



Temporal Variation and Statistical Significance Assessment of Seismic b -Value in Iraq and Surroundings

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Abstract

The b -constant in frequency - magnitude relationship is a crucial factor in seismic studies and seismic hazard assessment. This study aims to evaluate the temporal variation of the b -value and its statistical significance in Iraq and its surroundings. The earthquake catalogue used (1980–2019) is obtained from Onur's (2017) catalogue and updated by Basra University's seismic laboratory. The least squares and the maximum likelihood methods were used to calculate the b -value for two-time windows (five years and one year). The statistical significance of the b -value is evaluated using the Z-test and Utsa's test. Both methods used to calculate the b -value show insignificant differences, indicating no impact of the calculation method on it. The findings showed that the b -value decreases with time. Results of assessing the statistical significance of the b -value for both time windows show statistically significant differences in some years and statistically insignificant differences in others. It was suggested that the statistical significance of the b -value be assessed before it is interpreted.

Keywords:

b -value, statistical significance, Temporal variation, Utsa's test, Z-test

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1. Introduction

The distribution of earthquake magnitude and frequency is in accordance with the Gutenberg-Richter (GR) Law: $\log_{10} NC = a - bM$ (Gutenberg and Richter, 1944), where a and b are constants, M is the magnitude, and NC is the cumulative frequency of earthquakes with magnitude exceeding M . The frequency of minor to major earthquakes is represented by the b -value, which is empirically demonstrated to be 1.0 (Schorlemmer et al., 2005; Petruccioli et al., 2019). Whereas a b value greater than one denotes low stress, a fractured or fluid-rich environment, and a greater proportion of small tremors than large events, a b value equal to one indicates a normal stress distribution and is typical in active tectonic environments like diving zones or transform faults (Mogi, 1962; Scholz, 1968). A b value less than one implies high stress and a uniform fault system, a greater potential for large earthquakes, and a

higher frequency of large events relative to small events (Scholz, 2015; Urban and Závada, 2021). An inverse relationship between the b -value and the differential stress in the crust is evident from global data (Spada et al., 2013; Scholz, 2015; Dal Zillo et al., 2018). The b -value is vital when assessing seismic hazards. (Wiemer and Wyss, 2000).

The tectonic significance of b – constant is addressed in the context of its relationship with the stress state, crustal material heterogeneity, faulting style, earthquake depth, tectonic environments, and heat flow. There is an inverse relationship between differential stress and the b -value. (Wu et al., 2018). Many studies have shown that the heterogeneity of Earth's crust materials leads to an increase in the b -value (e.g., Mogi, 1962; Mori and Abercrombie, 1997). Different studies have shown that the b -value decreases with increasing focal depth. (e.g., Rigo et al., 2018; Al-Heety and Mohammad, 2021; Sharon et al., 2022). (Bora et al., 2018; Al-Heety and Mohammad, 2021; Sharon

et al., 2022; Rafea and Al-Heety, 2023; Taroni and Carafa, 2023). found that the normal faulting regions show a high b -value, while strike-slip and reverse faulting regions show moderate and low values of b , respectively. The b -values decrease inversely with the differential stress in the continental crust and subduction zones (Scholz, 2015). Numerous investigations revealed that high b -values are correlated with high heat flow values. (e.g., Bilim 2019; Cheng et al. 2020; Ormeni et al. 2023).

The spatiotemporal variation of the b -value was one of the subjects on which seismic studies have frequently focused (Utsu, 1999). The temporal variations are more difficult to identify and of a lower order than spatial variations (Wiemer et al., 1998; Wiemer and Wyss, 1997, 2002). In general, the b -value's spatiotemporal changes are clues for large earthquake precursors (Smith, 1981). The b -value can drop months or years before major earthquakes in the source region (Chen and Zhu, 2020; Nanjo, 2020; Xie et al., 2022a). Laboratory acoustic emission studies show that the b -value decreases as stress accumulates in rock samples before fracturing occurs. (Scholz, 1968; Amitrano, 2003; Goebel et al., 2013). The b -values frequently have a lot of uncertainty (Utsu, 1999). Therefore, it is difficult to attribute variations in the value $-b$ to statistical artifacts or actual tectonic signals (Gulia and Wiemer, 2021; Li and Luo, 2024).

Many authors investigated the statistical significance of the spatiotemporal variations of b -value in the frequency magnitude relationship (e.g., Wiemer et al., 1998; Wiemer and Wyss, 2002; Schorlemmer et al., 2004; Nanjo et al., 2012; Zheng and Zhou, 2014; Xie et al., 2022b; Chan et al., 2024; Mirwald et al., 2024).

2. Aim of Study

This study aims to investigate the temporal variation and the statistical significance level (p -value) of b -value in Iraq and its surroundings.

3. Materials and Methods

Earthquake Data

The earthquake data source of the study area is the earthquake catalog compiled by Onur et al. (2017) and updated by the Seismological Laboratory at the University of Basra, Iraq. The updated catalogue covers the period from 1st

January 1900 to 31 December 2019. The extracted earthquake catalogue covers the period from 1st January 1980 to 31 December 2019. It includes 33485 earthquakes that occurred between the latitudes 26° – 40°N and longitudes 36° – 52°E (Fig.1).

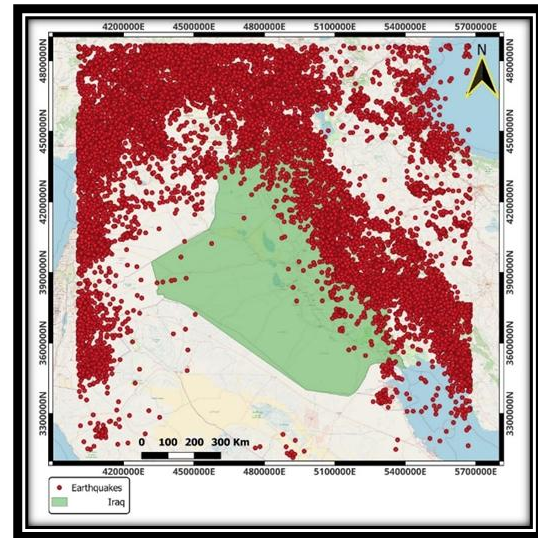


Fig. 1: Seismicity map of Iraq and surroundings for the period (1980-2019).

4. Methods

Completeness magnitude (M_c) estimation

The magnitude of completeness (M_c) of an earthquake catalog is the magnitude threshold over which we are (nearly) assured of recording every event. The number and geographic density of seismic stations, as well as the largest events in the earthquake database, have an effect on the M_c (Mignan et al., 2011). Estimating an earthquake catalog's M_c is the first step in the majority of seismological statistical analyses. The a and b values of the GR law are particularly impacted by M_c (Taroni and Carafa, 2023). The M_c represents the start of a linear segment of the frequency-magnitude distribution (Pavlenko and Zavyalov, 2022). Different techniques are used to calculate the completeness magnitude in earthquake catalogues. In the current study, the M_c was estimated using the maximum curvature (MAXC) technique suggested by Wiemer and Wyss (2000). The MAXC is the quickest way to estimate M_c and is a non-parametric approach. It establishes the first derivative of FMD's maximum and is most frequently used to discover the bin of magnitudes with the highest frequency in non-cumulative

FMD; this matches the previous approach, which is to find the maximum of the FMD first derivative. In the current study, the M_c was estimated for two-time windows: five years and one year.

Calculation of b -value

Least squares (Guttorp, 1987) and maximum probability (Aki, 1965) methods are the most often used techniques for calculating the b -value. The number of earthquakes used in the calculation of the b -value affects both techniques. The following equations are used to compute the b -value and the standard error (σ) using the maximum likelihood method (Aki, 1965):

$$b = \frac{1}{\ln(10)(M_{mean} - M_c)} \quad (1)$$

where M_{mean} is the mean magnitude of the earthquake group with $M \geq M_c$, and M_c is the completeness magnitude.

$$\sigma_b = b/\sqrt{N} \quad (2)$$

Where: N is the total number of events of the given sample.

Because the maximum likelihood method is most robust (Bengoubou – Valérius and Gibert, 2013), the b -value in the study area was calculated using the maximum likelihood. In the study, the least squares method was used only to investigate if the significance level (p -value) depends on the technique employed to estimate the b -value.

Statistical significance assessment of the b -value's temporal variation

To assess the level of statistical significance (p -value), the null hypothesis (H_0) is tested. Due to the null hypothesis (H_0), no significant change in the b -value has been seen over time, and the H_0 is accepted. If the null hypothesis is rejected, the alternative hypothesis (H_1) is adopted, and here the temporal variation of the b -value is statistically significant. When the b -value is low (typically less than 0.01 or 0.05), statistically significant variations indicate that these changes are unlikely due to random chance but to real natural changes. In the current study, the statistical test introduced by Utsu (1999) and the Z -test were used to assess the differences in b -value over time. In Utsu’s test, the AIC (Akaike Information Criteria, Akaike, 1974) is computed for each earthquake catalog. Then the difference (ΔAIC) between two catalogs with different b -values (b_1 and b_2) is calculated using the following equation:

$$\Delta AIC = -2(N_1 + N_2) \ln(N_1 + N_2) + 2N_1 \ln(N_1 + N_2 b_1/b_2) + 2N_2 \ln(N_2 + N_1 b_2/b_1) - 2 \quad (3)$$

Where N_1 and N_2 are the number of events in each catalog, and b_1 and b_2 are the b -value of each catalog time window.

The significance level (p -value) is given by the probability (Utsu, 1999):

$$p = e^{(-\Delta AIC/2)-2} \quad (4)$$

According to Utsu’s method, the difference between two b -values is highly significant when $\Delta AIC \geq 5$, significant difference when $2 \leq \Delta AIC < 5$, and insignificant difference when $\Delta AIC < 2$.

The statistical significance of the temporal variation of b -value in the study area was assessed also using Z -test. It is used for determining whether two populations are statistically different from one another: the Z -test. When performing a Z -test, a Z -score is computed (Warne, 2020). The Z -score is calculated using the following equation:

$$Z = \frac{b_1 - b_2}{\sqrt{SE(b_1)^2 - SE(b_2)^2}} \quad (5)$$

where b_1 and b_2 are the b -values of each catalog time window, and SE is the standard error for the b -value.

The Z -score was compared to critical values (e.g., 1.96 for $p = 0.05$). When $p \leq 0.05$, the two tested time windows are statistically significant.

5. Results

Completeness magnitude (M_c)

The M_c was estimated for a five-year window and a one-year window using the MAXC method. Figure (2) illustrates how to identify M_c using the MAXC method. The five-year and yearly variations of M_c and b -value are shown in Figure (3). Generally, the remarkable trend is that the M_c decreases with time. This result is interpreted in terms of increasing of the seismological stations and the improvement in analysis methods (Wiemer and Wyss, 2000).

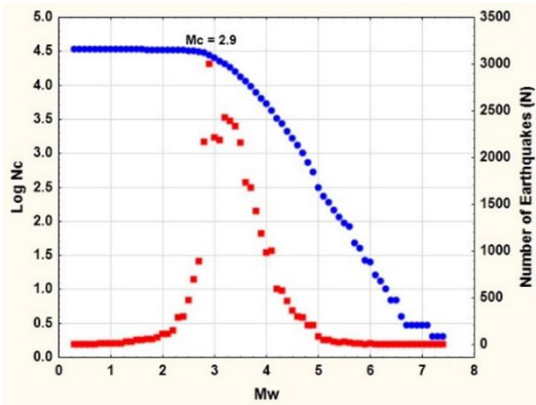


Fig. 2: The Maximum curvature (MAXC) method.

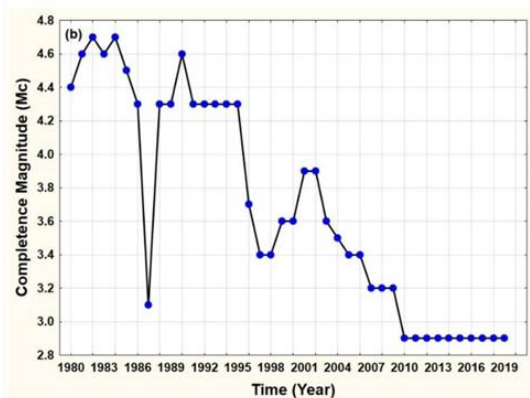
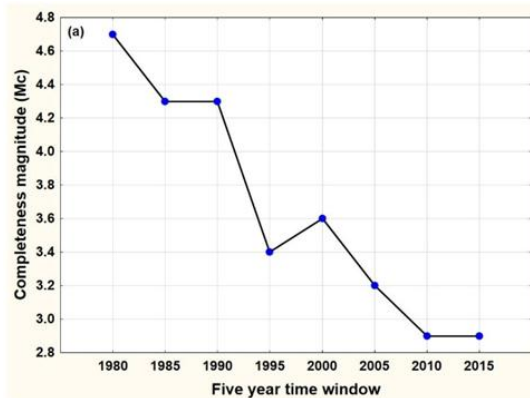


Fig. 3: Temporal variation of completeness magnitude (Mc: (a) Five-year time window, (b) yearly variation.

Temporal variation of b-value

The temporal variation of b-constant value in Iraq and surroundings was investigated in terms of the five-year and one-year time windows. In order to achieve stronger statistical confidence, a minimum of 100 events per time window was used to determine the b-constant value in the chosen time periods. The minimum number of events in the five-year time window and one-year time window are 117 and 216 events. Due to the insufficient number of events in the years 1980-1995, they were not included in the yearly variation assessment of the b-value. Results of the

calculation of the b-value for the selected time windows are listed in Tables 1 and 2.

Table 1: The b-value in the time window of five years.

Time Window	b - value	
	Least Square Method LSM	Maximum likelihood Method (MLM)
1980 -1984	1.10 ± 0.04	1.97 ± 0.18
1985 - 1989	1.35 ± 0.05	1.31 ± 0.08
1990 - 1994	0.84 ± 0.05	1.31 ± 0.07
1995 - 1999	1.20 ± 0.03	0.92 ± 0.02
2000 -2004	1.14 ± 0.02	1.24 ± 0.02
2005 - 2009	1.35 ± 0.03	1.35 ± 0.01
2010 - 2014	1.04 ± 0.01	0.94 ± 0.01
2015 - 2019	0.97 ± 0.02	0.69 ± 0.01

Table 2: The b-value in one year time window.

Time Window	b - value	
	Least Square Method LSM	Maximum likelihood Method MLM
1996	1.09 ± 0.02	1.08 ± 0.07
1997	0.90 ± 0.06	1.11 ± 0.06
1998	1.01 ± 0.02	1.08 ± 0.05
1999	1.41 ± 0.06	1.14 ± 0.07
2000	1.09 ± 0.04	1.27 ± 0.07
2001	1.26 ± 0.06	1.31 ± 0.09
2002	1.01 ± 0.05	1.20 ± 0.08
2003	1.09 ± 0.06	1.60 ± 0.05
2004	1.29 ± 0.03	1.27 ± 0.04
2005	1.06 ± 0.03	1.31 ± 0.03
2006	1.26 ± 0.07	1.55 ± 0.05
2007	1.28 ± 0.03	1.40 ± 0.03
2008	1.40 ± 0.06	1.60 ± 0.03
2009	1.62 ± 0.03	1.81 ± 0.04
2010	0.99 ± 0.02	1.03 ± 0.03
2011	1.02 ± 0.01	0.98 ± 0.01
2012	0.98 ± 0.03	0.98 ± 0.02
2013	1.02 ± 0.02	1.05 ± 0.03
2014	0.90 ± 0.02	0.67 ± 0.02
2015	0.99 ± 0.04	0.59 ± 0.03
2016	0.97 ± 0.05	0.55 ± 0.02
2017	0.82 ± 0.05	0.57 ± 0.02
2018	0.97 ± 0.02	0.83 ± 0.02
2019	0.98 ± 0.04	0.80 ± 0.04

The five-year and yearly temporal changes of b- value and Mc in Iraq and its surroundings are shown in Figure (4). The scatterplot of b-value against Mc for both time windows is illustrated in Figure (5).

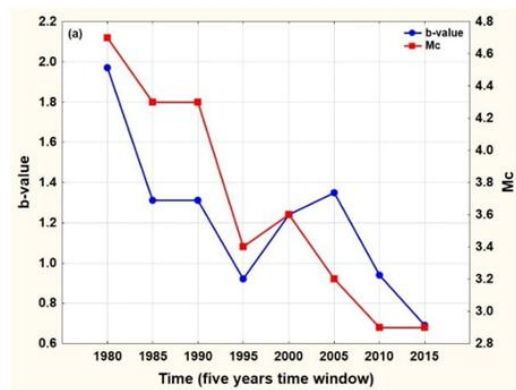


Fig. 5: Scatterplot of *b*-value against *Mc*: (a) five years' time window and (b) one year time window.

Statistical significance of the *b*-value's temporal variation

The statistical significance of the temporal variation of *b*-value in Iraq and surroundings was estimated using Utsu's test and Z-test. Results of the statistical significance tests of *b*-value for the selected two-time windows are listed in Tables (3 and 4). Results of the analysis of the statistical significance of the temporal variation (five-year time window) of the *b*-value showed an important compatibility between those assessed by Utsu's test and those estimated by the Z- test. The statistical significance test of *b*-value for the time window of five years showed statistically significant difference for all time windows except 1985-1989 window, while the yearly variation of the statistical significance of *b*-value exhibited insignificant differences for the years 1996-2002, 2004-2005, 2006-2007, 2010-2011, 2011-2012, 2015-2016, 2016-2017 and 2018-2019 and significant differences for other time windows.

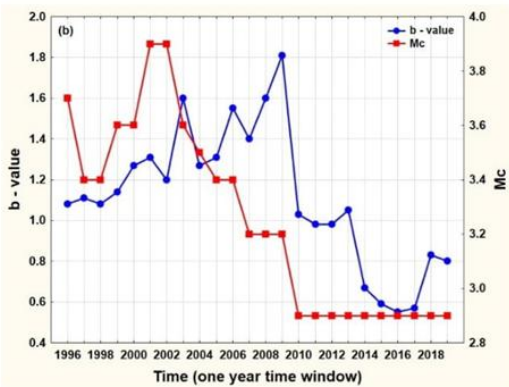


Fig. 4: Temporal variation of *b*-value and *Mc*: (a) five years' time window and (b) one year time window

Table 3: Results of the statistical significance tests of *b*-value for the time window of five years.

Time Period	Number of Earthquakes	Mc	b-value	Statistical difference type	
				Utsu's test	Z-Test
1980-1984	117	4.7	1.10	Significant	Significant
1985-1989	263	4.3	1.35	Insignificant	Insignificant
1990-1994	283	4.3	0.84	Significant	Significant
1995-1999	1474	3.4	1.20	Significant	Significant
2000-2004	2306	3.6	1.14	Significant	Significant
2005-2009	8241	3.2	1.35	Significant	Significant
2010-2014	8679	2.9	1.04	Significant	Significant
2015-2019	3939	2.9	0.97	Significant	Significant

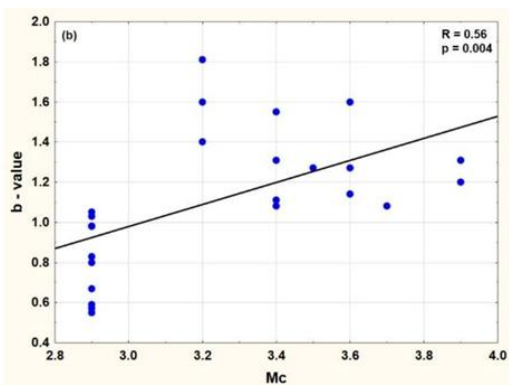
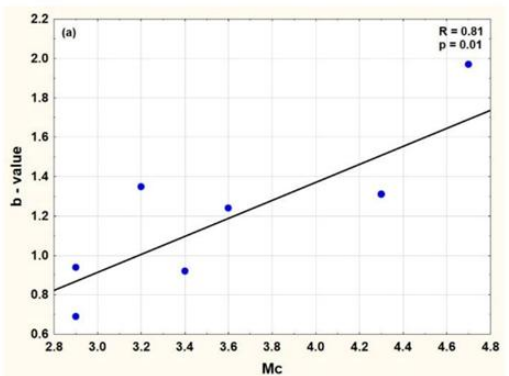


Table 4: Results of the statistical significance tests of b-value for the time window of one year.

Time Window	b-Value	Utsu-Test	Z-Test
1996	1.09		
1997	0.90	insignificant	insignificant
1997	0.90	insignificant	insignificant
1998	1.01	insignificant	insignificant
1998	1.01	insignificant	insignificant
1999	1.41	insignificant	insignificant
1999	1.41	insignificant	insignificant
2000	1.09	insignificant	insignificant
2000	1.09	insignificant	insignificant
2001	1.26	insignificant	insignificant
2001	1.26	insignificant	insignificant
2002	1.01	insignificant	insignificant
2002	1.01	significant	significant
2003	1.09	significant	significant
2003	1.01	significant	significant
2004	1.29	significant	significant
2004	1.29	insignificant	insignificant
2005	1.06	insignificant	insignificant
2005	1.06	significant	significant
2006	1.26	significant	significant
2006	1.26	insignificant	insignificant
2007	1.28	insignificant	insignificant
2007	1.28	significant	significant
2008	1.40	significant	significant
2008	1.40	significant	significant
2009	1.62	significant	significant
2009	1.62	significant	significant
2010	0.99	significant	significant
2010	0.99	insignificant	insignificant
2011	1.02	insignificant	insignificant
2011	1.02	insignificant	insignificant
2012	0.98	insignificant	insignificant
2012	0.98	significant	significant
2013	1.02	significant	significant
2013	1.02	significant	significant
2014	0.90	significant	significant
2014	0.90	significant	significant
2015	0.99	significant	significant
2015	0.99	insignificant	insignificant
2016	0.97	insignificant	insignificant
2016	0.97	insignificant	insignificant
2017	0.82	insignificant	insignificant
2017	0.82	significant	significant
2018	0.97	significant	significant
2018	0.97	insignificant	insignificant
2019	0.98	insignificant	insignificant

6. Discussion

Temporal variation of b-value

The mean of b- value for the five years and one time window are 1.21 ± 0.13 and 1.11 ± 0.06 , respectively. The obtained result shows that Mc and b-value decrease with time for both selected time windows (Fig. 4). In other words, b- value decreases as Mc declines. If the difference between the completeness magnitude and the maximum

magnitude is less than three, the b-value may be skewed. This indicates a tendency of the b-value to decline with a decrease in the completeness magnitude (Marzocchi et al., 2020). The temporal variation of the b-value for the five-year time window shows a gradual drop in the b - value for the period 1980 - 2015, with noticeable fluctuations, especially after 2005. The b-value annual change in the study area shows more frequent fluctuations with a significant rise from 1998 to 2008 and a sharp decline after 2010. Compared to the smoother trend of the five-year window, the one-year window shows more variability and records finer details.

The b- value in the study area was calculated using the least squares and maximum likelihood methods to investigate the impact of the calculation method on b- value as well as the statistical significance of the temporal variation to it. The results of the analysis of variance (ANOVA) between b- values calculated by both methods show insignificant differences ($p \leq 0.05$). This result is confirmed by a scatterplot of b-value calculated by the least squares method (LSM) against b-value estimated by the maximum likelihood method (MLM). Figure (5) exhibits a significant positive strong correlation relation at ($p \leq 0.05$) between the b-value calculated by LSM and the b-value estimated by MLM. This result shows that there is no impact of the method of calculation in b- value. El-Isa (2013) stated that if a significant number of events are used in the calculation, there is a reasonable correlation between the findings of the b-value calculation for both methods.

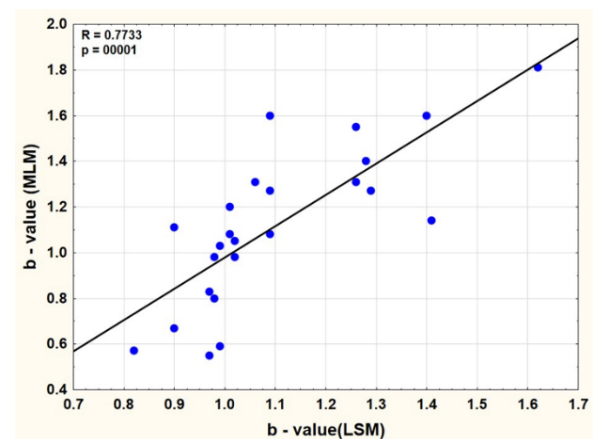


Fig. 5: Scatterplot of b-value (MLM) against b-value (LSM).

Statistical significance of the *b*-value's temporal variation

The result of the assessment of the statistical significance of the *b*-value temporal variation is listed in Tables 3 and 4. Utsu's test shows compatibility in assessing the statistical significance of the temporal variation of *b*-value with the Z- test. This result suggests the reliability of using one or both tests in estimating the statistical significance of spatiotemporal change of *b*-value. This result suggests the reliability of using one or both tests in evaluating the statistical significance of the spatiotemporal change of *b*-value. However, we need case studies using various earthquake catalogues to confirm this result. The tests used to assess statistical significance are not affected by the method used to calculate the *b*-value because there is no effect of the calculation method in estimating the *b*-value, as concluded in the current study. The statistically unimportant variations indicate that the *b*-value's temporal change is somewhat stable over time, and any fluctuations that are detected are probably within the range of typical statistical changes. If there is a negligible variation in the *b*-value amongst earthquake groups, they might not all have the same size distribution (Utsu, 1999). The *b*-value's notable temporal instability suggests that its change over time is not random and may be due to underlying variations in the area's stress or seismic activity. The temporal stability of the *b*-value was reported by some authors (e.g., Wiemer and Wyss, 2002; Schorlemmer et al., 2004; Mirwald et al., 2024). Other authors suggested instability temporal variation of *b*-value (Wiemer et al., 1998; Nanjo et al., 2012; Zheng and Zhou, 2014; Xie et al., 2022b; Chan et al., 2024). We suggested assessing the statistical significance of the *b*-value before interpreting it. Mirwald et al. (2024) stated that the *b*-value should be significant before interpreting any change in it.

7. Conclusion

In the current study, the temporal variation and statistical significance level of the *b*-value in Iraq and its surroundings were investigated. The following are the conclusions drawn from the obtained results:

1. For the two selected time windows, the M_c and *b*-values drop over time.
2. The *b*-value's temporal variation throughout the five years reveals a gradual decrease from 1980 to 2015, with noticeable fluctuations, particularly after 2005.
3. The *b*-value's annual change demonstrates more frequent fluctuations, rising significantly between 1998 and 2008 and then falling sharply after 2010.
4. The method used to determine the *b*-value does not influence the statistical tests used to evaluate statistical significance since the calculating method does not affect estimating the *b*-value.
5. The insignificant statistical differences indicate that the *b*-value's temporal change is relatively stable throughout time and that any fluctuations that are noticed are probably within the bounds of normal statistical changes.
6. The statistically significant temporal variation of the *b*-value suggests that *b*-value change over time is not random and may be due to underlying variations in the stress or seismic activity rate in the study area

8. Conflict Of Interest

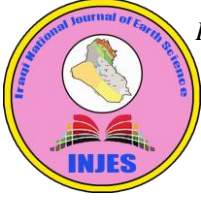
The authors declare that there are no conflicts of interest regarding the publication of this manuscript

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التغير الزمني وتقييم الأهمية الإحصائية لقيمة b في العراق والمناطق المحيطة

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الملخص

يمثل الثابت b في علاقة تكرار - المقدار الزلزالي عاملاً مهماً في دراسات الزلزالية والزلزالية التكتونية وتقييم المخاطر الزلزالية. يهدف البحث إلى دراسة التغير الزمني وتقييم الأهمية الإحصائية لقيم b في العراق والمناطق المحيطة. استخلص الفهرس الزلزالي لمنطقة الدراسة والذي يغطي الفترة من 1980 إلى 2019 من فهرس الهزات الأرضية المعد من قبل (Onur et al., 2017) والمحدث من قبل المختبر الزلزالي في جامعة البصرة. وظفت طريقة المربعات الدنيا وطريقة الاحتمالية القصوى لحساب قيمة b لنافتين زمنيتين (خمسة سنوات وسنة واحدة). استخدم اختبار أوتسو واختبار Z لتقييم الأهمية الإحصائية لقيمة b . أظهرت النتائج عدم وجود فروقات معنوية بين قيمة b المحسوبة بطريقة المربعات الدنيا مع تلك المحسوبة بطريقة الاحتمالية القصوى. أظهرت النتائج أيضاً انخفاض قيمة b مع الزمن ولكلا الناقتين. تراوحت نتائج تقييم الأهمية الإحصائية لقيمة b بين تغيرات مهمة احصائياً وتغيرات غير مهمة احصائياً ولكلا الناقتين. تطابقت نتائج تقييم الأهمية الإحصائية المحسوبة باختبار أوتسو مع تلك المحسوبة باختبار Z . نوصي بتقييم الأهمية الإحصائية لقيمة b قبل تفسيره.

الكلمات المفتاحية:

قيمة b ، الأهمية الإحصائية، التغير الزمني، اختبار أوتسو، اختبار زد

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