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# Seismicity analysis of the Southern Java region (2020-2024) based on the b-value and a-value using the maximum Likelihood method

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**ABSTRACT**
This study investigates the seismicity analysis of the Southern Java region using earthquake data obtained from BMKG Banjarnegara, comprising 1064 events recorded between 2020 and 2024. The study area spans coordinate 7.5°S-8.5°S and 108.31°E-109.50°E. The analysis was conducted using Microsoft Excel, ZMAP 7.0, and QGIS 3.28.2 to calculate the a-value and b-value, key parameters that describe the frequency and magnitude distribution of earthquakes. The magnitude of 2.6 was the most frequently observed, with 150 recorded events, while earthquakes occurring at a depth of 10 km were the most common, totaling 210 events. The high density of seismic occurrences reflects significant tectonic activity in the region. Using the maximum likelihood method, the b-value was determined to be approximately 1.09 ± 0.04, and the a-value was calculated at 5.754. The relatively low b-value suggests areas of elevated stress, implying potential for larger-magnitude earthquakes. Additionally, the spatial distribution of the a-value highlights regions of heightened seismic activity. These findings contribute to a deeper understanding of seismic behavior in Southern Java and offer valuable insights to support disaster risk reduction and earthquake mitigation efforts in the region.
**Keywords:**
b-value; a-value; Southern Java region; maximum likelihood method;

## Introduction

Geographically, Indonesia is located within the Pacific Ring of Fire, at the convergence of three major tectonic plates: the Indo-Australian, Eurasian, and Pacific plates. This condition causes Indonesia to be in an area with high seismic activity (Pambudi & Ulfa, 2024; Petrovic, 2023; Protschky, 2022; Siagian et al., 2014). The interaction of the three plates is dominated by convergent boundary planes that form subduction zones. These subduction zones are the main source of earthquake activity in the Indonesian region, including those recorded along the Southern Java region.

Based on the analysis of events, Java Island is one of the areas that often experiences the most earthquakes. According to the Indonesian Disaster Information Data (DIBI), in the period 2017 to 2022, Indonesia experienced 18,861 disasters, with the highest number occurring every year on Java Island with repeated events every year from 2017 to 2022 (Maulana Ichsan et al., 2024). In addition, Java Island has a high population density, which increases its vulnerability to disasters (Djalante, 2018; Donovan, 2010; Lavigne et al., 2008; Pasari et al., 2021). More specifically, the Southern Java region is located in an active subduction zone and directly adjacent to the Indian Ocean, which makes it highly vulnerable to large earthquakes and tsunamis. The region is also included in the Java megathrust segment, which has the potential to produce large-magnitude earthquakes that can trigger tsunamis.

Given the high risk of earthquakes in the Southern Java region, seismicity characteristics analysis is needed to determine the pattern of earthquake activity in the Southern Java region. This analysis is carried out by calculating the b-value and a-value, which together describe the frequency–magnitude distribution of earthquakes. The formulation for the determination of both b-value and a-value parameters is based on the Gutenberg-Richter frequency-magnitude distribution law, which is applied in various tectonic conditions and natural or artificial sources of seismicity. These parameters are essential, with the a-value representing the level of seismicity and the b-value reflecting the stress state of subsurface rocks (Antayhua-Vera et al., 2022; Muntafi, 2021; Pandey et al., 2017; Patel & Sinha, 2024).

Various statistical methods have been developed to estimate the a-value and b-value parameters in seismicity studies, each with its own advantages and limitations. Common approaches include the least squares method (El-Isa & Eaton, 2014; Li et al., 2012; Schaff & Richards, 2014; Wibowo & Sembri, 2017), the cumulative frequency method (Chochlaki et al., 2018; Luginbuhl et al., 2018; Pasari & Sharma, 2020; Xu et al., 2022), and the maximum likelihood method (Aki, K, 1965; Apriliani & Prastowo, 2021; Aslamia & Supardi, 2022; Güllü, 2012; Harmoko et al., 2023; Kijko, 1983, 1988; Kijko & Sellevoll, 1990; Ogata, 1999) and the related references therein. While the least squares method is simple to implement, it is highly sensitive to data incompleteness and outliers, often leading to biased parameter estimates. The cumulative frequency method improves on this by utilizing magnitude thresholds, but it may still suffer from underestimation in regions with sparse data. Conversely, the Maximum Likelihood Method is known as a more robust and statistically objective way to determine seismicity parameters (Marzocchi & Sandri, 2009; Xia et al., 2022). Various studies have proven that this method is capable of providing consistent and accurate b-value estimates, even when the earthquake data used is incomplete or varied. This approach can also reduce the influence of magnitude limits and errors due to data selection (Godano & Petrillo, 2023; Tinti & Gasperini, 2024; Xia et al., 2022). Due to these advantages, the Maximum Likelihood Method is now widely used in modern seismicity studies, especially in areas with sparse data such as southern Java. For this reason, this study uses this method to estimate the b-value and a-value because it has been proven to be efficient and reliable in various tectonic conditions.

In the present study, the maximum likelihood method was chosen due to these strengths, making it well-suited for evaluating the seismic characteristics of the Southern Java region. Importantly, no comprehensive study has examined the seismicity of the Southern Java segment using post-2020 data, despite its increased seismic activity in recent years. Thus, this study presents a novel contribution by offering an updated seismicity profile of a region with significant tectonic activity and disaster risk potential. The importance of this research is in its attempt to enhance and refresh our understanding of how earthquakes behave in one of Indonesia's most tectonically active areas. A number of previous studies have examined the seismicity of Java Island (Muntafi, 2021; Pasari et al., 2021), but most of them still rely on earthquake catalogs prior to 2020 and do not take into account the latest seismic trends or stress changes due to increased activity in the Java megathrust segment. By utilizing earthquake data from 2020–2024 and applying the Maximum Likelihood Method, this study presents more up-to-date estimates of the a-value and b-value parameters with a stronger statistical basis. These two parameters are key to identifying zones with high stress accumulation and areas with the potential to be the starting point of earthquakes. In addition, spatial mapping of these two parameters provides important insights for the preparation of seismic hazard maps and disaster risk reduction strategies in the densely populated and earthquake- and tsunami-prone southern coastal region of Java. Thus, this study not only enriches scientific knowledge about regional seismicity but also makes a real contribution to disaster mitigation and resilience planning efforts.

The structure of this paper is organized as follows. Section 2 presents the research methodology, detailing the dataset, analytical tools, and procedural steps undertaken throughout the study. Section 3 outlines the main results and discussion, beginning with an examination of the spatial and statistical distribution of earthquake occurrences in the study area. This is followed by a focused analysis of seismicity in the Southern Java region, based on the a-value and b-value parameters derived using the Maximum Likelihood estimation method. Lastly, Section 5 concludes the paper by summarizing the main findings and highlighting their implications for seismic hazard assessment in the region.

## Methods

To analyze the seismicity characteristics of the Southern Java region, we employ a systematic methodological approach. This section outlines the data sources, tools, and procedural steps taken throughout the research. The methodology was designed to ensure precision in estimating the a-value and b-value, which serve as indicators of seismic activity and stress accumulation in the Earth's crust.

In this research, earthquake data were obtained from the Geophysical Station of the Meteorology, Climatology, and Geophysics Agency (BMKG) Banjarnegara, covering the period from 2020 to 2024. As a geographical limitation of the research, the dataset focuses on the area bounded by coordinates 7.5°S to 8.5°S latitude and 108.31°E to 109.50°E longitude. This specific region was selected due to its historical seismic significance, most notably, the occurrence of the 2006 Pangandaran earthquake, a major seismic event that triggered a destructive tsunami. The presence of such a high-impact event indicates that the area is tectonically active and potentially has a high level of seismicity, making it a critical zone for ongoing seismic hazard assessment and monitoring. The dataset includes information on date, time, magnitude, depth, latitude, and longitude for 1064 earthquake events. Furthermore, the dataset was processed using several tools, including Microsoft Excel 2020 for initial data sorting and preprocessing, ZMAP 7.0 for statistical analysis of seismicity and maximum likelihood calculation, MATLAB for visualization and advanced statistical scripts, and QGIS 3.28.2 for spatial mapping and geospatial analysis.

The research procedure consisted of the following steps:

1. Data Collection and Preparation
   Earthquake event data were extracted from BMKG catalog and preprocessed using Microsoft Excel. Events were filtered based on completeness and spatial relevance to the Southern Java region.
2. Declustering
   To ensure that the seismicity parameters accurately represent independent seismic events, the Reasenberg declustering algorithm was applied using the ZMAP software. This procedure effectively removes dependent events, such as foreshocks and aftershocks, from the dataset, allowing the analysis to focus exclusively on mainshocks. By isolating these primary events, the reliability of the a-value and b-value estimations is significantly improved.
3. Frequency-Magnitude Distribution (FMD)
   The filtered data were analyzed to obtain the cumulative number of events above certain magnitude thresholds, which forms the basis of the Gutenberg–Richter law.
4. Estimation of Seismicity Parameters
   The a-value and b-value were estimated using the Maximum Likelihood Method following to the previous works by (Aki, K, 1965; Kijko, 1983, 1988; Kijko & Sellevoll, 1990; Ogata, 1999), which provides statistically robust results even for small or incomplete datasets. The b-value represents the slope of the logarithmic linear relation between the frequency of events and their magnitudes, defined as follows:

$$b = \frac{1}{\underline{M} - M_{min}} log\ log\ e \quad (1)$$

   where $\underline{M}$ is the average magnitude of the events, and $M_{min}$ is the minimum magnitude used in the analysis. In addition, the a-value represents the overall level of seismic activity, which can be defined as follows:

$$a = 10\ log\ log\ (N)\ + b.M_{min} \quad (2)$$

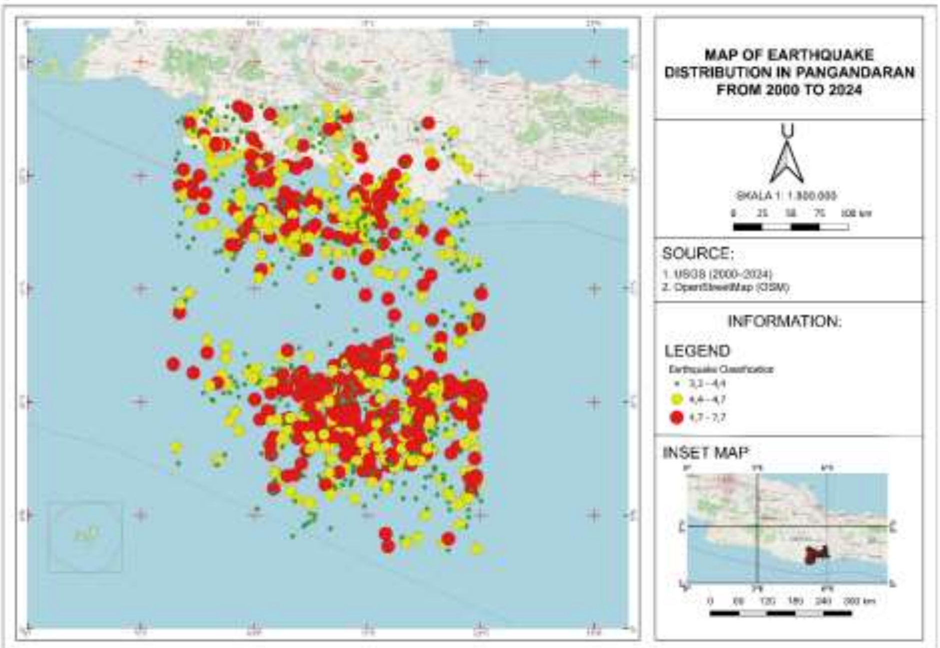
   where $N$ is the total number of events with magnitude $\geq M_{min}$.

5. Mapping and Visualization
   Spatial distribution maps of a-value and b-value were generated using QGIS. These maps allow visualization of regional variations in seismic activity and stress regime, aiding in seismic hazard assessment.

## Results and Discussions

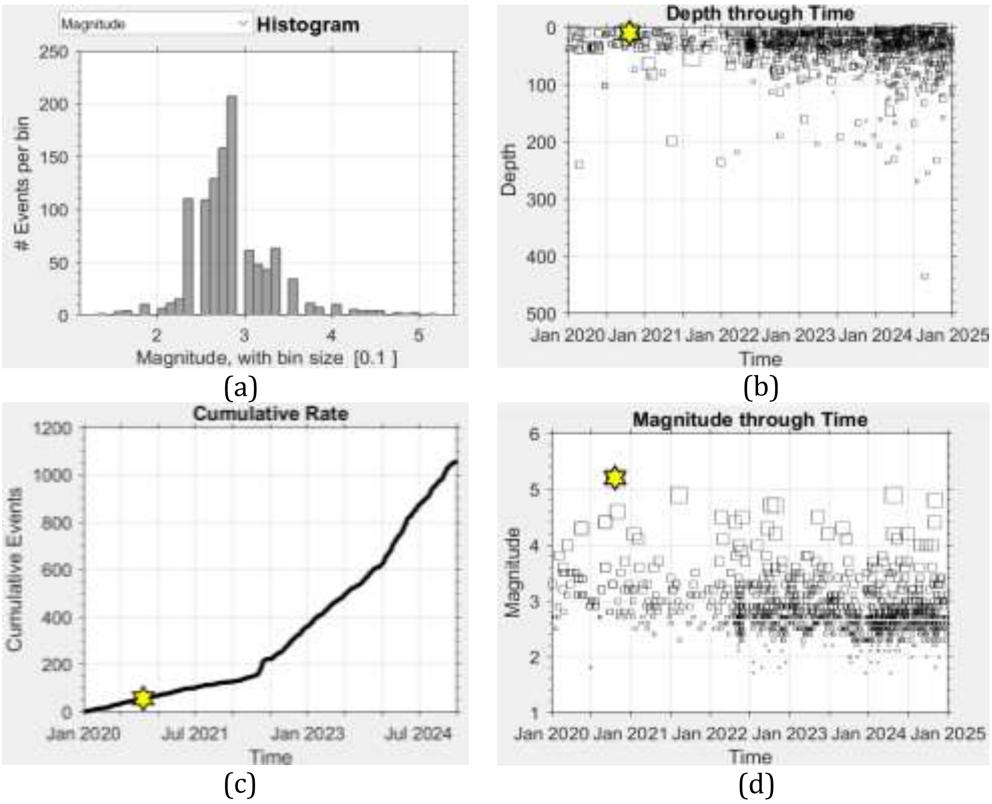
This section presents the findings obtained from the seismicity characteristics analysis conducted on the Southern Java region during the period 2020 to 2024. The results include the spatial and statistical distribution of earthquake events, along with the calculated a-value and b-value parameters using the maximum likelihood method. Each result is interpreted in the context of regional tectonic settings and seismic hazard implications. The discussion integrates these findings to provide insight into the seismic behavior of the study area, emphasizing zones of heightened activity and their potential impact on surrounding communities and infrastructure.

A total of 1064 earthquake events were recorded in the Southern Java Region between 2020 and 2024, based on data obtained from BMKG Banjarnegara. These events were subsequently visualized using QGIS version 3.28.2 as shown in Figure 1.




**Figue 1.** Earthquake distribution map of southern Java region. Most seismic events are in the range of 1.3-3.1 Mw, indicating that low-energy earthquake activity is more frequent than large-magnitude earthquakes.

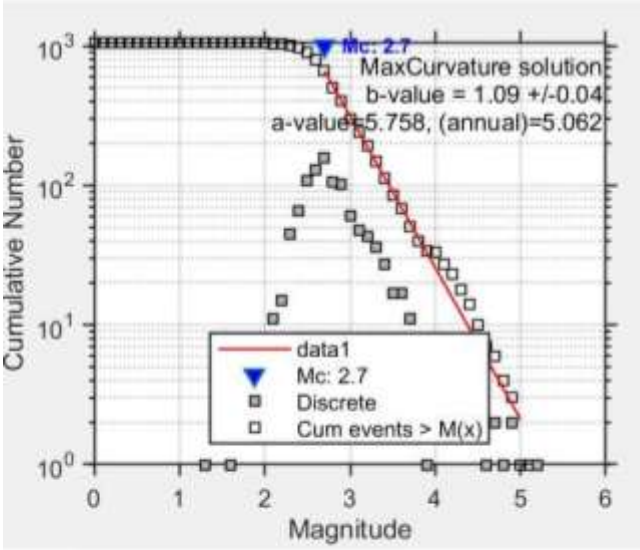
Based on the spatial distribution of earthquake epicenters in the Southern Java Region from 2020 to 2024, seismic activity is predominantly characterized by shallow offshore earthquakes. This is evidenced by the concentration of earthquake markers clustered along the southern offshore region of Java, indicating that most seismicity is associated with the active subduction zone. Further analysis of the frequency–magnitude distribution and cumulative event rate is presented in Figure 2. As shown in the figure, earthquakes with a magnitude of 2.6 occurred most frequently, accounting for 150 recorded events. In terms of depth, the majority of earthquakes were concentrated at 10 km, with a total of 210 events. The dense clustering of seismic events in this region reflects an elevated level of tectonic activity. Although the events were largely of low to moderate magnitude, the findings highlight the importance of continued analysis of seismic characteristics in Southern Java to enhance understanding of the potential for larger, more damaging earthquakes in the future.




**Figue 2.** Overview of seismic activity in Southern Java (2020–2024), consisting of 1064 events from BMKG data. Large events are marked with yellow stars. (a) Magnitude histogram with most events around 2.5–3.0; (b) Depth over time, dominated by shallow earthquakes (0–100 km), with large events marked by yellow stars; (c) Cumulative number of events showing a steady increase; (d) Magnitude over time with sporadic large events, especially in early 2020 and at the end of 2024.

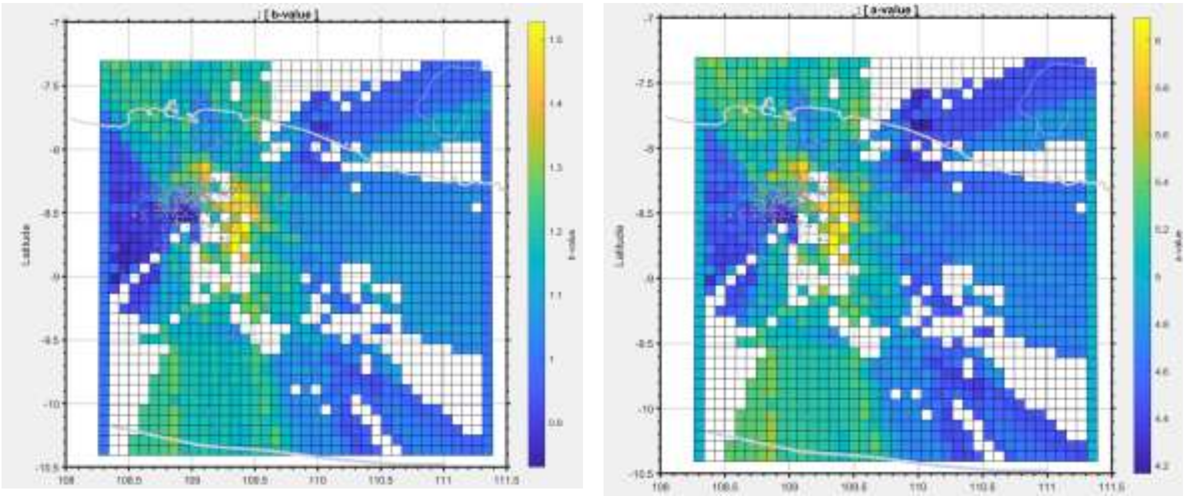
The seismicity characteristics of the southern Java region were analyzed by calculating the a-value and b-value using the maximum likelihood method. Prior to this calculation, a declustering process was performed using the Reasenberg algorithm, following the approaches of (Karapetyan et al., 2024; Reasenberg, 1985), to remove dependent events such as foreshocks and aftershocks, ensuring that only mainshock events were retained for analysis. This step is essential, as the estimation of a-value and b-value is based solely on mainshock data. Therefore, we computed the a-value and b-value, alongside the determination of the magnitude of completeness ($M_c$), which represents the minimum magnitude above which all seismic events are reliably detected within the study area during the specified period. The $M_c$ value is a critical threshold used in the computation of both seismic parameters and is illustrated in Figure 3. It was obtained by identifying the peak of the first derivative of the frequency–magnitude distribution curve.

Figure 3 shows that the b-value obtained is $1.09 \pm 0.04$, while the a-value is 5.754 Mw. The b-value and a-value are related in analyzing the seismicity of a region, where the b-value represents the relationship between the frequency of earthquake events and their magnitude. A b-value of 1.09 indicates seismicity consistent with typical tectonic activity, characterized by a higher frequency of small earthquakes compared to large ones. In general, a b-value of around 1.0 indicates that the region is under high tectonic stress and could experience more significant energy release. Meanwhile, the a-value of 5.754 reflects the level of seismic activity in the study area. The higher the a-value, the higher the level of seismic activity in an area (Apriliani & Prastowo, 2021; Aslamia & Supardi, 2022; Harmoko et al., 2023). In this case, the a-value obtained indicates that the southern region of Java has high seismic activity, in line with its position in the subduction zone between the Indo-Australian and Eurasian plates.




**Figue 3.** Distribution of earthquake events by magnitude in the southern Java region. The $M_c$ value is 2.7 Mw, indicating that the seismographic network employed is reliably capable of detecting and recording earthquakes with magnitudes of 2.7 Mw or greater.

The spatial distribution of the b-value and a-value can be further seen in Figure 4. In general, this analysis gives a summary of the earthquake patterns in Southern Java region, which can help with disaster planning and understanding the chances of future earthquakes.



(a) (b)

**Figue 4.** Spatial distribution maps of seismicity parameters in the southern part of Central Java for the period 2020–2024 using the Maximum Likelihood method: (a) b-value map; (b) a-value map.

The results of the b-value variation map show the distribution of the lowest b-value of 0.9 marked in dark blue, while the highest b-value is 1.5, marked in bright yellow. Lower b-values will generally indicate a higher level of tectonic stress, which has the potential to produce earthquakes with large energies. Conversely, higher b-values indicate areas of lower stress, which will often experience small magnitudes. The pattern of b-value distribution in the map shows variations that depend on the tectonic conditions of the study site (Apriliani & Prastowo, 2021; Aslamia & Supardi, 2022; Harmoko et al., 2023). The blue-colored areas indicate zones with high stress accumulation, which can be said to have the potential for large earthquakes. In contrast, the yellow and green colored zones indicate areas with more frequent energy release through small earthquakes. Furthermore, based on Figure 4, it can be seen that the lowest value of the lowest a-value is 4.0, which is marked in blue, while the highest value is 6.5, which is marked in dark blue. The spatial distribution of the a-value shows that the areas with high and low values are mostly in the sea area. This can be attributed to the dominance of seismic activity in the water area, which is caused by the existence of a subduction zone in the Southern Java region. This zone is the boundary between the convergent Indo-Australian and Eurasian plates, which plays a significant role in generating earthquakes in the region.

The spatial variation of a-value and b-value, as illustrated through mapping, provides valuable insights into the regional seismicity characteristics. Regions exhibiting both low a-values and low b-values are indicative of a lower frequency of seismic events but carry the potential for large-magnitude earthquakes. In contrast, areas characterized by high a-values and high b-values tend to experience more frequent seismic activity, predominantly involving low-magnitude events. Furthermore, regions with high b-values but low a-values generally show infrequent earthquake occurrences; however, when events do occur, they may be of relatively larger magnitude compared to those in high a-value regions (Apriliani & Prastowo, 2021; Aslamia & Supardi, 2022; Harmoko et al., 2023).

## Conclusion

This study has examined the seismicity of the Southern Java region from 2020 to 2024 through the estimation of a-value and b-value parameters using the Maximum Likelihood method. The results indicate that the region exhibits a b-value of approximately $1.09 \pm 0.04$ and an a-value of 5.754, suggesting a moderate to high level of seismic activity. Spatial variations of the b-value, ranging from 0.9 to 1.5, reveal potential zones of high stress accumulation, particularly in areas where the b-value is low, signaling the possibility of large-magnitude earthquakes. Similarly, the a-value ranges from 4.0 to 6.5, with higher values indicating regions of more frequent seismic activity. The distribution patterns of these parameters confirm that seismic events in this region are predominantly concentrated along the subduction zone, where zones with both low a-value and b-value are likely to generate significant earthquakes, whereas areas with high values of both parameters tend to experience frequent but lower-magnitude events.

Building upon these findings, future studies are encouraged to explore the depth-dependent variation of a-value and b-value, which would provide more detailed insights into the seismic behavior at different crustal levels and help identify potential zones of stress accumulation that may act as nucleation points for large earthquakes. Moreover, extending the temporal span of the dataset would enhance the robustness of the seismicity analysis and allow for the detection of longer-term patterns in earthquake occurrence. Such efforts would contribute significantly to improving seismic hazard assessment and informing more effective disaster mitigation strategies in the Southern Java region.

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## Conflicts of interest

The authors declare that there are no conflicts of interest.

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