

Spatio-Temporal Variation Seismicity Pattern in East Java Between 2002 and 2022 Based on the b-value and Seismic Quiescence z-value

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Abstract

East Java is one of the seismically active regions in part of the Sunda Arc whose seismicity pattern must be studied. Therefore, a spatio-temporal analysis of seismicity between 2002 - 2022 in East Java has been conducted. This analysis aims to investigate the seismotectonic conditions in the East Java region over the last twenty years, especially the seismicity patterns associated with significant earthquakes in East Java. The analysis was carried out by quantifying the spatial and temporal variations of seismicity parameters using b-value and z-value. The used data used are earthquake data from the USGS earthquake catalog during 2002 - 2022 in the East Java region. The analysis was performed using the ZMAP 6.0 program code using the maximum likelihood method. The results of the temporal analysis of b-values show that almost all significant earthquakes in East Java were characterized by a decrease in b-values of up to 0.2. Spatially, the significant earthquake on 10 April 2021 was associated with a low b-value (0.9). Temporal z-value analysis shows that the significant East Java earthquake was preceded by a quiet period (positive z-value) between 4 - 5 years (2003 - 2008 and 2012 - 2016). Spatial analysis of the z-value in the last 7 shows an increase in the z-value before the significant earthquakes occurred on 16 July 2019, 18 March 2020, and 10 April 2021. Therefore, the results of this study indicate that the b-value and z-value potentially can be used as precursors of the significant East Java earthquake.

Keywords: Earthquake, b-value, East Java, Precursor, Seismic parameter, Spatiotemporal variation, z-value

Abbreviation

Abbreviation	Meaning
USGS	United States Geological Survey
BMKG	Badan Meteorologi Klimatologi dan Geofisika
MMI	Modified Mercalli Intensity
IRIS	Intercorporated Research Institutions for Seismology
ISC	International Seismological Centre
ANSS	Advanced National Seismic System
M	Magnitude
M _w	Moment Magnitude
m _d	Duration Magnitude
m _l	Local Magnitude
m _s	Surface Wave Magnitude
m _b	Body Wave Magnitude
M _c	Magnitude of Completeness
R _{wl}	Average seismicity rate of window length

Abbreviation	Meaning
R_{bg}	Average seismicity rate of background
T_w	Time window
LTA	Long Term Average
GUI	Graphical User Interface
MATLAB	Matrix Laboratory

Introduction

East Java is prone to earthquake disasters due to its tectonic position and population. Tectonically, East Java is part of the Sunda arc, which is active both seismically and volcanically. Several damaging earthquakes have been recorded in East Java. Based on the catalog of damaging earthquakes released by the Meteorology, Climatology and Geophysics Agency (BMKG), during 1821 - 2018, 39 damaging earthquakes were recorded in the East Java region, with the largest earthquake intensity being IX on the Modified Mercalli Intensity (MMI) scale [1]. The largest earthquake in East Java ever recorded was 7.8 on 3 June 1994, followed by a tsunami on the southern coast of East Java. The last damaging earthquake in East Java was the earthquake on 10 April 2021 ($M = 6.1$), which resulted in several fatalities and damage in several areas of East Java, especially Malang, Lumajang and Blitar Regency. This earthquake was followed by another moderate earthquake in Blitar on 21 May 2021 with 6.8 moment magnitude (MW). Another earthquake occurred on 6 December 2022 with a magnitude of 5.9 MW associated with the outer rise earthquake. Therefore, a study of seismotectonics in the East Java region is required to be carried out.

Seismic parameter analysis is one method to obtain an overview of seismotectonic conditions in an area. These seismic parameters can be carried out by plotting earthquake data within a certain year range on a diagram so that the relation between Cumulative Frequency and Earthquake Magnitude is obtained, or what is known as the Gutenberg-Richter relation. This empirical relationship gives information about b-value parameters. The b-value is a constant in the relation which is the slope or gradient value of the linear relation. The b-value gives an idea of the stress accumulated in an area and the heterogeneity of the rocks in that area [2]. Seismic parameter analysis using the b-value has been applied in regions that also have seismic activity, i.e. the Garhwal Himalaya [3], the Sunda arc of West Sumatra and Java [4], Qinghai [5], Wenchuan [6], Northwest Sumatran offshore [7], and California [8]. These studies show that the b-value parameter indicates a precursor to a large earthquake.

The seismicity pattern of an area can also be analyzed by studying the pattern of seismicity rate. The existence of a doughnut pattern at the subduction zone in Japan has been reported [9]. The doughnut pattern occurs in connection with an area that tends to be quiet for a certain period. The pattern shows that the area accumulates stress to release as a large future earthquake. In order to determine the quiet zone in an active region, earthquake data can be analyzed statistically using the variance and average of earthquakes over a time span compared with earthquake data over a longer period. The result of this analysis is known as the z-value. The z-value is a statistical parameter that measures the significance of the rate of change over a period of time [10]. This value is obtained by comparing the standard deviation of a value above or below the mean seismicity of a set number if the seismicity data is distributed normally [11]. Seismic quiescence is defined as a decrease in the mean seismicity rate, as compared to the preceding in the same crustal volume. The level of decreasing in seismicity rate is expressed by the z-value [12]. Several studies have been conducted on the rate of seismicity in a region, including in Southwestern China [13], Eastern Turkey [14], Sakhalin [15], the Japanese subduction zone [16], and California [10]. These studies show a period of quiescence with a duration of several months to several years before a large earthquake occurs.

The study of seismicity parameters in East Java is not a novelty. The Incorporated Research Institutions for Seismology (IRIS) earthquake catalog data for 1990 - 2020 in East Java has been analyzed using the maximum curvature method to obtain variations in a-value, b-value and completeness magnitude (M_c) [17]. Furthermore, variations in a-value, b-value and fractal dimensions in the Java subduction area, including East Java, using combined data from the BMKG and ISC (International Seismological Centre) earthquake catalogs in the period 1906 to September 2020 has been analyzed [18]. The results of this analysis were used to model the maximum magnitude in the Java subduction zone. The spatial and temporal with BMKG, ISC and USGS (United States Geological Survey) data from 1962 - 2021 has been analyzed to obtain earthquake micro zonation in Malang Regency, East Java after the 10 April 2021 earthquake [19]. The HVSr analysis of microtremor signals has also been applied in areas most affected by the April 10 2021 earthquake in Malang Regency, East Java [20]. A more extensive study of b-value spatial variation in

the southern subduction zone of Java has also been conducted to determine its correlation with tectonic activity [21].

In this research, seismicity parameter studies will be carried out spatially and temporally for b-value and for the z-value. This is because z-value analysis has never been carried out in the East Java subduction zone by previous researchers. This is an advantage for analyzing the seismicity of an area when compared to analyzing it by relying on just one parameter. Seismotectonic analysis in a region by combining b-value and z-value parameters has been implemented by several researchers, including in the Kobe earthquake area [22], Western Anatolia, Turkey [23], the strike-slip fault system of Thailand-Myanmar [24], as well as in Crete, Greece [25]. These researches show a correlation between the analysis of the b-value seismicity parameters and the z-value seismic quiescence parameters. Generally, large earthquakes are preceded by low b-values and high z-values.

This analysis was carried out by complementing previous studies with more recent earthquake data (until the end of 2022) and a shorter range (starting in 2002). The data after 2000 is more reliable than the data before that period. The results of this research will be expected to provide an overview of the seismotectonic conditions in the East Java subduction zone area for a better understanding of seismotectonics, especially seismicity patterns in the East Java region related to significant earthquakes, specifically USGS defined significant earthquake based on earthquake magnitude and intensity parameters. This study is one method for analyzing the precursor phenomenon of a significant earthquake as an effort to mitigate earthquake disasters in East Java.

Tectonic condition of research area

East Java is located on the southeastern edge of the Eurasian plate. East Java itself is one segment of the active Sunda arc. This arc stretches 5,600 km from the Eastern Himalayas to the Banda Islands [26]. The Sunda Arc is the result of interaction between the Australian and Eurasian plates, which started at 45 Ma after Australia moved north, then subducted under Eurasia, which continues until the present [27]. The location of the subduction zone is in the south of East Java. The Indian-Australian Plate is converging at a 6 cm/year rate with an orientation of 7 - 15 ° in East Java. The oceanic plate was subducted below the Eurasian Plate to 660 km depth [28], [29]. The subducted oceanic plate has age variations that tend to get older towards the east. In the East Java subduction zone, the age of the subducted oceanic plate is around 100 - 150 Ma [30]. The asperity of the subduction zone in East Java increases due to the presence of several seamounts and plateaus. Plate tectonics results in the formation of volcanic arcs and active faults on the mainland of East Java. The active faults distribution in research is presented in **Figure 1**.

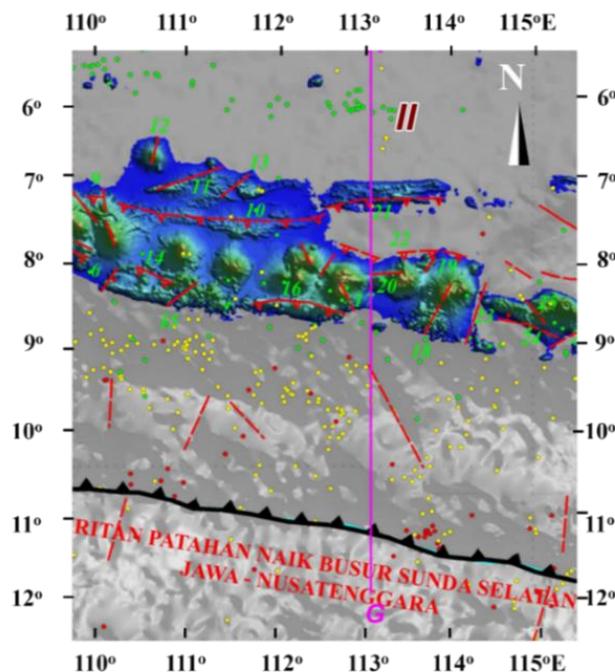


Figure 1 Map of active faults distribution in research [31].

Java Island subduction zone has been divided based on its seismogenicity, including the East Java subduction zone [32]. Shallow earthquakes appear in the East Java region up to a depth of 20 km related to shallow fault activity on land. Intermediate earthquakes (70 - 300 km) appear as intraplate activity in the Indian-Australian plate subducted beneath East Java. Meanwhile, earthquakes with deeper hypocenters (300 - 650 km) occurred in the Java Sea. Seismic tomography results show that the subducted Indian-Australian plate has a gap at a depth of 250 - 500 km. Earthquakes related to interplate activity also occurred around the Java Trench, the boundary between the Eurasian and Indian-Australian plates. An example of an interplate earthquake in East Java is the 3 June 1994 earthquake (M 7.8), which triggered a tsunami.

Materials and methods

Data acquisition

The data used to analyze seismotectonic parameters in this research is secondary data from the earthquake catalog obtained from the United States Geological Survey (USGS). The USGS earthquake catalog is a compilation of earthquake data obtained from various global earthquake catalogs that are part of the Advanced National Seismic System (ANSS) Composite Catalog (ComCat). The earthquake catalog includes information on earthquake parameters including hypocenter, magnitude, earthquake phase and earthquake amplitude. Previous seismicity studies also used earthquake data from the USGS earthquake catalog. Therefore, the USGS data catalog is reliable for seismicity analysis [33],[34].

The earthquake data includes tectonic earthquakes in the Eastern Java region with coordinate boundaries of $5^{\circ}30'$ - $13^{\circ}00'$ S dan $110^{\circ}00'$ - $115^{\circ}30'$ E between 2002 - 2022. The earthquake had a minimum magnitude value of 3.0. The research location is shown in **Figure 2**.

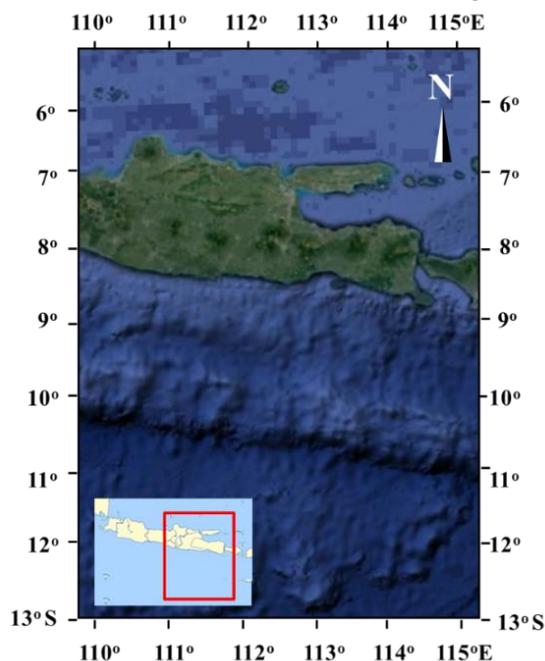


Figure 2 Research area location map.

Data conversion

The USGS earthquake catalog data consists of different magnitudes, i.e. body wave magnitude (m_b), duration magnitude (m_d), local magnitude (m_l), surface wave magnitude (m_s), and moment magnitude (M_w). In fact, seismicity data processing requires homogeneous magnitude units. Due to the heterogeneity of the magnitude scale, the magnitude scales were converted into the moment magnitude scale using the linear regression equation for earthquake magnitude conversion in Indonesia [17]. The linear regression equation this research used is shown in Eqs. (1) - (4). The reason for choosing the moment magnitude unit in this analysis is that moment magnitude describes the quantity of energy released during an earthquake which is proportional to the fault geometry and slip displacement. The magnitude is related to the magnitude of the moment, which is directly related to the geometry of the fault.

$$M_w = 0.6354 \times m_s + 2.3115 \quad (1)$$

$$M_w = 1.0332 \times m_b - 0.0834 \quad (2)$$

$$M_w = 0.125 \times m_l^2 - 0.389 \times m_l + 3.513 \quad (3)$$

$$M_w = 0.717 \times m_d + 1.003 \quad (4)$$

Earthquake data declustering

An earthquake, especially a significant earthquake, rather than being a single event generally occurs as a sequence of earthquakes. The data from the earthquake catalog were composed of mainshock events and secondary events (foreshocks and aftershocks). In this analysis, to determine the correlation between the occurrence of one mainshock and the next mainshocks, the earthquake data required to be declustered. This declustering process will remove secondary earthquake data according to specified parameters. In this research, the declustering process uses the Reasenber technique [35]. The parameters used in this decluster are the maximum time for aftershocks to occur is 970 days from the main earthquake, with an effective magnitude of 4.4, an epicenter error of 7 km, and a hypocenter depth error of 10 km.

The b-value analysis

After the declustering process, the main earthquake data obtained was analyzed using the Gutenberg-Richter relation. In this analysis, earthquake data is plotted in a Cartesian coordinate, with the abscissa being the earthquake magnitude (M) and the ordinate being the logarithm of the frequency or number of earthquakes (N). The results of this plot will produce a linear curve with the following linear regression equation [36]:

$$\log N = a - bM \quad (5)$$

In the linear regression equation, a is known as the a-value, which is the intersection of the curve and the abscissa. Meanwhile, b is the b-value, which is the slope of the curve. According to elastic rebound theory, the greater the magnitude of an earthquake, the smaller the number of earthquake events. Analysis of the magnitude of completeness M_c was carried out based on the results of the curve plot in the Gutenberg-Richter relation. The M_c value is the minimum magnitude that can still be analyzed in a seismic catalog. Complete magnitude is characterized by the distribution of earthquakes in Cartesian coordinates, which are non-linear. This is due to the limited amount of data in the catalog for small earthquake magnitudes, and the curve will not form a linear curve. Indirectly, the magnitude of completeness referred to the quality of earthquake data.

The b-value in this study was obtained using the maximum likelihood method with the help of the ZMAP program code [37]. ZMAP is Graphical User Interface (GUI) based software designed to help seismologists analyze seismicity parameters. The program code is run with MATLAB R2010a. The equation for determining the b-value is as follows [38]–[40].

$$b = \frac{1}{\bar{M} - M_{min}} \log e \quad (6)$$

\bar{M} is the average magnitude while M_{min} is the minimum magnitude of the given data sample. This b-value will vary with time. Meanwhile, the standard deviation value δb from the b-value is obtained from the following equation [40].

$$\delta b = 2,30b^2 \sqrt{\frac{\sum_{i=1}^n (M_i - \bar{M})^2}{n(n-1)}} \quad (7)$$

where n is the total number of events contained in the data and M_i is the magnitude analyzed.

In the ZMAP program code, spatial variations of the b-value are carried out by dividing the area being studied into grids. Thereafter, the b-value is calculated at the grid node points with the event radius and distance radius determined constant. Meanwhile, the temporal variation of the b-value is carried out using the sliding time window. Based on this concept, earthquake catalog data is divided into several data groups with predetermined window lengths. The b value is calculated for the first N earthquake events. After that, the window is shifted to calculate the b-value for the next window. The calculation process is carried out

simultaneously until the last data in the catalog is reached. The b-value obtained is the middle value of the window.

The z-value analysis

In z-value analysis, data in the earthquake catalog is sorted and plotted in a cumulative frequency curve. Subsequently, the time window to be used in the analysis is determined. The z-value is obtained from the standard deviation based on the Z test in statistics with the following equation [10].

$$z(t) = \frac{(R_{bg} - R_{wl})}{\sqrt{\frac{S_{bg}}{n_{bg}} + \frac{S_w}{n_w}}} \quad (10)$$

where $z(t)$ is the z-value variation over time, which is also known as the Long-Term Average (LTA(t)) function, R_{bg} and R_{wl} are the average seismicity rate covered in the window length T_w (foreground) and average seismicity rate in the entire period analyzed (background), respectively. Thereafter, the time window is shifted to calculate the next z-value.

Spatial variation of z-value is carried out by dividing the research area into several grids with size $0.05 \times 0.05^\circ$. At the grid node (intersection of a row and column in grid), calculations are made for the 50 closest earthquakes from the grid. After that, for a sample of 50 earthquakes, the earthquake rate was calculated within the specified time window (T_w). The seismicity rate was compared with the seismicity rate in the entire period (background) [15]. If the z-value is positive, the seismicity rate is decreasing. Whilst, the negative z-value indicates the increasing z-value.

Results and discussion

Seismicity analysis

Based on the acquisition of earthquake data from the USGS earthquake catalog within the specified year range, 1,202 earthquake data were obtained in the study area. After the declustering process, 278 secondary earthquake events were identified. Thus, only 966 main earthquake data remain. (Figure 3). The results of the completeness magnitude (M_c) analysis obtained in this study show a value of 4.4, as shown in Figure 4. Consequently, the earthquake data with a magnitude of less than 4.4 in this analysis is no longer used.

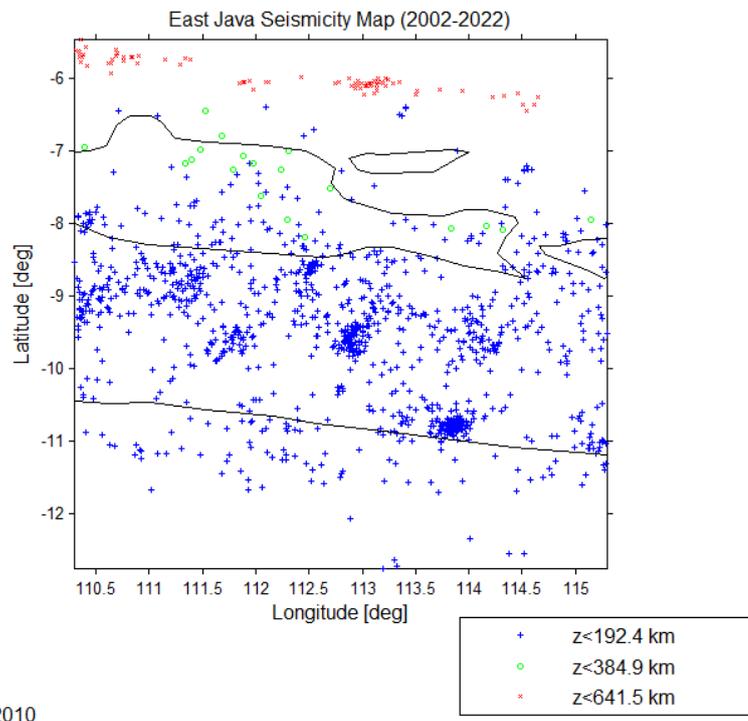


Figure 3 Seismicity map of East Java (2002 - 2022).

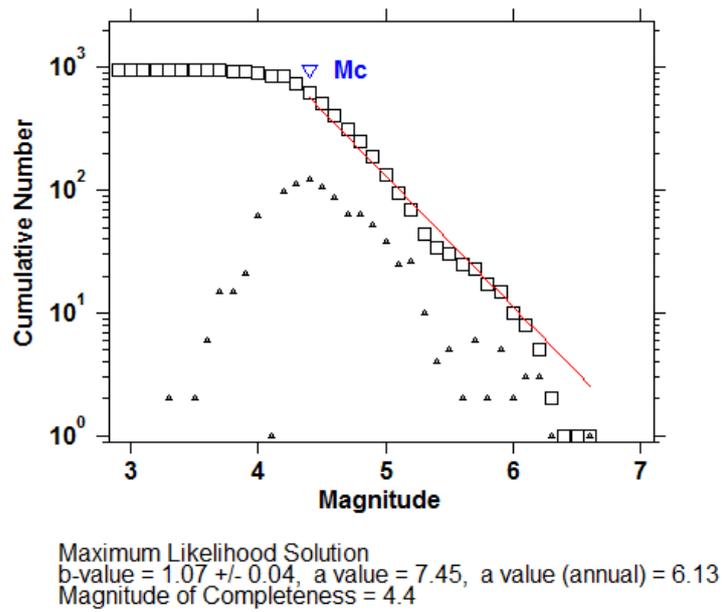


Figure 4 Magnitude of completeness analysis. The straight line (red color) shows the linear pattern plotted with the magnitude and the cumulative number of earthquake events.

Temporal variation of b-value

The temporal variation of b-value in this study was calculated using the maximum curvature method. The parameters used in the calculations are a sample window size of 58 events and an overlap 4. The results of the b-value variations obtained are presented in **Figure 5**. This figure also displays the significant earthquake events in East Java during the analyzed time period. Based on the b-value temporal variation, in 2004 - 2008, the b-value tended to increase and decrease with a minimum value of 0.7 and a maximum value of 0.9. After decreasing in 2008, the b-value continued to increase until it reached a peak of 1.3 in 2015. Furthermore, from late 2015 to early 2021, the b-value decreased until it reached a minimum value of 0.9. After that, until 2022, the b-value tends to increase to 0.2.

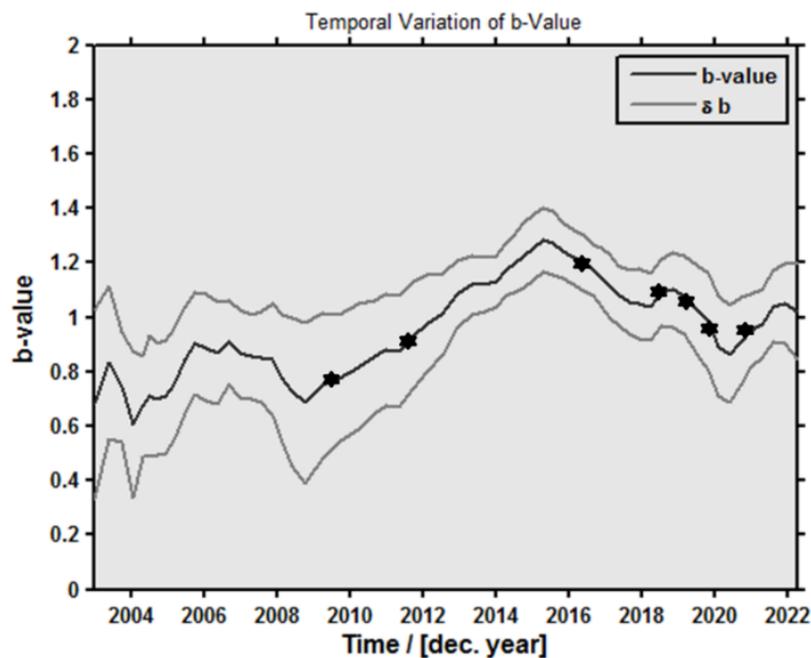


Figure 5 Temporal variation of b-value. The solid black line shows the average b-value, while the dotted black line is the standard deviation value. The black star symbol indicates significant earthquake events.

Spatial variation of b-value

In b-value spatial variation mapping, the research area is divided into grids, with the size of each grid being $0.05 \times 0.05^\circ$. In this analysis, the b-value at each node will be calculated for a constant radius of 50 km. The distribution map of b-values in the study area is shown in **Figure 6**. The b-values in areas with low seismic activity will not appear. Based on this map, the lowest b-value is 0.8, while the highest b-value is 1.8. The 10 April 2021 earthquake was in an area with a low distribution of b values (indicated with dark blue color). Meanwhile, the distribution of high b-values is in the southeastern region of the study. In general, the southern central region of East Java has a lower b-value than the eastern and western regions of East Java.

Temporal variation of z-value

The z-value needs to be analyzed temporally to determine changes in seismicity rate in the research area. In temporal z-value analysis, the value of the time window length is varied—generally, the wider the time window, the smoother the resulting LTA curve. The best results of z-value analysis are shown by applying a window length of 2 years, as shown in **Figure 7**.

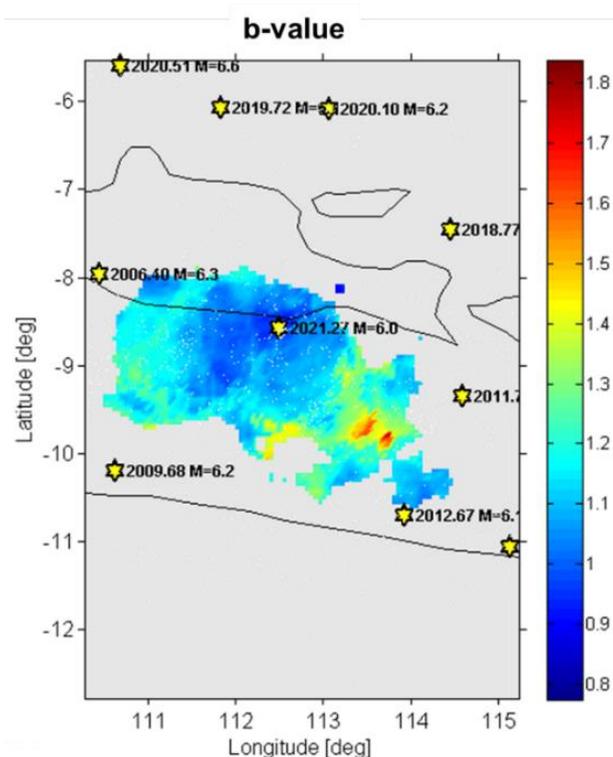


Figure 6 The b-value map of East Java. The yellow star symbol indicates the epicenter of significant earthquakes.

Based on the results of the temporal variations, the z-value tends to increase until it reaches a peak of 3.5 in 2004. After that, the z-value declined until it reached the lowest value of 4.0 in 2009. Furthermore, the z-value has increased again until it has been positive since 2012. After reaching its peak in 2014, the z-value is downward until 2022. If we analyze the period 2002 - 2022, there are 2 periods of positive z-value, including 2002 - 2008 and 2012 - 2017, as well as 2 negative z-value periods, including 2008 - 2012 and 2017 - 2022.

Spatial variation of z-value

The z-value spatial analysis helps to determine seismicity patterns in the research area by identifying the presence of earthquake quiescence zones which have the potential for earthquakes to occur in the future. The earthquake alarm cube modelling is carried out, so the z-value is easier to be analyzed, as in **Figure 8**. In this model, a 3D Cartesian coordinate system is visible, with the horizontal axis being the latitude and

longitude of the research area. Meanwhile, the z-coordinate axis shows the year being analyzed between 2002 - 2022. The red circle indicates the start of the alarm, indicating the position and year of the earthquake. The alarm duration is marked with a vertical blue line. Based on this model, the z-value is analyzed spatially in areas where alarms are indicated for 2015 - 2020.

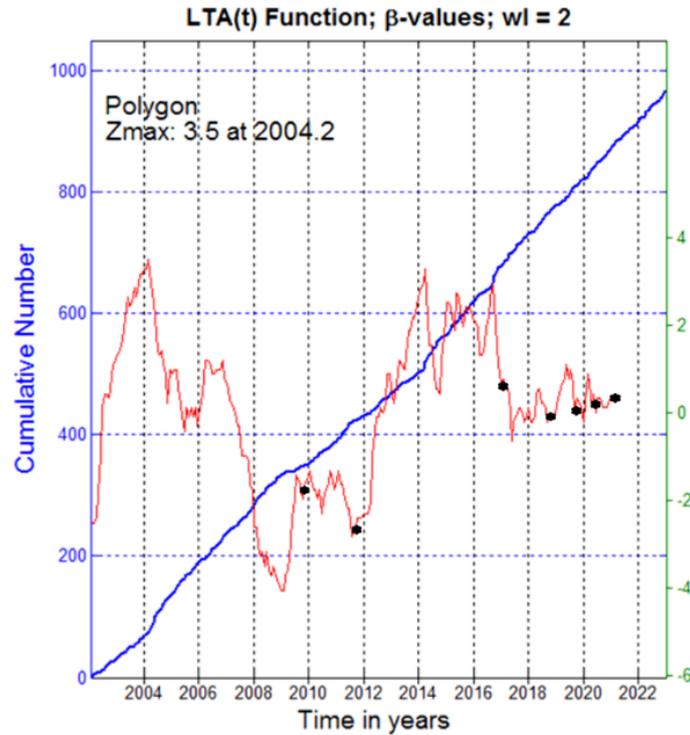


Figure 7 The z-value temporal variation during 2002 - 2022 with a red line indicated. The blue curve represents the cumulative number graph. Black dot symbols indicate significant earthquake events.

Alarm Cube of ; wl = 1.5; Zcut = 7.39

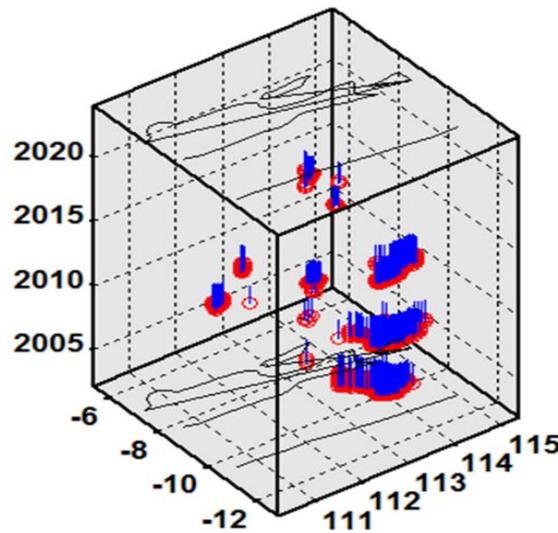


Figure 8 The 3D image coordinates, which are referred to as earthquake alarm cubes in the study area for a time window length of 1.5 years and cuts are made at a z-value of 7.39.

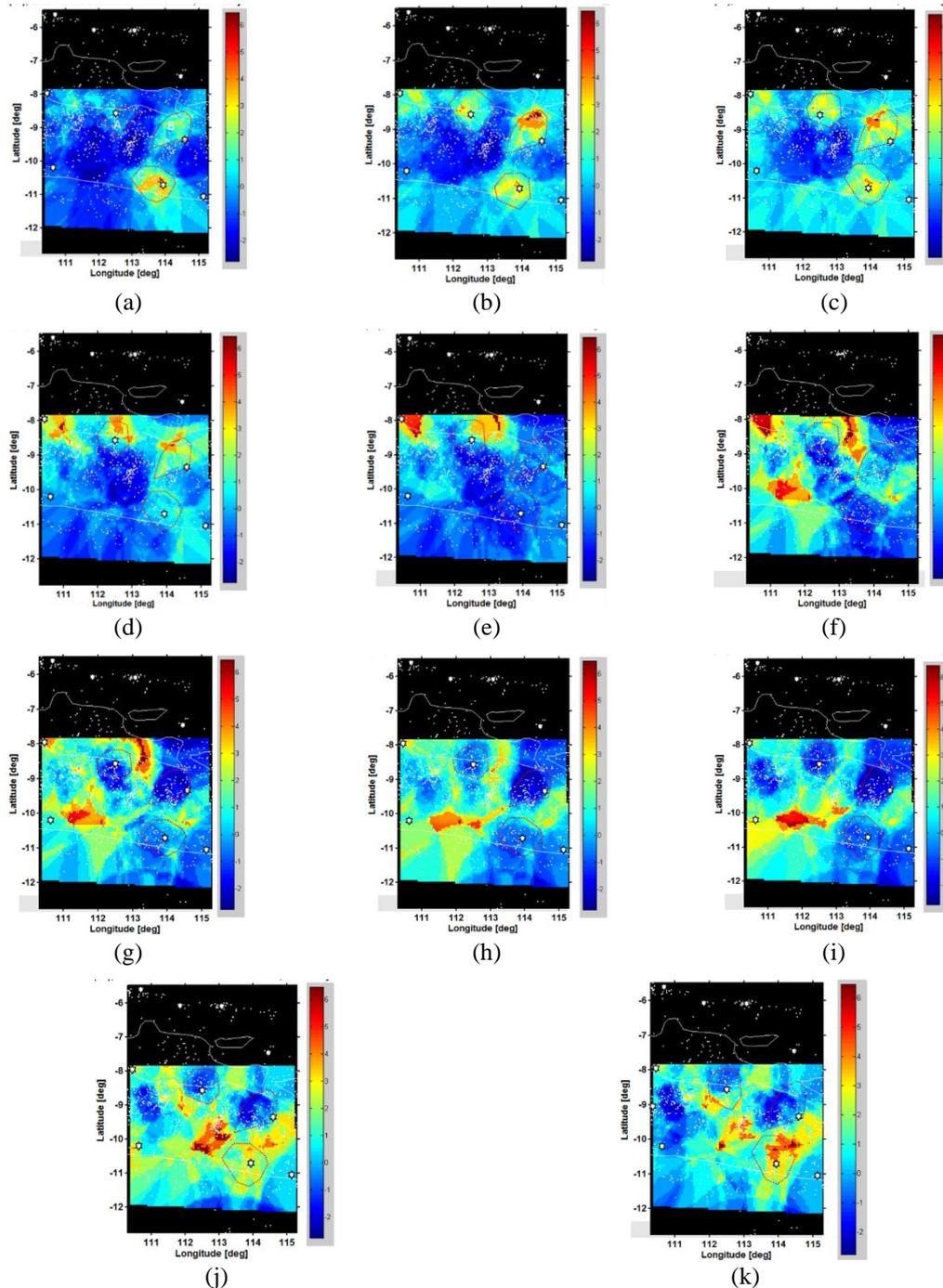


Figure 9 Results of z-value spatial analysis in the research area for the years (a) mid-2015, (b) early 2016, (c) mid-2016, (d) early 2017, (e) mid-2017, (f) early 2018, (g) mid-2018, (h) early 2019, (i) mid-2019, (j) early 2020, and (k) first quarter of 2020. Positive z-value anomalies are marked in yellow-red. Negative z-value anomalies are marked in light blue-dark blue. The yellow star marks indicate the location of the epicenter for earthquakes with a magnitude $M \geq 6.0$ in the study area. The red circles mark the presence of several z-value anomalies. The white dots show the distribution of earthquake epicenters. The white line shows the coastline of East Java.

Spatial variation of z-value was analyzed for window length varying 0.5 - 4.5 years. However, the best z-value spatial modeling was obtained for a time window of 2.5 years length, which was characterized by the appearance of clearly visible z-value anomalies. Then, for detecting the evolving of z value during analyzed time, the z-value was modeled for mid-2015 to early 2020 with an interval of 0.5 years. The z-

value spatial modeling for 2021 and 2022 cannot be displayed because the time interval is not covered by the 2.5-year length of the time window. The results of the spatial z-value analysis at the research location are shown in **Figure 9**. The z-value varies from -2.7 to 6.5 . The presence of positive z-value anomalies is circled with a red dotted line. If we observed the z-value from 2015 to 2020, the anomaly of the z-value evolved. The positive z-value anomaly observed in southeastern area during mid-2015 until mid-2017 turned negative in 2017 until early 2020. Whilst the negative anomaly in center area during mid-2015 turned positive in early 2016 and continued until mid-2017, and then reversed into negative in early 2018.

Discussion

The technique of combining seismicity parameters in the form of b-value and z-value in this research attempts to identify subtle precursors of significant and destructive earthquakes in East Java. Aforementioned, b-value indicates the level of accumulated stress in an area. Meanwhile, z-value marks changes in seismicity levels. Examination of the cumulative number of earthquake events in East Java shows that reliable earthquake data for analysis is earthquake data in the last 20 years (2002 - 2022).

Based on the results obtained from seismic parameter analysis in East Java, 5 of the 7 significant earthquakes that occurred were associated with a decrease in b-value, including the earthquakes of 16 November 2016 (5.7 MW), 10 October 2018 (6.0 MW), 16 July 2019 (5.7 MW), and 18 March 2020 (6.2 MW). Only two earthquakes occurred with increased b-value, including the quakes of 7 September 2009 (6.2 MW) and 13 October 2011 (6.1 MW). Even though the b-value increased by 0.1, the 10 April 2021 (6.0 MW) earthquake occurred in a decreasing b-value trend since 2015. Hence, the decrease in the b-value in East Java marks the occurrence of significant earthquakes. In comparison, the large Sumatran earthquakes of 2002 and 2005 were characterized by a significant decrease in b-value [7]. The 2008 Wenchuan earthquake in May 2008 was also characterized by an increase in b-value in the previous 1 - 6 years [6]. After that, in November 2007, the b-value decreased to 0.5. This value persisted until it increased again 2 months before the large earthquake occurred.

In the Gutenberg-Richter relation, low b-value indicates a gentle curve slope of regression linear line. Therefore, the low b-value implied that the earthquakes in that area are less likely to occur. This is associated with the accumulation of stress in local rocks due to plate tectonics [8]. If the rock can no longer restrain the stress, deformation of the rock will occur followed by faulting, resulting in an earthquake event. Furthermore, after the stress is released, the b-value will tend to increase.

The results of b-value temporal variation during 2002 - 2022 have similar pattern to the b-value analysis in East Java by previous study performed from 1980 - 2020 [18]. Increasing of b-value occurred since 1997 (b-value = 0.6) and peaked in 2012 (b-value = 1.5). After 2012, the b-value in East Java tends to decrease until 2020 (b-value = 0.9) [18]. The differences in the results of temporal variations in b-value with the previous research are due to the data regarding the earthquake catalog used in the analysis. However, the pattern obtained is still the same. The pattern of decreasing b-value in the 2010s also emerged in previous study, including 0.81 in the 2000 - 2010 period to 0.73 in the 2010 - 2020 period [17]. In this study, the analysis of b-value temporal variation from previous research was completed using recent data. From 2020 to 2022, the b-value began to increase after a sequence of earthquakes with a magnitude of more than 5.5, including 21 May 2021 (5.8 MW) and 26 December 2022 (5.9 MW) earthquakes.

The b-value spatial variation shows that the significant earthquake of 10 April 2021 (6.1 MW) was associated with low b-value (0.8 - 1.0). This result indicates that large amounts of stress have accumulated in the low seismicity area. Previous study observed low b-value in the southern subduction zone of East Java [21]. Research on b-value spatiotemporal variations in the Sunda arc using high precision data shows that the locations of earthquake hypocenter correlate to low b-values [4]. Similar research following the Great Sumatran earthquake also found that earthquake epicenters in northwest Sumatra in 2002 and 2004 were associated with low b-values indicating high stress accumulation [7].

The results of b-value analysis will be compared with z-value analysis to explain the seismicity patterns obtained from previous studies in East Java. Temporal z-value analysis exhibits that the 7 significant earthquakes in East Java during 2002 - 2022 occurred with decreasing trend and negative z-values. Two significant earthquakes with an increasing b-value trend, including 7 September 2009 (6.2 MW) and 13 October 2011 (6.1 MW), occurred during negative z-value period. This indicates that the earthquakes were preceded by a quiet period of earthquake activity since 2004.

Based on USGS catalog data, since 28 September 1998 in East Java, no earthquakes with a magnitude of $M \geq 6.0$ occurred. An earthquake with a magnitude of $M \geq 6.0$ occurred again on 7 September 2009. After that, the next earthquake quiet period occurred in 2012 - 2016, marked by a positive z-value. After 2016, the z-value was decreasing. An increasing seismicity rate during low z-value period was marked by

the occurrence of significant earthquakes on 16 November 2016 (5.7 MW), 10 October 2018 (6.0 MW), 16 July 2019 (5.7 MW), 18 March 2020 (6.2 MW), and 10 April 2021 (6.0 MW). Thus, the duration between quiescence in East Java is 7 - 8 years. The quiet period of the earthquake (negative z-value) endured about 5 years.

Interesting results were found in the spatial z-value analysis. These results are able to provide an overview of the z-value anomalies that evolved from 2015 to 2020. The location of the epicenter of the 10 April 2021 earthquake marked with the letter A in Figure 9 was preceded by a negative z-value in mid-2015. Then, the z-value changed to positive in early 2016 to mid-2017. The z-value changed again to negative from 2018 to 2020. This shows that the 10 April 2021 earthquake was preceded by 3 years quiescence period before the mainshock occurred.

Meanwhile, the location of 16 July 2019 earthquake (5.7 MW) epicenter marked with the letter C has had a positive z-value since 2015 and culminated in 2016. After that, the z-value changed to negative until it peaked in 2019. Anomalies of positive z-value also appeared in mid-2015 in the area marked with the letter B. This positive z-value anomaly continued to increase until early 2017. Then, it was accompanied by a decrease in z-value until mid-2019. Since then, the z-value returned positive until the first quarter of 2020. Note that zone B is the location of 18 March 2020 earthquake epicenter (6.2 MW).

Based on the z-value anomaly pattern, it is recognized that the significant earthquake in East Java was preceded by a quiet period (indicated by positive z-value) 2 - 3 years before the significant earthquake. This quiet period indicates the accumulation stress in the region, known as interseismic period. Later, the observed stress-accumulation would be stop abruptly. Shortly after that, the stress would be released. Hence, the impending significant earthquake occur. The seismic quiescence of the 1989 Sanriku, Japan earthquake (MW = 7.1) resisted around 2.5 ± 1 years [41]. The Landers (M = 7.5) and Big Bear (M = 6.5) earthquake also showed a reduction in seismicity of up to 75 % around the earthquake epicenter [10]. The anomaly was observed 4.5 years before the mainshock occurred. A seismic quiescence which lasted around 5 ± 1.5 years before the main earthquake occurred in the Eastern Turkey region [23]. Meanwhile, in Sakhalin a seismic quiescence showed with a duration of 2.7 years [15]. Thus, the z-value can be used as an earthquake precursor in the East Java region.

However, this research also required to be improved by adding earthquake data from earthquake catalogs based on local seismic networks. The data analyzed also needs to be added over a longer time interval. As a depiction, during 1975 - 2012, 3 of 4 large earthquakes that occurred in the Japan subduction zone were preceded by seismic quiescence that lasted more than 9 years [16]. Although this research employed data from the USGS catalog which is a global network, the addition of earthquake data recorded by a local seismic stations network is also required to increase the data reliability. The earthquake magnitude used greatly influences the variations in the b-value obtained [42]. However, this requires homogeneity in earthquake magnitudes [43]. Therefore, it is necessary to standardize the magnitude scale with more accurate linear regression. Relocation of the analyzed earthquake data is also necessary to obtain more accurate analysis results. The model obtained in this research also needs to be improved by analyzing the distribution of completeness magnitudes in East Java. Based on the results of this completeness magnitude analysis, we can identify areas reliably mapped by b-value.

This research shows that correlating the b-value and z-value both temporally and spatially can be used as a significant earthquake precursor in East Java. The low b-value anomalies and positive z-values characterize areas that have the potential for significant earthquakes. For example, the great Kobe earthquake in 1995 was characterized by a decrease in the b-value for 2 - 3 years, followed by an increase in the z-value several months before the large earthquake, followed by an increase in seismic activity [22]. Before the 2011 Chamoli earthquake, the area was characterized by low b-value and aseismic quiescence period of almost a year [3]. Decreasing b-value and increasing z-value observed before the 1 April 2011 earthquake on the island of Crete, Greece [25]. The correlation of z-value and b-value based on the Gutenberg-Richter relation has been observed in the strike-slip fault system at Thailand-Myanmar border [24]. Therefore, both b-value and z-value are seismicity parameters which potentially used to assess earthquake hazards as a mitigation effort in the area. This study improved the previous research in East Java, which only relied on b-value spatial and temporal variation.

Conclusions

Spatial and temporal analysis of seismicity parameters in East Java shows spatial variations in b-values ranging from 0.78 to 1.82. The location of the significant earthquake epicenter in East Java is associated with a low b-value, indicating that the stress accumulated in the area is large. Meanwhile, between 2002 - 2022, the b-value varies from 0.6 to 1.3. The significant earthquake event in East Java was

preceded by a decrease in the b-value of up to 0.2. The z-value fluctuates from -4.0 to $+3.5$. The seismic quiet period in East Java was observed in 2002 - 2009 and 2012 - 2016, characterized by a positive z-value. These significant earthquakes occurred when the z-value decreased. The quiet period for an earthquake with a positive z-value lasts 4 - 5 years with a period of 7 - 10 years. In the analysis of spatial variations in z-value, it is known that there are evolving z-value anomalies. The earthquakes of 16 July 2019, 18 March 2020, and 10 April 2021 were preceded by positive z-anomalies 2 - 3 years earlier. This shows that seismicity parameters can be used as precursors of significant earthquakes in the study area.

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