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TIME DEPENDENT SEISMIC HAZARD ASSESSMENT FOR HIMALAYAS AND ITS IMPLICATIONS

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ABSTRACT

Since the instrumental era, there has been a considerable increase in interest and relevant studies related to seismic hazard in the Himalayan region, necessitating its re-estimation with time following each destructive earthquake. Despite the capacity of classical approaches in capturing different facets of earthquake occurrence, its inability to capture time dependent occurrence of earthquakes makes ground for adoption of time dependent model, classical approaches are thus not so useful in dynamic system like Himalayas where they yield ineffective results in unrealistic predictions. This study examines non-Poissonian probabilities of exceedance in a time in future using stochastic models namely Lognormal, Brownian Passage Time, Gamma and Weibull distribution. Himalayas and its surroundings are noticeable as the region having multiple sources releasing tectonic energy; part of it may be affected by their own interactions, their varying geometry and different source of motion etc., making it a perfect case to validate different probabilistic models. The Himalaya is divided broadly into 4 SSZs viz. North-western Himalayas, Central gap region, Central Himalayas (Eastern Nepal and Sikkim) and Eastern Himalayas.

The study is done for two magnitude ranges viz: Mw≥6.0 and Mw≥7.0. The suitability among the used models in a Seismic Source Zone (SSZ) is checked based on Kolmogorov-Smirnov (K-S) test. SSZ I to IV have shown their adoption towards Gamma, Inverse-Gaussian, Lognormal and Invers-Gaussian models respectively for Mw≥6.0 and for Mw≥7.0 best model is Lognormal for SSZ I to III and Gamma for SSZ IV. The conditional probabilities for each SSZ are estimated using the best suited model for that specific SSZ.

KEYWORDS: Himalaya; Time-Dependent Seismic Hazard; Conditional Probabilities; Weibull Distribution; Gamma Distribution; Lognormal Distribution; Inverse-Gaussian distribution.

INTRODUCTION

The Himalayan region is seismically very active and existing tectonic activities there are the result of collision between Indian and Eurasian plate that started about 55Ma and is still going on [1, 2]. Rate of collision between Indian and Eurasian plates is approx. 30-50 mm/yr [3-5] out of which 15-20 mm/yr is absorbed by the Himalayas [e.g., 6-7, 5]. This collision cause shortening of Indian plate that is because of overlapping along principal thrusts namely Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT).

The high level of seismicity in Himalayas is related to the activation of various thrusts and faults from time-to-time as a result of the build-up of stresses [1] and cause earthquake. This region has been assigned as seismic zones IV and V in the seismic hazard zonation map of India (BIS 2002). Many major earthquakes (having magnitude greater than or equal to 8.0) and numerous moderate to large (having magnitude 6.0 - 8.0) earthquakes have occurred in Himalayan region in past. Some recent spurts of Himalayas having moderate (6.0 - 7.0) to large (7.0 - 8.0) moment magnitudes (Mw) are 1988 Myanmar EQ (7.3 Mw); 1988 Udayapur, Nepal EQ (6.9 Mw); 1991 Uttarkashi EQ (6.8 Mw); 1997 Bangladesh EQ (6.1 Mw); 1999 Chamoli EQ (6.8 Mw); 2005 Kashmir EQ (7.6 Mw); 2011 Sikkim EQ (6.9 Mw); 2015 Nepal EQ (7.8 Mw); 2015 Nepal EQ (7.3 Mw); 2016 Myanmar EQ (6.7 Mw).

Several attempts have been made in the past to analyse the seismic hazard in various parts of Indian subcontinent. It can be witnessed that there is a great scatter in earthquake epicenters even when tectonic features of a region are well known. This observation of the earthquake occurrences led to the assumption that earthquake events occur randomly in time, space and magnitude and thus forms a stochastically independent sequence of events in time and space. Based on this assumption of independence, a number of earthquake generation models have been used for the seismic hazard assessment, namely, Poisson, double Poisson, Markov, semi-Markov, regenerative point process and renewal process. These models are based on the fact that the time of occurrence and the magnitude of an earthquake in a region are independent of the time and magnitude of the previous and subsequent earthquakes. Classical approaches has extensively been applied in determining the seismic hazard for providing the appropriate design requirements of buildings and structures since it was first introduced by Cornell in 1968 [8-20]. Seismic hazard is the probability of occurrence of an earthquake with a magnitude greater than or equal to a particular value within a specified region and a given time period.

The issue of seismic hazard was addressed in India as early as 1956 when a seismic zoning map of India showing three SSZs were produced by India Meteorology Department [21]. But, there is a dependency between events as various studies [22-24] infer clustering in time for large earthquakes. Further, a study [25] proposes that occurrence of an earthquake on a particular fault is a gradual but continuous process of accumulation of strain energy on that fault that is interrupted when there is a sudden strain release from that fault and thus probability of earthquake occurrence reduces which can be understood as the occurrences of earthquakes in a seismic region depends on each other. This interprets earthquake occurrences as dependent on each other, thus probability of earthquake occurrences is calculated based on this understanding.

According to Time-dependent recurrence models, the probability of recurrence of an earthquake on a particular fault depends on the time elapsed since the last earthquake on that fault. These models results in very different estimate of hazard than the Poisson model, depending on the elapsed time since the last event and the average inter-arrival time. Studies from all over the world [26-31, 15-16] show that earthquake occurrences are time dependent. Some studies [32-40] compute the time dependent probabilities of earthquake occurrence using several methods in India.

[41] has estimated the conditional probabilities for the whole Indian region by dividing it into 24 SSZs and found that the conditional probabilities of occurrence of magnitude more than 6.0 were relatively more than the estimates using classical methods. [42], [43], [44] estimated probabilities of Mw=6 earthquake in 50 years and results were relatively less than time dependent studies.

In the present study Himalayan region has been divided into four SSZs (Figure 1) and the time-dependent conditional probabilities of earthquakes having moment magnitude, $M \geq 6.0$ and $M \geq 7.0$ are estimated using Weibull, Lognormal, Gamma and Inverse-Gaussian distributions. For conducting the studies a homogeneous and complete earthquake catalogue from year 1685 to 2018 is used. We aim to look into the physical processes in different parts of the Himalaya which restrict usage of classical hazard assessment methodology here.

METHODOLOGY AND STOCHASTIC MODELS

Conditional probabilities, that describe the likelihood of earthquake occurrence within a given time interval knowing that the event has not occurred since the last happening, can be computed using the recurrence intervals of past earthquakes in conditional probabilistic models. The conditional probabilities in the field of earthquakes studies have been applied for various regions of the world. In the present study time interval for which conditional probabilities are computed are 5, 10, 20, 30 and 50 yrs.

The conditional probability of earthquake occurrence is computed using statistical distributions, in which the recurrence time ‘t’ (i.e. a vector of random variables), represents the time interval between two successive earthquakes of a particular magnitude. If τ is small time interval from t in which the conditional probability of earthquake occurrence is to be computed, then the equation for conditional probability computation is given as $P\left(\frac{t+\tau}{t}\right) = \frac{F(t+\tau)-F(t)}{1-F(t)}$. Where, *F (t)* is cumulative distribution function (CDF) of a specific distribution that is used. The conditional probability is estimated using the equation for the time interval from t to $(t + \tau)$ assuming that no earthquake has occurred after the last occurrence. A brief description of the models introduced by Utsu (1984) that are applied in this study for the estimation of earthquake occurrences is given below. The Poisson distribution has also been used to compute the Poisson probabilities to make a comparison of the probabilities and the CDF for the Poisson model is given as:

$F(x) = 1 - e^{-\lambda t}$ that describes the probability of having x number of events in time t, where λ is representing the rate with which different magnitudes events are occurring. The most suitable model for the region is selected on the basis of the Kolmogorov-Smirnov test.

The Kolmogorov-Smirnov test is a statistical test for estimating goodness of fit [45] which depends on the maximum difference between theoretical and observed cumulative probabilities which should be less than the critical value. If, D_n is the maximum difference between the observed and theoretical CDF and $D_{n\alpha}$ is assumed to be the critical value, then to accept a model following equation should follow.

$$P(D_n \leq D_{n\alpha}) = 1 - \alpha \tag{1}$$

where, α is the significance level (that is 0.05 in this study).

1. Weibull Model

This distribution was introduced in 1951 by Waloddi Weibull [46] and [47] suggested that this model can be used to assess the earthquake recurrences. The general form of two parameters with parameters β (dimensionless), shape parameter and α, scale parameter the Weibull probability density *(f(x))* and distribution *(F(x))* functions for variable $x \geq 0$ is given as:

$$Pf(x) = \frac{\beta}{\alpha}(x/\alpha)^{\beta-1}e^{-(x/\alpha)^{\beta}} \tag{2}$$

$$F(x) = 1 - e^{-(x/\alpha)^{\beta}} \tag{3}$$

The parameters β and α can be estimated using graphical procedures viz. mean rank, median rank or symmetrical CDF method or analytical procedures viz. Maximum Likelihood Estimation (MLE), Method of Moments (MOM) or Least-Square (LS) method. Here, the MLE method is used to calculate the Weibull's parameters. The shape and scale parameters can be calculated as $\beta = \frac{1}{\frac{\Sigma(xi^{\beta}Ln(xi))}{\Sigma xi^{\beta}} - \frac{1}{n}\Sigma Ln(xi)}$ and $\alpha = \frac{\Sigma xi^{\beta}}{n}$.

where, x is a random sample of size n.

2. Lognormal Model

The most widely used distribution in statistics is the normal distribution. It sustains for the whole range of the axis (– inf., + inf.) hence it is not a lifetime distribution. Two modified forms of this distribution for positive variables are: the lognormal distribution and the truncated normal distribution. The lognormal distribution of a random variable 'x' having size 'n' is closely related to the normal distribution if the natural logarithm of x follows a normal distribution. PDF and CDF for the distribution are given as:

$$f(x) = \frac{1}{\sigma x\sqrt{2\pi}} exp^{\frac{-(lnx-\mu)^2}{2\sigma^2}} \tag{4}$$

$$F(x) = \varphi\left(\frac{\ln(x)-\mu}{\sigma}\right) \tag{5}$$

where, ϕ is the CDF of the normal distribution, and σ and μ are the mean and the standard deviation of the logarithm of x. The MLE has been used for estimating the parameters of this distribution that are given as, $\mu = \frac{\Sigma_i ln(x_i)}{n}$ and $\sigma^2 = \frac{\Sigma_i(ln(x_i)-\mu)^2}{n}$.

3. Gamma Model

The PDF and CDF of Gamma Distribution with two parameters α and λ for a continuous random variable x can be written as:

$$f(x) = \frac{x^{(\lambda-1)}exp^{(-x/\lambda)}}{\lambda^{\alpha}\Gamma\alpha} \tag{6}$$

where $\Gamma\alpha$ is the gamma function and is given as $\Gamma\alpha = \int_0^{\infty} t^{\alpha-1}exp^{-t}dt$

and $$F(x) = \frac{1}{\Gamma\alpha}\int_0^{x/\lambda} u^{\alpha-1}exp^{-u}du \tag{7}$$

'α' and 'λ 'are the shape and scale parameters, respectively. The MLE method is used to estimate the model as follows:

$$ln(\alpha) - \psi(\alpha) = ln\left(\frac{1}{n}\sum_{i=1}^{n} xi\right) - \frac{1}{n}\sum_{i=1}^{n} ln(xi) \text{ and } \lambda = \frac{1}{\alpha n}\sum_{i=1}^{n} xi$$

$\psi(\alpha)$ is the digamma function that is the derivative of the logarithm of a gamma function.

4. Inverse-Gaussian Model

If 'x' is a random variable distributed according to the inverse Gaussian model, then it's PDF and CDF can be written as:

$$f(x) = \sqrt{\frac{\lambda}{2\pi x^3}} exp(-\frac{\lambda(x-\mu)^2}{2\mu^2 x}) \tag{8}$$

$$F(x) = \phi\left\{\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu}-1\right)\right\} + exp\left(\frac{2\lambda}{\mu}\right)\phi\left\{-\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu}+1\right)\right\} \tag{9}$$

where λ and μ are the model parameters that are estimated using MLE method as $\mu = \frac{\sum_1^n xi}{n}$ and $\frac{1}{\lambda} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{xi} - \frac{1}{\mu}\right)$.

SEISMOTECTONICS OF THE HIMALAYA

The Himalaya which extends for a length of about 2400 Kilometres from west to east is one of the most seismically active and highly complicated tectonic regions of the world [48-49]. The surroundings of the MBT and the MCT are the epicenters of the Himalayan seismicity. MCT is exposed more clearly in the central Himalaya than eastern Himalaya and better in the western Himalaya. Western Himalayan region is having the clustered seismicity which is different from seismicity in the central Himalaya which may be due to the variation in distance between thrusts and the presence of numerous transverse faults. Although the entire Himalaya is seismically active, the western and eastern syntaxes are more active than central due to its complex geometry which clearly justifies that there are some lateral differences in seismicity along the strike of thrust and whole Himalaya is not behaving similarly and hence one single model cannot be used for assessing the seismic hazard along the entire belt.

The first step in assessing the seismic hazard of a region is to divide it into major seismotectonic segments in the form of SSZs. The entire Himalaya has been divided into four major SSZs based on seismotectonic, seismicity distribution, topography variations, and other various constraints that were considered in previous studies [50-52, 42-43] (Figure 1).

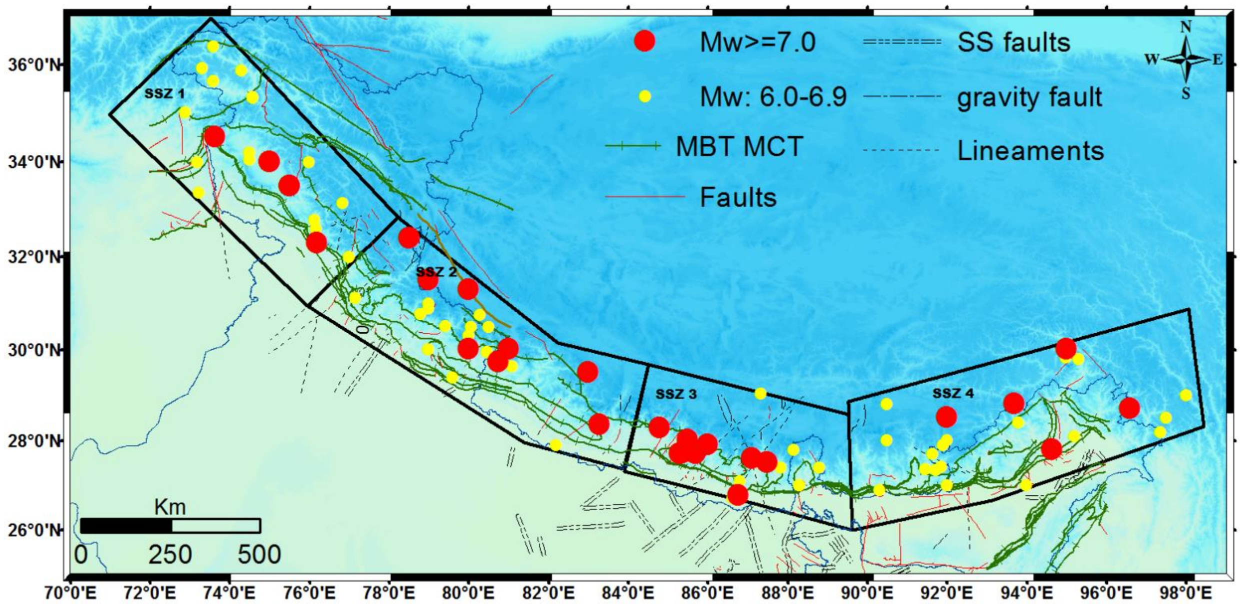


Fig. 1 Seismotectonics of the Himalayan seismic region showing major faults/folds/lineaments along with the locations of earthquakes of Mw≥6.0. This also shows the boundaries of four major SSZs for which probabilities of occurrences of future earthquakes have been calculated

SSZ 1 covers the North-Western Himalayan region where seismicity follows the NW-SE trend of Himalayas which sharply take a turn and change its trend to East-West to form Kashmir-Hazara syntax. This syntax is the main tectonic feature of this area. Along with this syntax the major structures of this region are Main Karakoram Thrust (MKT), the Main Mantle Thrust (MMT) or the Indus Suture SSZ, the Main Boundary Thrust (MBT), and the Salt Range Thrust (SRT) or the main frontal thrust (MFT) [81]; The very widespread Karakoram Fault (KKF) which is the most noticeable tectonic feature present in this region, Kishtwar fault (KF) against which MCT ended in Jammu and Kashmir; Sundarnagar fault, one of the most important transverse faults of this area, dextral in nature and goes across extending from Higher Himalaya to Frontal Belt and is thought to have changed the trend of Himalayas from NW-SE to N-S.

SSZ 2 having Easterly-South Easterly trend extends from Kaurik fault having normal type of faulting in the west to Judi fault having strike-slip faulting in the east; both are the transversal faults across the Himalayas. Areas where Himalayan longitudinal trend is intersected by some transverse faults and changes its direction are potentially having higher seismicity. Active faults of this region are Tanakpur fault, Karnali Fault, Samea, Dangsi Fault, Takhola, and Andhi fault among which Tanakpur, Karnali, Samea, and Dangsi Fault [53-54] closely spaced with each other lies towards the western side of this source SSZ. The strike of the transverse lineaments generally varies from northwest to northeast. There is a concentrated cluster of seismic events in west Nepal in an area traversed by both NW and NE-oriented cross fractures; clustering of events is related to locally active transverse features, rather than to the major Himalayan thrust system [53]. Seismicity is mainly close to MCT but there is scattered seismicity to the north of MCT also. There is a SSZ lying between longitude 79 to 81 and latitude 29 to 31 that is having a good number of events of magnitude around 6.0. Possible reason for this narrow SSZ of seismicity might be related to the locking of main Himalayan thrust in this region that is releasing energy beneath the higher Himalayas and making area around MCT relatively active. Seismicity to the north of MCT might suggest that some of the transverse faults present in the area are seismically active. Second cluster of magnitude 6.0 events at longitude 83 to 84 and latitude 31 to 32 have small number of events. Reason for this cluster might be transverse fault present there.

SSZ 3 extends from Judi fault to the west to up to Sikkim Himalayas in the east after which there is great change in factors as defined previously in the present study. Seismically active faults of this source SSZ are the Judi, Kathmandu, and the Motihari-Gourisankar, Motihari- Everest, Kanchendzonga and Pumea-Everest lineaments [53], and a few of their parallel, unnamed other lineaments. Main seismicity here is associated with the MCT and the active transverse faults. An oldest event that badly damaged Kathmandu happened in 1255 AD and the intensity associated with the event reached at least X; there was a site amplification effect induced by the basin geometry that magnifies the intensity of the earthquake damage [55]. Another major upheaval was a magnitude 7.8 earthquake event in 1934, had its epicentre some 60 km south of MBT [56] under the East Patna graben. Due to closeness of the epicenter of this earthquake to the northeast striking faults confining the East Patna Graben, it was initially thought to be associated with these faults [57]. But such impulsive type of event cannot be associated with MBT or MFT that support only creep type of movements. So this was thought to be occurred on portion of the basement thrust between MBT and MFT i.e on Main Himalayan Thrust (MHT) [58]. Recent great earthquake of this SSZ is April 2015 event having moment magnitude 7.8 which ruptured the Main Himalayan Thrust (MHT).

The high seismic activity in SSZ 4 has been a subject of great interest and studied over the past decade. The Eastern Himalaya rises abruptly from the adjoining plains and differs from rest of the Himalayan trend. Himalayas trending E-W takes sharp turn to change its trend to NE near 92.5^0 E longitudes resulted into considerable amount of seismicity that is associated with the eastern Himalayas, evident with a noticeable intensity of epicentres there; but most of the earthquakes are near MCT. The Eastern Himalayan Syntaxes joins the Main Boundary Thrust (MBT) in the Himalayas with the Burma Arc. Namcha Barwa i.e. the highest peak in the region marks the termination point of Syntax. Mishmi hills located to the east of Brahmaputra channel resisting the continuation of the Himalayan fold beyond Namcha Barwa. The union of these two different systems, viz. Himalayan and the Mishmi thrusts results into high seismicity of the region. The seismicity of the Eastern Himalaya is related to the shallow thrust faulting dipping towards the north. The 1950 great Assam earthquake was perhaps related to the Himalayan longitudinal trend [59]. Along the Assam syntaxial SSZ, several NW–SE trending thrusts, including the Lohit-Mishmi thrusts, appear to be quite active up to 100km depth.

DATA AND RESOURCES

A homogeneous and complete earthquake catalogue is one of the most important ingredients for the assessment of seismic hazard of an active region of the world. In the present study, it has been compiled for the time period 1255-2017 using different national and international seismological agencies e.g., India

Meteorological Department (IMD), India, International Seismological Centre (ISC), U.K., Global Centroid Moment Tensor catalogue of Harvard (GCMT) National Earthquake Information Centre (NEIC) of United States Geological Survey (USGS) and other published literatures. The earthquake events for the period 1964-2017 are collected from India Meteorological Department (IMD), National Earthquake Information Centre of USGS and ISC of UK (United Kingdoms). For the time period 1890-1964, earthquake events have been collected from a published catalogue of [60]; and [61] and others. Main contributors for the period prior to 1890, that is for the non-instrumental or historical period, are [62-66] and others. Some additional data have been collected from [67-74].

The compiled earthquake catalogue was available in variable magnitude scales viz. moment magnitude (Mw), surface wave magnitude (M_s), body-wave magnitude (m_b) and local magnitude (M_L). In order to use the catalogue for the study, it is made suitable using catalogue homogenization, declustering, and completeness analysis. For homogenization of magnitude scales, all magnitudes were converted into moment magnitude (Mw) using established empirical relations between different magnitude scales. Earthquake magnitudes in pre-instrumental data have been converted using empirical conversion relations given by [60]; Chung & Bernreuter [75] and Hanks & Kanamori [76]. Conversion equations for magnitude scales Ms and mb with Mw given by Scordilis [77] for the instrumental period have been used in the present study. Once homogenization is done, the catalogue has been declustered using the windowing method of Uhrhammer [78] to obtain main shocks and independent events by removing all the foreshocks and aftershocks from the catalogue. The time period for which data is complete was estimated using the Stepp method [79]. The present catalogue was found to be complete from 1685 to 2017 for Mw $\geq$ 7.0 and 1795 to 2017 for Mw $\geq$ 6.0.

RESULTS

Conditional probabilities for $M \geq 6.0$ and $M \geq 7.0$

The earthquake catalogue is prepared and treated from year 1795 to 2017 for Mw $\geq$ 6.0 and from year 1685 to 2017 for Mw $\geq$ 7.0. The earthquake data used in the present study is listed in Table 1a, b, c, and d for SSZ I to IV respectively to estimate the conditional probability. Four models, namely- Weibull, Lognormal, Gamma, and Inverse-Gaussian shows varying hazard rates over time and their applicability on the specific region may shed light on the physical process in gathering and releasing energy in the form of earthquakes, which is cyclic in nature.

The results are different from classical approach which do not shows any change in hazard with time for interpretation of the stresses remaining in the region after the occurrence of an earthquake event. All the four stochastic models are tested in all the four SSZs delineated in this study and among them the most suitable model for a region is estimated using K-S goodness of fit test. Year of previous earthquake occurrence for each SSZ are mentioned at the bottom of Table 1a, b, c, and d. Parameters of the models, mean occurrence rates and Kolmogorov-Smirnov test values for both magnitudes are listed in Table 2.

A total of 20 events (or 19 recurrence intervals) were found for computation of probabilities of earthquakes of M $\geq$ 6.0 in SSZ 1 that occurred during year 1775 – 2005, 22 events (21 recurrence intervals) in SSZ 2 during 1720-1999, 17 events (16 recurrence intervals) in SSZ 3 during 1681-2015 and 22 events (21 recurrence intervals) in SSZ 4 during 1696 – 2017. Using K-S test the models that are best fitted in the SSZ I to IV are Gamma, Inverse-Gaussian, Lognormal, and Inverse-Gaussian, respectively. The estimated model parameters for the models along with the mean rate of occurrence and KS stat values are listed in Table 2. The model parameters were estimated using Maximum Likelihood Estimation (MLE) method. The expected mean interval for the SSZs was calculated as 14.2, 13.9, 21.9 and 16.9 years in SSZ I to IV, respectively using the best-fitted models in the SSZs (Table 2).

Table 1: The Earthquake Catalogue for Zone1 (a) to Zone 4 (d) for magnitude M ≥ 6.0 is represented in this table. Non numbered events are not considered in calculations. Lon: Longitude, Lat: Latitude, Mw = Moment Magnitude

Table 1 (a)

	Location		Time of Event			Size
Sr. No.	**Lon (°E)**	**Lat (°N)**	**Year**	**Month**	**Date**	**M_w**
Zone 1						
1	75	34	1735	1	1	7.5
2	75	34	1778	1	1	7.7
3	75	34	1803	1	1	7.0
4	74.5	34.2	1828	6	6	6.4
5	75.5	33.5	1863	1	1	7.0
6	76	34	1871	4	1	6.0
	74.3	35.9	1871	5	22	6.0
7	73.2	34	1878	3	2	6.8
8	75.5	33.5	1884	5	30	7.3
9	77	32	1901	11	18	6.2
10	76.2	32.3	1905	4	4	7.8
11	76.18	32.6	1914	10	9	6.3
12	76.83	33.14	1917	5	9	6.0
13	73.59	36.38	1943	9	24	6.8
14	76.13	32.78	1945	6	22	6.3
15	74.58	35.34	1949	8	1	6.0
16	73.32	35.95	1972	9	3	6.3
17	72.9	35.03	1974	12	28	6.2
18	73.6	35.68	1981	9	12	6.1
19	74.59	35.35	2002	11	20	6.3
20	73.64	34.52	2005	10	8	7.6

Year of the Last event of Mw≥6.0 is 2005, Mw≥7.0 is 2005

Table 1 (b)

Zone 2						
	Location		**Time of Event**			**Size**
Sr. No.	**Lon (°E)**	**La (°N)**	**Year**	**Month**	**Date**	**Mw**
1	80	30	1720	7	25	7.5
2	80	31.3	1751	1	1	7
	80	30	1803	5	22	6.4
3	79	31.5	1803	9	1	7.5
4	79	30	1809	1	1	6.3
	79	30.9	1816	5	26	6.4
5	81	30	1816	8	28	7.5
6	79.6	29.4	1833	5	30	6
7	77.17	31.12	1858	8	11	6
8	79	31	1906	6	13	6
9	80.28	30.76	1911	10	14	6.5
10	80.75	29.73	1916	8	28	7.2
11	80.05	30.5	1926	7	27	6
	80.5	30.5	1927	10	8	6
12	83.28	28.35	1936	5	27	7
13	80	30.3	1945	6	4	6.4
14	82.2	27.9	1953	8	29	6
15	78.55	32.38	1955	6	27	6
16	79.95	29.99	1958	12	28	6.5
17	80.46	29.96	1964	9	26	6
18	78.5	32.39	1975	1	19	7
19	81.09	29.63	1980	7	29	6.5
20	78.79	30.77	1991	10	19	6.8
21	79.42	30.51	1999	3	28	6.5

Year of the Last event of Mw≥6.0 is 1999, Mw≥7.0 is 1975

Table 1 (c)

Zone 3						
	Location		Time of Event			Size
Sr. No.	Lon (ºE)	Lat (ºN)	Year	Month	Date	Mw
1	87.1	27.6	1681	1	1	7.9
2	85.5	28	1767	7	1	7.9
3	85.33	27.7	1826	10	29	6
4	85.7	27.7	1833	8	26	7.7
5	88.3	27	1849	2	27	6
6	88.3	27	1852	5	18	6.4
7	85.3	27.7	1866	5	23	7
8	85.3	27.7	1869	7	7	6.5
9	88.3	27	1899	9	25	6
10	87.5	27.5	1903	9	5	7.7
11	86.76	26.77	1934	1	15	8.1
12	87.84	27.4	1965	1	12	6
13	88.8	27.4	1980	11	19	6.2
14	86.63	26.72	1988	8	20	6.8
15	87.33	29.03	1993	3	20	6.2
16	88.15	27.8	2011	9	18	6.9
17	84.79	28.28	2015	4	25	7.8

Year of the Last event of Mw≥6.0 is 2015, Mw≥7.0 is 2015

Table 1 (d)

Zone 4						
	Location		Time of Event			Size
Sr. No.	Lon (ºE)	Lat (ºN)	Year	Month	Date	Mw
1	94.633	27.8	1696	1	1	7.7
2	92	28.5	1806	6	11	7.7
3	94	27	1846	12	10	6
4	95	30	1905	2	17	7.1
5	92	28	1906	5	12	6.5
6	90.5	28.8	1909	8	4	6.5
7	97.5	28.5	1911	7	1	6.5
8	91.64	27.7	1915	12	3	6.7
9	91.71	27.34	1941	1	21	6.5
10	92	27	1943	2	8	6
11	93.7	28.8	1947	7	29	7.3
12	98	29	1949	7	15	6
	95.3	29.8	1950	2	23	6
13	90.5	28	1950	2	26	6
14	96.6	28.7	1950	8	15	8.4
15	91.9	27.9	1950	8	16	6.7
	93.7	28.8	1950	8	21	6
16	93.8	28.4	1951	4	14	6.5
	93.7	28.8	1951	10	18	6
17	95.21	28.1	1956	8	22	6
18	90.3	26.9	1960	7	29	6.4
19	91.86	27.42	1967	9	15	6
20	91.46	27.37	2009	9	21	6.1
21	97.35	28.19	2015	7	18	6.1
22	94.98	29.83	2017	11	17	6.4

Year of the Last event of Mw≥6.0 is 2017, Mw≥7.0 is 1950

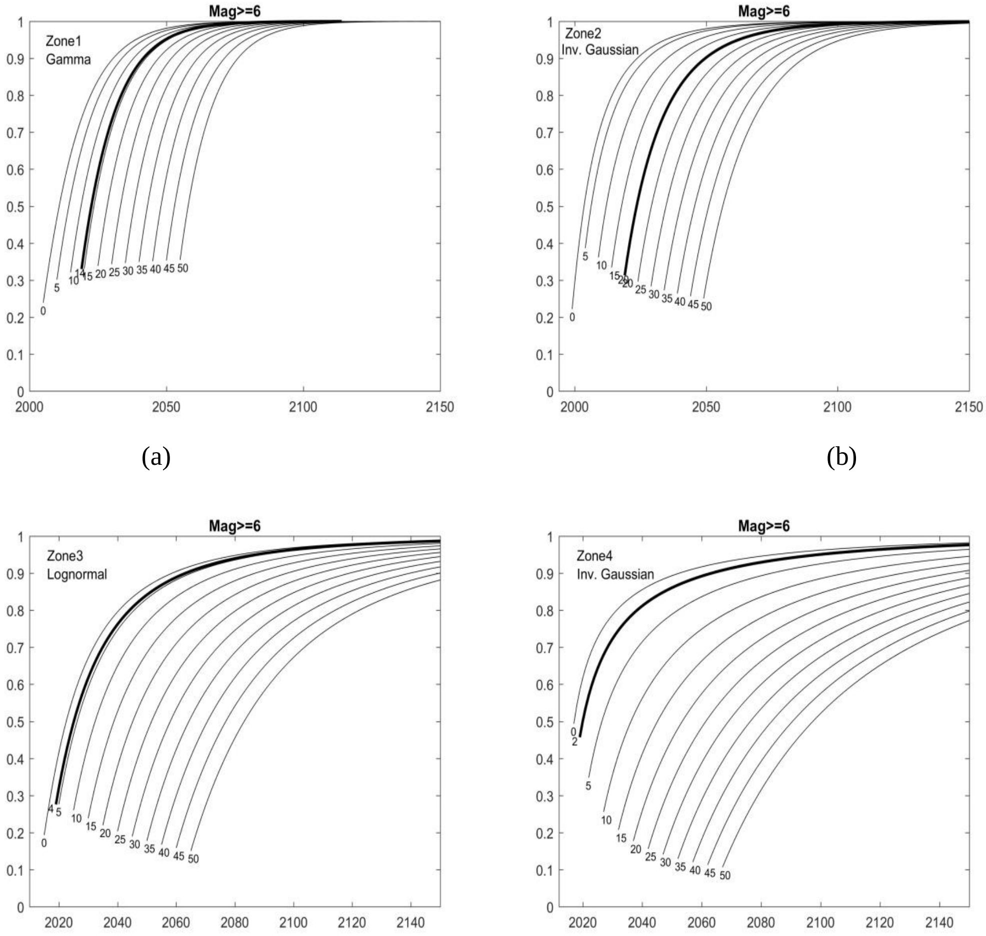
Table 2: This table is showing the Model parameters, KS stat values and expected mean for all the four models in all the four zones for magnitudes Mw ≥ 6.0 and Mw ≥ 7.0

		Weibull				Lognormal				Gamma				Inverse-Gaussian			
Zones	**Mw**	**α**	**β**	**KS**	**Mean**	**μ**	**σ**	**KS**	**Mean**	**λ**	**α**	**KS**	**Mean**	**μ**	**λ**	**KS**	**Mean**
Zone1	**≥6**	15.0	1.2	0.1564	14.2	2.2	1.0	0.1609	15.3	1.3	10.8	0.1521	14.2	14.2	10.3	0.1756	14.2
	≥7	51.0	1.7	0.2465	45.4	3.6	0.6	0.2392	46.2	3.0	15.2	0.2635	45	45.0	115.8	0.2606	45
Zone2	**≥6**	14.8	1.2	0.2413	14.0	2.3	0.9	0.1861	13.8	1.5	9.4	0.2485	13.95	14.0	14.3	0.1850	13.95
	≥7	47.8	1.6	0.1523	42.9	3.5	0.7	0.1147	44.4	2.5	17.0	0.1346	42.5	42.5	82.3	0.1234	42.5
Zone3	**≥6**	21.0	1.0	0.1292	20.9	2.5	1.1	0.1192	21.9	1.1	18.8	0.1414	20.9	20.9	12.8	0.1267	20.9
	≥7	63.0	2.7	0.2895	56.0	3.9	0.5	0.2524	56.8	5.8	9.7	0.2804	55.7	55.7	286.7	0.2713	55.67
Zone4	**≥6**	12.0	0.7	0.2340	15.9	1.7	1.5	0.1778	16.5	0.6	29.8	0.2819	16.9	16.9	3.4	0.1530	16.90
	≥7	64.7	1.0	0.2924	63.2	3.5	1.7	0.2985	140.2	0.9	67.5	0.2885	63.5	63.5	12.8	0.4448	63.50

Table 3: The Probabilities for M ≥ 6.0 for increasing time interval from year 2019 is represented in this table. First four columns are using the best suitable model amongst the used model in the study and last four columns are showing the Poisson probabilities.

Time-Interval (Mw ≥ 6)	Zone 1	Zone 2	Zone 3	Zone 4	Poisson Zone 1	Poisson Zone 2	Poisson Zone 3	Poisson Zone 4
5	0.33	0.31	0.28	0.46	0.44	0.56	0.55	0.45
10	0.56	0.52	0.47	0.62	0.68	0.81	0.80	0.70
15	0.71	0.65	0.60	0.71	0.82	0.92	0.91	0.84
20	0.81	0.75	0.69	0.77	0.90	0.96	0.96	0.91
25	0.88	0.81	0.75	0.81	0.94	0.98	0.98	0.95
30	0.92	0.86	0.80	0.83	0.97	0.99	0.99	0.97
35	0.95	0.90	0.84	0.86	0.98	1.00	1.00	0.99
40	0.97	0.92	0.86	0.87	0.99	1.00	1.00	0.99
45	0.98	0.94	0.89	0.89	0.99	1.00	1.00	1.00
50	0.99	0.95	0.90	0.90	1.00	1.00	1.00	1.00
55	0.99	0.97	0.92	0.91	1.00	1.00	1.00	1.00
60	0.99	0.97	0.93	0.92	1.00	1.00	1.00	1.00
65	1.00	0.98	0.94	0.93	1.00	1.00	1.00	1.00
70	1.00	0.98	0.95	0.93	1.00	1.00	1.00	1.00
75	1.00	0.99	0.95	0.94	1.00	1.00	1.00	1.00
80	1.00	0.99	0.96	0.95	1.00	1.00	1.00	1.00
85	1.00	0.99	0.96	0.95	1.00	1.00	1.00	1.00
90	1.00	0.99	0.97	0.95	1.00	1.00	1.00	1.00
95	1.00	1.00	0.97	0.96	1.00	1.00	1.00	1.00
100	1.00	1.00	0.97	0.96	1.00	1.00	1.00	1.00

Conditional probabilities ($P(t/\tau)$) estimate the probability of occurrence of future earthquakes in particular time interval (t) for different elapsed time (τ) since the last occurrence in a region. $P(t/\tau)$ is computed for each SSZ using the best-fitted models for all the combinations of τ and t using the model parameters estimated. The graphs for conditional probability for all combinations of τ and t for $M \geq 6.0$ are shown in Figure 2a, b, c and d. The curve in bold in Figure 2a-d is for the present scenario for which the τ equals to the time between the last occurrence and year 2019. The probabilities estimated for τ equal to the time since the last occurrence to the year 2019 (that are respectively 14, 20, 5, and 2 years for SSZ 1 to 4) having time interval as 5 to 100 years with an interval of 5 years are listed in Table 3. In this table, the probabilities computed using Poisson distribution is listed in the last four columns for SSZ 1 to 4. The estimated conditional probabilities from the year 2019 show probabilities less than 50% in next 5 years, while in next 10 years, SSZ 1, 2 and 4 show higher probability (50-70%) as compared to SSZ 3 (<50%). These conditional probabilities reach 70-90% in SSZ 1, 2, 4 and more than 50% in SSZ 3 in next 20 years, while longer time interval of 30 years, this probability reaches more than 0.9 in SSZ 1 and 70-90% in SSZ 2, 3 and 4.



(a) (b)

(c) (d)

Fig. 2 Conditional probabilities for different elapsed time (t) for Earthquake M ≥ 6.0 (a) Zone 1, Gamma (b) Zone 2, Inverse-Gaussian (c) Zone 3, Lognormal (d) Zone 4, Inverse-Gaussian for different elapsed times (τ) indicated below the curves

For Mw ≥ 7.0, there are 7 events (6 recurrence intervals) in SSZ 1 during 1775 – 2005, 7 events (6 recurrence intervals) in SSZ 2 during 1720-1975, 7 events (6 recurrence intervals) in SSZ 3 during 1681-2015 and 5 events (4 recurrence intervals) in SSZ 4 during 1696 – 1950 that are used for computing the probabilities. K-S test values show (Table 2) the Lognormal is most fitted to SSZ I to III and Gamma to SSZ IV 4 for Mw ≥ 7.0. Lesser the value of KS stat more best is the fit. KS stat values along with the expected mean of all the models and the model parameters are listed in Table 2. The statistical model parameters are estimated using MLE method. Expected mean recurrence interval using the fitted models for the four SSZs are respectively 46.2, 44.4, 56.8 and 140.2 years. For the computation of probabilities for events having M ≥ 7.0 the events for 1685 to 1795 time period are considered.

The conditional probability graphs for Mw ≥ 7.0 are shown in Figure 3a, b, c and d that are computed using the best-fitted models for all the combinations of τ and t. The bold curve in Figure 3a-d is for the present scenario for which the τ equals to the time between the last occurrence and year 2019. The probabilities for the time intervals as 10 to 200 years and τ as the time since the last occurrence to the year 2019 are listed in Table 4. The time interval is taken from 10 to 200 years with an interval of 10 years for this magnitude range. Table 4 lists the probabilities calculated using the Poisson distribution in the last four columns for the four SSZs. Changing probabilities with time are shown in this figure for time interval as 10, 20, 30, 40, 50, and 100 years. This figure can best represent the change in probabilities. The probabilities of having an earthquake of M ≥ 7.0 for 10 and 20 years interval are less than 50% in all the SSZs. In 30 and 40 years probabilities are increased in SSZ I and II from 50-70% range to 70-90% but both SSZ III and IV are still having less than 50% probabilities. In 50 years probabilities have been increased in SSZ III and

IV to the second stage that is to 50-70%. In 100 years probabilities in SSZ 1 to 3 are more than 90% and it is 70-90% in SSZ IV.

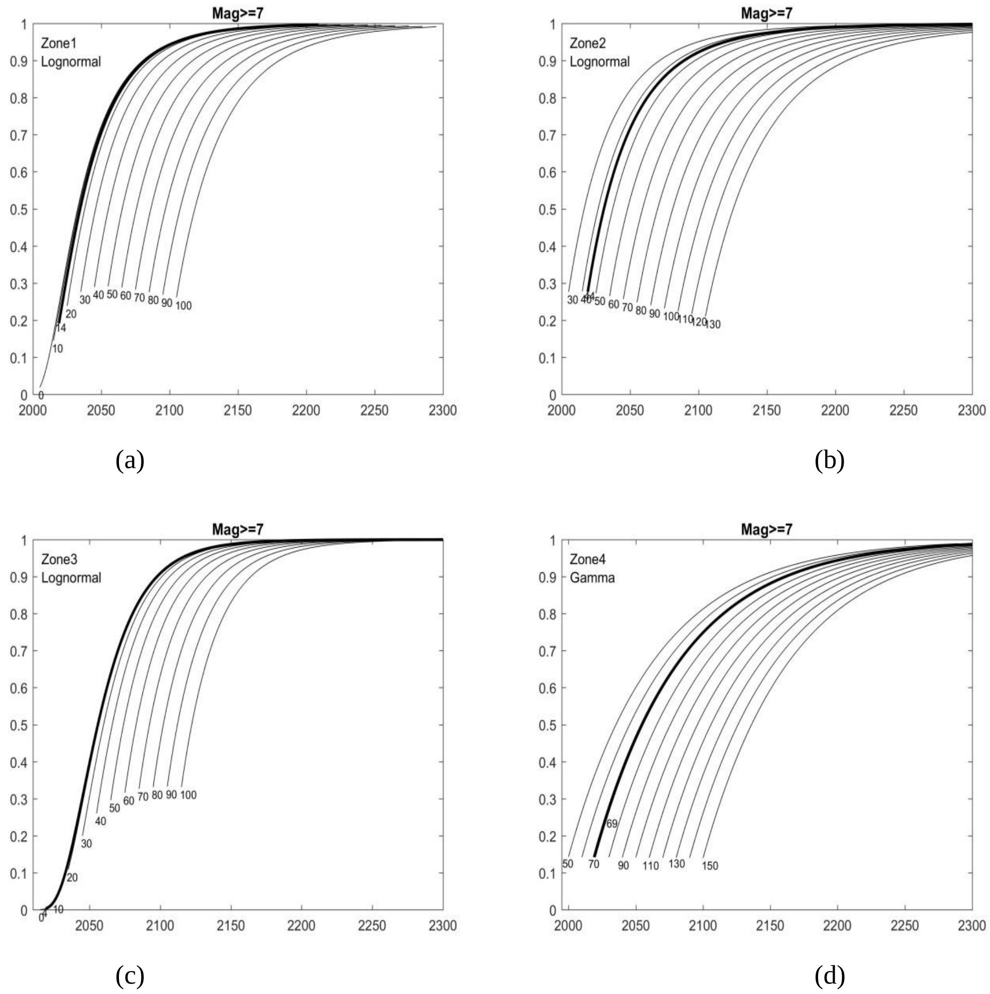


Fig. 3 Conditional probabilities for different elapsed time (t) for Earthquake Mw $\geq$ 7.0 (a) Zone 1, Lognormal (b) Zone 2, Lognormal (c) Zone 3, Lognormal (d) Zone 4, Gamma for different elapsed times (τ) indicated below the curves

Table 4: The Probabilities for the present scenario for M $\geq$ 7.0 for increasing time interval is shown in this table. First four columns are using the best suitable model amongst the used model in the study and last four columns are showing the Poisson probabilities

Time-Interval (Mw $\geq$ 7)	Zone 1	Zone 2	Zone 3	Zone 4	Poisson Zone 1	Poisson Zone 2	Poisson Zone 3	Poisson Zone 4
10	0.19	0.28	0.00	0.14	0.08	0.14	0.06	0.08
20	0.40	0.47	0.05	0.26	0.15	0.27	0.12	0.16
30	0.57	0.61	0.19	0.37	0.22	0.37	0.18	0.23
40	0.70	0.71	0.38	0.46	0.28	0.46	0.23	0.29
50	0.78	0.78	0.55	0.53	0.34	0.54	0.28	0.35
60	0.85	0.83	0.69	0.60	0.39	0.61	0.33	0.41
70	0.89	0.87	0.79	0.66	0.44	0.66	0.37	0.46
80	0.92	0.90	0.86	0.70	0.49	0.71	0.41	0.50
90	0.94	0.92	0.91	0.75	0.53	0.75	0.45	0.54
100	0.96	0.94	0.94	0.78	0.56	0.79	0.48	0.58
110	0.97	0.95	0.96	0.81	0.60	0.82	0.52	0.62
120	0.98	0.96	0.97	0.84	0.63	0.84	0.55	0.65
130	0.98	0.97	0.98	0.86	0.66	0.87	0.58	0.68
140	0.99	0.97	0.99	0.88	0.69	0.89	0.60	0.70
150	0.99	0.98	0.99	0.90	0.71	0.90	0.63	0.73

160	0.99	0.98	0.99	0.91	0.74	0.92	0.65	0.75
170	0.99	0.99	1.00	0.92	0.76	0.93	0.67	0.77
180	0.99	0.99	1.00	0.93	0.78	0.94	0.70	0.79
190	1.00	0.99	1.00	0.94	0.79	0.95	0.72	0.81
200	1.00	0.99	1.00	0.95	0.81	0.95	0.73	0.82

DISCUSSION AND CONCLUSIONS

The current research aims to investigate the earthquake occurrence model adaptability in seismically distinct sections of the Himalayas. The transverse features have played an essential part in dissecting regional characteristic and driving individual blocks to behave differently in releasing strain energy. The rotational differential movement is one of the unambiguous attributes while the differential movement in the blocks has yet to be proven by accounting for different occurrence models being followed by each, albeit the Himalayas have experienced strike-slip earthquakes in thrusting environment. Seeing such facts we can quantify the difference in physical processes going on in different parts of the Himalaya. Therefore, goodness of fit test is used to find the applicability of a particular model which will specify the nature of that SSZ. The seismic hazard obtained using classical approaches is found to be resulting in higher hazard values for smaller magnitudes (Table 3) and it is giving lower hazard for high magnitudes (Table 4). It has been observed that earthquakes occurrence as estimated by Poisson distribution is not in compliance with the real scenario as checked from the available earthquake catalogues. Of course, these probabilities are an ensemble of many cycles but even then some of it must be reflected in the catalogues.

There are some studies that are done for Indian regions like study for Hindukush and northeast region of India has been carried out by Parvez and Ram [36] using Weibull, Lognormal and Gamma and latter for the whole Indian subcontinent Parvez and Ram [37]. They observed that Gamma and Weibull models are the most suitable models for the Indian sub-continent. Yadav [10] applied three stochastic models, namely, Weibull, Gamma, and Lognormal, in the northeast and adjoining region of India and found that the Gamma is the most suitable for this region. Sharma and Kumar [39] applied Weibull for Indian region. Chingtham et al. [80] used Weibull and Lognormal distributions for Northwest Indian region and found Lognormal to be the best-suited model for this region. The results and the best suitable models for various regions for this study are explained in the following section.

For Mw $\geq$ 6.0, SSZ 1 is adapting Gamma distribution which means the hazard rate of the region will become constant with increasing time from the last occurrence. This can be interpreted in the form of stress as the stress drop is partial in such regions and the region has still got the stresses which may result in the form of strain release to produce moderate-sized earthquakes. From past seismicity information, it is evident that this region is experiencing frequent earthquakes of size 6.0. For Mw $\geq$ 7.0, Inverse-Gaussian is best suitable which interprets that the hazard in a region for a magnitude range starts decreasing after crossing the mean interval time of that size event. It can be thought it like the stresses in such regions might be releasing in some other forms of energy inside the earth. This can be understood as SSZ 1 becomes less hazardous for large earthquakes with increasing elapsed time and this region has a constant hazard for moderate-sized earthquakes. In this region two different models are fitting for varied magnitude sizes means this zone is behaving in two different ways means there can be two different types of sources present in this region.

For SSZ 2, Inverse-Gaussian for Mw $\geq$ 6.0 and Lognormal for Mw $\geq$ 7.0 are found to be the most suitable distributions which indicates that the hazard in this area is decreasing for both moderate and large earthquake events as the time elapsed since the last earthquake increases. This reveals that the stress drops of the events are higher. Therefore, either the region is not capable of restoring the strain energy at faster rate which means that the next event will take a longer time to occur or the stresses might be releasing continuously either in the form of smaller events or in some other forms inside the earth and no such big event will occur in such regions. This region is considered to be the seismic gap region.

Seismic gap hypothesis suggest that the potential for a future shock is small immediately after an earthquake event and this ability increases as time passes on; This indicates that earthquakes are non-random phenomenon and this non randomness gives rise to the hope that time of earthquake occurrence can be predicted based on the available data using statistical procedures. Time-dependent models are well coordinating with these facts as these models consider the time elapsed since the last occurrence to estimate the probability of earthquake occurrences. Whereas the Time-Independent models only consider the recurrence intervals of catalogue events as input data and does not consider the time since the proceeding event.

In SSZ 3, for both magnitude ranges the Log-normal distribution is best adapted by the region. This model suggests that it takes almost time equals to the mean interval time for the hazard to reach its maximum value and if at that time there isn't any event occurrence is there then the hazard will start decreasing. Stress drop in this region is higher and it takes a longer time for stresses to build and an earthquake to occur. Like the recent 2015 Gorkha earthquake having a magnitude 7.8 occurred after 1934 Bihar-Nepal earthquake, that had a magnitude of 8.1. It took almost 80 years to build the stresses for a large earthquake to occur.

In SSZ 4, for Mw $\geq$ 6.0 the Inverse-Gaussian distribution is best suitable for the region and for Mw $\geq$ 7.0, the Gamma distribution is most suitable. This can be understood like, there is continuous stress drop for moderate earthquakes but if the mean occurrence time for such evet crossed then it will take a longer time for the next event to occur. Like there was a gap after the 1967 event that had a magnitude 6.0 after which the next earthquake occurred in 2009 (Table 1 (d)). This is because the mean occurrence of time had crossed and then the hazard started decreasing. For large events the SSZ is adopting the Gamma model according to which the region will take a long time to build the stresses but once the stresses build there is a constant hazard in the region. Different models suiting for the magnitude ranges indicated the source interactions in the regions.

These Time-Dependent models are best used for understanding a region more precisely. Suitability of particular distribution describes the different physical processes responsible for earthquake occurrence. The heterogeneous and complex tectonics of Himalayas, differentiated movement of plate motion, different stress release pattern (spatially and temporally), locking/unlocking of faults/thrusts, Seismogenic source interactions are some of the reasons responsible for different probabilistic models representing the earthquake occurrence in these four SSZs.

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