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Spatial and Temporal Variability of Earthquake b-Values: Insights into Seismic Heterogeneity Along the Southern Java Subduction Zone

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ABSTRACT

Purpose of the study: This study aimed to characterize the spatial and temporal variation of *b-value* in the southern Java subduction zone and identify areas exhibiting distinctive seismicity patterns through an integrated analysis of earthquake magnitude distribution, seismic activity, and associated estimation uncertainty.

Methodology: Earthquake data from the BMKG and NEIC-USGS catalogues covering 1973–2011 were processed through magnitude homogenization, declustering, and magnitude-completeness assessment. The Gutenberg–Richter relationship and maximum-likelihood estimation were applied using ZMAP V.06 implemented in MATLAB 7.04. Spatial analysis used 0.1° × 0.1° grids with 80 events per calculation, while temporal variation was evaluated using a moving-window approach.

Main Findings: The regional magnitude of completeness was *Mc* = 4.6, with a regional *b-value* of 0.968 ± 0.02 and an *a-value* of 6.06. Spatial *b-values* ranged from 0.6 to 2.0, with low values south of Central and East Java and high values around the Sunda Strait. Temporally, *b-values* fluctuated between 0.9 and 1.2, with several decreases preceding relatively large earthquakes. Standard deviations ranged from 0.1 to 0.6.

Novelty/Originality of this study: This study integrates regional, spatial, temporal, and uncertainty analyses of *b-value* to provide a differentiated characterization of seismicity across southern Java. By combining Gutenberg–Richter parameters, spatial mapping, moving-window analysis, and standard-deviation assessment, the study demonstrates that regional-average *b-values* can conceal localized seismic regimes and provides a more comprehensive framework for interpreting seismic heterogeneity.

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1. INTRODUCTION

Earthquakes are among the most destructive natural hazards because their occurrence can release substantial seismic energy within a short period and generate cascading impacts on infrastructure, communities, and coastal environments. Understanding earthquake occurrence is therefore essential for characterizing seismic hazard and strengthening evidence-based disaster mitigation strategies [1]-[3]. Statistical characterization of earthquake frequency and magnitude provides an important basis for evaluating the spatial distribution and temporal evolution of seismicity [4]-[6]. Such characterization is particularly important in tectonically active regions where earthquake sequences may exhibit substantial variations in magnitude distribution and occurrence rate [7]-[9].

Indonesia represents a highly active seismotectonic region because several major tectonic plates interact across the Indonesian archipelago. The southern Java region is particularly important because the Indo-Australian Plate converges with and subducts beneath the Eurasian Plate along the Sunda subduction system [10], [11]. This tectonic configuration generates persistent deformation, stress accumulation, and earthquake activity along the southern margin of Java. Recent observations from the southern Java region continue to demonstrate that moderate-to-strong earthquakes can occur offshore and affect populated areas of Java [12].

The seismicity of southern Java cannot be adequately described solely by earthquake frequency because earthquake occurrence reflects heterogeneous geological structures, stress conditions, fault configurations, and variations in earthquake magnitude [13]-[15]. The distribution of earthquakes may therefore change considerably across both geographic locations and observation periods [16]-[18]. Previous observations indicate that b-values can vary laterally, with depth, and across different faulting environments [19]-[21]. Temporal changes can also emerge over shorter observation windows, particularly around earthquake sequences and periods of changing stress conditions [22]-[24]. Consequently, a spatially and temporally resolved analysis is required to identify heterogeneous seismic regimes that may be obscured by regional-average parameters.

A fundamental statistical framework for describing earthquake size distribution is the Gutenberg–Richter frequency–magnitude relationship, expressed as $\log N(M) = a - bM$ [25]-[27]. In this relationship, N(M) represents the cumulative number of earthquakes with magnitude equal to or greater than M, while a and b characterize seismicity and magnitude distribution, respectively [28], [29]. The b-value represents the relative proportion of small and large earthquakes, with higher values indicating a greater proportion of smaller events within the analyzed earthquake population [30]-[32]. Therefore, spatial and temporal variations in b-value can provide a quantitative basis for investigating changes in earthquake-size distributions and their relationship with regional seismotectonic conditions.

Previous studies have demonstrated that b-value can serve as a useful parameter for investigating the spatial heterogeneity of seismicity and the temporal evolution of earthquake populations. Schorlemmer et al. demonstrated systematic differences in b-values among normal, strike-slip, and thrust faulting regimes, supporting its interpretation as an indicator associated with differential stress [16]. Spatial mapping has also shown that heterogeneous b-value patterns can remain persistent within particular fault segments and may provide information beyond a single regional-average value [1]. Temporal analysis has further identified significant b-value anomalies preceding or accompanying major earthquake sequences in tectonically active regions [22]. In Indonesia, seismotectonic analysis using the Gutenberg–Richter relationship and maximum-likelihood estimation has likewise demonstrated substantial spatial variability in both a- and b-values [33].

Despite these developments, important scientific gaps remain in understanding the combined spatial and temporal behavior of earthquake-size distributions along the southern Java subduction zone. Earlier research on southern Java analyzed earthquake catalogs from 1973–2011 and identified spatial b-values ranging from 0.6 to 2.0 and temporal values between 0.9 and 1.2. However, the earlier analysis was based on an historical catalog and therefore does not capture subsequent changes in earthquake occurrence and catalog completeness. Moreover, regional-average b-values may conceal localized anomalies associated with heterogeneous fault structures, stress conditions, and earthquake clustering [1]. A more integrated spatial-temporal assessment is consequently needed to reassess the seismotectonic characteristics of southern Java using an appropriately processed earthquake catalog and robust estimation procedures.

The urgency of this research arises from the need to improve quantitative understanding of seismicity in one of Indonesia's most tectonically active regions and to support more spatially informed earthquake-hazard assessment. The present study therefore aims to characterize the spatial and temporal variation of b-value in southern Java and to identify areas exhibiting distinctive seismicity patterns. The analysis adopts the Gutenberg–Richter relationship, magnitude-completeness assessment, earthquake declustering, and maximum-likelihood estimation to obtain more reliable seismotectonic parameters. The principal contribution is an integrated interpretation of b-value variability across space and time, enabling localized seismic regimes to be distinguished from broader regional patterns. This approach is expected to provide a stronger quantitative basis for interpreting seismicity characteristics and supporting earthquake-risk mitigation along the southern Java subduction zone.

2. RESEARCH METHOD

2.1. Study Area and Earthquake Catalogue

This study investigated the seismicity of southern Java within the geographic boundaries of 5.5°–12.0° S and 105°–115° E. The study area encompasses the southern margin of Java and the associated subduction zone between the Indo-Australian and Eurasian plates [34], [35]. The earthquake catalogue was compiled from the

Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) and the National Earthquake Information Center of the United States Geological Survey (NEIC-USGS) [36], [37]. The catalogue covered the period from 1973 to 2011 and initially contained 3,399 earthquake events. The available catalogue parameters included earthquake origin time, epicentral latitude and longitude, focal depth, and magnitude.

Figure 1 presents the geographical location of the study area and the distribution of earthquake epicenters used in the analysis. The spatial extent was selected to represent the regional seismicity associated with the southern Java subduction system rather than focusing on a single earthquake source.

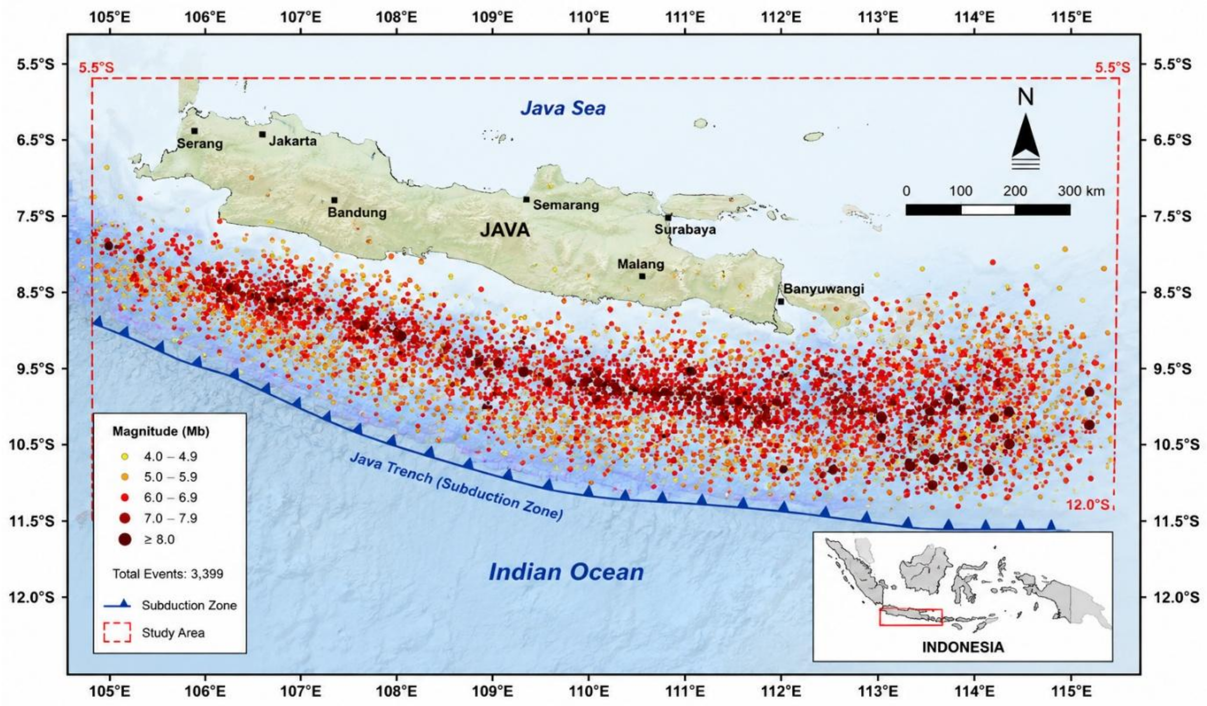

Figure 1. Location of the southern Java study area and spatial distribution of earthquake epicenters from the BMKG and NEIC-USGS catalogues during 1973–2011.

2.2. Earthquake Catalogue Preparation

The earthquake catalogue was subjected to several preprocessing procedures before the estimation of seismotectonic parameters. First, earthquake events were selected according to the geographic boundaries of the study area. Because the original catalogue contained different magnitude scales, the reported magnitudes were converted into body-wave magnitude (mb) to obtain a more homogeneous magnitude dataset [38]-[40]. The conversion procedures followed the magnitude relationships specified in the original study [41]-[43].

The homogenized catalogue was subsequently examined for dependent earthquake events. Foreshocks and aftershocks can introduce temporal clustering and bias the frequency–magnitude distribution when they are treated as independent observations. Therefore, catalogue declustering was conducted using ZMAP V.06 to obtain a catalogue dominated by independent earthquake events. The original 3,399 events were reduced to 3,017 independent events after declustering.

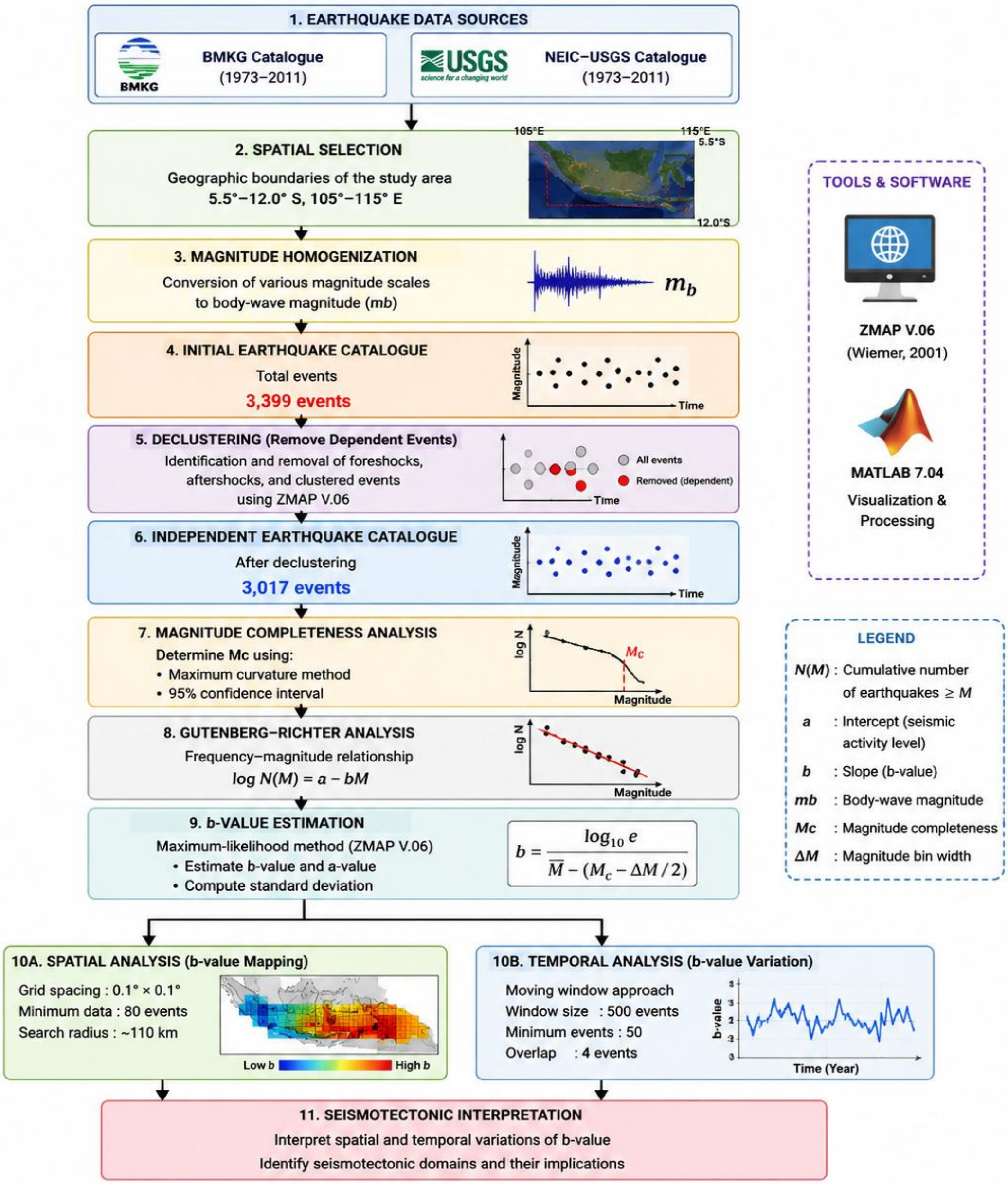

Figure 2. Workflow of earthquake-catalogue preparation and seismotectonic analysis

2.3. Magnitude Completeness

Magnitude completeness (Mc) was determined before estimating the b-value because the reliability of the Gutenberg–Richter relationship depends strongly on the completeness of the earthquake catalogue [44], [45]. Mc represents the lowest magnitude above which earthquakes are assumed to be sufficiently and consistently detected by the seismic monitoring network [46], [47]. The original analysis determined Mc using a combination of the maximum-curvature approach and a 95% confidence-interval criterion [48]-[50].

The frequency–magnitude distribution was constructed from the declustered catalogue to identify the magnitude range in which the catalogue exhibited complete reporting. The resulting regional Mc was 4.6, indicating that earthquakes with magnitudes equal to or greater than 4.6 were sufficiently represented for subsequent b-value estimation in the original catalogue.

The selection of Mc was treated as an essential quality-control step because changes in Mc alter the number of earthquake events included in the b-value calculation and may consequently influence the estimated parameter.

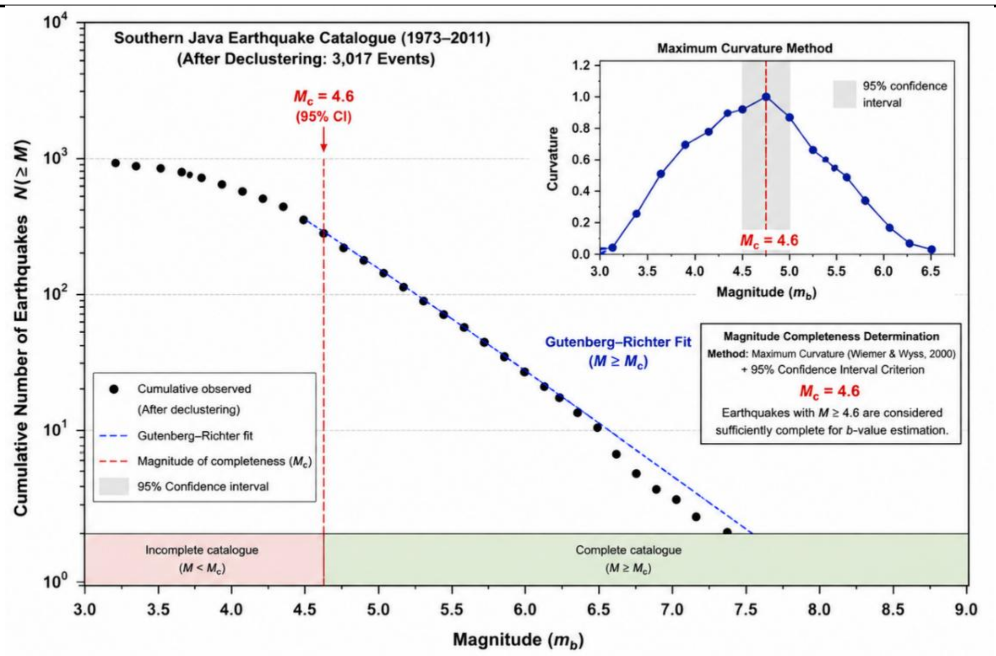

Figure 3. Frequency–magnitude distribution and determination of the magnitude of completeness (Mc) for the southern Java earthquake catalogue.

2.4. Gutenberg–Richter Frequency–Magnitude Relationship

Earthquake magnitude distribution was characterized using the Gutenberg–Richter frequency–magnitude relationship:

$$log_{10}\, N\,(M) = a - bM \qquad ...(1)$$

where (N(M)) represents the cumulative number of earthquakes with magnitude greater than or equal to (M), (a) represents the level of seismic activity, and (b) describes the relative distribution of earthquake magnitudes. The slope of the frequency–magnitude distribution corresponds to the b-value and provides a quantitative measure of the proportion of small and large earthquakes within the investigated seismic population.

A high b-value indicates a relatively greater proportion of small-magnitude earthquakes, whereas a low b-value indicates a relatively greater contribution from larger-magnitude events. Because the b-value may vary spatially and temporally, it was estimated independently for different spatial and temporal windows rather than relying exclusively on a single regional value.

2.5 Maximum-Likelihood Estimation of b-Value

The b-value was estimated using the maximum-likelihood method following the formulation implemented in ZMAP. This approach was selected because it provides a statistically robust estimation of the b-value and reduces potential bias associated with conventional linear regression of the Gutenberg–Richter relationship.

For a magnitude-complete catalogue, the maximum-likelihood estimate of the b-value can be expressed as:

$$b = \frac{log_{10}^{e}}{\bar{M}\ (M_c - \frac{\Delta M}{2})} \qquad ...(2)$$

where is the mean magnitude of earthquakes with $M \geq M_c$, M_C is the magnitude of completeness, represents the magnitude bin width, and log_{10}^{e} is approximately 0.4343.

2.6. Spatial Analysis of b-Value

Spatial variation in b-value was investigated by dividing the study area into regular grid points and estimating the parameter for earthquakes surrounding each grid location. The original analysis used a grid spacing of 0.1° × 0.1° and a minimum sample of 80 earthquake events or an equivalent spatial radius of approximately 110 km.

For each spatial window, the b-value, a-value, and associated standard deviation were calculated. Overlapping spatial windows were used to improve the continuity and reliability of the resulting b-value distribution. The resulting values were then mapped to identify regions characterized by relatively high and low b-values.

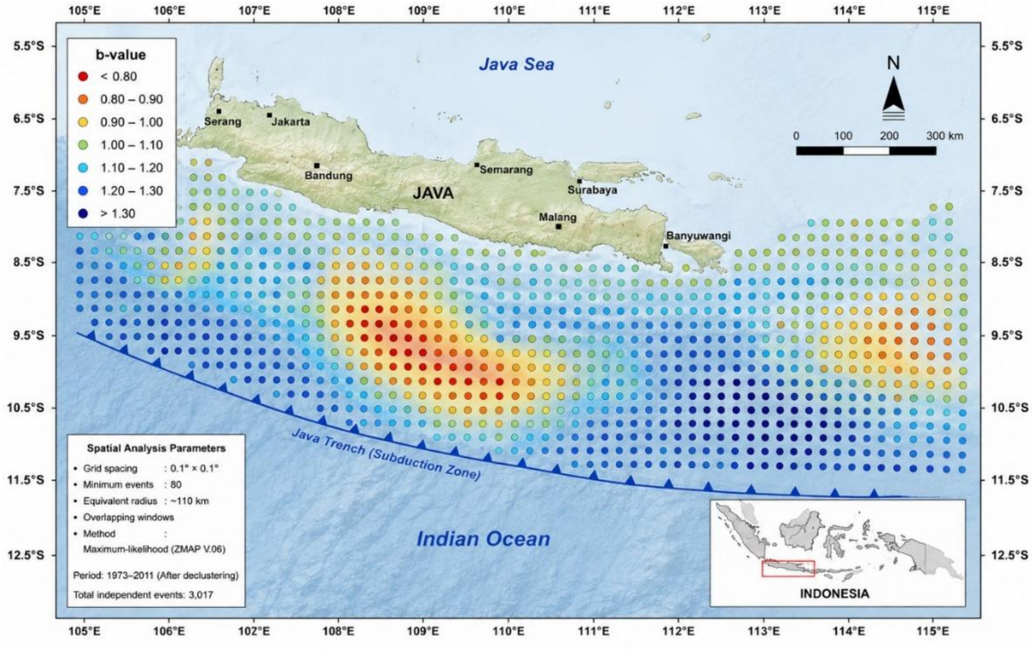

Figure 4. Spatial distribution of b-values across the southern Java study area.

2.7. Temporal Analysis of b-Value

Temporal variation in b-value was analyzed using a moving-window approach. A fixed number of earthquake events was selected sequentially from the earthquake catalogue, after which the observation window was shifted forward and the b-value was recalculated. This procedure enables changes in the earthquake-size distribution to be examined through time rather than representing seismicity by a single value for the entire observation period.

In the original analysis, a sample window of 500 events was applied, with a minimum number of 50 events and an overlap of four events for the temporal assessment. The resulting temporal sequence of b-values was examined to identify periods characterized by anomalously high or low b-values and to compare these variations with the regional earthquake occurrence pattern.

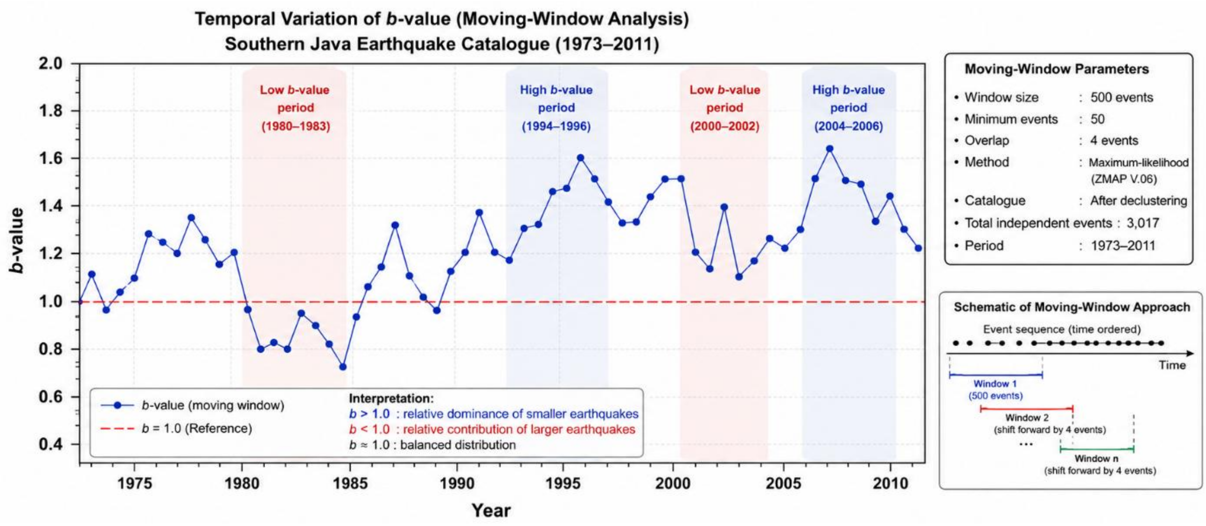

Figure 5. Temporal variation of b-value calculated using the moving-window approach.

2.8. Data Processing and Visualization

The earthquake catalogue was processed using ZMAP V.06 implemented in MATLAB 7.04. The analytical sequence included catalogue selection, magnitude homogenization, declustering, magnitude-completeness determination, frequency–magnitude analysis, maximum-likelihood estimation, and spatial-temporal visualization of the seismotectonic parameters.

The methodological workflow is summarized in Figure 2 to facilitate reproducibility of the analysis. The principal outputs were the magnitude-completeness value, regional Gutenberg–Richter parameters, spatial b-value distribution, temporal b-value variation, and associated measures of uncertainty.

3. RESULTS AND DISCUSSION

3.1. Earthquake Catalogue Characteristics and Magnitude Completeness

The earthquake catalogue used in this study was compiled from the BMKG and NEIC-USGS earthquake catalogues for the southern Java region during 1973–2011. The initial catalogue contained 3,399 earthquake events and included information on origin time, epicentral coordinates, focal depth, and magnitude. Because the catalogue consisted of events reported using different magnitude scales, the magnitudes were homogenized into body-wave magnitude () before subsequent seismotectonic analysis. The catalogue was then declustered using ZMAP V.06 to reduce the influence of dependent events, particularly foreshocks and aftershocks, resulting in a catalogue dominated by independent earthquake events. The use of declustering was intended to obtain a more representative frequency–magnitude distribution for subsequent estimation of the Gutenberg–Richter parameters. The original analysis explicitly identified declustering as a step for removing the influence of foreshocks and aftershocks and obtaining independent events.

The completeness of the earthquake catalogue was assessed prior to the estimation of the b-value. The magnitude of completeness (M_c) was determined using a combination of the maximum-curvature method and a 95% confidence-interval criterion. The completeness of the earthquake catalogue was assessed prior to the estimation of the b-value. The magnitude of completeness (Mc) varied temporally during the observation period, with values ranging from approximately 4.1 to 5.1. The temporal variation was relatively higher during the earlier part of the catalogue and generally decreased after approximately 1995, indicating an improvement in the capability of the earthquake catalogue to record lower-magnitude events over the later observation period.

For the overall frequency–magnitude distribution, the regional magnitude of completeness was Mc = 4.6. This value indicates that earthquakes with magnitudes of approximately 4.6 and above were sufficiently represented in the combined BMKG and NEIC-USGS catalogue for the regional Gutenberg–Richter analysis. Using earthquakes above the magnitude of completeness (Mc), the maximum-likelihood estimation produced a regional b-value of 0.968 ± 0.02 and an a-value of 6.06. These parameters provide the baseline characterization of the earthquake-size distribution and seismic activity of southern Java before the spatial and temporal analyses were performed. The estimated b-value is close to unity, indicating that the regional earthquake population contains a substantial proportion of smaller-magnitude events relative to larger events. The a-value of 6.06 represents the overall level of seismic activity associated with the analysed catalogue.

Figure 6 presents the frequency–magnitude distribution of the southern Java earthquake catalogue, including the determination of and the Gutenberg–Richter relationship.

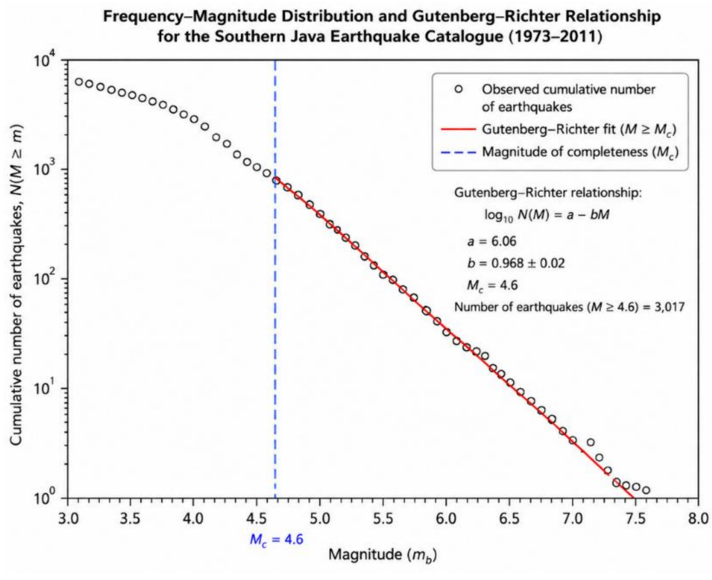

Figure 6. Frequency–magnitude distribution and Gutenberg–Richter relationship of earthquakes in southern Java during 1973–2011

3.2. Gutenberg–Richter Parameters

The Gutenberg–Richter frequency–magnitude relationship was used to characterize the regional earthquake-size distribution in southern Java. Based on the magnitude-complete portion of the earthquake catalogue (), where , the maximum-likelihood estimation yielded a **b-value of** and an **a-value of 6.06**. These parameters represent the regional characteristics of earthquake magnitude distribution and seismic activity, respectively.

The estimated b-value of 0.968 is close to unity, indicating that the frequency–magnitude distribution of earthquakes in southern Java is broadly characterized by a relatively large proportion of smaller-magnitude events compared with larger-magnitude events. The value is also close to the b-values reported for several regions within the Circum-Pacific belt. The original study reported that the southern Java b-value was slightly lower than the global value approaching unity reported by Wyss (1973), while remaining comparable with values observed in other Circum-Pacific regions.

Table 1. Comparison of the regional b-value for southern Java with selected Circum-Pacific regions

Region	b-value
Southern Java	0.968 ± 0.02
South America	0.80
Kermadec	0.97
Tonga	0.95
New Hebrides	0.80
Kuril	0.82
Kamchatka	0.95
Western Aleutians	0.84
Eastern Aleutians	0.88

Note: Circum-Pacific values are reproduced from the comparison presented in the original study based on Carter and Berg (1981).

The comparison shows that the b-value obtained for southern Java () is very close to the values reported for the Kermadec region () and Tonga (), and is somewhat higher than those reported for South America (0.80), New Hebrides (0.80), Kuril (0.82), Western Aleutians (0.84), and Eastern Aleutians (0.88).

The regional a-value of 6.06 indicates the overall level of seismic activity represented by the earthquake catalogue. In the original analysis, the relatively high a-value was interpreted as indicating relatively high earthquake activity in southern Java. However, because the a-value is dependent on the number of earthquake events included in the analysis, its interpretation should be considered together with the catalogue completeness and observation period.

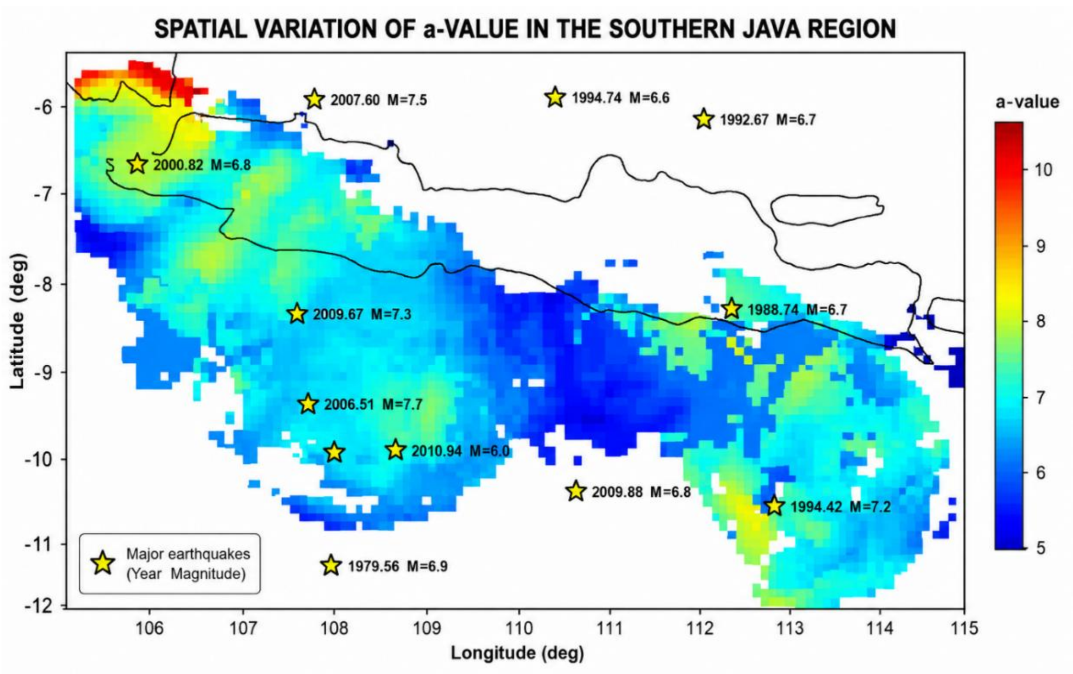

Figure 7. Spatial distribution of b-values across the southern Java study area.

Table 2. Summary of spatial variations in seismotectonic parameters

Parameter	Minimum	Maximum	Main spatial pattern
b-value	0.6	2.0	Low values south of Central and East Java; high values around the Sunda Strait
a-value	5	10	Higher values particularly around the Sunda Strait

Source: Results of the present study based on the 1973–2011 earthquake catalogue.

The reliability of the spatial b-value estimates was further evaluated through their standard deviation. The standard deviation ranged from approximately 0.1 to 0.6 across the study area. Larger standard deviations were associated with areas where the number of observations was relatively limited. To reduce this source of uncertainty, the analysis used 80 earthquakes for each spatial calculation, exceeding the minimum sample size of 50 events recommended in the original methodological framework.

Overall, the spatial analysis indicates that southern Java cannot be adequately characterized by a single regional b-value. The contrast between the low-b-value zones south of Central and East Java and the high-b-value zone around the Sunda Strait indicates the presence of distinct spatial earthquake regimes. The regional value of approximately 0.968 therefore represents an average condition, while the spatial distribution provides more detailed information about variations in earthquake-size populations across the study area.

3.3 Spatial Variation of b- and a-Values

The spatial b-value was estimated using the maximum likelihood method based on the earthquake catalogue after considering the magnitude of completeness.

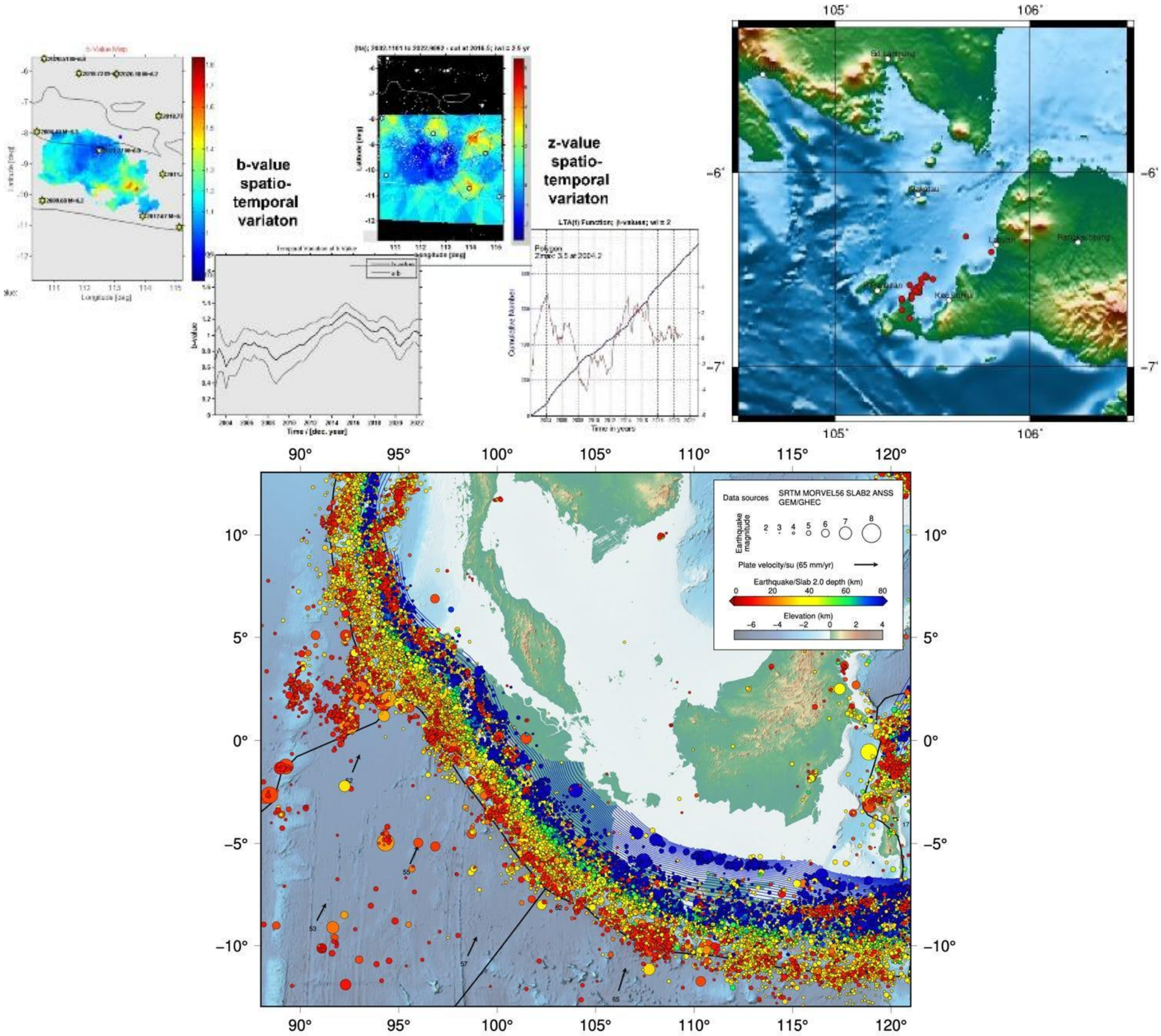

Figure 8. Spatial variation of b-value in southern Java

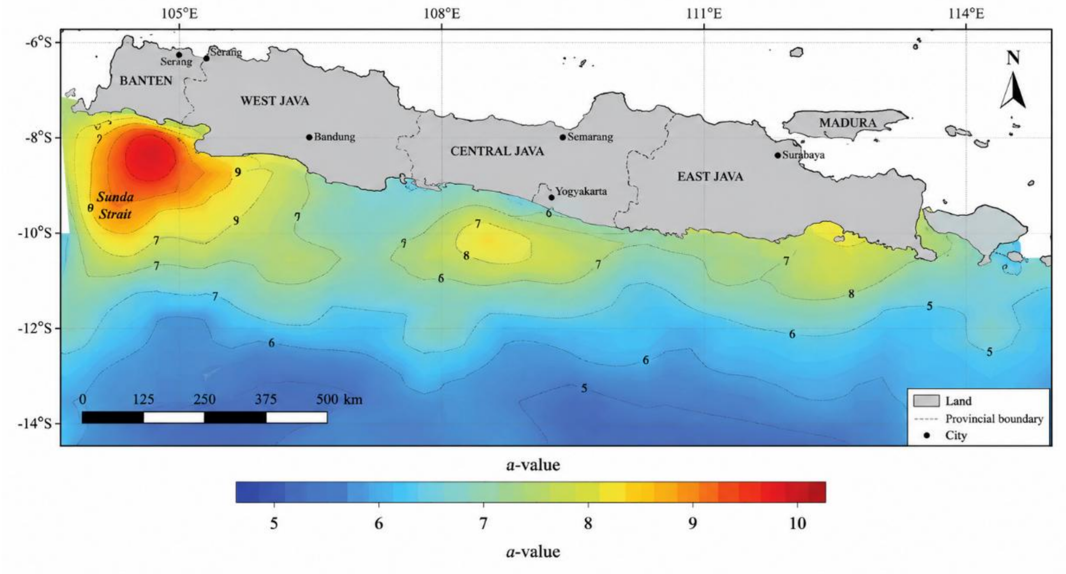

Figure 9. Spatial variation of a-value in southern Java

As shown in Figure 8, the lowest b-values, approximately **0.6**, are concentrated in the Indian Ocean south of Central Java and southern East Java. In contrast, relatively high b-values, reaching approximately 2.0, occur around the Sunda Strait. This spatial contrast indicates that the earthquake magnitude-frequency distribution is not uniform throughout southern Java.

The spatial distribution of b-value can also be interpreted in relation to the stress conditions of the study area. The results indicate that areas characterized by relatively low b-values are associated with comparatively higher stress conditions, whereas higher b-values may reflect lower stress and greater heterogeneity of the rock medium. The occurrence of relatively large earthquakes in areas characterized by lower b-values further supports the relationship between b-value and the regional stress regime.

The spatial distribution of the a-value exhibits a pattern broadly comparable to that of the b-value. The estimated a-values range from approximately 5 to 10, with higher values particularly concentrated around the Sunda Strait. Since the a-value represents the level of seismic activity, the relatively high a-values indicate a comparatively high rate of earthquake occurrence in this region.

The combination of b- and a-value distributions provides a more comprehensive description of the seismic regime. A relatively high b-value around the Sunda Strait indicates a greater proportion of smaller-magnitude earthquakes, while the relatively high a-value indicates a comparatively high level of earthquake activity. This suggests that the Sunda Strait represents a region characterized by relatively frequent seismic activity but dominated by earthquakes of comparatively smaller magnitude. The original study similarly interpreted the high b-value in this region as indicating relatively high seismic activity with a lower proportion of large earthquakes.

Conversely, the low b-values observed south of Central and East Java indicate a different earthquake magnitude distribution and may reflect relatively higher stress conditions. Therefore, the spatial variation of the b- and a-values demonstrates that southern Java should not be considered a homogeneous seismotectonic region. Instead, distinct spatial regimes can be identified, particularly between the low-b-value areas in the southern Central and East Java sectors and the high-b-value area around the Sunda Strait.

3.4. Cumulative Earthquake Occurrence and Moment Release

The temporal evolution of earthquake occurrence and seismic moment release was examined to identify changes in the seismic activity of the southern Java region during the observation period. The cumulative number of earthquakes and cumulative moment release are presented in Figures 7 and 8, respectively.

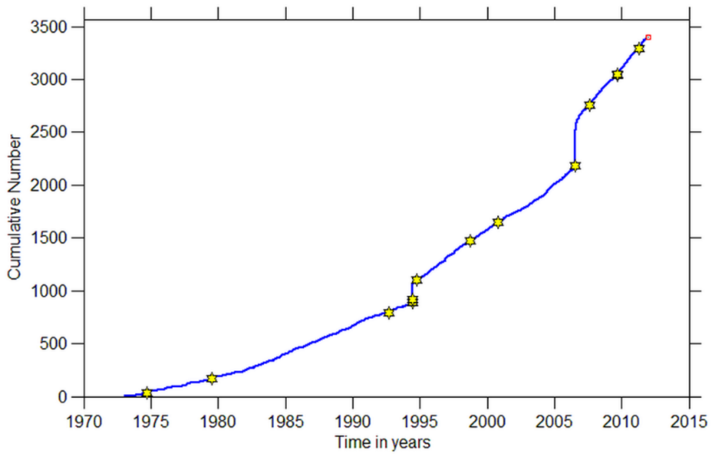

Figure 10. Cumulative number of earthquakes in southern Java during 1973–2011

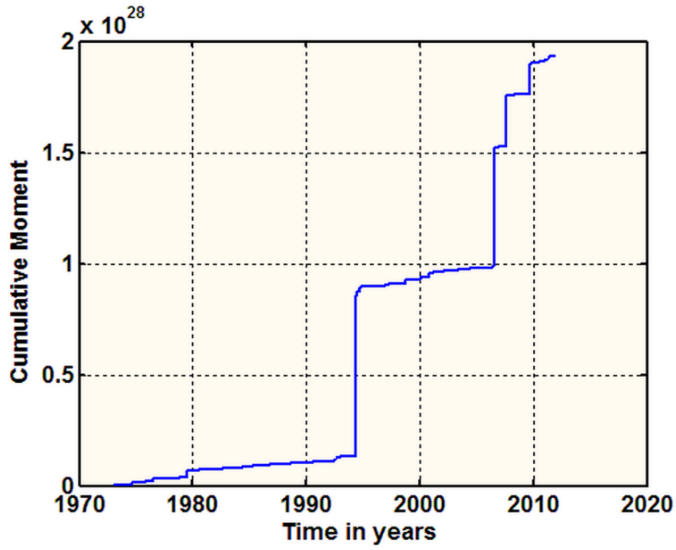

Figure 11. Cumulative seismic moment release in southern Java during 1973–2011

The cumulative earthquake plot shows a generally increasing trend throughout the observation period, indicating the continuous occurrence of earthquakes in the study region. Although the overall trend is relatively steady, a noticeable change in the slope occurs around 2004. This change indicates an increase in the cumulative number of recorded earthquakes after 2004, particularly following the 26 December 2004 Aceh earthquake. Thus, the temporal distribution of earthquake occurrence was not completely uniform throughout the 1973–2011 observation period.

The cumulative moment-release curve exhibits a different temporal characteristic. The curve shows a semi-periodic pattern of approximately 15 years, indicating that the release of seismic moment was not distributed uniformly through time. A marked increase in cumulative moment release is observed beginning around 1990, reflecting periods characterized by relatively large contributions to the total seismic moment released in the region.

The difference between the cumulative earthquake-occurrence curve and the cumulative moment-release curve is important for interpreting the seismicity of southern Java. The cumulative number of earthquakes primarily reflects the frequency of earthquake occurrence, whereas cumulative moment release is more strongly influenced by the occurrence of relatively large-magnitude earthquakes. Consequently, an increase in the number of earthquakes does not necessarily correspond to a proportional increase in seismic moment release.

The change in the cumulative earthquake trend around 2004 and the increase in moment release beginning around 1990 indicate that seismic activity in southern Java underwent temporal fluctuations during the study period. These results provide complementary evidence to the b-value analysis, demonstrating that the earthquake population and the energy released by earthquakes vary through time. Therefore, the cumulative occurrence and moment-release analyses support the interpretation that the southern Java region exhibits temporal heterogeneity in its seismic activity.

3.5. Temporal Variation of b-Value

The temporal variation of the b-value was analyzed to examine changes in the earthquake magnitude-frequency distribution throughout the observation period. The analysis was performed using a moving-window approach, with a sample window of 500 earthquake events, a minimum of 50 events, and an overlap of four events between successive windows. This approach was used to identify temporal fluctuations in the b-value and to examine whether changes in the magnitude distribution occurred before relatively large earthquakes.

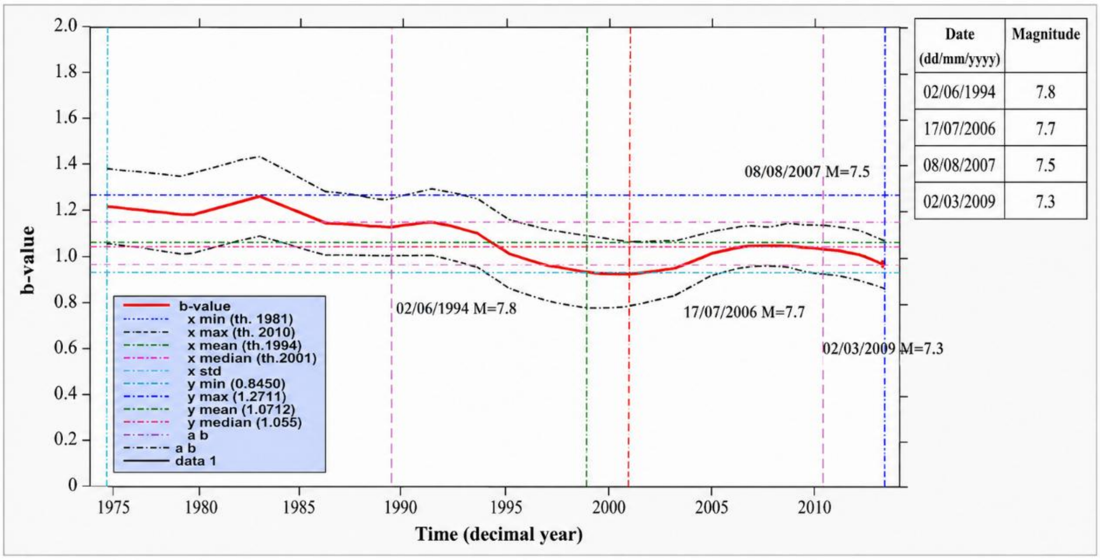

Figure 12. Temporal variation of b-value in southern Java during 1973–2011

The temporal analysis shows that the b-value fluctuated between approximately 0.9 and 1.2 during the observation period. This range indicates that the magnitude-frequency distribution of earthquakes varied through time rather than remaining completely constant. The temporal variation complements the spatial analysis presented previously, demonstrating that the seismotectonic characteristics of southern Java vary not only geographically but also temporally.

A decreasing trend in the b-value was observed before several relatively large earthquakes, particularly those occurring in 1994, 2006, 2007, and 2009. The decrease was particularly apparent before the 2006 and 2007 earthquakes, although the changes occurred within a relatively short period before the events. These observations suggest that changes in the b-value may occur in association with changes in the earthquake population preceding some large earthquakes.

However, the temporal behavior of the b-value does not show a consistent pattern before all major earthquakes. Therefore, the observed decreases cannot be interpreted as definitive evidence that b-value variations can be used as a reliable earthquake precursor. Rather, the results indicate the potential existence of temporal variations in the earthquake magnitude distribution that may be associated with changing seismotectonic conditions. The original study consequently emphasized the need for further investigation to establish the consistency of b-value variation as a potential precursor of major earthquakes.

The observed temporal variation is consistent with the interpretation that b-value may be related to changes in stress conditions within the Earth's crust. Previous observations discussed in the original study indicate that a decrease in b-value can be associated with an increase in stress within a rock volume. Nevertheless, because the temporal trend identified in southern Java is not consistently observed before every major earthquake, the relationship should be regarded as an indicator of temporal seismicity variation rather than a predictive relationship.

Overall, the temporal analysis demonstrates that the b-value in southern Java varied within the range of 0.9–1.2 during 1973–2011, with several decreases preceding major earthquake events. When considered together with the spatial b-value distribution and cumulative earthquake occurrence, these findings indicate that the seismicity of southern Java is characterized by both spatial heterogeneity and temporal variability. The results therefore reinforce the importance of analyzing b-value variations across both space and time when characterizing the seismotectonic behavior of the southern Java region.

The reliability of the spatial b-value estimates was further evaluated using the standard deviation of the calculated b-values. The standard deviation provides an indication of the uncertainty associated with the estimated b-value in each spatial grid. The results show that the standard deviation varies between approximately 0.1 and 0.6 across the southern Java region.

The spatial distribution of standard deviation indicates that the uncertainty of the b-value estimates is not uniform throughout the study area. Areas with relatively larger standard deviations indicate greater uncertainty in the estimated b-values. Such variability is generally associated with differences in the number and distribution of earthquake events available within each spatial calculation area. In particular, a relatively large standard deviation can result from an insufficient number of observations, which may increase the variability of the estimated b-value.

To reduce this potential sampling bias, the analysis used 80 earthquake events for each spatial grid. This number exceeds the minimum of approximately 50 events recommended for b-value estimation using the maximum likelihood method. The use of a consistent number of events for each calculation therefore provides a basis for comparing the spatial distribution of b-values across the study region.

The observed standard-deviation range of 0.1–0.6 should be considered when interpreting the spatial b-value map. In areas with smaller standard deviations, the estimated b-values are comparatively more stable, whereas areas with larger standard deviations require greater caution because the corresponding b-value estimates are subject to greater uncertainty. Therefore, interpretation of spatial differences in b-value should consider both the estimated b-value itself and its associated standard deviation.

Overall, the standard-deviation analysis supports the reliability assessment of the spatial b-value distribution. Although uncertainty varies between spatial grids, the use of 80 events per grid provides a relatively consistent sampling basis for the maximum-likelihood estimation. The results therefore strengthen the interpretation of the observed spatial heterogeneity in b-value, while also emphasizing that areas with relatively high standard deviations should be interpreted cautiously.

3.6. Standard Deviation and Uncertainty of b-Value

Therefore, interpretation of spatial differences in b-value should consider both the estimated b-value itself and its associated standard deviation. Overall, the standard-deviation analysis supports the reliability assessment of the spatial b-value distribution. Although uncertainty varies between spatial grids, the use of 80 events per grid provides a relatively consistent sampling basis for the maximum-likelihood estimation. The results therefore strengthen the interpretation of the observed spatial heterogeneity in b-value, while also emphasizing that areas with relatively high standard deviations should be interpreted cautiously.

The overall findings of this study further demonstrate that the seismicity of southern Java is characterized by substantial spatial and temporal heterogeneity. Although the regional *b*-value of 0.968 ± 0.02 is close to unity, the spatial distribution ranges from approximately 0.6 to 2.0, indicating considerable differences in earthquake magnitude-frequency characteristics across the study area. Low *b*-values concentrated south of Central and East Java contrast with higher values around the Sunda Strait, while temporal analysis shows fluctuations between approximately 0.9 and 1.2, including several decreases before relatively large earthquakes. These findings are consistent with previous studies showing that *b*-value variations are associated with differences in stress conditions and seismotectonic environments. Schorlemmer et al. [16] demonstrated systematic variations in earthquake-size distributions across different stress regimes, while Schorlemmer et al. [1] showed that spatially heterogeneous *b*-value patterns can provide more detailed information than a single regional average. Similarly, Nuannin et al. [22] reported temporal *b*-value anomalies associated with major earthquake sequences. However, the present findings also show that decreases in *b*-value do not occur consistently before every major earthquake, indicating that temporal *b*-value variation should be interpreted as an indicator of changing seismicity conditions rather than as a deterministic earthquake precursor.

Recent studies published within the last five years further support the spatial and temporal interpretation obtained in the present study. A recent investigation in East Java by Hisyam et al. [51], based on earthquake data from 2002–2022, found that significant earthquakes were generally associated with relatively low *b*-values and that temporal decreases in *b*-value occurred before several major events, indicating potential changes in stress conditions before earthquake occurrence. The present findings show a comparable pattern, particularly in the southern East Java sector, where *b*-values reached approximately 0.6 and several temporal decreases were observed before relatively large earthquakes. However, unlike the East Java study, the present analysis covers a broader southern Java subduction system and shows that *b*-value decreases were not consistently observed before every major earthquake. A similar conclusion was reported by Chan et al. [52], who found that many large earthquakes in Taiwan occurred in areas characterized by low *b*-values, whereas significant temporal changes were not consistently detected near all epicentral regions. Moreover, Gong et al. [53] reported that major earthquakes in the eastern Tibetan Plateau tended to occur in low-*b*-value regions and that the temporal *b*-value commonly decreased before major events and increased afterward, reflecting stress accumulation and release. In comparison, the present study provides additional evidence that the relationship between low *b*-values, stress conditions, and major earthquake occurrence is also observable in the southern Java subduction environment, while simultaneously demonstrating that this relationship is spatially heterogeneous and temporally non-uniform. Therefore, the present findings support recent evidence that *b*-value is a useful indicator for characterizing stress-related seismic heterogeneity, although its interpretation should be integrated with other seismotectonic parameters rather than being treated as a standalone earthquake prediction tool.

The novelty of the present study lies in the integrated interpretation of regional, spatial, temporal, and uncertainty characteristics of the *b*-value within the southern Java subduction system. Rather than relying only on a regional Gutenberg–Richter parameter, the analysis demonstrates that the regional *b*-value conceals substantial localized variation, ranging from low-*b*-value zones south of Central and East Java to high-*b*-value zones around the Sunda Strait. The integration of spatial mapping with temporal analysis and standard-deviation assessment provides a more comprehensive representation of seismicity by simultaneously considering earthquake magnitude distribution, its temporal evolution, and the uncertainty associated with local estimates. This approach therefore contributes to a more differentiated characterization of southern Java as a seismotectonically heterogeneous region and provides additional evidence that localized seismic regimes may not be adequately represented by regional-average parameters alone.

These findings have important implications for the interpretation of seismicity and earthquake-hazard assessment in southern Java. The identification of localized low-*b*-value zones suggests that spatially resolved seismicity parameters should complement regional assessments, particularly when evaluating areas characterized by different earthquake magnitude distributions. In addition, temporal monitoring of *b*-value may provide useful information regarding changes in seismicity conditions when interpreted together with other seismotectonic indicators. Nevertheless, this study is limited by the use of an earthquake catalogue covering the 1973–2011 period, temporal variations in catalogue completeness, and differences in the uncertainty of spatial *b*-value estimates, as reflected by standard deviations ranging from approximately 0.1 to 0.6. Furthermore, because decreases in *b*-value were not consistently observed before all major earthquakes, the results do not support the use of *b*-value as a standalone predictive parameter. Future studies should therefore incorporate more recent earthquake catalogues and integrate additional parameters, such as focal mechanisms, hypocentral depth, geodetic deformation, and stress-field information, to further investigate the physical mechanisms underlying spatial and temporal variations in *b*-value.

4. CONCLUSION

This study demonstrates that the seismicity of southern Java during 1973–2011 was characterized by significant spatial and temporal heterogeneity. The analysis of the declustered earthquake catalogue produced a regional magnitude of completeness of Mc = 4.6, a regional *b-value* of 0.968 ± 0.02, and an *a-value* of 6.06, indicating that the overall earthquake magnitude distribution was close to the global *b-value* of unity. However, the regional parameter did not fully represent the localized seismic characteristics, as the spatial *b-value* distribution ranged from approximately 0.6 to 2.0. Low *b-values* were concentrated south of Central and East Java, whereas higher values occurred around the Sunda Strait, indicating the presence of distinct seismic regimes across the southern Java subduction system. Temporal analysis further revealed *b-value* fluctuations between approximately 0.9 and 1.2, with decreasing trends observed before several relatively large earthquakes, although this pattern was not consistently present before all major events. The standard deviation range of approximately 0.1–0.6 further indicates that uncertainty should be considered when interpreting localized *b-value* estimates. Overall, the integrated analysis of regional, spatial, temporal, and uncertainty characteristics demonstrates that *b-value* is a useful parameter for characterizing seismic heterogeneity in southern Java, but it should not be interpreted as a standalone predictor of earthquake occurrence. Future studies should incorporate more recent and higher-resolution earthquake catalogues and integrate *b-value* analysis with focal mechanisms, hypocentral depth, geodetic deformation, and stress-field data to provide a more comprehensive understanding of seismic processes and earthquake hazards in southern Java.

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