Application of K-means clustering and B-value algorithms for analysis of earthquake-dangerous zones in Java Island

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ABSTRACT

Java Island is an island with a high earthquake vulnerability. Therefore, earthquake mitigation measures are needed to reduce the impact of earthquakes. Earthquake mitigation is done by knowing the zones with a high risk of earthquakes and high levels of rock stress. The methods used to map earthquake-prone zones are K-means clustering and B-value. The K-means clustering method can provide earthquake clusters based on their characteristics and the B-value can produce rock stress conditions in the area. The results of this study are that the K-means clustering method produces 7 earthquake clusters with 5 classifications of very low, low, medium, high, and very high. In contrast, the B-value process has a high B-value with a value of 1.2-1.5 in West Java and a low B-value with a value of 0.9-1.2 in the central to the eastern part of Java.

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1. INTRODUCTION

Java Island is characterized by high seismic activity driven by the active seismotectonic arc system encompassing the island [1]. Earthquakes, the primary manifestation of this seismic activity, result from sudden energy releases in the earth's crust. These seismic events are typically triggered by tectonic plate movements or magmatic activity, which release energy that propagates to the surface, inducing ground shaking [2].

Geological studies indicate that nearly all regions of Java are at high risk for earthquakes [3]. The elevated earthquake risk on Java Island highlights the need for comprehensive seismotectonic studies using historical data. Seismotectonics involves creating a detailed earthquake catalog to analyze seismic activity across regions. Recurrent earthquakes in an area indicate a predisposition to future events of similar magnitude, often due to active faults. [4]. This forms the basis for using historical earthquake data to map areas susceptible to seismic hazards.

Assessing earthquake potential in a region requires an in-depth analysis of tectonic conditions and seismic activity [5]. Identifying earthquake-prone areas involves recognizing patterns and relationships among past seismic events [6]. Various methodologies exist for this purpose, with one practical approach being the clustering of seismic events to identify specific clusters with shared characteristics, combined with an analysis of the local rock vulnerability.

The K-means clustering algorithm is a robust method for grouping data points based on their proximity to randomly chosen centroid points [7]. This algorithm is particularly effective for clustering large datasets and optimizing similarity measures by minimizing distances between data points and centroids [8]. Its applicability to extensive datasets makes it advantageous for seismotectonic studies.

In addition to clustering, seismic hazard potential can be further analyzed by determining seismic B-value parameters. The B-value, derived from the earthquake frequency-magnitude distribution per the Gutenberg-Richter law, is instrumental in regional vulnerability mapping and guiding disaster risk mitigation strategies [9].

The maximum likelihood parameter estimation method calculates the B-value, offering a statistically robust approach for seismotectonic analysis [10]. This method effectively resolves issues related to magnitude voids and provides stable estimations of seismic activity parameters [11].

This study's primary objectives are to utilize the K-means clustering algorithm to delineate earthquake-prone clusters within the study area and conduct a B-value analysis to assess the stress levels in the rocks of Java Island. These analyses aim to identify regions with heightened vulnerability to earthquakes, inform mitigation strategies, and enhance disaster preparedness.

2. METHODS

2.1. K-means clustering algorithm

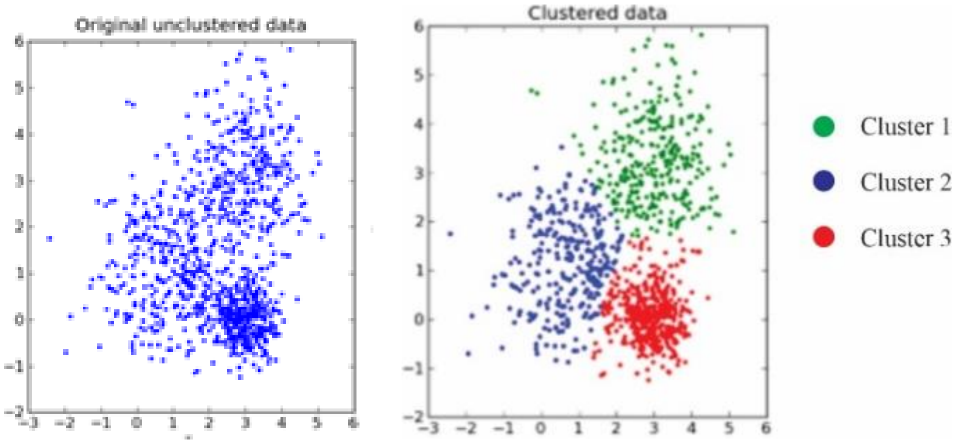
The K-means algorithm is an iterative clustering algorithm that partitions data sets into several k clusters determined at the beginning. The K-means algorithm is simple to implement and run, relatively fast, adaptable, and common in practice. Historically, K-means has been one of the most essential algorithms in data mining [12].

K-means clustering is a non-hierarchical data clustering method that seeks to partition existing data into one or more clusters or groups [13]. This method partitions into clusters or groups so that data with the same characteristics (high intra-class similarity) are grouped into the same cluster, and those with different characteristics (law inter-class similarity) are grouped into other groups. The clustering process begins by identifying the data to be clustered, Xij (i=1,...,n; j=1,...,m), where n is the amount of data to be clustered and m is the number of variables.

$$d_{ik} = \sqrt{\sum_{i=1}^{n} (Xi - Yi)^2} \quad (1)$$

Where Xi is the training value and Yi is the testing value.

A data will be a member of the k-th cluster if the data distance to the center of the k-th cluster is the smallest compared to the distance to the center of the other clusters. This value can be calculated using (1). Next, group the data that are members of each cluster. A comparison of clustering results is depicted in Figure 1, Figure 1(a) shows the original data before clustering and Figure 1(b) shows the data after clustering.



(a) (b)

Figure 1. Results of the K-means clustering algorithm on (a) original data before clustering and (b) data after clustering [14]

2.2. B-value algorithm
2.2.1. Gutenberg-Richter law
An area's seismicity level is studied through the distribution of earthquake magnitude-frequency [15]. Mathematically, it is summarized by the Gutenberg-Richter law as (2).

$$Log\ N = a - b\ M \tag{2}$$

Where N is tectonic earthquake frequency, a is the parameters of the annual seismic condition regression model, and b is the parameters of the tectonic conditions' regression model.

Mathematically, the Gutenberg-Richter law in the form (2) is a straight-line equation between log N as the response variable on the vertical axis and M as the manipulation variable on the horizontal axis. In this case, the a-value parameter is the point of intersection of the straight line with the vertical axis. At the same time, the B-value is the straight-line gradient of the earthquake frequency-magnitude statistical distribution [16], [17].

2.2.2. Estimation of B-value parameters
B-value is a tectonic parameter that includes geological environmental conditions [18]. A high B-value is associated with a high heterogeneity medium, and a low B-value is associated with a soft rock condition and a low heterogeneity medium [19], [20]. The decrease in B-value is directly proportional to the increase in the stress level before a big earthquake occurs. B-value indicates the slope or gradient of the linear equation of the relationship between the frequency of earthquake occurrence and magnitude. The decrease in B-value is directly proportional to the increase in the stress level before a big earthquake occurs. The B-value varies in each region depending on the subsurface rock structure [21]. B-value can be calculated by the equation given by (3) [22].

$$b = \frac{\log e}{\bar{M} - M\ min} = \frac{0.4343}{\bar{M} - M\ min} \tag{3}$$

Where $Mmin$ is the minimum magnitude, $\bar{M}$ is the average magnitude, and $Log\ e$ is 0.4343.

3. RESULTS AND DISCUSSION
Java Island, Indonesia, situated on the Pacific Ring of Fire, is highly susceptible to earthquakes, making advanced analytical methods essential for effective disaster preparedness. Traditional seismic analysis provides valuable information but often lacks integration with contemporary data analytics techniques. This study bridges that gap by combining K-means clustering with B-value analysis, offering a more detailed and accurate mapping of earthquake-prone zones across Java Island. By leveraging these advanced techniques, the research delivers enhanced insights into seismic risk patterns, leading to improved strategies for risk management and mitigation tailored to the region's specific geological conditions.

Our findings show that higher seismic activity levels, as identified by K-means clustering, are closely linked to lower B-values, which indicate increased rock stress and a higher potential for significant earthquakes. This contrasts with previous studies like Petersen *et al*. [23], which primarily used probabilistic seismic hazard assessments without clustering techniques. Our results are consistent with those of Wiemer and Wyss [24], who noted that lower B-values signify higher stress conditions. However, we extend this understanding by combining K-means clustering with B-value analysis for a more detailed spatial view. To further refine risk predictions, future work could integrate additional seismic parameters or geological factors, enhancing the accuracy of earthquake zone identification. This combined approach offers a more nuanced understanding of seismic risks than traditional methods, potentially improving disaster preparedness and mitigation strategies.

This study conducted a detailed analysis of earthquake-prone zones on Java Island using K-means clustering and B-value distribution techniques. Although these methods offer valuable insights into seismic risks, several limitations could impact the accuracy and generalizability of the results. The analysis relies on historical earthquake data from 1970 to 2021, which may not reflect the most recent seismic activity or emerging trends. Additionally, the study is confined to Java Island, limiting the applicability of the findings to regions with different geological contexts. To improve the robustness of risk assessments, future research should integrate additional seismic parameters such as ground motion data, fault lines, and geological factors like soil composition. Investigating temporal variations in B-values and incorporating real-time seismic data could enhance the precision of risk predictions. This would allow for a more dynamic and accurate assessment of earthquake hazards, ultimately improving disaster preparedness and mitigation strategies across various regions.

3.1. K-means clustering

The study used seven clusters, labeled Cluster 1 through Cluster 7, to classify earthquake-prone areas into five distinct risk zones: very low, low, moderate, high, and very high. This classification provides a nuanced understanding of seismic risk across different regions. The clusters are mapped and categorized based on their earthquake activity and depth, reflecting varying levels of susceptibility. The details of these classifications and their spatial distribution are illustrated in Figure 2.

Cluster 1 experienced 220 earthquakes, with the deepest recorded at 329 kilometers and the highest magnitude reaching 6.4 on the Richter scale. The average depth in this cluster is 78.11 kilometers, and the average magnitude is 4.57. With 423 earthquake incidents documented, Cluster 1 is notably earthquake-prone. This elevated seismic activity is primarily due to its proximity to the subduction zone located off the southern coast of Java and the Sunda Trench in the Sunda Strait. Additionally, active faults such as the Baribis and Cimandiri faults significantly influence the high frequency of shallow crustal earthquakes. Cluster 1 spans the southern Indian Ocean off West Java and includes the West Java Province, indicating a region with a high susceptibility to seismic events due to its geological setting and active fault systems.

Cluster 2 is a very high earthquake-prone area. The area has an average depth of 50.5 kilometers and a magnitude of 4.54 on the Richter scale. The average depth of 50.5 kilometers is the shallowest earthquake depth. In addition, the number of earthquake events that occurred from 1970-2021 was as many as 853 earthquakes, which means that shallow earthquakes happen in the area quite often. The site includes the Indian Ocean and around the Cilacap district. The earthquake hazard in the area is due to the subduction zone between the Eurasian and Australian plates which are in contact with the area.

Cluster 3 is situated in the Java Sea and is characterized by its significantly lower frequency of earthquake events than other clusters. This cluster's earthquakes have an average magnitude of 4.81 on the Richter scale, with magnitudes ranging from 4.0 to 6.7 Richter scale. Notably, the average depth of earthquakes in Cluster 3 is 586.85 kilometers, indicating that these are deep-focus earthquakes. In the case of Cluster 3, the deep depths suggest that these earthquakes are linked to the complex interactions between the subducting plates in the Java Sea region. Despite the high magnitude range, this cluster's relatively low frequency of seismic events, combined with the deep earthquake depths, categorizes it as a shallow earthquake-prone zone. This classification reflects a lower likelihood of significant seismic activity than regions with shallower and more frequent earthquakes.

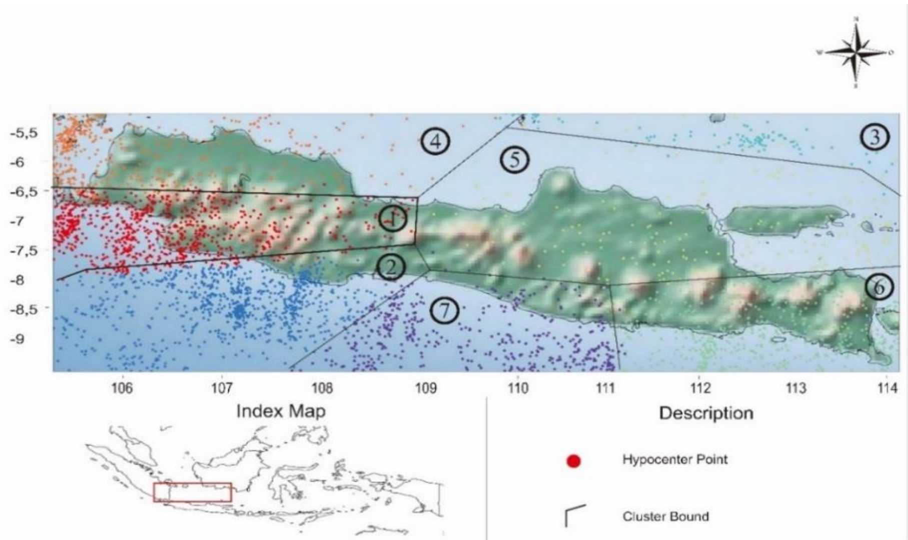


Figure 2. K-means clustering map in Java Island

Cluster 4 is located in Banten, Jakarta, and West Java on the north side, an area with a low earthquake hazard. The number of earthquakes that occurred in the area reached 848 incidents. The earthquake points in the area have a maximum depth of 371.7 kilometers and a maximum magnitude of 6.9 Richter scale with an average depth of 105.37 kilometers which is still a moderate earthquake depth and an average magnitude of 4.5 Richter scale. Based on geological data, the morphology of Banten, Jakarta, and northern West Java is plains and hills that are wavy to steep. The area is composed of Tertiary rocks in the form of sedimentary rocks and quaternary deposits in the form of coastal alluvial deposits, river alluvials, and young volcanic debris rocks. The subduction zone was formed due to the collision between the Eurasian continental plate and the Indo-Australian Ocean plate around the Cretaceous (about 66 million years ago) and is still active today.

In cluster 5,214 earthquakes occurred from 1970 to 2021. Cluster 5 is located at latitude -5.862 to -7.5 and longitude 109.6167-114.5464. Who can see that the hypocenter points are spread across the island of Java. Recorded depths range from 0 kilometers to 337.7 kilometers. The magnitude in this cluster has an average Richter scale of 4.43. The magnitude range of these earthquakes is classified as earthquakes that are felt but do not cause significant damage. Based on the depth and magnitude, cluster 5 is a moderate earthquake-prone zone. These earthquakes occur more often in the ocean than on land. Although the East Java region rarely experiences earthquakes with large magnitudes, this region is classified as an area with relatively high seismic activity.

East Java's geology primarily comprises alluvium and young volcanic products, covering 44.5% of the area, with Miocene deposits making up about 12.33%. These young rocks make East Java prone to low-magnitude earthquakes and landslides, particularly in the southern and eastern regions with more volcanoes than the north [25]. The region's geological features include a volcanic path leading to the subduction zone on the south coast, increasing disaster potential. Seismotectonically, East Java is influenced by several active fault structures, including the Bumiayu, Kebumen-Semarang-Jepara, Lasem, Rawapening, Opak, Pacitan, Wonogiri, Pasuruan, and Jember faults.

Cluster 6, located in southern East Java, exhibits moderate earthquake activity with an average magnitude of 4.678 and a depth of 103.27 kilometers. This cluster spans the southern coast of Lumajang, Jember, and Banyuwangi, characterized by coastal plains and hills. It consists of Tertiary sedimentary rocks, limestone, volcanic debris, and quaternary alluvial deposits, some of which have been weathered. The tectonic interactions between the Eurasian and Indo-Australian plates influence the area’s seismic activity. The moderate earthquake activity is likely due to active faults in the sea south of Jember, although the specific faults have not been precisely identified.

Cluster 7, located in Central Java and Yogyakarta, has 822 recorded incidents with a maximum depth of 393.7 kilometers and a maximum magnitude of 6.5 Richter scale. The depth ranges from 0 to 393.7 kilometers, averaging 66.26 kilometers, indicating medium-depth earthquakes with an average magnitude of 4.6 Richter scale. This makes Yogyakarta and Central Java earthquake-prone areas. The region lies on the Eurasian continental plate near a subduction zone formed by its collision with the Indo-Australian plate, which has been ongoing since the Late Cretaceous. The plates move at speeds of ±0.4 and ±7 cm/year, respectively. This collision creates subduction zones, volcanic pathways (including Mount Merapi), and various geological structures. The subduction zone south of Yogyakarta, about 256 kilometers from Parangtritis Beach, and seismic sources from both subduction zones and active faults contribute to the area's earthquake risk. The region also experiences interplate zone earthquakes with shallow epicenters and occasional Benioff zone seismic activity.

3.2. B-value

Figure 3 is a B-value mapping from the earthquake catalog in Java from 1970 to 2021. The map is generated from B-value processing using the maximum likelihood method in the MATLAB software. The map is processed using earthquake data for 1970 to 2021 with coordinates, time of occurrence, magnitude, and hypocenter depth parameters.

The result of the mapping of B-values in Java Island is that Java Island is dominated by blue, meaning that the B-value in that area is 0.9-1.2. The dark blue region shows a relatively low B-value correlated with relatively high pressure. This is due to the presence of energy stored in the surface rocks, so the potential for large earthquakes is relatively high. Meanwhile, the dark red area has a high B-value. Areas with low B-values are located in the central and eastern parts of Java Island. An area with a low B-value indicates that the area has a high accumulated stress, so it has great potential for the possibility of a major earthquake. Areas with low B-values have a more tremendous potential for large-scale earthquakes to occur.

Characteristically, the B-value in the Java Island region which is classified as high is worth more than 1.3 and is located in the western part of Java Island which correlates with a low level of stress (large heterogeneity of rocks) so it has relatively higher seismic activity but with an insignificant magnitude. So big (generally rarely big earthquakes). Nevertheless, some experts say that the B-value is constant and has a value of around 1. The difference in the B-value results is due to differences in data and calculation methods used. However, most argue that the B-value varies with the area and depth of the epicenter, and depends on the heterogeneity and space distribution of the stress of the volume of rock that is the source of the earthquake.

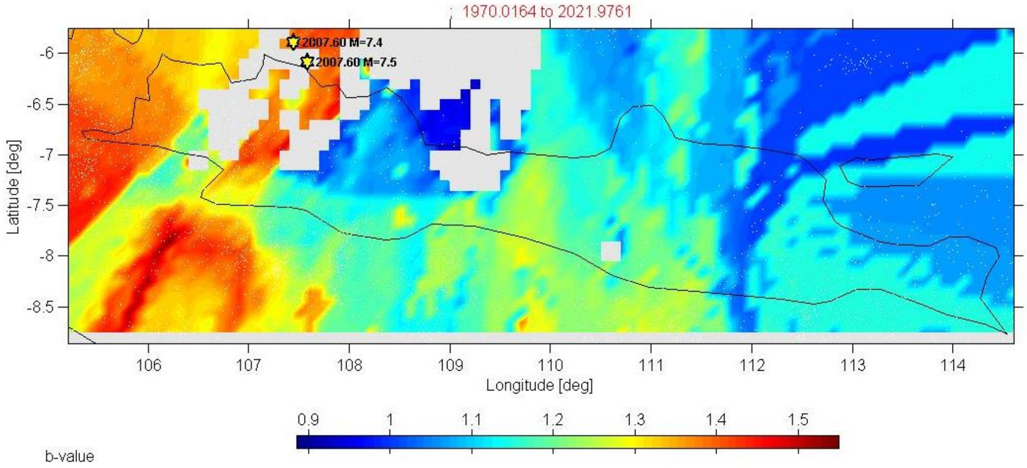


Figure 3. The B-value distribution map resulting from the B-value mapping software MATLAB in Java Island and its surroundings is based on earthquakes that occurred in 1970-2021 using Maximum Likelihood estimation

3.3. Correlation between K-means clustering and B-value distribution map

The correlation between K-means clustering and B-value distribution in earthquake analysis can reveal important insights into earthquake-prone zones and their underlying stress conditions. This correlation helps to identify which high-risk seismic zones (clusters) are associated with specific stress conditions in the rock. High-risk clusters generally coincide with low B-values, indicating areas of higher stress that are more likely to experience significant earthquakes. This integrated approach enhances the understanding of seismic hazards by combining spatial patterns of earthquake activity with underlying stress conditions.

The results of combining earthquake cluster maps and b values are shown in Figure 4. The K-means clustering map shows earthquake-prone zone clusters and the B-value map shows the distribution of rock stress levels in Java Island. Earthquake analysis on Java Island was carried out based on earthquakes that occurred from 1970 to 2021.

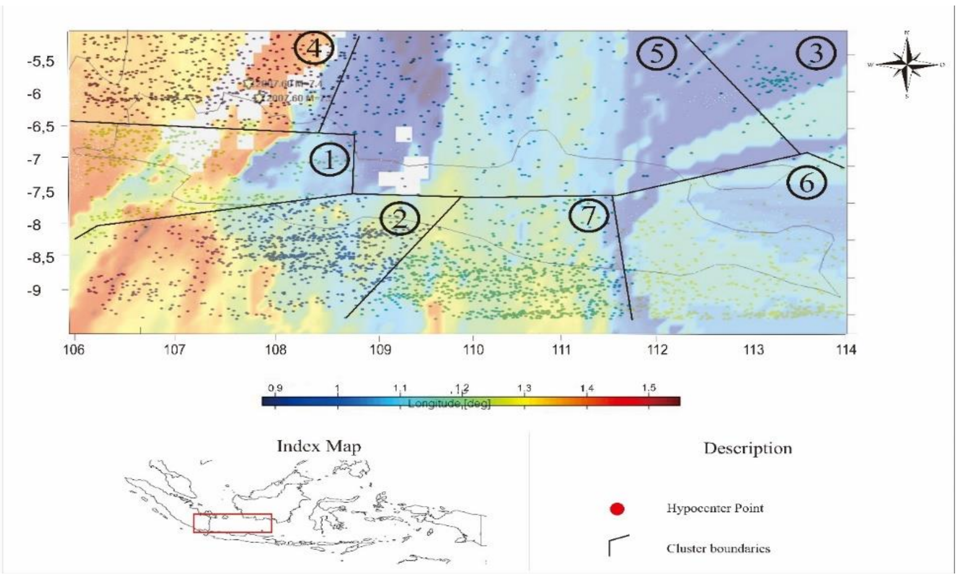


Figure 4. Correlation between B-value map and K-means clustering map

Based on the K-means clustering map, areas with high earthquake-prone levels are in clusters 1, 2, and 7. Earthquakes that occur in clusters 1, 2, and 7 have shallower average depths and larger magnitudes stronger when compared to other clusters.

The B-value distribution map shows high values with a range of 1.2-1.5 in the western part of Java Island, which means that the area has low stress and high rock heterogeneity. Low B-values with values of 0.9-1.2 are in the central to eastern parts of Java, which are interpreted to have high stress and rock heterogeneity which tends to be homogeneous. Even though a low B-value indicates high rock resistance, it can be interpreted that there is an increased accumulation of energy so a large earthquake can occur.

The central and eastern parts of Java have a low B-value of 0.9-1.2. Areas with low B-values are interpreted as areas with high rock homogeneity and rock resistance to high stress so that the number of earthquake events that occur is relatively less than those with high B-values. This can be proven by the K-means clustering zone, which produces a relatively low level of earthquake vulnerability. Based on the overlay between the K-means Clustering map and the B-value map, it produces earthquake-prone areas, as shown in Table 1.

Table 1. Earthquake-prone zone in Java Island based on K-means clustering correlation and B-value distribution map

Cluster	B-value Range	Vulnerability Level	Location
2	1.3-1.5	Very High	Tasikmalaya, Banjar, Cilacap and its surroundings
1	1.3-1.5	High	Mostly East Java provinces
7	1.2-1.3	High	Provinces of southern Central Java and Yogyakarta
5 and 6	1.1-1.2	Medium	Most of the provinces of Central Java and East Java
4	1.3-1.5	Low	DKI Jakarta and Banten Provinces
3	0.9-1.1	Very Low	Java Sea

Very high earthquake-prone areas, namely cluster 2 with high b-values, are in the Tasikmalaya, Banjar, Cilacap, and surrounding areas. The high earthquake-prone areas, namely clusters 1 and 7, are located in most West Java provinces, the southern part of Central Java, and Yogyakarta. Moderate earthquake-prone areas, namely clusters 5 and 6, are located in most Central Java provinces and East Java. Low earthquake-prone areas, namely cluster 4, are in DKI Jakarta and Banten provinces. The earthquake-prone area is shallow, namely cluster 3, which is in the waters of the Java Sea.

Our research shows that integrating K-means clustering with B-value distribution offers a nuanced understanding of earthquake-prone zones by identifying areas with high rock stress and increased seismic activity. This approach provides more detailed spatial analysis than traditional methods. Future research should include recent seismic events and additional geological factors like fault lines and ground motion data to improve risk assessments. Exploring practical methods for real-time seismic monitoring integration could enhance dynamic risk assessments. These refinements could improve earthquake predictions and disaster preparedness, providing valuable insights for managing seismic risks more effectively.

4. CONCLUSION

The results of K-means clustering on Java Island are divided into 7 clusters, namely very low, low, medium-high, and very high earthquake-prone clusters. The results of the B-value distribution of the maximum likelihood method, high B-values are located in the western part of Java Island with a value of 1.2-1.5 and low B-values are located in the central to the eastern part of Java Island with a value of 0.9-1.2. The results of the overlay between the K-means clustering map and the B-value map produce very high earthquake-prone areas in the Tasikmalaya, Banjar, Cilacap, and surrounding areas. High earthquake-prone areas are in most of West Java province, southern part of Central Java province, and Yogyakarta. Areas prone to earthquakes are located in most Central Java provinces and East Java. Low earthquake-prone areas are in DKI Jakarta and Banten Provinces. Very low earthquake-prone regions are in the waters of the Java Sea.

Recent observations indicate that combining K-means clustering with B-value distribution provides a more detailed understanding of earthquake-prone zones on Java Island. Our findings prove that higher seismic activity levels are linked to lower B-values, reflecting increased rock stress and a higher potential for significant earthquakes rather than being caused by increased seismic events alone. This approach extends previous research by integrating machine learning techniques with traditional seismic analysis, enhancing the accuracy of risk assessments and offering valuable insights for improving disaster preparedness and mitigation strategies.

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