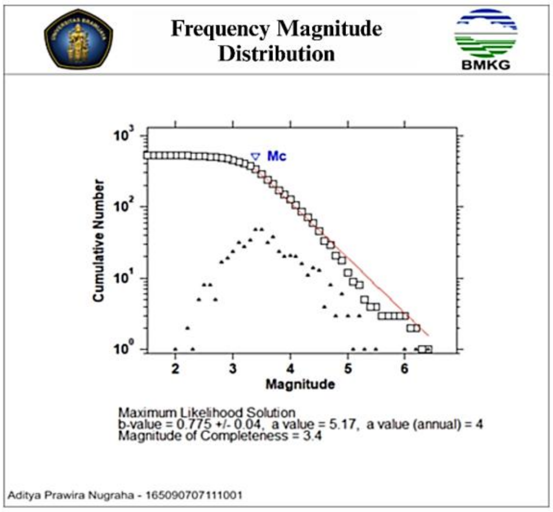

Figure 7. Frequency-magnitude distribution graph for the entire Special Region of Yogyakarta during the period 2006–2020

The above image is a frequency-magnitude distribution graph for the entire Special Region of Yogyakarta during the period 2006–2020, where the x-axis represents magnitude and the y-axis represents earthquake occurrence frequency. Based on this graph, the estimated b-value is 0.775 with a standard deviation of 0.04. The estimated a-value is 5.17, and the magnitude of completeness (Mc) is 3.4.

3.3 a-Value Result

The figure below shows the distribution map of the a-value in the Special Region of Yogyakarta, using a constant radius of 111 km with a grid size of 0.1° x 0.1° and a minimum number of events Mc = 10. Based on this distribution map, it is observed that offshore areas far from the coastline exhibit low to moderate a-values ranging from 4.5 to 5.5. Meanwhile, offshore areas close to the coastline as well as onshore regions near the coastline show relatively high a-values.

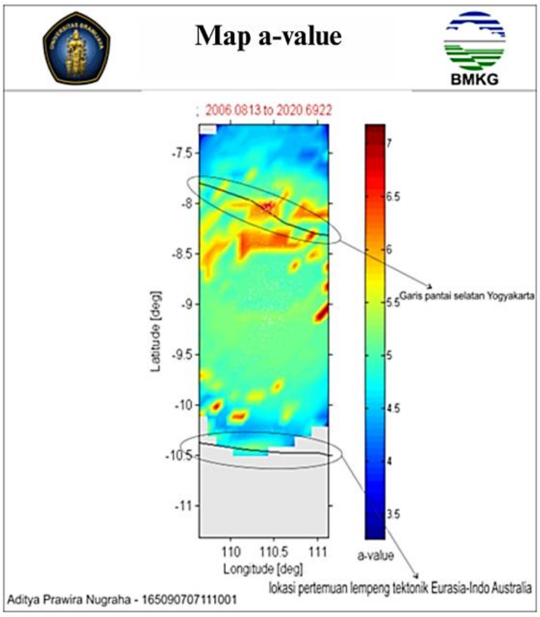

Figure 8. Distribution map of the a-value in the Special Region of Yogyakarta

3.4 b-value Result

The figure below shows the distribution map of the b-value in the Special Region of Yogyakarta. A constant radius of 111 km was used with a grid size of 0.1° x 0.1° and a minimum number of events greater than Mc = 10. Based on the b-value distribution map, it is observed that there is a difference in b-values between areas close to the coastline and those farther away. Coastal areas exhibit relatively high b-values ranging from 1 to 1.1, whereas in regions that where areas near the coastline exhibit relatively high b-values ranging from 1.0 to 1.1. In contrast, regions located farther inland or away from the coastline show lower b-values, typically below 1.0. This variation in b-value distribution may reflect differences in the stress regime, rock heterogeneity, and seismic activity between coastal and inland zones. Higher b-values near the coast could indicate a higher proportion of smaller magnitude earthquakes or more fractured rock conditions, while lower b-values inland might suggest more stable geological conditions with fewer small events.

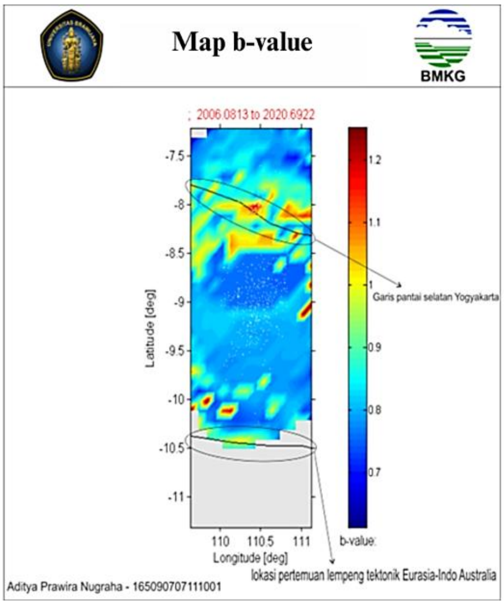

Figure 9. Distribution map of the b-value in the Special Region of Yogyakarta

3.5 Earthquakes Density

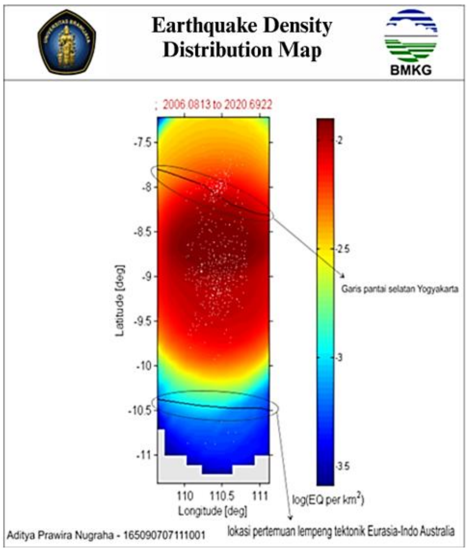

Figure 10. Earthquake density distribution map in the Special Region of Yogyakarta

The figure above shows the earthquake density distribution map in the Special Region of Yogyakarta. Areas indicated by dark red colors represent the highest earthquake densities, indicating that these regions experience the most frequent seismic events. Conversely, areas shown in dark blue represent the lowest earthquake densities, reflecting regions with relatively sparse seismic activity.

3.6 Earthquakes Recurrence

3.6.1 Earthquakes Recurrence M = 6

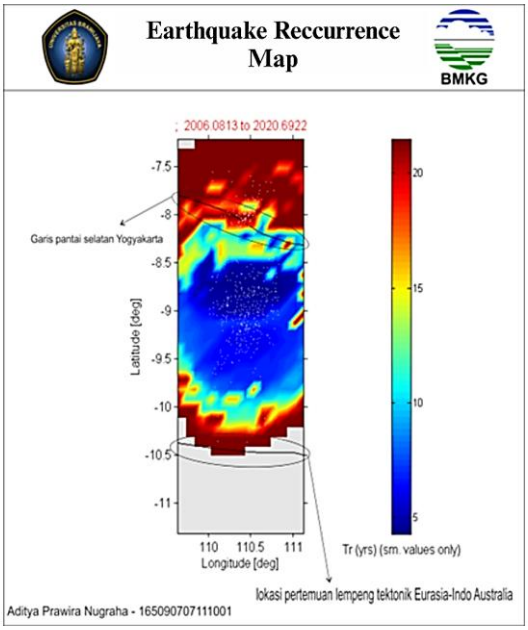

Figure 11. Earthquake recurrence map for magnitude 6.2 events

The figure above shows the distribution map of the a-value in the Special Region of Yogyakarta, using a constant radius of 111 km with a grid size of 0.1° x 0.1° and a minimum number of events Mc = 10. Based on this distribution map, it is observed that offshore areas far from the coastline exhibit low to moderate a-values ranging from 4.5 to 5.5. Pada wilayah laut yang dekat dengan garis pantai serta wilayah darat yang dekat dengan garis pantai mempunyai nilai-a (*a-value*) yang cukup tinggi, yaitu 5,5-6,5. Offshore areas near the coastline, as well as onshore regions close to the coast, exhibit relatively high a-values ranging from 5.5 to 6.5. In contrast, inland areas far from the coastline show lower a-values between 3.5 and 4.5. Based on this distribution map, it is evident that regions near the coastline have relatively higher seismic activity. Meanwhile, areas located farther from the coast demonstrate lower seismic activity levels.

3.6.2 Earthquakes Recurrence M = 6.2

The figure below shows the earthquake recurrence map for magnitude 6.2 events. The area indicated by dark blue, which corresponds to the southern sea region of the Special Region of Yogyakarta, is estimated to experience earthquake recurrence with a magnitude of 6.2 approximately every 10 years. The area shown in light blue represents regions with a potential earthquake recurrence interval of about every 15 years. The area shown in light blue represents regions with a potential earthquake recurrence interval of about every 15 years. Areas indicated by green-yellow colors correspond to regions with an estimated earthquake recurrence interval of approximately every 20 years. Regions marked in red represent areas with a potential earthquake recurrence interval of around every 25 years. The area shown in reddish-brown indicates regions with an estimated earthquake recurrence interval of approximately every 30 years.

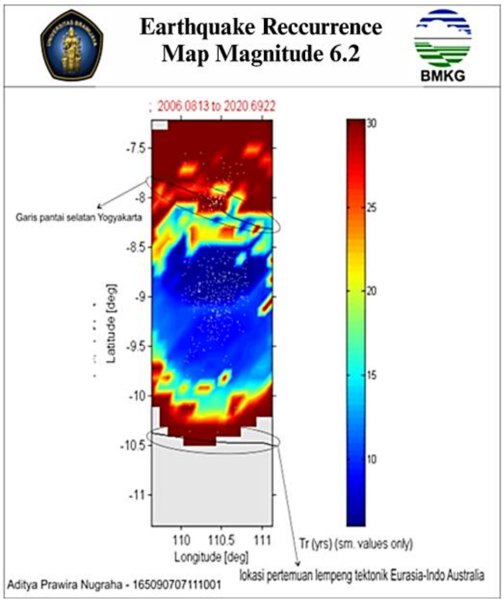

Figure 12. Earthquake recurrence map for magnitude 6.2 events

3.6.3 Earthquake Recurrences M = 6,4

The figure bellow shows the earthquake recurrence map for magnitude 6.4 events. The area indicated by dark blue, corresponding to the southern sea region of the Special Region of Yogyakarta, is estimated to experience earthquake recurrence with a magnitude of 6.4 approximately every 10 to 15 years. The area shown in light blue represents regions with a potential earthquake recurrence interval of about every 20 years. Areas indicated by green-yellow colors correspond to regions with a possible earthquake recurrence interval around 25-30 years. The area shown in reddish-brown indicates regions with an estimated earthquake recurrence interval of approximately every 30 years. Areas indicated in red represent regions with a potential earthquake recurrence interval of approximately every 35 to 40 years. The areas shown in brown indicate regions where the ZMAP tool was unable to estimate earthquake recurrence intervals. This limitation is likely due to insufficient data availability in those regions.

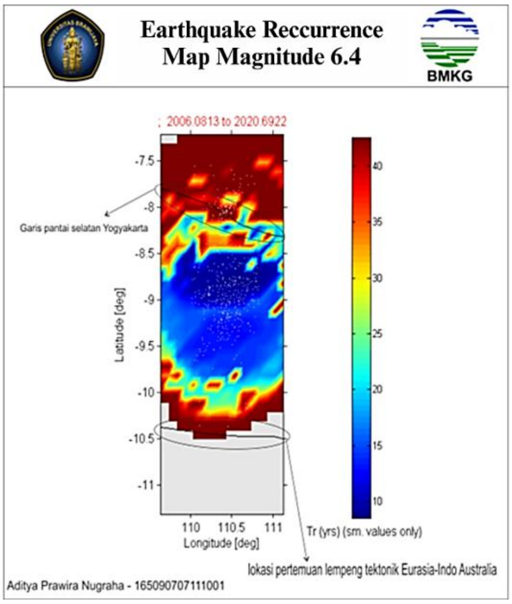

Figure 13. Earthquake recurrence map for magnitude 6.2 events

4. CONCLUSION

Based on the research conducted, several conclusions can be drawn as follows:

1. The a-value results from this study indicate that offshore areas far from the coastline have low to moderate a-values ranging from 4.5 to 5.5. Offshore areas near the coastline, as well as onshore regions close to the coast, exhibit relatively high a-values between 5.5 and 6.5, suggesting that regions near the coastline experience relatively higher seismic activity. In contrast, inland areas far from the coastline show lower a-values..
2. The highest earthquake density is found along the coastline extending toward the convergence zone between the Eurasian and Indo-Australian tectonic plates. This indicates that seismic events occur more frequently in coastal areas approaching this tectonic plate boundary.
3. Based on the earthquake recurrence potential mapping, the area that requires caution due to its destructive earthquake potential is the southern sea region of the Special Region of Yogyakarta. In this area, there is a possibility of earthquake recurrence with a magnitude 6 approximately every 5 to 10 years, magnitude 6.2 every 10 to 15 years, and magnitude 6.4 approximately every 10 to 20 years.

DECLARATION

Author Contribution

This research focused on analyzing the potential of destructive earthquake in the Special Region of Yogyakarta using variation in b-value.

Conceptualization, Wiyono.; methodology, Wiyono and Budiarta.; software, Budaiarta.; validation, Wiyono and Sri Herwaningsih.; formal analysis, Budiarta.; investigation, Aditya Prawira Nugraha; resources, Sri Herwiningsih.; data curation, Wiyono and Aditya Prawira Nugraha.; writing—original draft preparation, Wiyono and Aditya Prawira Nugraha.; writing—review and editing, Budiarta and Sri Herwiningsih.; supervision, Sri Herwiningsih.; project administration, Wiyono. All authors have reviewed and approved the final version of the manuscript.

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Conflict Of Interest

The author declare no conflict of interest.

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