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TIME-DEPENDENT SEISMIC HAZARD ASSESSMENT FOR NEPAL HIMALAYAS

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Abstract

Theoretical research works and past experience have proven seismic hazard assessment using time-dependent model provides more realistic results than using time-independent models for large magnitude events. The earthquakes having large magnitudes follow elastic rebound theory of earthquake occurrence; hence their probability of occurrence increases with the time since the last seismic event. The Himalaya belt formed by two converging plates has differential convergence rate over the entire arc, which results into a non-uniform seismic behavior over the entire mountain chain. One of the examples is the Nepal region spreading over one-third of the Himalayas (or about 800 km from 2500 km long arc) and is a prominent part of the Himalaya has experienced many earthquake events which sometime do not follow the classical approaches and models of seismic hazard. It is one of the most seismically prone countries of the world. The Nepal, from its western to eastern end, comprises different geology and tectonics and therefor behaving differently in earthquake occurrence terms. It is in this context that the Nepal region of the Himalaya has been chosen for the present study. The Time-dependent seismic hazard analyses have been conducted for the Nepal region to have a better understanding of the processes going on there.

In the present work, to study Nepal Himalayas with respect to time-dependent models, two stochastic models have been selected *viz.* Weibull distribution and Log-normal distribution. The distributions have distinguishable properties that can be used to interpret the seismic behavior for more clear understanding of the physical phenomenon of the area based on its adoption towards a particular distribution. The probabilities of earthquakes have been calculated for earthquakes having moment magnitude greater than 5.5, 6.0, 6.5, and 7.0. The model adoption has been selected using goodness of fit tests. The Nepal region is segregated into two seismogenic source zones (*i.e.* Western Nepal and Eastern Nepal) on the basis of seismicity and tectonics. Fitting of different type of model for different magnitude range, for same region interprets that the region has got different types of sources that are generating various sizes of earthquakes there.

Keywords: Nepal Himalayas; Time-dependent seismic hazard; Weibull distribution; Log-normal distribution

1. Introduction

Nepal is a part of the Himalaya, approximately 800 km in length situated at its central segment. It is one of the most seismically prone countries in the world. Since, the Himalaya has witnessed many varied sizes earthquakes; many of them occurred in Nepal. The great earthquakes of Nepal which had magnitudes greater than 7.5 occurred in years 1255, 1408, 1505, 1833, 1934 and 2015 [1]. Among the major historical earthquakes, the 1934 Bihar-Nepal earthquakes (M_w=8.4) was most disastrous among the historical events of Nepal with a maximum intensity of X (MMI), caused extensive damage in the eastern half of Nepal and resulted in more than 8500 deaths and hugeloss to buildings [2]. This caused extensive damage to human lives and huge economic loss to Nepal. The damages from future earthquakes are expected to rise due to tremendous rise in population and structures. Recent earthquakes that have affected the country significantly are 1980 event having surface wave magnitude (M_S) 6.6, 1988's of M_S 6.8, 2011 of magnitude 6.8 and 2015 having moment magnitude 7.8 and 8.1 as surface wave magnitude. The event affected more than 7,90,000 buildings of Nepal that were fully or partially damaged, caused 8778 fatalities and 22,303 injuries (Government of Nepal, 2015, http://drrportal.gov.np/) [3]. The earthquake of 2011 occurred on September 18 and affected five countries, namely Nepal, India, Bangladesh, Bhutan and China. Similarly 2015 Nepal event also caused significant loss of life and property in these countries. Several fault studies [e.g., 4, 5, 6, 7, 8, 9, 10] have identified four major longitudinal faults (STDS, MCT, MBT, and MFT), a longitudinal Bari Gad fault, and a number of transverse faults as well as their associated minor faults in Nepal. Such faults caused higher seismicity in the Himalaya [11](Sharma and Arora, 2005). To reduce the impact of catastrophic seismic events that can occur due to movement along these faults, it is very important to evaluate the potential location, predicted exposure level and distribution of earthquake events using various techniques. A comprehensive understanding of the geodynamic processes in the Himalaya is the corner stone of such intrinsic efforts, where the ultimate goal is to establish a framework within the Himalayan environment that facilitates sustainable development of the mountain chains.

The classical mathematical models applied to carry out both Deterministic and Probabilistic Seismic Hazard Assessment (DSHA and PSHA) assume that the seismicity rate is Time-independent *i.e.*, the rate of seismicity remains constant in a finite time period. Various such studies have been done for Himalayan region [12, 13, 14, 15](Sharma, 2003; Sharma and Shanker, 2001; Sharma and Linholm, 2012; Sharma and Dimri, 2003)some of which were done specifically for Nepal Himalayan region [16, 17, 18](Shrestha, 2014; Thapa et al., 2017; stevens et al, 2018). This assumption, albeit used for mathematical simplicity, has indeed been a stark contrast to the physical process of strain release through earthquake occurrence [19, 20, 21]. This is therefore imperative to examine the current level of seismic hazard in the Himalaya through the prism of Time-dependent hazard models. İn this work the Time dependent probabilities for various magnitude ranges have been estimated using two statistical distributions namely, Weibull and Lognormal. These models have distinguishable properties that can help to understand a seismic source in a better way. The compatibility of the intercurrence data of earthquakes with a statistical distribution is tested with a "*goodness of fit test"*. The Kolmogorov-Smirnov test has been used for the selection of the most suitable model for a specific seismic zone.

2. Study area and Data

The Nepal region considered for this study is given in Fig. 1. The seismic and tectonic features of Nepal are shown in the figure.

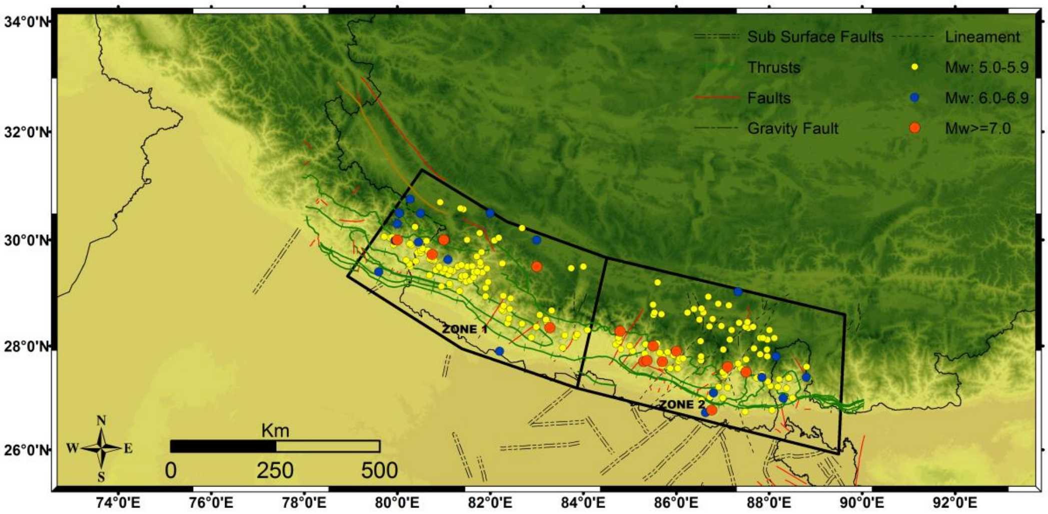


Fig. 1: Seismicity and Tectonic map of Nepal

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 Gutenberg & Richter [22]; Gutenberg [23]; and Rothe [24] and others. Main contributors for the period prior to 1890, that is for the non-instrumental or historical period, are Baird-Smith [25], Oldham [26], Milne [27], Lee *et al.* [28], Quittmeyer & Jacob [29] and others.

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 Gutenberg [30]; Chung & Bernreuter [31] and Hanks & Kanamori [32]. Conversion equations for magnitude scale Ms and mb with Mw given by Scordilis [33] for the instrumental period has been used in the present study. Once homogenization is done, the catalogue has been declustered using the windowing method of Uhrhammer [34] 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 [35]. The completeness year for the catalogue is given in Table 1.

Table 1: Completeness year

Sr. No.	Magnitude	Year
1	5.5-6.0	1900
2	6.0-6.5	1795
3	6.5-7.0	1750
4	≥7.0	1680

3. Methodology

The conditional probability technique has been applied in the past in different regions of the world for various seismogenic zones and faults to assess the seismic hazard [36, 37, 38, 39 etc.]. The evaluation of seismic potential can be performed as a function of probability for occurrences of an earthquake event during a specified time period in a particular seismogenic zone. The conditional probability means the probability of occurrence of the next earthquake event during a specified time interval after certain elapsed time from the previous event [40]. 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 $\left(\frac{x+dx}{x}\right) = \frac{F(x+dx)-F(x)}{1-F(x)}$. 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 + τ)* assuming that no earthquake has occurred after the last occurrence. It is observed that the conditional probability depends on the shape of the curve as well as on the width of time interval τ. A brief description of some of the models given by Utsu [41], which have been applied in the present study for the estimation of earthquake occurrences, is given below. The most suitable model for the region is selected on the basis of the Kolmogorov-Smirnov test.

Kolmogorov-Smirnov Test

It is one of the most widely used statistical tests for estimating the goodness of fit [42]. In this test, the difference between observed and theoretical cumulative probabilities is calculated and the maximum difference between these should be less than the critical value. The critical value is relied on the size of the sample and on significance level (α) (which is taken as 0.05 in this study). If F (t) is observed CDF and F1 (t) is observed CDF for a used model: the equation for the K-S test can be expressed as

$$D_n = \max|F1(t) - F(t)| \tag{1}$$

where D_n is the maximum difference between the observed and theoretical CDFs'. If $D_{n\alpha}$ is assumed to be the critical value, then to accept a model following equation should follow

$$D_n = \max|F1(t) - F(t)| \tag{2}$$

3.1 Weibull Model

This distribution was introduced in 1951 by Waloddi Weibull [43] 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:

$$f(x) = \frac{\beta}{\alpha}(x/\alpha)^{\beta-1}e^{-(x/\alpha)^{\beta}} \quad (3)$$

$$F(x) = 1 - e^{-(x/\alpha)^{\beta}} \quad (4)$$

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 $\beta = \frac{1}{\frac{\sum(xi^{\beta}Ln(xi))}{\sum xi^{\beta}} - \frac{1}{n}\sum Ln(xi)}$ and $\alpha = \frac{\sum xi^{\beta}}{n}$. Where, *x* is a random sample of size *n*.

3.2 Log normal 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 Log normal 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:

$$f(x) = \frac{1}{\sigma x\sqrt{2\pi}} exp^{\frac{-(lnx-\mu)^2}{2\sigma^2}} \quad (5)$$

$$F(x) = \varphi\left(\frac{\ln(x)-\mu}{\sigma}\right) \quad (6)$$

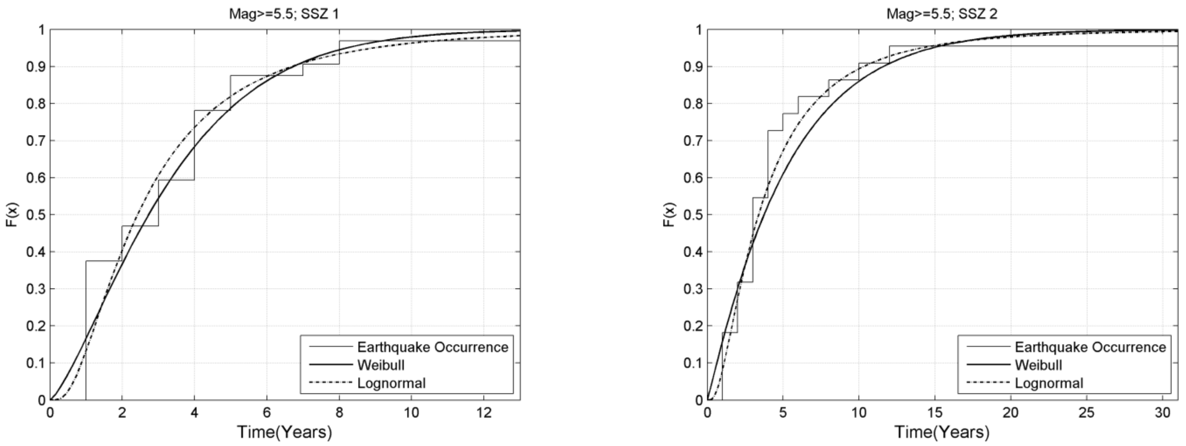
Where, ϕ is the CDF of the normal distribution, and σ and μ are the mean and the standard deviation of the logarithm of *x*. The MLE has been used for estimating the parameters of this distribution that are given as, $\mu = \frac{\Sigma_i\, ln(x_i)}{n}$ and $\sigma^2 = \frac{\Sigma_i(ln(x_i)-\mu)^2}{n}$.

4. Results

The earthquake data for $M_w \geq 5.5$ used in the present study is listed in Table 2 (a) and (b) for SSZ 1 and 2, respectively. Considering the completeness of the prepared catalogue, the data for Mw ≥ 5.5, Mw ≥ 6.0, Mw ≥ 6.5 and Mw ≥ 7.0 are taken from the year 1900 to 2017, 1795 to 2017, 1750 to 2017 and 1685 to 2017, respectively, to estimate the conditional probability in the seismogenic zones of the Nepal region found for this study. The statistical distributions, namely Weibull and Log-Normal, show varying hazard rates with time, and their applicability in a specific region may throw light on the physical process, which shows cyclic accumulation and release of energy in the form of earthquakes. In this work two distributions have been applied and tested in two seismic source zones (SSZ), and the model fitting best for a specific zone is estimated using the K–S test.

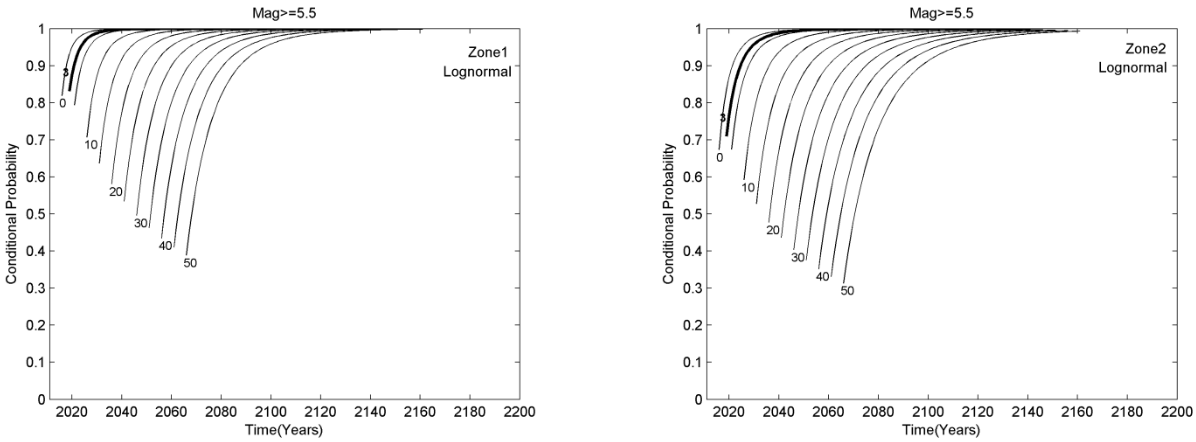
For the computation of probabilities of earthquakes of $M_w \geq 5.5$, a total of 33 events (32 recurrence intervals) are used in zone 1 during 1911–2016, 23 events (22 recurrence intervals) in zone 2 during 1903–2016. The suitability of the models is estimated based on the K–S results, revealing that the model that fits best in zone 1 and 2 is the Log-Normal. The model parameters are estimated using the MLE method. The CDF curves for *F(x)* $(1 - \int_0^x f(x)dx)$, where x is the time interval, are shown in Fig. 2 (a) and (b) for two zones. These graphs indicate that the cumulative probability takes almost 7 and 10 years to reaches 90% in SSZ 1 and 2 respectively. The conditional probability P(t/s) estimates the probability of occurrence of future earthquakes in a particular time interval (t) for different elapsed times (s) since the last occurrence in a region. P(t/s) is computed for each zone using the best-fit models for all the combinations of s and t using estimated model parameters. Graphs of the conditional probability for all combinations of s and t for $M_w \geq 5.5$ are shown in

Fig. 3(a) and (b). The curve in bold in Fig. 3 is for the present scenario, for which "τ" equals the time between the last occurrence and the year 2019. These results indicate that both the zones are having higher probabilities for this magnitude earthquake.



(a) (b)

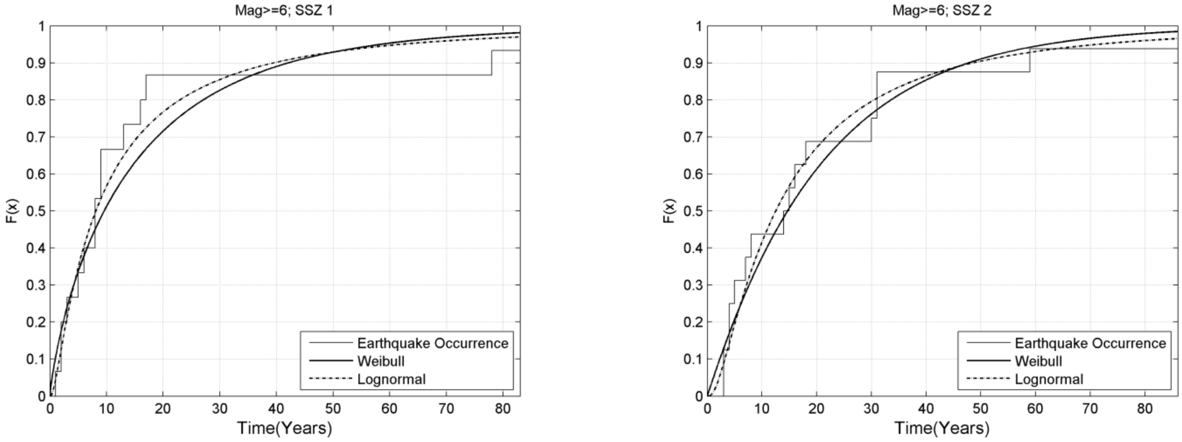
Fig. 2: CDF for $M_w \geq 5.5$



(a) (b)

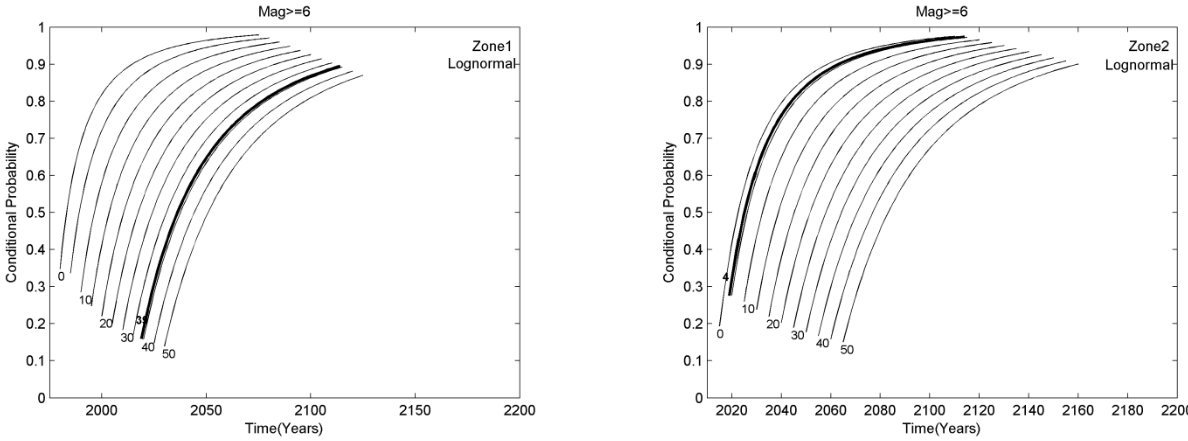
Fig. 3: Conditional probabilities for (a) SSZ 1 and (b) SSZ 2 for $M_w \geq 5.5$.

For the computation of probabilities of earthquakes of $M_w \geq 6.0$, a total of 16 events (15 recurrence intervals) are used in zone 1 during 1720–2015, 17 events (16 recurrence intervals) in zone 2 during 1681–2015. The suitability of the models is estimated based on the K–S results, revealing that the model that fits best in zone 1 and 2 is the Log-Normal. The model parameters are estimated using the MLE method. The CDF curves for *F(x)* $(1 - \int_0^x f(x)dx)$, where x is the time interval, are shown in Fig. 4 (a) and (b) for two zones. These graphs indicate that the cumulative probability takes almost 75 years and 60 years to reaches 90% in SSZ 1 and 2 respectively. Graphs of the conditional probability for all combinations of s and t for $M_w \geq 6.0$ are shown in Fig. 5(a) and (b). The curve in bold in Fig. 5 is for the present scenario, for which "τ" equals the time between the last occurrence and the year 2019. These results indicate that both the conditional probability is reaching 80% in 50 to 60 years in SSZ 1 and it is taking almost 10 to 15 years in SSZ 2 to reach its 80%.



(a) (b)

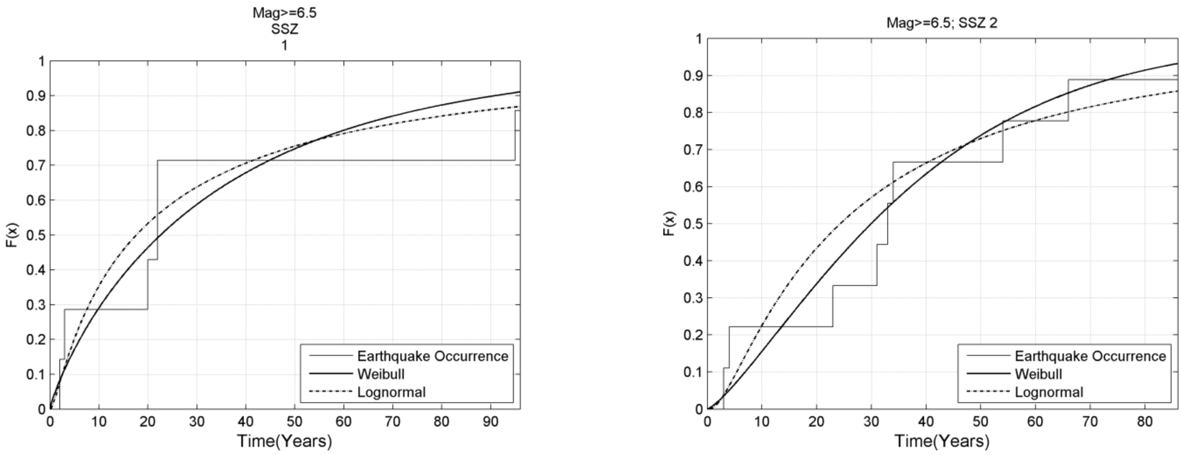
Fig. 4: CDF for $M_w \geq 6.0$



(a) (b)

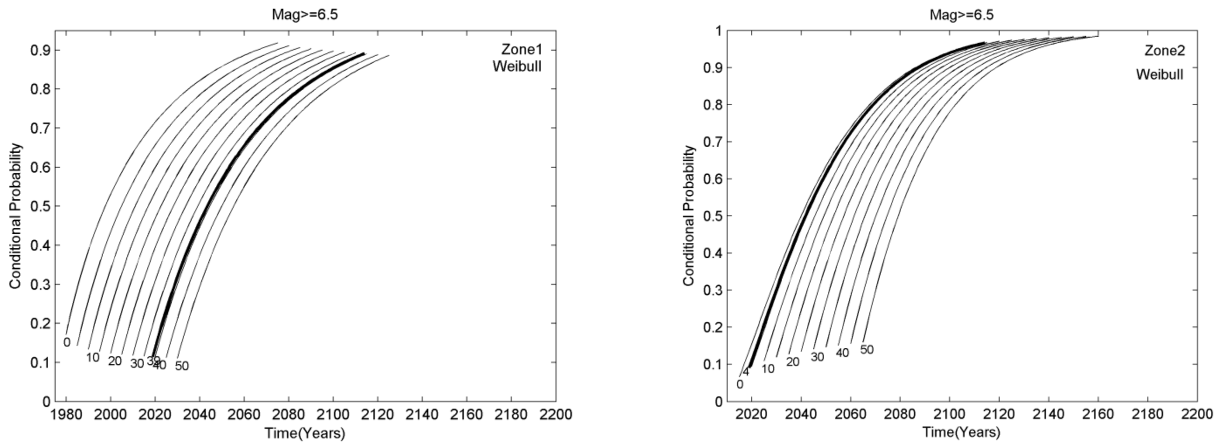
Fig. 5: Conditional probabilities for (a) SSZ 1 and (b) SSZ 2 for $M_w \geq 6.0$.

For the computation of probabilities of earthquakes of $M_w \geq 6.5$, a total of 8 events (7 recurrence intervals) are used in zone 1 during 1720–1980, 10 events (09 recurrence intervals) in zone 2 during 1681–2015. The suitability of the models is estimated based on the K–S results, revealing that the model that fits best in zone 1 and 2 is the Weibull. The model parameters are estimated using the MLE method. The CDF curves for $F(x)$ $(1 - \int_0^x f(x)dx)$, where x is the time interval, are shown in Fig. 6 (a) and (b) for two zones. These graphs indicate that the cumulative probability takes almost 95 and 65 years to reaches 90% in SSZ 1 and 2 respectively. Graphs of the conditional probability for all combinations of s and t for $M_w \geq 6.5$ are shown in Fig. 7(a) and (b). The curve in bold in Fig. 7 is for the present scenario, for which "τ" equals the time between the last occurrence and the year 2019. The conditional probabilities are reaching 80% in 55-60 years in SSZ 1 and 30 to 40 years in SSZ 2. This indicates that SSZ2 is more earthquake prone than SSZ1.



(a) (b)

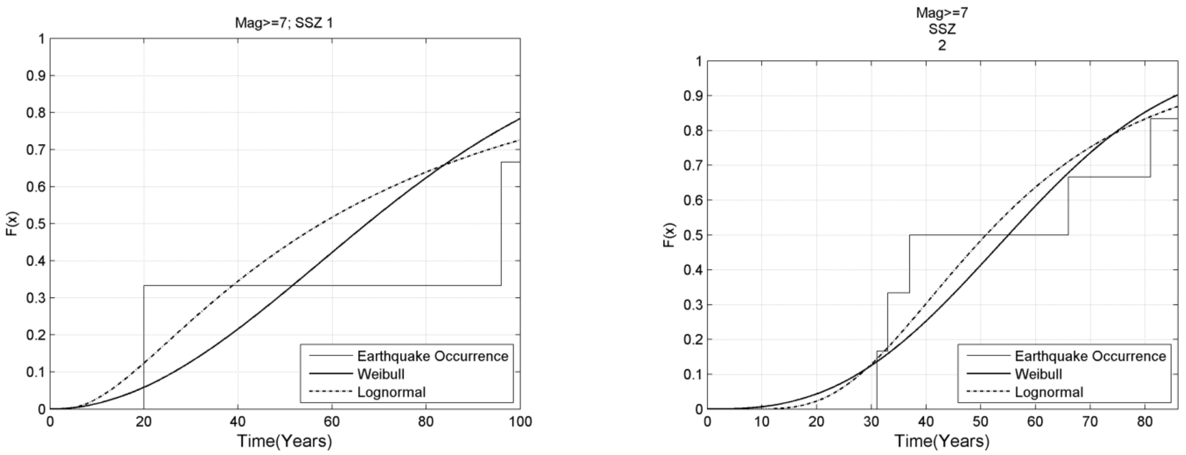
Fig. 6: CDF for $M_w \geq 6.5$



(a) (b)

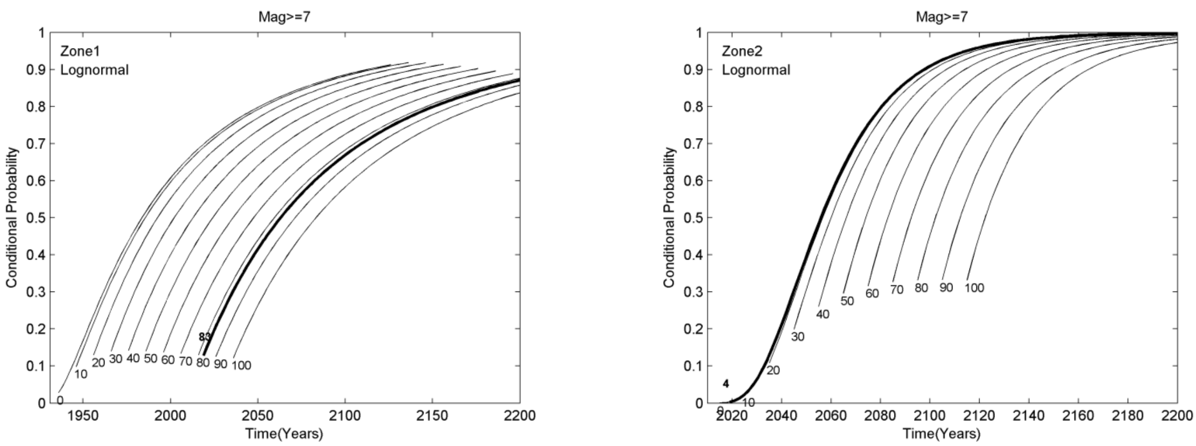
Fig. 7: Conditional probabilities for (a) SSZ 1 and (b) SSZ 2 for $M_w \geq 6.5$.

For the computation of probabilities of earthquakes of $M_w \geq 7.0$, a total of 4 events (3 recurrence intervals) are used in zone 1 during 1720–1936, 7 events (6 recurrence intervals) in zone 2 during 1681–2015. The suitability of the models is estimated based on the K–S results, revealing that the model that fits best in zone 1 and 2 is the Log-Normal. The model parameters are estimated using the MLE method. The CDF curves for *F(x)* $(1 - \int_0^x f(x)dx)$, where x is the time interval, are shown in Fig. 8 (a) and (b) for two zones. These graphs indicate that the cumulative probability is taking more than 100 years to reaches 90% in both the zones. The conditional probability graph for all combinations of s and t for $M_w \geq 7.0$ are shown in Fig. 9(a) and (b). The curve in bold in Fig. 9 is for the present scenario, for which "τ" equals the time between the last occurrence and the year 2019. These results indicate that for SSZ 1, the conditional probabilities are taking almost 200 years to reach 70% and for SSZ 2, it is taking 60-70 years for reaching 80%.



(a) (b)

Fig. 8: CDF for $M_w \geq 7.0$



(a) (b)

Fig. 9: Conditional probabilities for (a) SSZ 1 and (b) SSZ 2 for $M_w \geq 7.0$.

Table 2: *Earthquake catalogue for (a) Zone 1 and (b) Zone 2*

(a)

Long	**Lat**	**year**	**month**	**date**	**mag**
3	29.5	1505	6	6	8.2
80	30	1720	7	25	7.5
80	30	1803	5	22	6.4
81	30	1816	8	28	7.5
79.6	29.4	1833	5	30	6
80.28	30.76	1911	10	14	6.5
83	30	1913	3	6	6.6
80.75	29.73	1916	8	28	7.2
82	30.5	1918	4	28	6
80.05	30.5	1926	7	27	6
80.5	30.5	1927	10	8	6
80.4	29.6	1935	3	5	5.8

(b)

Long	**Lat**	**year**	**month**	**date**	**Mw**
85.37	27.72	1255	6	7	8.4
86.8	27.1	1260	1	1	6.9
87.5	27.5	1344	1	1	7.7
86	27.9	1408	8	1	8
87.1	27.6	1681	1	1	7.9
85.5	28	1767	7	1	7.9
85.33	27.7	1826	10	29	6
85.7	27.7	1833	8	26	7.7
88.3	27	1843	8	10	5.7
88.3	27	1849	2	27	6
88.3	27	1852	5	18	6.4
88.3	27	1863	3	29	5.7

83.28	28.35	1936	5	27	7	85.3	27.7	1866	5	23	7
81.5	30	1937	4	30	5.6	85.3	27.7	1869	7	7	6.5
81.5	30	1940	4	10	5.5	88.3	27	1899	9	25	6
80	30.3	1945	6	4	6.4	87.5	27.5	1903	9	5	7.7
82.2	27.9	1952	11	8	5.5	86.76	26.77	1934	1	15	8.1
82.2	27.9	1953	8	29	6	86.5	28.5	1939	6	4	5.7
83.83	28.17	1954	9	4	5.5	86.69	28.93	1951	5	28	5.5
79.95	29.99	1958	12	28	6.5	85.7	27.8	1952	10	19	5.5
80.9	29.5	1963	1	30	5.5	86.9	28.8	1958	11	23	5.5
80.46	29.96	1964	9	26	6	88	28.3	1961	9	29	5.5
83.06	28.59	1965	6	1	5.5	85	28	1962	1	11	5.5
80.79	29.62	1966	12	16	5.9	87.84	27.4	1965	1	12	6
81.57	29.24	1970	2	12	5.5	86.38	28.7	1967	3	2	5.5
81.38	29.32	1974	12	23	5.5	87.95	27.93	1971	12	4	5.5
81.46	29.33	1976	5	10	5.5	85.51	28.59	1974	9	27	5.7
80.27	29.93	1979	5	20	5.8	85.94	27.82	1978	10	4	5.5
81.09	29.63	1980	7	29	6.5	88.8	27.4	1980	11	19	6.2
81.79	29.52	1984	5	18	5.8	86.63	26.72	1988	8	20	6.8
83.74	29.47	1987	8	9	5.6	88.11	28.15	1990	1	9	5.7
81.61	29.51	1991	12	9	5.8	87.33	29.03	1993	3	20	6.2
81.9	28.94	1992	6	2	5.5	85.34	28.03	1997	1	31	5.5
80.5	29.8	1997	1	5	5.7	86.97	28.38	2000	9	6	5.5
82.26	29.56	2001	11	27	5.5	87.13	28.77	2001	4	28	5.5
81.42	30.57	2002	6	4	5.6	88.15	27.8	2011	9	18	6.9
81.65	29.4	2015	12	18	5.6	84.79	28.28	2015	4	25	7.8
80.63	29.98	2016	12	1	5.5	86.53	27.8	2016	11	27	5.6

5. Discussions

The present work is done to understand the pattern of earthquake occurrence in seismically active Nepal region. Using the goodness of fit test Log-Normal was found to be the most suitable for both the zones for $M_w \geq 5.5$, $M_w \geq 6.0$ and $M_w \geq 7.0$. Adaptability towards Log-Normal distribution can be interpreted as the probability immediately after an earthquake event is smallest and this probability increases upto the mean occurrence time and if an earthquake event hasn't occurred, the probability starts decreasing. The probability is largest after a particular time of last occurrence. For $M_w \geq 6.5$, the most suitable model is Weibull which means the earthquake probabilities keeps on increasing with time after occurrence of a seismic event. Both the zones are showing same characteristics toward adapting a renewal model. Adaptability towards different models for a specific magnitude range indicates the presence of different types of sources which are generating such events. There a number of transversal faults present in Nepal region which have played an important roles in generating seismic events and also dissect the regional features and therefore forcing the individual blocks to behave differently in releasing strain energy. The earthquake occurrences estimated using classical approach is not in compliance with the real scenario (Bajaj and Sharma, 2019). The probabilities are the result of many cycles but some of it must be reflected in the catalogue and which can be best understood with the use of Time-Dependent models.

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