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Probabilistic Seismic Hazard Assessment Using Gumbel's Extreme Value Distribution in the Himalayan Arc (71.6°E – 97°E and 37.5°N – 26.6°N)

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Abstract

The Himalayan arc, formed by the ongoing collision of the Indian and Eurasian plates, ranks among the most seismically active zones worldwide. For this study, a probabilistic seismic hazard assessment was carried out using Gumbel's Extreme Value Distribution (Type-I) applied to a declustered earthquake catalog spanning 1900 to 1 April 2025. To reflect tectonic variability across the region (71.6°E–97°E; 26.6°N–37.5°N), the arc was subdivided into five segments: Far Western, Western, Central-I, Central-II, and Eastern Himalaya.The study makes it clear that the risk of earthquakes goes down from west to east across the Himalayan arc. In the western parts of the Western Himalaya, big earthquakes tend to happen very rarely, with a Mw 7.5 earthquake happening every 9,300 years. The central region, on the other hand, has much shorter intervals. The Central-II Himalaya is especially at risk because Mw 7.5 events happen about every 127 years and Mw 8.0 events happen about every 407 years. That means there is more than a 55% chance that an Mw ≥ 7.5 earthquake will happen in the next 100 years. It is interesting that the eastern Himalaya is more likely to have earthquakes than the western parts.

These results highlight the arc's crucial spatial heterogeneity in seismic risk. In addition, the information contained in these results is so large there are many indicators for better preparing for catastrophes and a greater sense of the importance of developing strong infrastructure and construction guidelines. Two regions that require the most attention to strong infrastructure and building guidelines are Central-II and Eastern Himalayas due to their fragile conditions. If there are even minor changes to current planning and building regulations, then the impact of these changes on future events will be immense.

Keywords Gumbel's Extreme Value Distribution, Himalayan regions, Return periods

1. Introduction

Himalayan arc is one of the most seismically active continental collision zones over the world (Kumar et al., 2001). This collision zone is a result of Indian and Eurasian plate movements converging. This collision produces major thrust fault systems, particularly the Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), and Main Central

Thrust (MCT) resulting in considerable shortening of the earth's crust (Avouac, 2003; Seeber & Armbruster, 1981). As time goes on, strain builds up along fault lines and gets released periodically in earthquakes of different magnitudes. This makes the area prone to big earthquakes (Wesnousky, 1999).

The seismic activity records of the region are large-scale in destruction. The 1934 Bihar–Nepal earthquake (Mw 8.0) and the 1950 Assam earthquake (Mw 8.6) were massive in intensity. 2015 Gorkha earthquake (Mw 7.8) also caused damage in Nepal (Bilham, 2019; Tiwari et al., 2022; Tiwari & Paudyal, 2022), Nepal was struck by the Mw 7.8 Gorkha earthquake followed by an intense aftershock sequence. It was one of the most destructive earthquakes in the Himalayan arc, causing more than 8 900 fatalities. In this study, we analyzed the dataset (429 events, magnitude of completeness Mc). The 2023 Bajhang (Mw 5.7) earthquake in western Nepal, for instance, looking at recent events including the Jajarkot (Mw 6.4) earthquake (Tiwari & Paudyal, 2025), but also the 2025 Tibet earthquake (Mw~7.0) (Xu et al., 2025) shows that there is seismic hazard throughout the Himalayan collision zone even across the main thrust systems, north the Himalayan region.

The Elastic Rebound Theory states that stress slowly accumulates along locked faults until the fault strength is exceeded (Reid, 1910). This results in fault rupture and release of energy. Even though the exact timing of an earthquake is difficult to determine (Geller et al., 1997), it is possible to estimate when and where earthquake activity may occur, based on strain build-up at a regional scale. Similarly, the likely magnitude of the earthquake can also be derived from models, like Gumbel's Extreme Value Distribution. Also, an examination of the b-value, along with the fractal analysis of fault networks, demonstrates the scaling behavior and concentration of earthquakes (Boulanouar et al., 2025; Tiwari & Paudyal, 2023). Fault analysis combining probabilistic models may provide a better framework for estimating seismic hazard in Himalaya region. The plates are continuously converging at a rate of 40−50 mm/year, giving rise to tectonic processes in the Himalayan region (Ader et al., 2012; Molnar & Tapponnier, 1975) in addition to previously published campaign GPS points and leveling data and determine the pattern of interseismic coupling on the Main Himalayan Thrust fault (MHT).

1.1 Seismic Hazard Assessment and Earthquake Recurrence

The seismic behaviors of regions with large earthquakes historically are important for seismic hazard assessment. Statistical methods use historical and instrumental earthquake data to estimate the probabilities of future earthquakes (Cornell, 1968). The irregular recurrence of earthquakes, i.e. long seismic cycles, and the incompleteness of palaeoseismic records makes it difficult to ascertain the frequency of major earthquakes (Kumar et al., 2006)

Extreme Value Theory (EVT) is generally used to estimate return periods focused on rare high impact events by statistically modelling their maximum magnitudes (Coles,

2001) Within EVT, Gumbel's Extreme Value Distribution (Type I) is extensively applied due to its efficacy in characterizing the upper tail of the earthquake magnitude distribution (Gumbel, 1958). This approach has been successfully applied in seismically active regions such as Turkey, Bangladesh, and Zimbabwe to estimate return periods and annual exceedance probabilities for large earthquakes.

We estimate the return period and exceedance probability of significant seismic events using Gumbel's Extreme Value Theory, applying this method to earthquake data from the Himalayan region to assess the likelihood of future large earthquakes. Understanding these recurrence patterns is essential for improving disaster preparedness, strengthening resilient infrastructure, and reducing long-term seismic risk, especially as urbanization and population density continue to rise along the Himalayan arc.

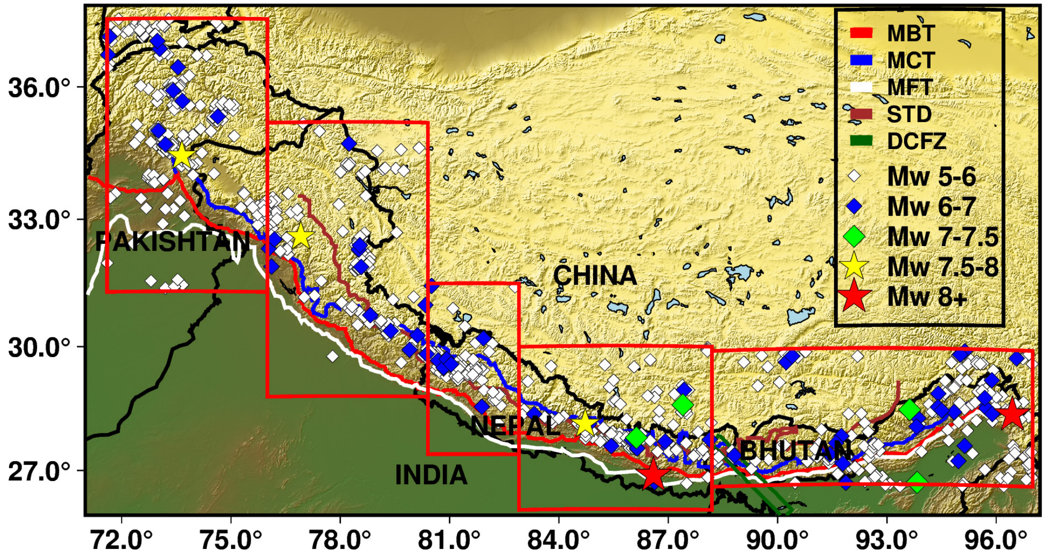

Figure 1. Seismotectonic map showing the epicentre of earthquakes of Himalaya and adjacent regions shows the major tectonic features, viz. Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), and Main Central Thrust (MCT) and Dhubri–Chungthang Fault Zone (DCFZ). It also maps previous earthquakes that have occurred between 1900 to 1 April 2025 and marks their magnitudes from Mw 5 to 8 and above, allowing you to see briefly where stronger seismic events have taken place.

This study focuses on the Himalayan arc, which is a seismically active area at the longitude of 71.6°E to 97°E and latitude of 26.6°N to 37.5°N. These regions belong to Pakistan, India, Nepal and Bhutan. The Indian and Eurasian tectonic plates converge in this area which is also crossed by the major fault systems like Main Frontal Thrust, Main Boundary Thrust and Main Central Thrust. The design of the tectonic structure governs the accumulation and release of strain which in turn will lead to mild to significant earthquakes (Nakata, 1989).

To carry out comprehensive statistical modeling with Gumbel's extreme value distribution (EVD), the study area was classified into five different seismic zones as shown in figure 1. The implemented zonation allows for risk assessment of specific regions with respect to return times and exceedance probabilities. It also highlights the spatial variation in seismicity of the Himalayan arc and facilitates hazard assessment.

1.2 Gumbel's Extreme Value Distribution

The Gumbel Extreme Value Distribution (EVD), also known as Type I extreme value distribution (Brookes, 1955). This tool is used in seismology. It helps assess maximum earthquake magnitudes. This allows for estimating return periods and exceedance probabilities. This method is useful in areas with large seismic records and variable recurrence patterns, like the Himalayas.

The cumulative distribution function (CDF) is given by

$$F(x) = \exp\left[-exp\left(-\frac{x-\mu}{\beta}\right)\right] \qquad (I)$$

where x is the annual maximum magnitude, μ is the location parameter, and β is the scale parameter (Kotz & Nadarajah, 2000; Tiwari & Paudyal, 2024). The corresponding probability density function (PDF) (Coles, 2001) is found by differentiating the CDF:

$$f(x) = \frac{1}{\beta} exp\left[-\left(\frac{x-\mu}{\beta} + exp\left(\frac{x-\mu}{\beta}\right)\right)\right] \qquad (II)$$

The location parameter μ and scale parameter β were determined using the method of moments and validated by maximum likelihood estimation (MLE).

The Himalayas are tectonically complex, and strain accumulates at these locations releasing in high-magnitude earthquakes following intermittent releases. Gumbel's EVD describes the seismicity of the Himalayas effectively. By utilizing this technique to assess earthquake catalogs, the frequency of extreme events can be estimated in segments of the arc. Overall, it gives a quantitative insight of seismicity.

2. Data and Methodology

The earthquake catalog used in the current study was obtained from European-Mediterranean Seismological Centre (EMSC) (Bossu et al., 2025) and International Seismological Centre (ISC-GEM) (Di Giacomo et al., 2018) of the Himalayan arc. The period from 1900 to 1 April 2025 contributes to the coverage for both instrumental and historical data. Only events with moment magnitude (Mw) ≥ 5.0 were duly considered for uniformity. The duplicate entries were removed and the catalog was declustered according to the Reasenberg algorithm (Reasenberg, 1985) to remove foreshocks and aftershocks. Thus, only independent mainshocks were kept for statistical analysis. Catalogues were used to extract annual maximum quake magnitudes for each zone.

According to Extreme Value Theory (EVT) one can just work with the extreme values of the variables. Since there will always be at least one extreme event in a year, it is sufficient to use only the extreme events for the hazards. Therefore, EVT approach ensures the database has been filtered to contain only the largest events.
The study region covers 71.6°E–97°E longitude and 26.6°N–37.5°N latitude, which includes parts of Pakistan, northern India, Nepal, Bhutan, and southern Tibet. For regional analysis, the Himalayan arc was divided into five seismic zones: The seismic catalog for the Himalayan arc indicates numerous variances between its key components. In the Far Western Himalaya (31.3°N–37.5°N, 71.6°E–76°E), 254 earthquakes with a magnitude of Mw ≥ 5.0 were found. After declustering, these earthquakes were found to be 191 separate events. The Western Himalaya (28.8°N–35.2°N, 76°E–80.4°E) had 126 events, but only 123 of them were left after dependent events were removed. After declustering, the number of events in the Central-I Himalaya (27.4°N–31.5°N, 80.4°E–82.9°E) went from 79 to 71. In the Central-II Himalaya (26.03°N–30°N, 82.9°E–88.2°E), there were 129 events, and 92 of them were kept as independent. There were 175 events in the Eastern Himalaya (26.6°N–29.9°N, 88.2°E–97°E), but after declustering, there were only 169 independent events. The present findings enhance the dataset on independent seismicity, facilitating improved regional models of earthquake recurrence and hazard potential.
This zonation follows the framework of Tiwari et al. (2025) and reflects variations in fault segmentation, geological structures, and regional seismicity patterns. This research uses Gumbel's Extreme Value Distribution (EVD, Type I) to calculate return periods and exceedance probabilities for significant earthquakes. The return period (T) for an earthquake of magnitude M was calculated as:

$$T(M) = \frac{1}{1 - F(M)} \qquad (III)$$

with F(M) is the cumulative possibility of event happening of size M or less.
Different time windows (50 and 100 years) exceeded likelihoods were also found using

$$P(T, M) = 1 - exp\left(-\frac{t}{T(M)}\right) \qquad (IV)$$

where t is the specified time window.

3. Result and discussion

The Gumbel extreme-value framework indicates spatially varying recurrence intervals among Himalayan segments (Figure 2), consistent with a west-to-east gradient in seismic potential and necessitating segment-specific hazard evaluations (Table 1).

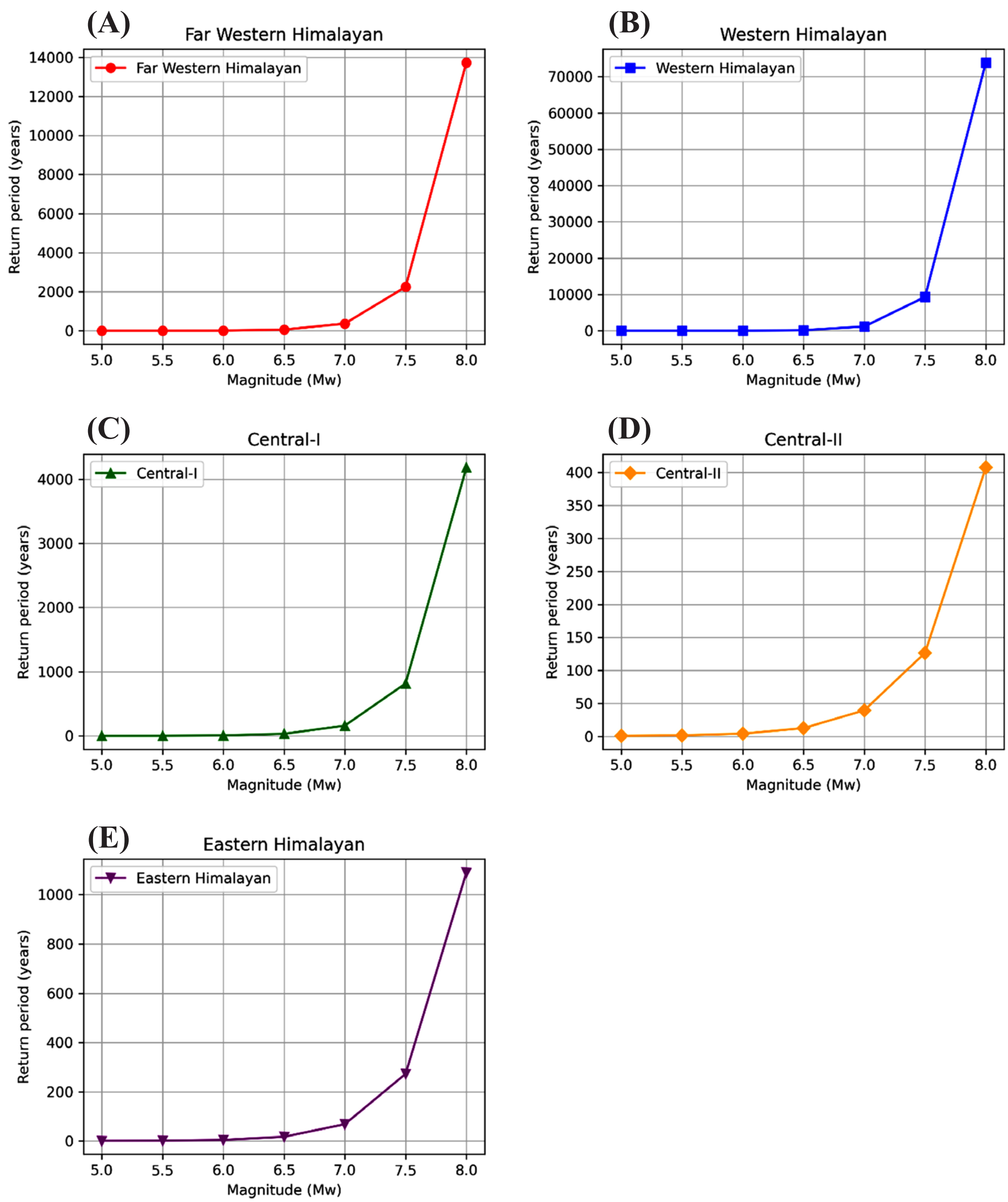

Figure 2. Gumbel extreme value distribution plots showing the relationship between earthquake magnitude (Mw) and return period for five distinct seismic regions of the Himalayas:(A) Far Western Himalaya, (B) Western Himalaya, (C) Central-I Himalaya (D) Central-II Himalaya, and (E) Eastern Himalaya

Gumbel extreme value analysis reveals distinct recurrence intervals for major earthquakes across the five primary segments of the Himalayas (Figure 2), illustrating a pronounced west-to-east gradient in seismic potential.

Table 1. Estimated magnitude, return period, and risk level of major earthquakes for the major segments of the Himalayan region.

	Far Western Himalaya			Western Himalaya			Central-I Himalaya			Central-II Himalaya			Eastern Himalaya		
(Mw)	Annual Cumulative N (events/yr)	Return Period (yr)	Expected Number in 100 years	Annual Cumulative N (events/yr)	Return Period (yr)	Expected Number in 100 years	Annual Cumulative N (events/yr)	Return Period (yr)	Expected Number in 100 years	Annual Cumulative N (events/yr)	Return Period (yr)	Expected Number in 100 years	Annual Cumulative N (events/yr)	Return Period (yr)	Expected Number in 100 years
5.0	0.97785	1.02	97.79	0.96566	1.04	96.566	0.9868	1.01	98.68	0.936	1.1	93.6	0.977	1.02	97.66
5.5	0.46364	2.16	46.36	0.34624	2.88	34.624	0.5705	1.75	57.05	0.575	1.7	57.5	0.609	1.64	60.91
6.0	0.09684	10.33	9.68	0.05217	19.16	5.217	0.1520	6.58	15.20	0.233	4.3	23.3	0.209	4.78	20.93
6.5	0.01652	60.55	1.65	0.00673	148.56	0.673	0.0317	31.57	3.17	0.079	12.7	7.9	0.057	17.53	5.70
7.0	0.00272	367.75	0.27	0.00085	1174.9	0.085	0.0063	159.71	0.63	0.025	39.7	2.5	0.015	68.60	1.46
7.5	0.00045	2246.61	0.04	0.00011	9317.5	0.011	0.0012	816.30	0.12	0.008	126.8	0.8	0.004	272.86	0.37
8.0	0.00007	13737.81	0.01	0.00001	73909.2	0.001	0.0002	4180.73	0.02	0.002	407.4	0.2	0.001	1089.77	0.09

The area known as the Far Western Himalaya (Figure 2 A) experiences moderate recurrence with return periods of approximately 10 years for Mw 6.0, 368 years for Mw 7.0, 2,247 years for Mw 7.5, and nearly 13,700 years for Mw 8.0. In the Western Himalaya (Figure 2 B), the return times are quite considerable. The return times are around about 19 years with Mw 6.0. However, with Mw 7.0, the return time increases sharply to over 1,175 years. The return times for Mw 7.5 and Mw 8.0 are quite lengthy as well. The return times for Mw 7.5 is around 9,300 years. Similarly, the return time for Mw 8.0 is around 74,000 years. This means there is a low probability of significant earthquakes.

Recurrence patterns change dramatically in the orogen's center. The Central-I Himalaya segment (Figure 2 C) exhibits a trend of regular intermediate seismicity (Mw 6.0 every ~7 years) but infrequent major earthquakes. Return times for Mw 7.0 are ~160 years, Mw 7.5 is ~816 years, and Mw 8.0 is nearly 4,000 years. The Central-II Himalaya segment (Figure 2 D) is the most seismically active, with shortest recurrence intervals across all magnitudes: around 4 years for Mw 6.0, 40 years for Mw 7.0, 127 years for Mw 7.5, and 400 years for Mw 8.0.

The Eastern Himalaya (Figure 2 E) experiences moderate seismicity more frequently than other parts, with Mw 6.0 occurrences occurring every 5 years. The recurrence intervals for Mw 7.0, 7.5, and 8.0 are approximately 69, 273, and 1,090 years, respectively. In the preceding work, return periods calculated for the Western Himalayan region from 1907 to 1976, were reported as ~203 years for M8.0 and ~10 years for M6.0 for Kashmir and Himachal Pradesh, ~222 years for M8.0 and ~11 years for M6.0 for the India–Western Nepal Border, and ~160 years for M8.0 and ~9 years for M6.0 for the Nepal–Sikkim Border, respectively, by Srivastava & Dattatrayam (1986). Similarly, Shanker et al. (2007) calculated the return periods for the Western Himalayan region from 1905 to 2005, which were reported as ~79 years for M7.0 and ~234 years for M7.5, respectively, using the Gumbel method. Similarly, return periods estimated using the Poisson process for the Far-Western, Western, and Central Himalaya regions from 1963 to 2004 were reported as 24.5 years, 5.6–13.9 years, and 22.9 years for magnitude 6.0 earthquakes, and 292.5 years, 88.8–158.7 years, and 309.3 years for magnitude 7.0 earthquakes, respectively, by Yadav et al. (2012).

There is a significant variation in seismic hazards in the regions, which is west to east in increasing seismicity. The western and far western parts can be expected to show very long return times for major events, thus unlikely in either a historical or planning window. The central and eastern regions exhibit moderate seismicity, with the Center-II segment presenting a high likelihood of large-magnitude earthquakes (Mw > 7.5) on societally relevant timescales.

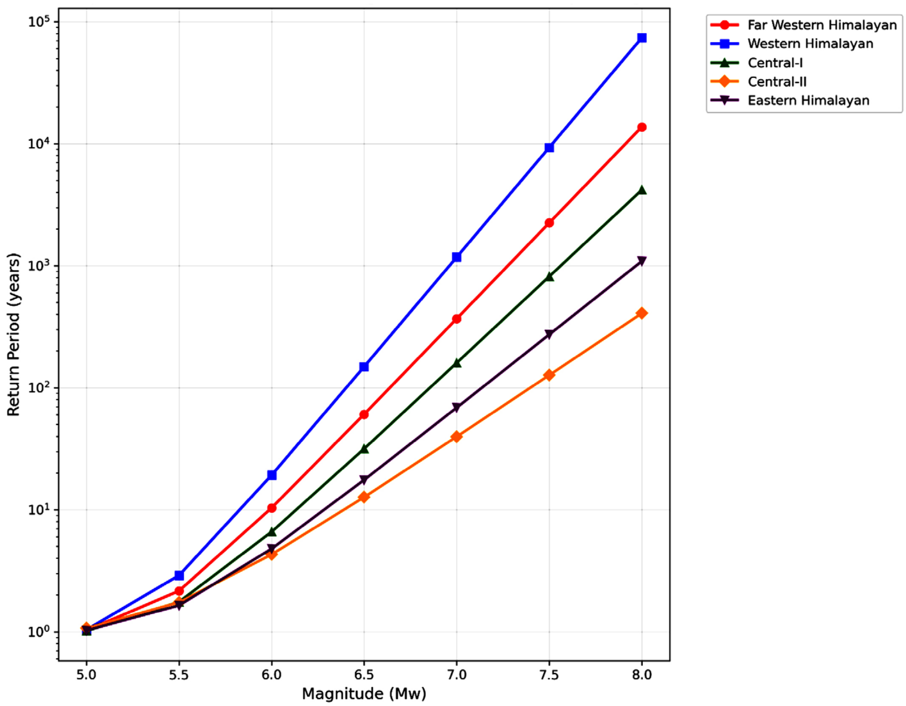

Figure 3. Plot of earthquake return periods with magnitude (Mw 5.0-8.0) over five seismic regions in the Himalayas.

Figure 3 presents Gumbel extreme value derived Mw estimates for a 100-year return period across Himalayan segments: Far Western Mw 6.6–6.8, Western Mw 6.4–6.6, Central-I Mw 6.8–7.0, Central-II Mw 7.3–7.5, Eastern Mw 7.1–7.2. The observed west-to-east gradient corresponds to variations in fault segment geometry, locking depth, prior seismicity, and accumulated strain. The comparatively lower Far West reflects truncated rupture potential due to segmented thrusts, whereas Central-II exhibits elevated rupture potential due to longer, more continuous thrusts.
The Himalayan region exhibits a 100-year return-period Mw spectrum from 6.4 to 7.5. Spatial heterogeneity in tectonic regime, fault-segment geometry, locking depth, strain accumulation, and historical seismicity drives this variability.

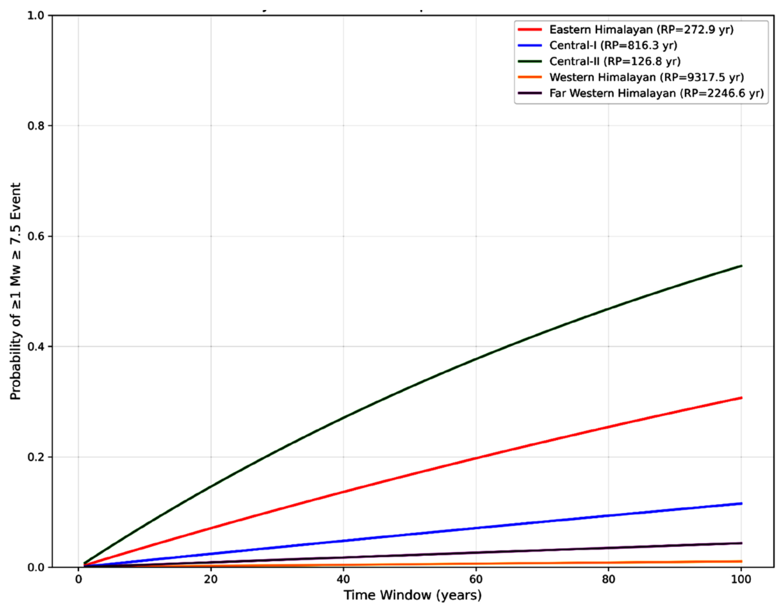

Figure 4. Probability of occurrence for one or more events of $M_w \geq 7.5$ earthquakes over increasing time windows for the five Himalayan seismic regions. The curves illustrate how probability accumulates with time, varying significantly due to each region's distinct return period.

The accompanying figure 4 shows the huge and geographically different risk of a big earthquake that could happen along the Himalayan arc. The main point is that the chance of a Mw ≥ 7.5 event is not the same everywhere; it is higher in some areas. The Central-II Himalaya seems to be the most dangerous area, with a 55% chance of experiencing such a catastrophic earthquake in the next 100 years. Even within a condensed 50-year timeframe, this risk remains significantly elevated, at 32%. The probability of a significant earthquake occurring in the Eastern Himalaya within the next century is 31%. On the other hand, the chances of a major earthquake in the other areas drop significantly. For the Central-I, Far Western, and Western Himalayan regions, the likelihood is very low, less than 12% over the next 100 years. This is a huge difference; in fact, the probability of an earthquake in the highest-risk area (Central-II) is 50 times greater than in the lowest-risk area (Western). The large variation from place to place suggests that local factors such as fault geometry, depth of locking, strain accumulation and recent seismicity dominate hazard over broad plate-scale tectonics. We should focus our efforts and resources on risk reduction in the Central-II and Eastern regions, where the probability and potential impact of large events are greatest.

4. Conclusion

This research applies Gumbel's Extreme Value Distribution on a complete earthquake catalogue to assess the seismic hazard and recurrence periods of large earthquakes along the five major segments of the Himalayan arc. The study shows that seismic potential trends positively from west to east. This highlights the notable regional variations in earthquake recurrence patterns.

The farther western and the western Himalayan regions have the longest return Period for high-magnitude events ($Mw \geq 7.5$). As a result, such events are less likely to occur quickly. Compared to the other geological areas, the seismic hazard in Central-II Himalaya is the highest. Also, it has been found to exhibit the shortest return periods. Thus, an earthquake of Mw 7.5 has a return period of about 127 years. While the one with a Mw 8.0 value has a return period of 407 years. As a result, this area now has a greater than 50% chance of having a $Mw \geq 7.5$ event in the next 100 years. The eastern Himalaya is also significantly more dangerous than the western regions.

Variations in local tectonics between regions give rise to differences in seismic hazard risk across regions, which include the configuration of fault segments, the point at which they lock, and their history of accumulating stress and releasing it. Results indicate that there are heterogeneous differences in seismic risk across the Himalayas and that assessments of risk for a given fault segment need to be done separately from other segments.

This study provides important information for long-term earthquake risk reduction. The results indicate that stringent building codes, infrastructure development, and preparedness should get priority, especially in the Central-II and Eastern Himalayas. Future studies must integrate these statistical models with geodetic data on current strain rates. This will improve the probabilistic forecasts, which may help protect the public in the densely populated, tectonically active region.

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