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Temporal Change and Spatial Distribution Analysis of *b*-value and *a*-value in Sumatra

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Abstract. The study of seismicity is very important to be conducted in the region of interest, such as Sumatra which has high seismicity. The seismicity can be learned by using a statistical approach through the *b*-value and *a*-value parameters. The *b*-value describes the stress accumulation of rock while the *a*-value describes the seismic activity. The objective of this research is to analyse the temporal change and spatial distribution seismicity based on *b*-value and *a*-value parameters in Sumatra by using an updated earthquake catalog from 1964 to 2022. This research found that in 1965 and 1972 have b-values greater than 2 temporally. In the spatial distribution analysis, Sumatra was dominated by b-value less than 1.91. Six clusters were found to have the lowest b-value. It might indicate high seismic stress accumulation spatially in these clusters. The temporal change and spatial distribution analysis were validated by using four destructive earthquakes in Sumatra, such as Sumatra-Andaman, Nias-Simeulue, Mentawai, and Pasaman Barat earthquakes. The *b*-values were found to be less than 1 either temporally or spatially. The large earthquake was confirmed to have a low *b*-value. This indicates high seismic stress accumulation. These results can be used for further seismic hazard analysis and decision support for disaster mitigation purposes.

1 Introduction

Sumatra is one of among islands in Indonesia with high earthquake activity. The seismicity rate is ~14.078 to ~17.185 earthquake per year from 2000 to 2020 [1]. The Mw 9.1 Sumatra-Andaman earthquake on December 26, 2004 [2], the Mw 8.6 Nias-Simeulue earthquake on March 28, 2005 [3], the Mw 7.8 Mentawai earthquake on October 25, 2010, the Mw 6.2 Pasaman Barat earthquake on February 25, 2022 are some destructive earthquake phenomena in Sumatra that took many lives and high economy loss. The earthquake in Sumatra occurred because Sumatra is surrounded by an oceanic plate including India Plate, Burma Plate, Sunda Plate, and Australia Plate. These plates are moving relative to these three plates at rate of ~13 mm/year to ~77 mm/year [4], this region also known as megathrust. Sumatra also have 19 main active faults called Sumatran Fault Zone (SFZ). These faults are located from Northern Sumatra to Southern Sumatra. They are slipping at rate ~11 mm/year to ~27 mm/year [5]. Besides the SFZ, some local faults have been identified in Aceh Province such as Extension of Batee Fault, Langsa Fault, and Alas Fault [6], Lampahan Fault, Samalanga Fault, Geureudong Fault, Pameu Fault, Nisam Fault [7], and Panteraja Fault [8]. The illustration of the Sumatran tectonic setting is shown in Figure 1.

An earthquake always occurs at anytime and anywhere. The time and location of the earthquake is unpredictable. However, we can learn the seismic activity (hereafter seismicity) by using the historical earthquake data through the statistical approach [9]. The main parameters to study the seismicity are called b-value and a-value. The b-value can be used to estimate the stress of rock and the a-value indicate the rate of seismicity. The high b-value is considered to low stress of the rock [10,11] while the low b-value is considered to high accumulated stress of rock [12,13]. The b-value also measures the relative number between small and large earthquakes [14,15].

The [16] have been conducted research regarding to the seismicity in the Northern Part of Sumatra. They concluded that the seismicity in the Northern Part of Sumatra was high. They divided the catalog into two-time windows from 1970 to 2005 which is in range of the Sumatra-Andaman (2004) and Nias (2005) earthquakes also from 2006 to 2020 which is after these two big earthquakes. According to their research, the big earthquake was mostly preceded by the low of b-value and a-value. Other research has been conducted by [12] for the aftershock's seismicity on December 26, 2004 and March 28, 2005 earthquakes in the Northwest Part of Sumatra. They used ISC and NEIC earthquake catalog from December 26, 2004 to June 30, 2005. They concluded that the 2004 earthquake was preceded ≈6 months by a significant drop in b-value. By the low b-value, it indicates the high potential of new large shocks. Globally, the average of b-value was found to be 1 [17,18]. However, some studies found the b-value varied from 0.2 to 2.0 [19].

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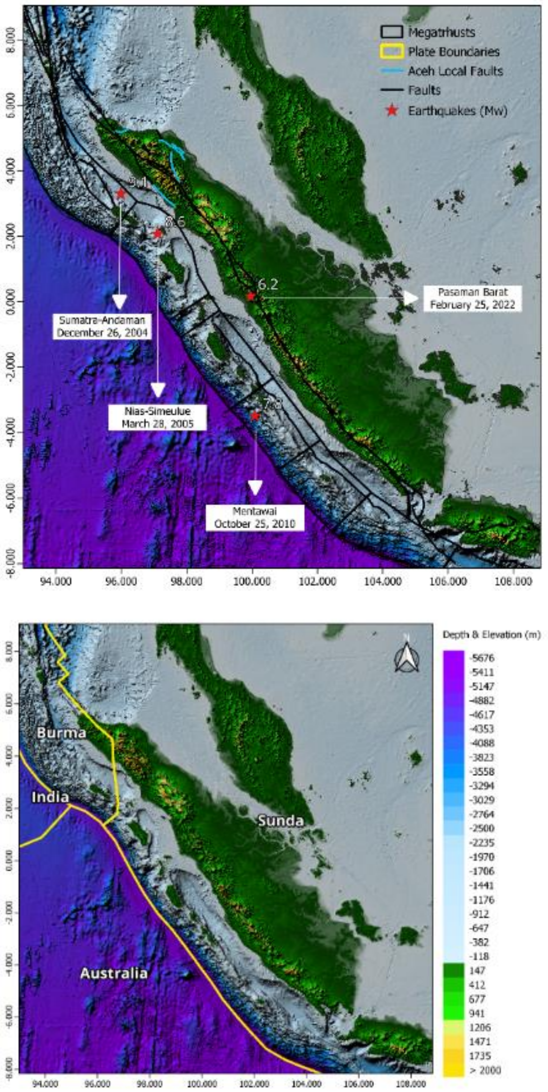


Fig 1. Active Faults and Megathrusts (top), plates boundaries (bottom) in Sumatra

Understanding seismicity can be helpful for further seismic hazard analysis. We can extract a new insight regarding the current seismicity over time and use this parameter to risk calculation and mitigation purposes. Therefore, the objective of this research is to conduct an analysis of the seismicity in Sumatra by using updated earthquake catalogs through temporal changes and spatial distribution of b-value and a-value.

2 Data and Methodology

The earthquake catalogs were retrieved from Meteorology, Climatology and Geophysics Agency (BMKG), International Seismological Centre (ISC), and United States Geological Survey (USGS) from October 10, 1906 to the December 30, 2022. The catalog from BMKG had been relocated by [20] and catalog from ISC and USGS had been reviewed by their agency. There were 73.881 earthquakes from these three catalogs. The non-moment magnitude (M_w) unit was converted to M_w unit by using equation as written in equation (1) [21]. The catalog was declustered by using [22] method to obtain mainshock only through ZMAP program [23], where the parameters of declustering process are shown in Table 1. We evaluated the declustered earthquake catalog (hereafter called mainshocks) distribution in time domain that must follows Poisson distribution by using Kolmogorov-Smirnov test where the p-value must greater than 0.05 [24]. We considered to use the data with magnitude greater than Mw 3 and with depth in range 10 to 300 Km. The temporal changes of b-value and a-value analysis were analyzed more than 50 events per year while the spatial distribution of b-value and a-value analysis were analyzed more than 50 events per grid (0.5° x 0.5°). The b-value was calculated by using Linear Regression as written in equation (2b) [25] and standard

$$M_w = \begin{cases} 1.0107m_b + 0.0801 & for\ 3.7 \leq m_b \leq 8.2 \\ 0.6016M_s + 2.476 & for\ 2.8 \leq M_s \leq 6.1 \\ 0.9239M_s + 0.5671 & for\ 6.2 \leq M_s \leq 8.7 \end{cases} \tag{1}$$

$$a = \frac{(\Sigma X)(\Sigma X^2)-(\Sigma X)(\Sigma XY)}{n(\Sigma X^2)-(\Sigma X)^2} \tag{2a}$$

$$b = \frac{n(\Sigma XY)-(\Sigma X)(\Sigma Y)}{n(\Sigma x^2)-(\Sigma X)^2} \tag{2b}$$

$$b_{std} = b/\sqrt{N} \tag{3}$$

Table 1. Parameters of Reasenberg's declustering method

Parameters	Standard	Min	Max
$\tau_{min}(days)$	1	0.5	2.5
$\tau_{max}(days)$	10	3	15
p_1	0.95	0.9	0.99
x_k	0.5	0	1
x_{meff}	1.5	1.6	1.8
r_{fact}	10	5	20

deviation of b-value was calculated by using equation (3), where N is the number of earthquakes at magnitude completeness (M_c) [26]. The equation (2a) was used to calculate the *a-value*.

3 Results and Discussions

3.1 Declustering Earthquake Catalog

There were 73.881 earthquakes from the initial catalog in Sumatra. Then, there were 51.715 earthquakes (mainshocks) after declustering was applied. Based on Kolmogorov-Smirnov test, before and after declustering, both catalogs were Poisson distributions, where the p-values were 0.500034 and 0.500048, respectively, as shown in Figure 2. Although the initial catalog is a Poisson distribution with a p-value greater than 0.05, but this catalog still has foreshocks, aftershocks, and mainshocks. However, the declustered catalog gives the higher p-value than the initial catalog. This means that the declustering process successfully removes 22,166 of the foreshocks and aftershocks.

The mainshock catalog was then filtered for magnitude and depth parameters. The mainshock catalog has magnitudes ranging from M_w 2 to M_w 9.1, as shown in Figure 3 (a). Then, the earthquakes below M_w 3 were removed from the mainshock catalog. Although

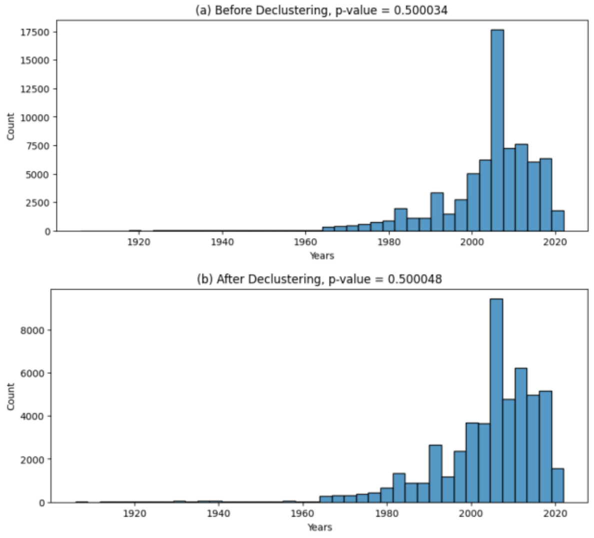


Fig 2. Number of earthquake distributions with the p-value of Kolmogorov-Smirnov test (a) before declustered and (b) after declustered

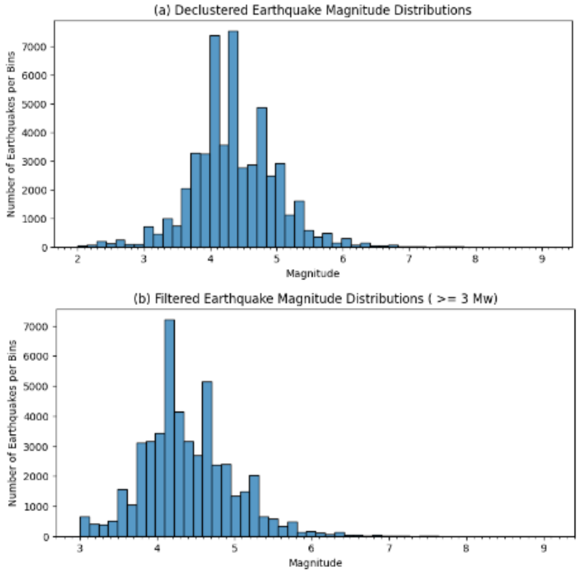
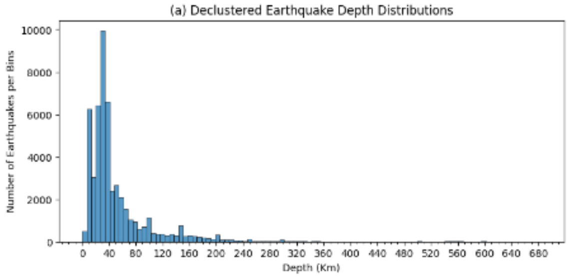


Fig 3. Earthquake magnitude distributions (a) before magnitude filtering and (b) after magnitude filtering above Mw 3.

the earthquakes above Mw 6.5 were also quite few, these earthquakes were not removed because the large earthquakes were important to be analysed. The filtered magnitude distributions of mainshock catalog are shown in Figure 3 (b).



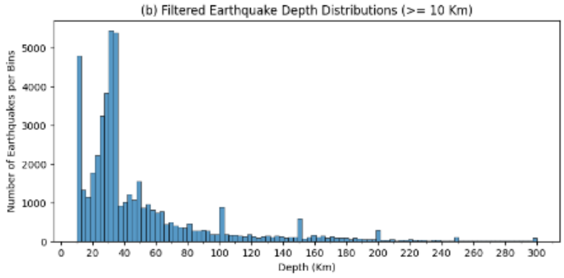


Fig 4. Earthquake depth distributions before (a) depth filtering and (b) after depth filtering above 10 Km

Furthermore, the mainshock catalog has a depth in the range 0 Km to 684 Km, as shown in Figure 4 (a). The earthquakes less than 10 Km and more than 300 Km depth were removed from the mainshock catalog because these earthquakes did not have much activity. The filtered depth distributions are shown in Figure 4 (b). Finally, there are 49.166 mainshock in the filtered catalog.

3.2 Temporal Change Analysis of *b*-value and *a*-value

The temporal change analysis of Sumatra's seismicity is described by the *b*-value and *a*-value parameters. In general, the mainshock catalog has a *b*-value of 0.98 (+/-0.01) and an *a*-value of 8.73, as shown in Figure 5 (a). Seismicity in Sumatra is dominated by M_w 4.3 earthquakes from 1906 to 2022. In detail, the temporal change analysis is divided per year as shown in Figure 6. More than 50 events per year were selected

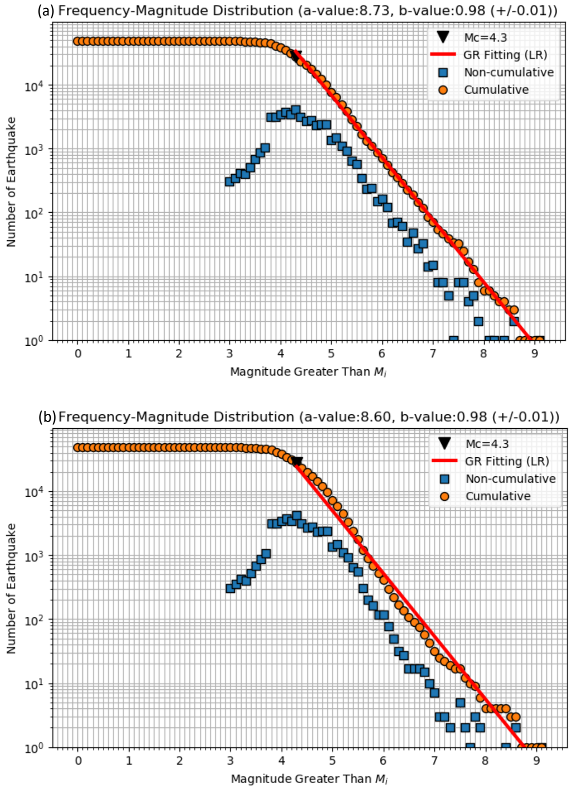
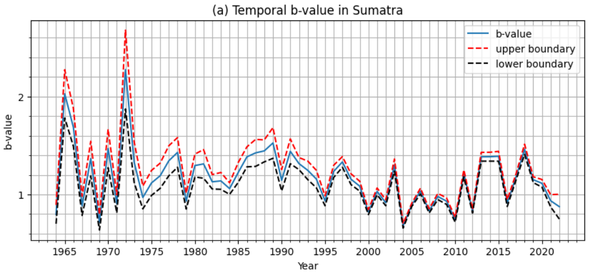


Fig 5. Frequency-Magnitude Distribution (FMD) of (a) declustered catalog from 1906 - 2022 and (b) filtered catalog from 1964 - 2022 in Sumatra

to be analyzed. Then, the range of years has changed to 1964 - 2022 with the earthquake more than 50 events per year. Then, the *b*-value and *a*-value for this period are 0.98 +/- 0.01 and 8.6, respectively, as shown in Figure 5 (b). There is a slight change in the a-value, which has dropped to 8.6 because of the decrease in the number of earthquakes.



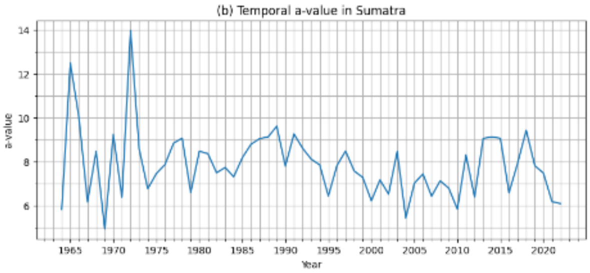
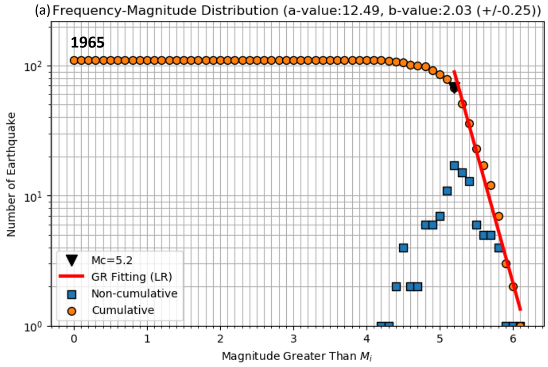


Fig 6. Temporal b-value (top) and a-value (bottom) in Sumatra from 1964 – 2022



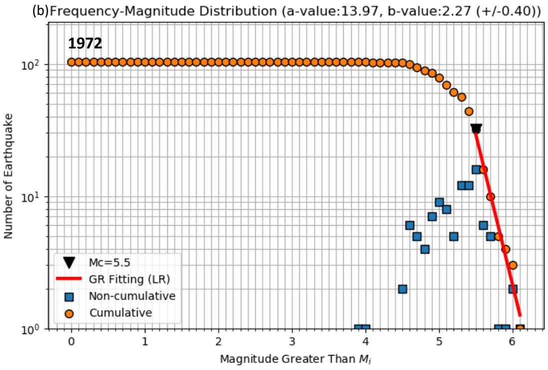


Fig 7. The Frequency-Magnitude Distribution (FMD) for earthquake in Sumatra (a) in 1965 and (b) in 1972

This research found two significant high *b*-values and *a*-values which are in 1965 and 1972. In 1965, the *b*-value is 2.03 +/- 0.25 and the *a*-value is 12.49. In 1972, *b*-value is 2.27 +/-0.4 and the *a*-value is 13.97. The high *b*-value indicates high seismicity with the small earthquakes of these years. The small earthquakes are distributed in the range of M_w 4 and M_w 6.1 as shown in Figure 7. The Mw 5.2 and Mw 5.5 are the dominant magnitudes in these years respectively. In the range 1964 - 2022, the lower magnitude tends to have higher *b*-values. Otherwise, the higher magnitude tends to have lower *b*-values. This is the correlation between the *b*-value and the maximum moment magnitude (M_w) per year as shown in Figure 8.

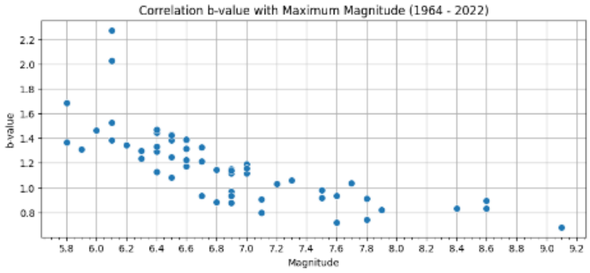


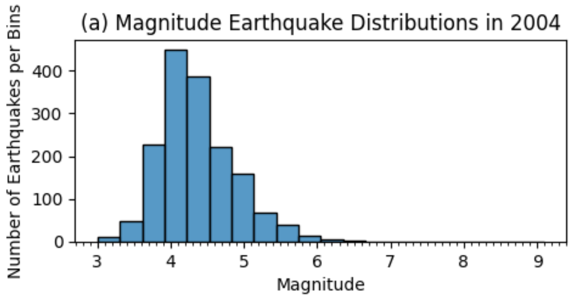
Fig 8. The correlation *b*-value with maximum magnitude per year (1964 – 2022).

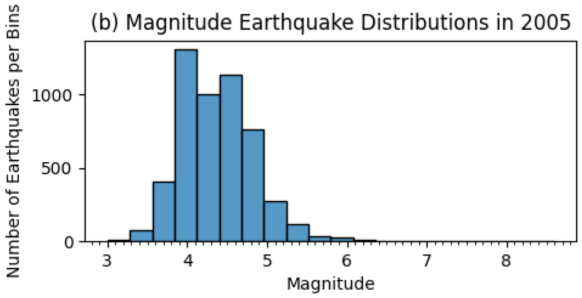
The temporal *b*-value and *a*-value were validated with some destructive earthquakes in Sumatra, as shown in Table 2. The temporal *b*-values corresponding to the year of occurrence of the destructive earthquakes is found to be less than 1 (global *b*-value). The lowest b-value is for the year 2004. This refers to the 2004 Sumatra-Andaman earthquake. It can tell us that the high seismic stress accumulation generates large earthquake with low *b*-value. The large or destructive earthquake in Indonesia can be identified with magnitude greater than 5 [27]. Furthermore, in 2005 the *b*-value and *a*-value are higher than the other three years, as written in Table 2. This is because the earthquakes in the magnitude ranging M_w 4 to M_w 5 occur more frequently in 2005 than in the other three years (Figure 9). In other words, the seismicity in 2005 has low seismic stress accumulation with number of small earthquakes frequently active.

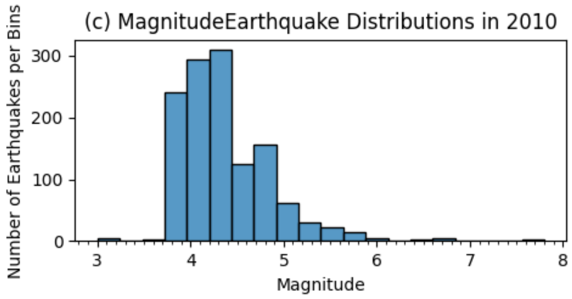
Table 2. The temporal b-values and a-values in Sumatra for each year that might correspond to destructive earthquakes

Location (Year)	M_w	b-value (std)	a-value
Sumatra-Andaman (2004)	9.1	0.67 +/- 0.02	5.43
Nias-Simeulue (2005)	8.6	0.89 +/- 0.01	7.02
Mentawai (2010)	7.8	0.74 +/- 0.02	5.84
Pasaman Barat (2022)	6.2	0.87 +/- 0.12	6.09

This could be one of the factors of the M_w 8.6 earthquake in Nias-Simeulue, which could be affected by the high frequency of small earthquakes or high seismic activity rate. In 2010 and 2022, the *b*-values decrease from the previous year respectively (see Figure 6). It indicates high seismic stress accumulation of these years. The low *b*-values in 2010 might correspond to Mentawai earthquake and in 2022 might correspond to Pasaman Barat earthquake (see Table 2). In 2022 does







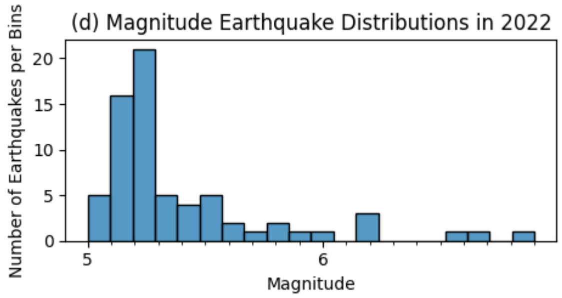


Fig 9. Magnitude distributions for (a) 2004, (b) 2005, (c) 2010 and (d) 2022

not has as much earthquake activity as the other three years. There are only 69 mainshocks that has been identified from the catalog. However, there are some earthquakes greater than M_w 6 that occur in this year. Based on this validation, three out of four destructive earthquakes show that the *b*-values tend to decrease before large earthquakes occur.

3.3 Spatial Distribution Analysis of *b*-value and *a*-value

Spatial analysis of *b*-value and *a*-value in Sumatra from 1964 to 2022 was shown in Figure 10. The *b*-value varied from ≤ 0.63 to ≥ 2.68 and the *a*-value varied from ≤ 3.9 to ≥ 14.27. Sumatra is dominated by *b*-value less than 1.91 and *a*-value less than 10.40. The spatial *b*-value and the *a*-value were validated to the destructive earthquakes (green stars in Figure 10 and Table 3), the Mentawai earthquake has the lowest b-value even though its magnitude is smaller than the Sumatra-Andaman earthquake. These values are not very different. Overall, the *b*-values of the destructive earthquakes in Table 3 are less than 1. The spatial analysis confirms that the low *b*-value indicates the high seismic stress accumulation and causes the large earthquake. Meanwhile, the Pasaman Barat earthquake gives the highest seismic activity (*a*-value). It might be because this earthquake occurred in active faults, which are much more frequent spatially in the range of 1964-2022.

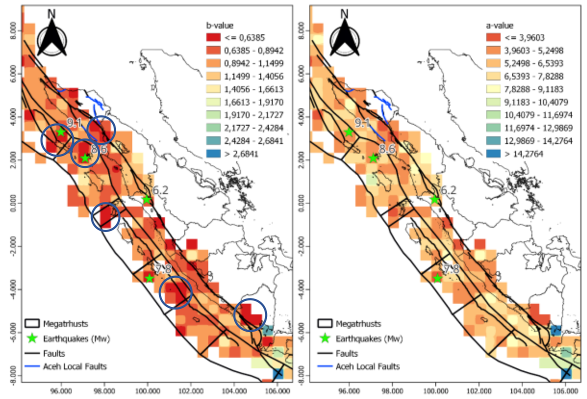


Fig 10. The spatial of *b*-value and *a*-value in Sumatra from 1964-2022

Table 3. The spatial of *b*-value and *a*-value in Sumatra from 1964 to 2022 that might correspond to destructive earthquake

Location (Year)	M_w	b-value (std)	a-value
Sumatra-Andaman (2004)	9.1	0.508 +/- 0.03	4.091
Nias-Simeulue (2005)	8.6	0.536 +/- 0.04	4.085
Mentawai (2010)	7.8	0.500 +/- 0.06	3.475
Pasaman Barat (2022)	6.2	0.866 +/- 0.10	5.288

Six clusters were found with the lowest *b*-value (≤ 0.63) spatially, as shown in the blue circle in Figure 10. Four clusters are in megathrust segments, such as Sumatra-Andaman, Nias-Simeulue, Batu, and Mentawai-Pagai. Two clusters are in active fault areas, such as in Tripa, Renun, and Semangko-Timur A faults. These areas might indicate high seismic stress accumulation with their seismic activity rate and produce large earthquakes.

This study provides information about the recent seismic activity in Sumatera. By using the parameters of this study, it is very possible to update the seismic hazard in Sumatera. Through the same method, the calculation of seismic activity parameters in Indonesia could be done using the latest earthquake catalog around Indonesia. Finally, the seismic hazard maps of Indonesia could also be updated. It is very useful for decision support for disaster mitigation purposes, such as developing earthquake-resistant buildings and locating buildings before development based on seismic hazard maps.

4 Conclusions

The temporal change and spatial distribution analysis through the *b*-value and *a*-value parameters have been conducted in Sumatra. These analyses made use of an earthquake catalog from 1964-2022 that retrieved from BMKG, USGS and ISC catalog. In temporal change analysis, there are two periods of the year that have significantly high *b*-value and *a*-value. They are in 1965 and 1972. The *b*-value in 1965 is 2.03 +/- 0.25 and the *a*-value is 12.49. Then, *b*-value in 1972 is 2.27 +/-0.4 and the *a*-value is 13.97. The high *b*-value shows the low seismic stress or high seismicity with small earthquake of these years. The temporal change and spatial distribution were validated by four destructive earthquakes in Sumatra such as Sumatra-Andaman, Nias-Simeulue, Mentawai and Pasaman Barat, all the *b*-values are less than 1. This confirms that the large earthquake has the low *b*-value or high seismic stress accumulation. Furthermore, this research also finds six the lowest *b*-value clusters in Sumatra spatially. Four clusters located in megathrust areas and the rest of two clusters located in active fault areas. These areas might have high seismic stress accumulation that could generate large earthquakes. Further research should be conducted to describe the seismic stress accumulation in Sumatra comprehensively, especially for these clusters. This result can be used for a preliminary study of seismic hazard analysis in Sumatera and decision-making support of disaster mitigation.

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