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Regional patterns of seismic b-values variations in the Himalayan region (71.6°E – 95.5°E and 37.5°N – 26.6°N)

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Abstract

This study conducts a detailed seismic hazard assessment of the Himalayan region. It focuses on studying how b-values, based on the Gutenberg–Richter law, vary throughout location and time. These fluctuations assist measuring tectonic stress and provide insights into the region's seismic activity. This research focuses on five Himalayan sub-regions: Far Western, Western, Central-I, Central-II, and Eastern. It incorporates earthquake data spanning 1964 – 2023 obtained from the International Seismological Centre. The data were de-clustered using the Reasenberg method and examined by Maximum Likelihood Estimation. The results demonstrated considerable spatial variability in b-values across the Himalayan sub-regions. The Far Western Himalayas displayed the greatest b-value (0.93 ± 0.02), indicating frequent smaller earthquakes and lesser tectonic stress. In contrast, the Eastern (0.68 ± 0.02) and Central-I (0.69 ± 0.03) regions had the lowest b-values, implying more stress accumulation and a greater risk of future strong earthquakes. Temporal fluctuations, as a decrease in b-values preceding to the 2015 Gorkha earthquake (Mw 7.8) and a subsequent increase in Central-II (1.19 ± 0.03), highlighted the retention and release cycles. The Eastern Himalayas, particularly the Dhubri-Chungthang fault zone seismic gap in Bhutan, are considered a key high-risk zone. This region, with b-values ranging from 0.65 to 0.75, has remained unruptured since the 1934 Bihar-Nepal earthquake (Mw 8.4). The findings showed the influence of the continual convergence of the Indian and Eurasian plates (~20 mm/year) on strain heterogeneity. This study underlines the vital demand for intensive seismic monitoring, resilient infrastructure, and disaster readiness in low b-value areas to alleviate catastrophic risks in one of the globe's most tectonically active regions.

Keywords: b-value; Gutenberg–Richter law; Himalayan region

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1. Introduction

The Himalayan Mountain Range, the tallest mountain chain in the world, traverses five countries – India, Nepal, Bhutan, China (Tibet), and Pakistan – and extends over 2,400 km in southern Asia.[1] The continual collision between the Indian and Eurasian tectonic plates, which began around 50 million years ago (Mya) after the Neo-Tethys Ocean closed, is responsible for its construction.[2] The Indian Plate subducted northward beneath Eurasia between 70 and 50 Mya, closing the Tethys Ocean and leaving

behind the Indus-Tsangpo Suture Zone, a geological indicator of the ancient oceanic crust, was the primary step in the orogenesis of the Himalayas.[3] The continental collision phase (50 – 40 Mya) resulted in massive crustal shortening, folding, and thrust faulting, which uplifted the Greater Himalayas through systems, such as the Main Central Thrust, while the Main Boundary Thrust and Main Frontal Thrust distinguish the Lesser Himalayas and the young, sediment-rich Siwalik Hills, respectively.[4,5] Ongoing northward convergence of the Indian Plate at 5 – 10 mm/year sustains tectonic activity, driving uplift of peaks, such as Mount Everest and accumulating stress along major faults, such as the Main Himalayan Thrust (MHT), a primary source of strong earthquakes.[6,7] This dynamic process ensures continued seismic hazard in the region, exemplified by historical earthquakes and the persistent risk of future events as strain energy is episodically released.[8,9]

An earthquake is defined as the sudden release of accumulated stress along locked tectonic plate boundaries or intraplate zones, where abrupt crustal movement generates seismic waves.[9,10] In the Himalayas, this process is driven by the ongoing India-Eurasia collision, which has generated significant seismicity linked to strain release along the MHT.[2,6] One of the notable seismic activities in the Himalayas is the 1905 Kangra earthquake (Mw 7.8), where a segment of the western Himalayan front was ruptured, releasing stress accumulation in the Kangra reentrant.[11,12] The Bihar-Nepal earthquake (Mw 8.1) in 1934 involved slip along a ~250 km portion of the MHT, illuminating shallow decollement dynamics.[13-16] The 1950 Assam-Tibet earthquake (Mw 8.6) highlights the complexity of oblique convergence near the eastern Himalayan syntaxis, where thrust and strike-slip faulting combine to produce bimodal faulting.[17,18] The 2005 Kashmir earthquake (Mw 7.6) highlighted strain partitioning in the western syntaxis, with thrust and strike-slip components.[8,19,20] Most recently, the 2015 Gorkha earthquake (Mw 7.8) in central Nepal ruptured a 150 km × 60 km patch of the MHT, leaving deeper segments unbroken and underscoring heterogeneous coupling.[8,21-23] These events, spanning the MHT's strike, reveal segmented rupture behavior and variable locking depths, with GPS-derived convergence rates (~18 – 20 mm/year), suggesting ongoing strain accumulation.[6]

By analyzing the b-value in the Gutenberg–Richter law, this study aims to identify zones of differential stress accumulation, potential asperities, and fault maturity across the Himalayan region (71.6°E – 95.5°E and 26.6°N – 37.5°N), subdivided into five distinct sub-regions. Based on the probabilistic seismic hazard assessment report of India, tectonic features, and geology, the region has been broadly divided into four sections,[26-28] with the western section further subdivided for improved analysis. As a result, As a result, we have categorized the Himalayan region into five zones: Far Western, Western, Central-I, Central-II, and Eastern (Figure 1). Each of these zones has been defined based on distinct geological and tectonic characteristics to ensure a comprehensive assessment.

1.1. Frequency magnitude distribution

The frequency-magnitude distribution (FMD) of earthquakes[29] is a fundamental statistical relationship in seismology. It describes how the frequency of earthquakes scales with their magnitude, using the following equation:

$$\log N = a - bM \quad \text{(I)}$$

In Equation I, N is the cumulative number of events having magnitude $\geq M$; M is the magnitude of earthquakes; the constant a is the seismicity of the region; and b is the b-value of the earthquake frequency magnitude distribution.[29] The b-value, a key parameter in the Gutenberg–Richter law, quantifies the relative frequency of small to large earthquakes, where a lower b-value indicates a higher likelihood of large-magnitude events due to elevated tectonic stress, while a higher b-value reflects frequent small earthquakes and lower crustal strain.[30-32] To assess regional stress accumulation and evaluate the seismic hazard potential, seismologists have analyzed spatial and temporal fluctuations in b-values around the globe. As an example, researchers analyzed spatiotemporal variations in b-value within the subducting slab before the 2003 Tokachi-oki earthquake (M 8.0), Japan, to identify precursory seismic signatures.[33] Similarly, the b-value anomalies were noticed before the Assam Earthquake on April 28, 2021.[34] In addition, the low b-value anomaly identified in the west of Gorkha highlights the zone with potentially strong seismic activity in the future.[35]

2. Data and methods

An extensive earthquake catalogue covering a long period is essential for studying the seismic activity of any region. In this study, we focused on the Himalayas, located between 71.6°E and 95.5°E, and utilized earthquake data for the period from 1964 to 2023, from the International Seismological Centre catalogue.[36-38] The earthquake magnitudes in the catalogue are reported in mb (body-wave magnitude). The dataset comprises both dependent (foreshocks and aftershocks) and independent (mainshocks) events, but to ensure accurate analysis, only independent earthquakes are considered by applying de-clustering using the Reasenberg algorithm.[39] The de-clustering process was carried out in ZMAP

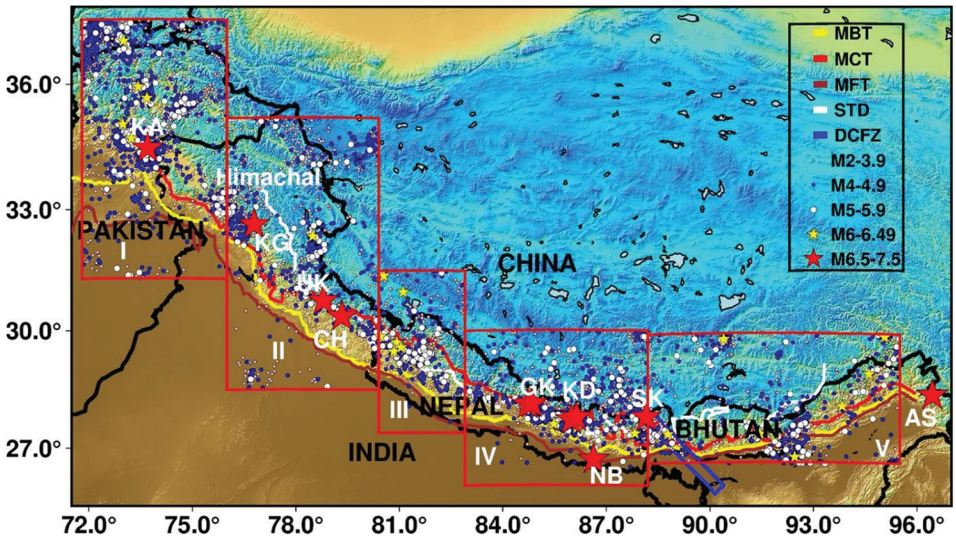

Figure 1. Study region with earthquake distribution. Red star indicates the earthquake >6.4 mb and notable past earthquakes, and red rectangular box are subdivided regions. UK stands for Mw 6.8 Uttar Kashi earthquake, CH stands for Mw 6.4 Chamoli earthquake, GK stands for Mw 7.8 Gorkha earthquake, NB stands for Mw 8.4 Nepal-Bihar earthquake, KA stands for Mw 7.6 Kashmir earthquake, SK stands for Mw 6.9 Sikkim earthquake, KG stands for Mw 7.8 Kangra earthquake, and AS stands for Mw 7.8 Assam earthquake. The blue rectangle stands for Dhubri-Chungthang Fault Zone (DCFZ).[24,25]

software (Swiss Seismological Service, Switzerland).[40] The segmented study regions are:

(i) Far Western Himalayan region (31.3°N – 37.5°N and 71.6°E – 76°E): A total of 3445 earthquake events with a magnitude of 3.0 mb or greater were recorded. After applying the de-clustering process, 47 clusters were identified, and following the removal of dependent events, 2867 independent events were retained.

(ii) Western Himalayan region (28.8°N – 35.2°N and 76°E – 80.2°E): A total of 1040 earthquake events with a magnitude of 3.0 mb or greater were recorded. After the de-clustering process, 24 clusters were identified, and following the removal of dependent events, 1004 independent events were retained.

(iii) Central-I Himalayan region (27.4°N – 31.5°N and 80.2°E – 82.9°E): A total of 529 earthquake events with a magnitude of 3.0 mb or greater were recorded. After the de-clustering process, 11 clusters were identified, and following the removal of dependent events, 494 independent events were retained.

(iv) Central-II Himalayan Region (26.03°N – 30°N and 82.9°E – 88.2°E): A total of 1482 earthquake events with a magnitude of 3.0 mb or greater were recorded. After the de-clustering process, 35 clusters were identified, and following the removal of dependent events, 1079 independent events were retained.

(v) Eastern Himalayan region (26.6°N – 29.9°N and 88.2°E – 95.5°E): A total of 767 earthquake events with a magnitude of 3.0 mb or greater were recorded. After the de-clustering process, 8 clusters were identified, and following the removal of dependent events, 706 independent events were retained.

The b-value was determined using the maximum likelihood estimate approach, which remains unaffected by large-magnitude earthquakes. In addition, the magnitude of completeness was computed using the first derivative of the frequency-magnitude curve.[32] The formula[41,42] for b-value estimation is as follows:

$$b = \frac{\log_{10} e}{M_a - (M - \frac{\Delta M}{2})} \quad \text{(II)}$$

where M_a is the average of all magnitudes; M is the minimum magnitude in the catalogue; and ΔM is the binning width of the catalogue. The standard deviation in b-value (δb), as recommended elsewhere,[43] is provided in the following:

$$\delta b = 2.3b^2 \sqrt{\frac{\sum_i^N \left(M_i - M_a\right)^2}{n_s\left(n_s - 1\right)}} \quad \text{(III)}$$

where M_i denotes the individual earthquake magnitudes; M_a is the average magnitude of all the earthquakes considered; and n_s refers to the total number of earthquake samples used in the calculation. The expression $\sum_i^N \left(M_i - M_a\right)^2$ represents the sum of the squared differences between each magnitude and the mean magnitude.

3. Results and discussion

As mentioned in the past literature, temporally declining b-values precede major earthquakes, signaling stress concentration,[44,45] and spatially, low b-values correlate with locked, high-stress zones, while high b-values reflect fractured, aseismic regions.[46,47] Together, these patterns highlight the utility of b-values in mapping stress heterogeneity and identifying seismogenic potential. To better understand these dynamics, we investigated spatial and temporal b-value variations in the Himalaya to quantify stress heterogeneity and earthquake likelihood. The estimated b-values for all five regions (Far Western, Western, Central-I, Central-II, and Eastern) are illustrated in Figure 2, with their corresponding numerical values provided in Table 1.

The Far Western region (Figure 2A) exhibits the highest b-value (0.93 ± 0.02), indicating a predominance of small magnitude earthquakes, which is a common feature of tectonically active zones. Conversely, the Central-I (Figure 2C) and Eastern regions (Figure 2D)

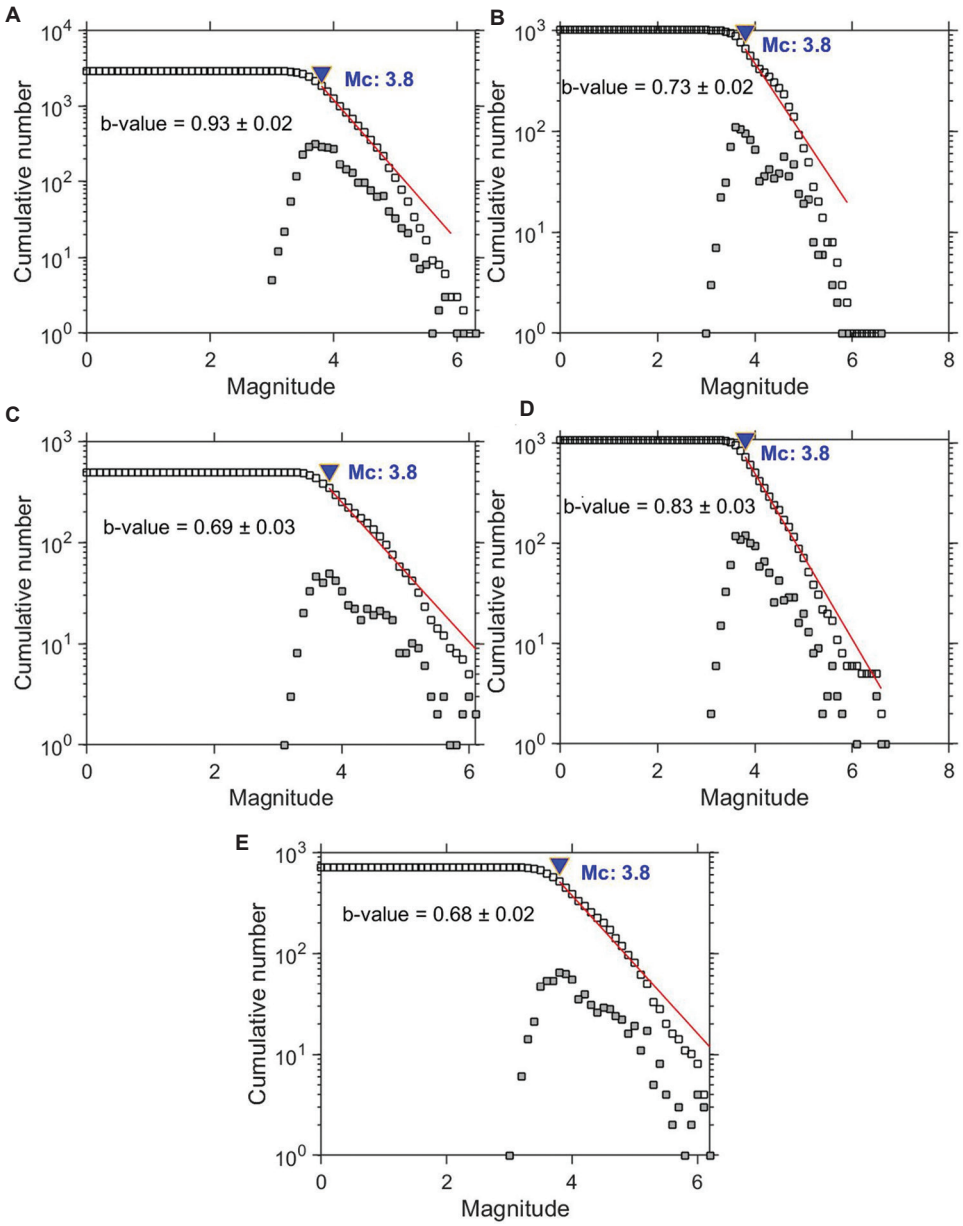

Figure 2. b-value and magnitude of completeness plots of Far Western Himalayan region (A), Western Himalayan Region (B), Central-I Himalayan Region (C), Central-II Himalayan Region (D), and Eastern Himalayan Region (E)

Table 1. b-value and magnitude of completeness in five regions of the Himalayan

Region	b-value	Magnitude of completeness (Mc)	Magnitude range (in M_b)
Far Western	0.93±0.02	3.8	3 – 6.9
Western	0.73±0.02	3.8	3 – 6.6
Central I	0.69±0.03	3.8	3 – 6.1
Central II	0.83±0.03	3.8	3 – 6.9
Eastern	0.68±0.02	3.8	3 – 6.2

have the lowest b-values (0.69 ± 0.03 and 0.68 ± 0.02, respectively), suggesting a lower frequency of small earthquakes and a greater potential for stress accumulation, which may contribute to the occurrence of larger seismic events.[48,49] Meanwhile, the Western (Figure 2B) and Central-II (Figure 2D) regions demonstrate moderate b-values (0.73 ± 0.02 and 0.83 ± 0.03, respectively), reflecting a more balanced seismic activity pattern.[50,51] These variations in b-values provide crucial insights into seismic behavior and potential hazard levels across different regions. In the preceding work, b-values calculated for the Himalayan region from 1900 to 2015, were reported as 0.98, 0.86, 0.85, and 0.74 for the Western, Central-I, Central-II, and Eastern zones, respectively, by Pudi *et al.*[26] Similarly, other studies have analyzed b-values across the Himalayas, demonstrating differences in stress and seismic hazard. Tiwari and Paudyal[52] discovered a b-value of 0.68 ± 0.03 in western Nepal (central Himalaya), indicating a high-stress zone with locked faults. Kumar and Sharma[53] reported b-values ranging from 0.7 to 1.1 in central Nepal (central Himalaya), showing stress heterogeneity after the 2015 Gorkha earthquake. Pathak *et al.*[54] discovered a high-stress environment in the Kumaun region of the western Himalayas, with a b-value of 0.59 ± 0.11. Similarly, Yadav *et al.*[55] reported low b-values ranging from 0.6 to 0.7 in the northeastern Himalayas, particularly along the MHT, indicating locked faults and high seismic potential. These low b-values across locations show the Himalayan belt's enormous stress and earthquake vulnerability.

The temporal fluctuations in b-values over the study region indicate varying stress regimes and seismic activities (Figure 3).

In the Far Western Himalaya (Figure 3A), a decrease in b-value from 1.04 (July 15, 1990) to 0.97 (November 11, 2015) during the 1980 – 2020 period signifies ongoing stress accumulation along the MHT.[56] The initial elevated b-value indicated stress relaxation through frequent little earthquakes, but the subsequent decline suggested an increase in strain concentration. The Western Himalayas (Figure 3B) exhibited a low b-value of 0.84 on August 30, 1995, associated with stress accumulation preceding the 1991 Uttarkashi (Mw 6.8) and 1999 Chamoli (Mw 6.4) earthquakes, influenced by locked parts of the Main Central Thrust.[57,58]

In the Central-I Himalayas (Figure 3C), the b-value of 0.94 recorded on December 14, 2006, throughout the period from 1995 to 2015 indicated moderate stress conditions with ongoing strain building along the MHT. In contrast, the Central-II Himalayas (Figure 3D) saw a significant increase in the b-value to 1.19 on May 10, 2015, following the Gorkha earthquake, indicating stress release through aftershocks.[59] The Eastern Himalayas (Figure 3E) exhibited consistently elevated and constant b-values (0.97 in 2014; 0.99 in 2016) from 1990 to 2015, indicating reduced stress attributable to crustal variability. This region constitutes a seismic gap that has remained unruptured since the 1934 Bihar-Nepal earthquake (Mw 8.4), with locked faults quietly collecting strain.[8,14] Our findings align with previous studies analyzing b-value variations in the Himalayas. Chetia *et al.*,[49] for example, observed b-value varying from 0.4 to 3.3 on the Himalayan and forehead region from 1964 to 2020.

The low b-value zones of the Himalayan region, extending from west to east, demonstrate a significant increase in seismic hazard potential (Figure 4).

In the Far Western Himalayas (72°E – 76°E) (Figure 4A), significant stress accumulation (b = 0.7 – 0.9) is noted in Himachal Pradesh, historically associated with the 1905 Kangra earthquake (Mw 7.8), where locked parts of the MHT maintain localized strain.[60] Proceeding eastward, the Western Himalayas (76°E – 80°E) (Figure 4B) display the sub-region's minimal b-values (0.6 – 0.7) in Uttarakhand (77°E – 79°E), which correlate with the Main Central Thrust and its rupture history, encompassing the 1991 Uttarkashi (Mw 6.8) and 1999 Chamoli (Mw 6.4) earthquakes.[23,58,61] Further east, the Central-I Himalayas (80.5°E – 82.5°E) (Figure 4C) in mid-western Nepal exhibit significantly low b-values (0.6 – 0.65), indicating unruptured segments of the MHT that have preserved residual stress following the 2015 Gorkha earthquake (Mw 7.8).[62] In proximity to this, the Central-II Himalayas (83°E – 88°E) (Figure 4D) exhibit a pronounced disparity: The western sector (83°E – 85°E) (Figure 4B) saw post-2015 stress release (b = 0.9 – 1.05), but the eastern sector (85°E – 88°E) retains low b-values (0.65 – 0.8), indicating persistent strain accumulation in central Nepal. The Eastern Himalayas (89°E – 95°E) (Figure 4D) are the most hazardous, with Bhutan's DCFZ gap (91°E – 93°E) exhibiting the lowest b-values (0.65 – 0.75) in the entire region.[24] This seismic gap, which has remained unruptured since the 1934

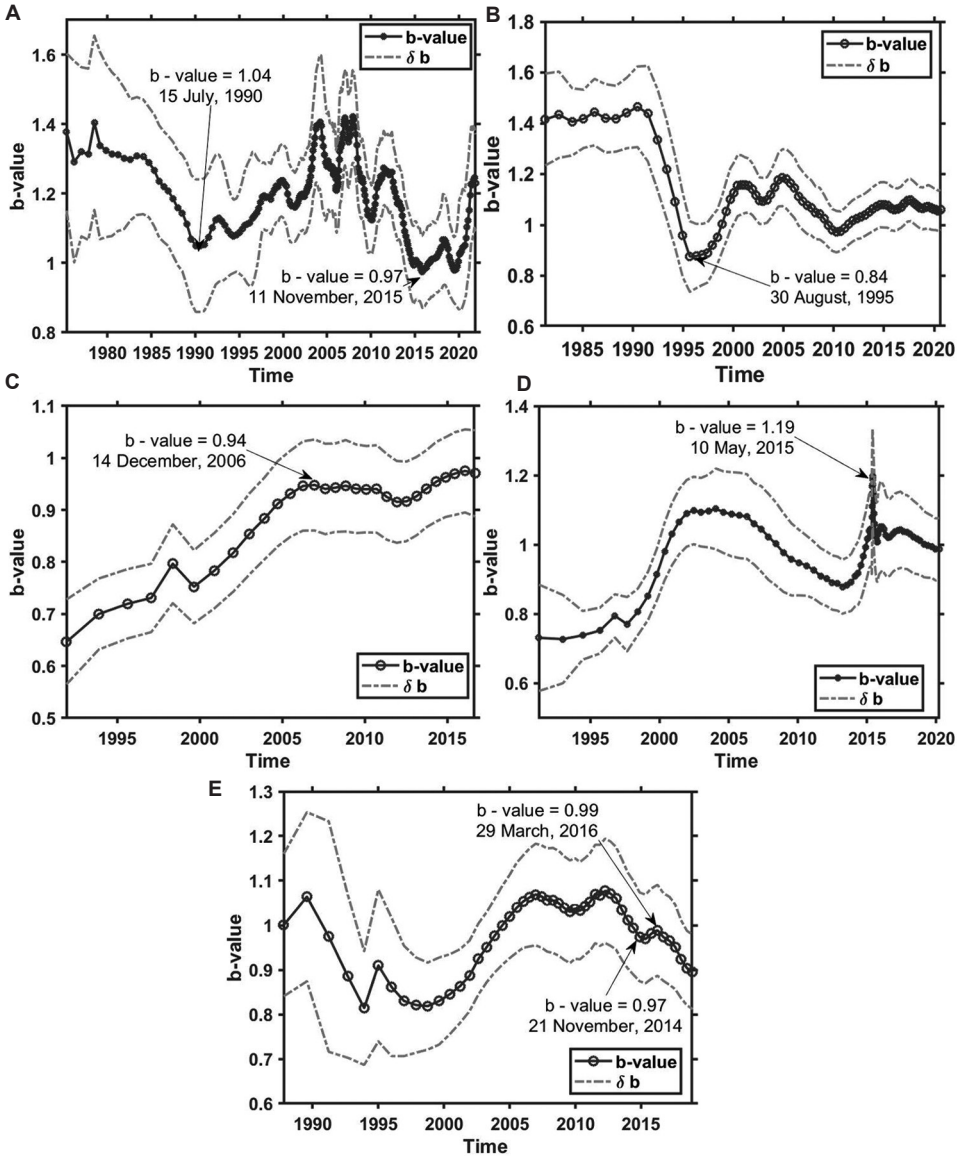

Figure 3. A time series analyzing b-value across Far Western Himalayan region (A), Western Himalayan Region (B), Central-I Himalayan Region (C), Central-II Himalayan Region (D), and Eastern Himalayan Region (E)

Bihar-Nepal earthquake, contains significant stress on the MHT, indicating an immediate threat of a mega-thrust event.[63] The west-to-east gradient from moderate strain to catastrophic potential highlights the Himalayas' dynamic tectonic interactions, driven by the Indian and Eurasian plates' continuous convergence (~20 mm/year). Thus, monitoring and disaster resilience are crucial in high-risk areas, such as Bhutan and central Nepal.

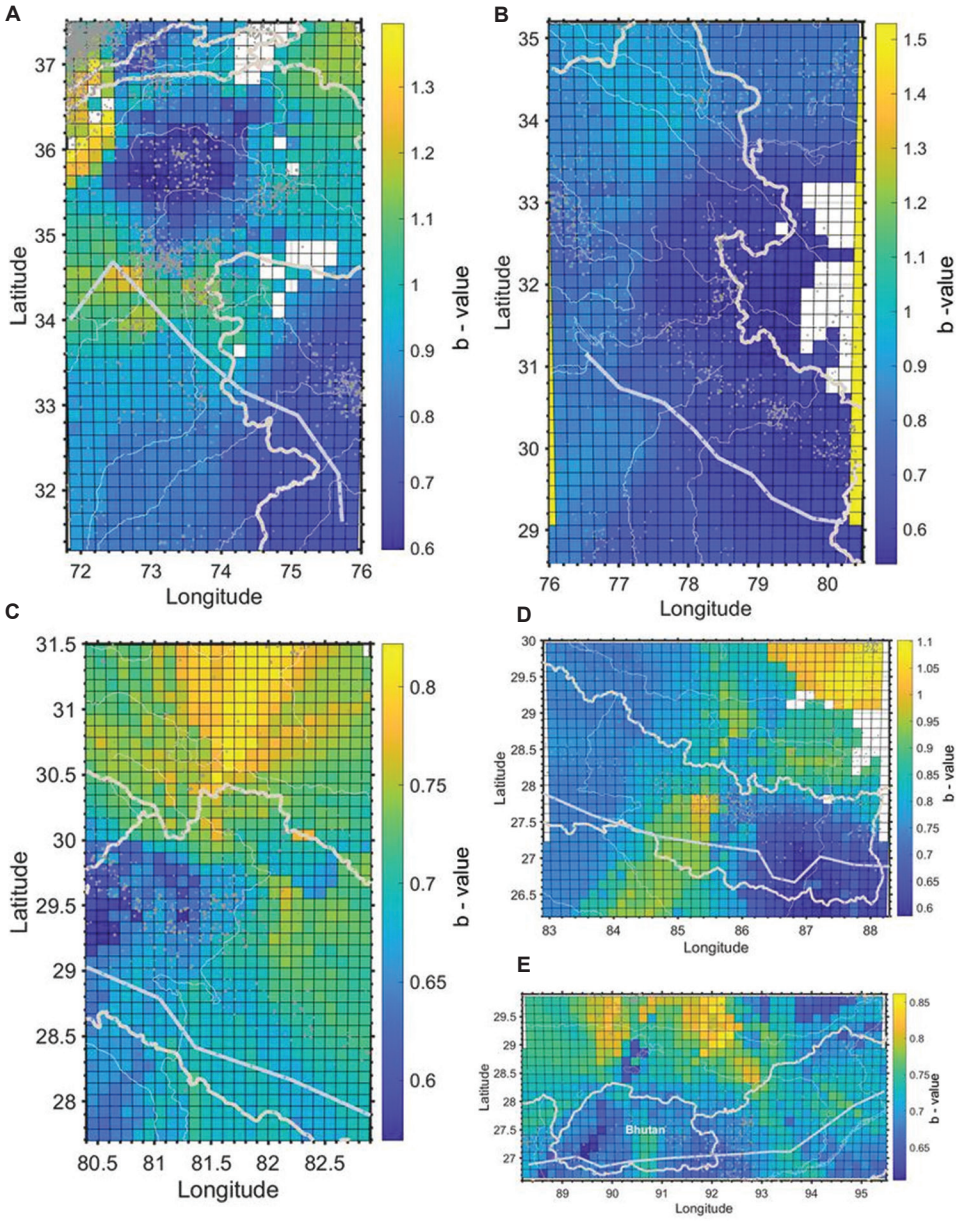

Figure 4. Spatial distribution of b-values across Far Western Himalayan region (A), Western Himalayan Region (B), Central-I Himalayan Region (C), Central-II Himalayan Region (D), and Eastern Himalayan Region (E)

4. Conclusion

In this study, earthquake data were obtained from the International Seismological Centre catalogue covering the Himalayan arc region between 71.6°E and 95.5°E for the period 1964 – 2023. The analysis was based on body-wave magnitude (mb), and to ensure accuracy, dependent events (foreshocks and aftershocks) were removed using the Reasenberg de-clustering algorithm implemented in MATLAB, allowing for the evaluation of only independent events (mainshocks).

The results of the investigation demonstrate clear spatial and temporal changes in b-values across distinct Himalayan sub-regions. Among the five zones investigated, the Far Western Himalayas demonstrated the greatest b-value (0.93 ± 0.02), which predicts a lower amount of tectonic stress accumulation and a dominance of small-magnitude earthquakes. In contrast, the Eastern Himalayas and Central-I region had the lowest b-values (0.68 ± 0.02 and 0.69 ± 0.03, respectively), indicating a higher accumulation of stress and a greater likelihood of big, devastating seismic occurrences.

Temporal analysis showed dynamic changes in b-values over time. For instance, the b-value in the Far Western Himalayas decreased from 1.04 in 1990 to 0.97 in 2015, reflecting increasing tectonic strain before the 2015 Gorkha earthquake (Mw 7.8). Similarly, the Western Himalayas recorded a b-value of 0.84 in 1995, which was associated with subsequent major earthquakes, including the 1991 Uttarkashi (Mw 6.8) and 1999 Chamoli (Mw 6.4) events. The Central-II region showed a sharp increase in b-value to 1.19 during 2015, attributed to stress release from aftershock activity. Notably, the Dhubri-Chungthang seismic gap in Bhutan, with a persistent b-value of 0.65 – 0.75, remains unruptured since the 1934 Bihar-Nepal earthquake (Mw 8.4), indicating a silent but critical accumulation of strain, potentially making it a future earthquake hotspot.

The interpretation of these results is significant. Low b-values point to regions with high stress accumulation and fewer small earthquakes, which are more prone to host large seismic events. Conversely, high b-values indicate frequent small earthquakes and lower potential for major seismic rupture. The temporal decrease in b-values in certain regions can serve as a potential indicator of impending earthquakes, whereas post-event increases often reflect stress release through aftershocks.

This work sheds light on the spatial and temporal patterns of seismicity over the Himalayan region. It helps to improve seismic hazard assessment and disaster risk mitigation strategies by identifying high-stress and earthquake-prone areas. The findings emphasize the significance of ongoing monitoring, particularly in low b-value zones, such as the DCFZ gap, and call for increased earthquake preparedness and mitigation activities in these susceptible locations.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Investigation: Ram Krishna Tiwari
Methodology: Ram Krishna Tiwari
Supervision: Harihar Paudyal
Visualization: Anil Subedi, Dilip Parajuli, Santosh Dharel, Anil Neupane, Hari Subedi, Bishow Raj Timsina
Writing – original draft: Anil Subedi, Dilip Parajuli, Santosh Dharel, Anil Neupane, Hari Subedi, Bishow Raj Timsina
Writing – review and editing: Ram Krishna Tiwari, Harihar Paudyal

Availability of data

Data are freely available from the websites of the International Seismological Center.

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