Probabilistic analysis of seismic data for earthquake forecast in North East India and its vicinity

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Seismic data for 100 years (1918–2018) were analysed for probabilistic analysis in the forecast of probable future earthquakes above $M_w \geq 5.0$ in North East India (20°–30°N and 86°–98°E) and its vicinity. The best distribution for seismic data allows probabilistic analysis to ascertain mean occurrence period $E(t)$ for earthquakes of $M_w \geq 5.0$. Here, Kolmogorov–Smirnov statistics has been utilized constrained by Weibull distribution to achieve the best fit on the dataset. $E(t)$ is found to be 74 days approximately with 50% probability. Similarly, cumulative probability function indicates a time period of 140 days with 80% probability, while 400–500 days of recurrence time period is embedded with 90–100% probability for an earthquake of $M_w \geq 5.0$ to recur following the occurrence of the last earthquake.

Keywords: Cumulative probability function, earthquake forecast, probabilistic analysis, seismic risk.

EARTHQUAKES are catastrophic events that occur without a hint, causing huge loss to life and property. Earthquake prediction studies started way back in late 1970, and a landmark was the short-term prediction of the Heicheng earthquake of 4 February 1975 in China[1]. Earthquake prediction is a complex process to determine exactly when and where an earthquake will occur[2]. The North East (NE) India region is highly vulnerable to earthquakes falling in seismic zone-V (ref. 3). This provides a huge opportunity in finding the precursor to an earthquake, and successful prediction might also be possible in the near future. A successful medium-term prediction of the 6 August 1988 earthquake (M_w ~7.5) NE India encouraged such studies in the country[4]. Earthquakes are random phenomena and statistical analysis is a prominent tool for earthquake prediction studies.

Probability analysis measures the likelihood of an event to occur and is derived from the term ‘probable’ (Latin ‘probabilis’), meaning approvable[5]. The scientific application of probability today is from advanced modern mathematics, which can be dated back to 16th century[6]. Another significant application of probability theory in everyday life is reliability. In 1805, Legendre[7] proposed the theory of least squares, and introduced it in his new methods for determining the orbits of comets. There are several proposed probabilistic approaches for forecasting the time of future earthquake[8,9]. Several distributions like double exponential[10], Gaussian[8], Weibull[8,9], log-normal[11], gamma[12] and Pareto[13] are used to compute and analyse the conditional probability of occurrence of future earthquakes. The probabilistic seismic hazard analysis in NE, India has been performed by various researchers[14–17]. Yadav *et al.*[15], in their analysis of earthquakes of $M_w \geq 7$ reported that the estimated cumulative and conditional probabilities show similar recurrence period of about 13–20 years from the occurrence of the last earthquake (1995) for future large earthquakes in the study region. In Japan earthquakes were observed to occur at regular time intervals and these models were applies by Utsu[12]. He comparatively studied the models using various distributions and proposed that all models were acceptable. Rikitake[18] applied Weibull and log-normal models to study seismic hazard in Japan, and predicted that the probability of seismic risk is very high in that country. Nishenko and Bullard[11] normalized the recurrence time of large earthquakes for different earthquake provinces and the recurrence time was analysed by applying log–normal and Weibull distributions. They concluded that log–normal distribution was the best fit. Various researchers have emphasized that probabilistic analysis is a prominent tool for earthquake prediction studies. Significantly difficulty arise for selecting the best distribution that fits the temporal earthquake data, which is random and further depends on the seismicity pattern and behaviour pertinent to study region.

In the present study, Kolmogorov–Smirnov statistics is applied to establish the recurrence time having proper distribution for earthquakes of magnitude $M_w > 5.0$ in NE India and its vicinity during 1918–2018. This study is an approach towards assessment of seismic hazard besides forecasting probable future earthquakes in which seismic recurrence time has been estimated in a probabilistic

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framework. The theory of probability can be applied in everyday life for assessment of risk and modelling based on the population with specific distribution[19]. For forecasting techniques, in general, stationary condition is required and it plays prominent hypothetical standard or criteria in the analysis of time-series data. The recurrence time for earthquakes of magnitude $M_w \geq 5.0$ in NE India and its vicinity indicates stationary condition. So a distribution has to be established such that it satisfies the analysis and fits the observed recurrence time well in order to fit an appropriate time-series model towards long-term as well short-term successful forecast of earthquakes.

Seismotectonic features of the region

One of the most complex tectonic regions of the world, NE India and its adjoining area is one of the sixth most seismically active regions of the world[4]. The region wedges between the collision boundaries of the Himalayan plate in the north and Indo-Burmese plate in the east (lat. 20°–31°N and long. 86°–98°E). It has produced two great earthquakes ($M \geq 8.0$) since 1897. The plate boundary zones and intraplate area are the main components of NE India[20]. In the middle of plate boundary zones, the broad tectonic domains are the Eastern Himalayan collision belt to the north, which includes the Trans-Himalayan Tethyan zone; the Andean-type granodiorite margin comprising the main boundary thrust (MBT) and main central thrust (MCT), and the Assam syntaxis zone where the Himalayan and Burmese arc meets the Mishmi Block. This zone is folded and thrusted by the Lohit and Mishmi Thrust and the Indo-Burma subduction zone to the east, where the Indian lithosphere is considered to be subducting below the Indo-Burma Ranges. The intraplate part of the region comprises the Shillong Plateau, the Mikir Hills and the Assam valley jawed between the Himalayan and Burmese arc, Tripura folded belt, Brahmaputra Valley and the intermountain depression of upper Assam[21]. During the last 120 years or more, the region experienced 20 large ($M_w \geq 7.0$) and two great earthquakes, viz. 12 June 1897 (M_w >8.5)[22] and 15 August 1950 ($M_w \sim 8.7$)[23–25]. These two great earthquakes have caused extensive destruction in the region[26,27]. The Kopili and Bomdila Faults in NE India comprise Neogene–Quaternary sediments, which were deposited directly over the Archean basement. The Kopili Fault zone is approximately 300 km long and 100 km wide. It is a NW–SE trending strike–slip fault[23,28,29]. The tectonic disposition of this fault delineates the two Precambrian massifs on either side – the Shillong Plateau and the Mikir Hills. It is bounded by the MBT to the north and by the NE–SW trending Belt of Schuppen to the south (Figure 1). The Bomdila Fault trends along WNW–ESE direction and is a strike–slip fault about 400 km long. The northern part of the fault mostly lies in the Gondwana, Paleogene and Neogene sediments. This fault is bounded to the east and south by the Belt of Schuppen, and to the west by the Mikir massif. In the north, the fault also cuts across the Himalayan fold belt[30].

The Kopili Fault was the seat of two large earthquakes (Figure 1). One of these events occurred during 1869 ($M_w \sim 7.7$) at the southeastern end of the fault transgressing Naga-Disang Thrust, while the other event (1943; $M_w \sim 7.2$) occurred further north of the 1869 event, within a span of about 75 years (ref. 31). Intense seismic activity has been observed to a depth of about 50 km beneath the Kopili Fault, and it continues to the MCT in the Bhutan Himalaya. Although the MCT is dormant[32], intense activity is observed at the region where the Kopili Fault meets the MBT and MCT[33–35]. This is evidenced by the 19 August 2009 earthquake ($M_w \sim 5.1$) in the Assam Valley that occurred at the centre of the Kopili Fault zone and the 21 September 2009 strong Bhutan Himalaya earthquake ($M_w \sim 6.3$) which occurred at the northern end of the Kopili Fault where it meets the MCT[35]. The earthquakes of 19 August 2009 and 21 September 2009, are shallow focus (depth ~10 km), showing right lateral strike–slip faulting[34]. This indicates that the Kopili Fault zone is under compressional stress from the Indo-Burma arc to the east and from the Himalayan arc to the north, and is characterized by transverse tectonics. The Bomdila Fault lies in a tectonically active region which crisscrosses the MCT, MBT and Naga-Disang Thrust along the NW-SE direction. The earthquake events along Bomdila Fault occur in a diffused pattern having post-collisional intracratonic characteristics[30]. Characteristically, the Upper Brahmaputra Valley between the Bomdila Fault and almost near NW-trending Mishmi

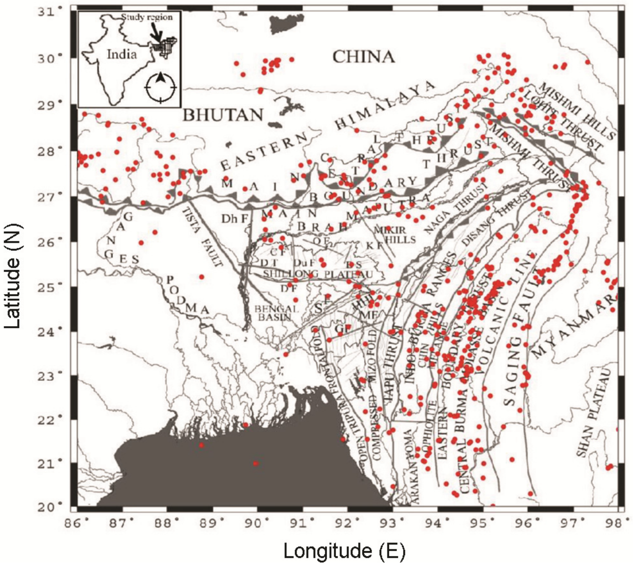

Figure 1. Earthquake events of $M_w \geq 5$ during 1 January 1918 to 12 September 2018 in North East India and its border region (20°–30°N and 86°–98°E) subjected to probabilistic analysis.

Thrust in the northeast is mostly devoid of any earthquakes, which is known as the Assam Gap[36].

Seismic data

The seismic data accrued for probabilistic analysis pertain to earthquakes of magnitude $M_w \geq 5.0$ for 100 years during the period 1 January 1918 to 12 September 2018. A catalogue was prepared from seismological bulletins of CSIR-NEIST, Jorhat; ISC, USGS, GEM. The fundamental assumption for utilizing earthquake catalogue for data analysis should follow a stationary Poisson process and should occur independent of each other. The catalogue should consist only of main shocks, whereas fore- and aftershocks are rejected. We have adopted the declustering method of Reasenberg[37], which is governed by the cluster method. After declustering of the database, we have used the maximum likelihood algorithm provided by ZMAP[38] to perform a Gutenberg–Richter regression[39]. Here, the magnitude range of earthquake catalogues indicate relatively high magnitude of completeness ($M_C = 4.7$) for the region. Most of these data are carefully chosen so that earthquakes of magnitude $M_w \geq 5.0$ alone are considered for probabilistic analysis towards estimation of a suitable time frame for the occurrence of future probable earthquakes, having $M_w \geq 5$, in the NE-India region.

Methodology

Earthquakes are random phenomena and statistical analysis is a prominent method for exemplifying seismic hazard. Here, we have chosen time in units of days and frequency distribution as series unit of recurrence time[40,41]. The Kolmogorov–Smirnov statistics has been utilized to establish proper distribution for the earthquakes datasets. To compare the calculated statistics, the D-critical table value can be determined as

$$D_{n;\,0.05} = \frac{1.36}{\sqrt{n}}, \tag{1}$$

where $n > 35$.

The critical table value is estimated to be 0.06028 for $n = 509$ and $\alpha = 0.05$, and hence the calculated test statistics evinces that Weibull distribution probably fit the earthquake data better than other statistics. The approach also establishes the mean occurrence period $E(t)$.

To establish the earthquake recurrence time, Weibull distribution is found to be the most suitable for earthquake dataset. Accordingly when two earthquakes occur, the random variable time T (in days) between the two earthquakes gives the probability density function of T (a random variable) as[42]

$$f(t;\, \alpha, \beta) = \beta \alpha^{-\beta} t^{\beta-1} \exp(-\alpha^{-\beta} t^{\beta}),$$

$$0 < t < \infty,\ \alpha > 0,\ \beta > 0, \tag{2}$$

where α is continuous scale parameter and β is continuous shape parameter.

The cumulative distribution and reliability can be expressed as

$$F(t) = 1 - \exp(-(t/\alpha)^{\beta}), \tag{3}$$

$$R(t) = \exp(-(t/\alpha)^{\beta}). \tag{4}$$

From Weibull Law for two parameters, the moment of the kth order can be given by

$$E(t^k) = \sum_{i=1}^{k} \alpha^i \Gamma_i, \tag{5}$$

where gamma function (Γ_i) is

$$\Gamma_i = \Gamma(1 + i/\beta) = \int_0^{\infty} t^{i/\beta} e^{-x} \mathrm{d}t. \tag{6}$$

Thus $E(t)$ can be represented by

$$E(t) = \alpha \Gamma(1 + 1/\beta). \tag{7}$$

In addition, a reliability function is also established, which is a function of time, in that every reliability value has an associated time value. Here reliability function is derived after cumulative density function is ascertained.

Results and discussion

Earthquakes of magnitude $M_w \geq 5.0$ for 100 years (1 January 1918 to 12 September 2018) in NE India and its vicinity are considered here for probabilistic analysis and forecast from seismic recurrence time-frame for future earthquakes ($M_w \geq 5.0$) in the same region (Figure 1). The depth of the events are mostly shallow (about 79.6% of the total earthquakes) to intermediate (about 20.4% of the total earthquakes) which ranged from 4 to 183 km. Applying Dickey–Fuller statistics to the recurrence time, we estimated alpha = 0.05, and P-value <0.0001 during 1918–2018. The computed P-value is observed to be lower than the significance level $\alpha = 0.05$, and hence we disregard the null hypothesis and accept the hypothesis that there is no unit root for the series and the series is stationary.

To find the best distribution for recurrence time of earthquakes in NE India and its vicinity, various distributions were applied to the data. In order to find the best fit among the distributions, Kolmogorov–Smirnov test statistics was applied to seismic recurrence time data of M_w >5 in NE India and its vicinity. Table 1 shows the calculated Kolmogorov–Smirnov test statistics and best fits listed rank-wise. It is observed that the Weibull analysis fits best for the earthquake dataset utilized (Figure 2). The parameters α (continuous scale parameter) and β (continuous shape parameter) estimated using maximum likelihood estimation (MLE) are 56.81 and 0.68 respectively. Substituting the values of α and β in eq. (2), the earthquake dataset is best modelled by the Weibull distribution as

$$f(t;\alpha,\beta) = (0.68)(56.81)^{0.68} t^{(0.68-1)} \times \exp(-56.81^{-0.68} t^{\,0.68})23. \quad (8)$$

Table 1. Kolmogorov–Smirnov test statistics calculated values for the establishment of proper distribution for earthquake data

Rank	Distribution	Kolmogorov–Smirnov statistics
1	Weibull	0.08858
2	Gamma	0.11858
3	Lognormal	0.1276
4	Exponential	0.19891
5	Rayleigh	0.40273

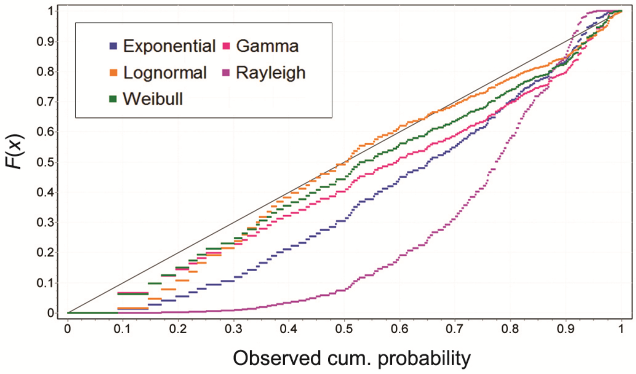

Figure 2. Plot showing analysed probability function of some widespread distributions considered to have the best fit for the analysis of random phenomena. It is noticeably discernible that Weibull distribution has the best fit for the earthquake dataset.

The mean occurrence period $E(t)$ is estimated using eq. (7). The mean occurrence time of earthquakes (M_w ≥5.0) in NE India and its vicinity is found to be 74 days approximately. Figure 3 shows the occurrence time of an earthquake with M_w ≥5.0 in the region. While estimating $E(t)$, the cumulative probability function indicates a time period of 140 days with 80% probability for an earthquake of M_w ≥5.0 to recur following the occurrence of an earthquake in NE India and its vicinity. Alternatively, 400–500 days of recurrence time period is observed with 90–100% probability respectively for an earthquake of M_w ≥5.0 to recur following the occurrence of an earthquake (Figure 3). The validation of these estimates is constrained by the estimation of reliability function.

Figure 4 indicates the probability of occurrence of an earthquake having magnitude $M_w \geq 5.0$ in NE India and its vicinity at an interval of t days after the occurrence of an earthquake of magnitude $M_w \geq 5.0$. Since the date of occurrence of the last earthquake is 12 September 2018, probabilistic analysis used in this study envisages the occurrence of three more earthquakes of magnitude $M_w \geq 5.0$ (Table 2). These are found to occur well within the estimated mean occurrence time period $E(t)$. The occurrence time period of these events is 59, 18 and 29 days respectively, from the preceding earthquake event. Table 3 shows the percentage of recurrence time of earthquakes from 1918 to 2018 of M_w ≥5 in NE India and its vicinity. It is observed that 83.49% of recurrence time ranges within 100 days. On 4 April 2016 (IST), a shallow depth (55 km) earthquake event of M_w ~6.7 occurred 30 km west of Imphal, India. This particular event

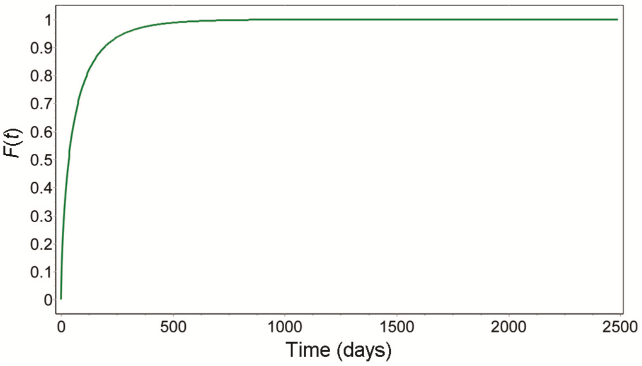

Figure 3. Cumulative probability function graph showing the occurrence risk of an earthquake with $M_w \geq 5$ in NE India and its border region. The probability of occurrence of an earthquake ($M_w \geq 5$) preceding the last earthquake in NE India and its border region with $M_w \sim 5$ or above in 140 days is estimated to be 80%.

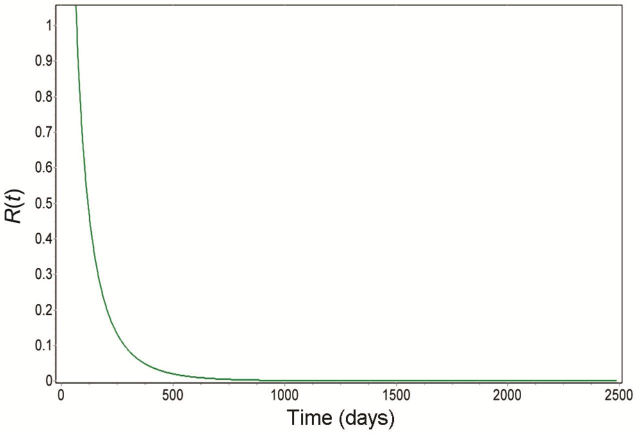

Figure 4. Plot showing the reliabilty function ($R(t)$) for an earthquake in NE India and its vicinity (20°–30°N and 86°–98°E).

Table 2. Listing of earthquakes that followed the one on 12 September 2018 used for the probabilistic analysis of $M_w \geq 5$ along with the occurrence time period. The three earthquake events had occurrence time period ranging between the calculated $E(t)$

Date of occurrence	Magnitude (M_w)	Occurrence time period (days)	Latitude (°N)	Longitude (°E)	Depth	Place
12 September 2018	5.3	–	26.3711	90.1611	10	Sapatgram, North East India
10 November 2018	5.2	59	23.9724	93.3925	52.39	Churachandpur, NE India
28 November 2018	5.4	18	27.1986	96.9185	11	Tezu, NE India
27 December 2018	5	29	23.3862	94.5614	90.96	Mawlaik, NE India–Myanmar border

$E(t)$ is mean occurrence time/period of earthquake of $M_w \geq 5$ in North East India and its vicinity.

Table 3. Percentage of recurrence time of earthquakes of $M_w \geq 5$ from 1918 to 2018 in NE-India and its vicinity

Recurrence time range (days)	Percentage of earthquakes (%)
Within 100	83.49705
101–200	10.21611
201–300	2.946955
301–400	0.982318
401–500	0.196464
501–600	0.392927
601–700	0.196464
701–800	0.196464
801–900	0.196464
>901	1.178782

Table 4. Weibull distribution parameters and mean occurrence period estimated for the four zones of the study region

Parameters	Zone I	Zone II	Zone III	Zone IV
Alpha	263.87	161.95	1770.86	97.82
Beta	0.691487	0.558575	0.817586	0.78344
$E(t)$	337.98	269.30	1976.14	112.54

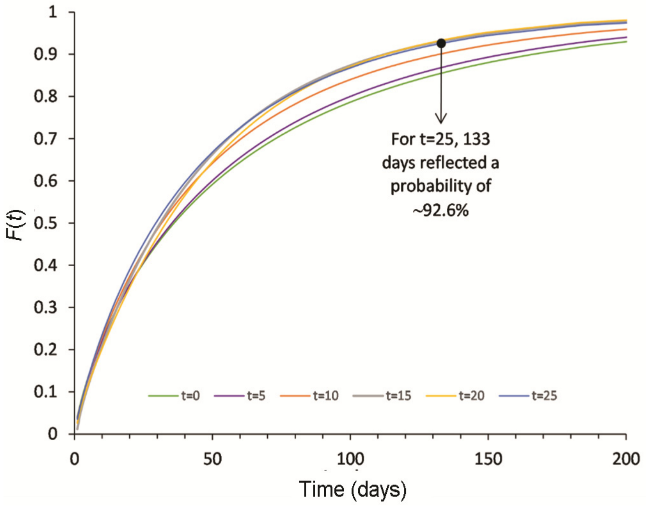

Figure 5. Cumulative probability function graph of regrouped and segmented data of recurrence period for different time windows: $t = 0$ (1918), $t = 5$ (1923), $t = 10$ (1933), $t = 15$ (1948), $t = 20$ (1968), $t = 25$ (1993). It is discernible that the estimated cumulative probabilities show similar recurrence period of about 15–25 years from the occurrence of the last earthquake (1933) for the forecast of large earthquakes ($M_w \geq 5$) in the NE India region and its vicinity.

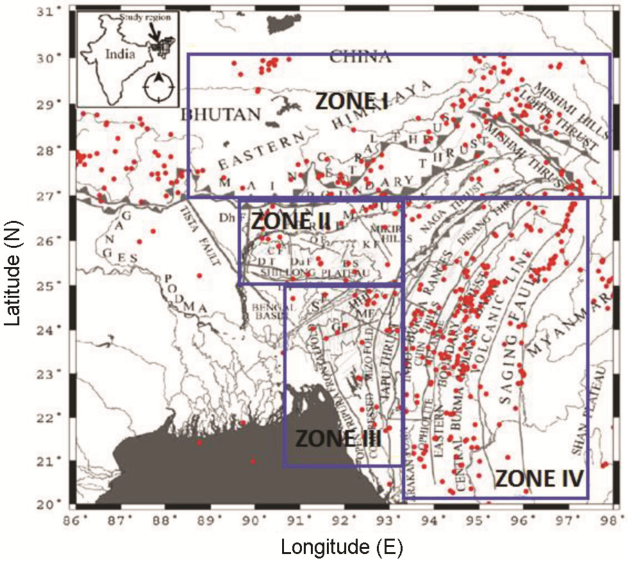

Figure 6. Map showing different zones of the study region depending on the number of earthquakes during the period of study: zone I between 27.0°–30.0°N and 88.5°–98.0°E; zone II between 25.0°–26.99°N and 89.7°–93.3°E; zone III between 21.0°–24.99° and 90.7°–93.3°E, and zone IV between 20.2°–26.99°N and 93.31°–97.4°E.

recurred following the last earthquake of $M_w \geq 5$ with a recurrence time of 133 days. By regrouping and segmenting the data of different time windows – $t = 0$ (1918), $t = 5$ (1923), $t = 10$ (1933), $t = 15$ (1948), $t = 20$ (1968), $t = 25$ (1993) – it is observed that recurrence time of 133 days (for $t = 15$, $t = 20$, $t = 25$) reflects a probability of nearly 92.6% (Figure 5). The present analysis indicates that the estimated cumulative probabilities show similar recurrence period of about 15 (1948) – 25 (1993) years (Figure 5) from the occurrence of the last earthquake (1933) for the forecast of large earthquakes ($M_w \geq 5$) in NE India and its vicinity.

The study region has been divided into four source zones based on tectonic-cum-structural regime, with a number of the earthquakes ($M_w \geq 5.0$) in each zone (Figure 6). To evaluate the recurrence time, the four zones are divided as follows: zone I between 27.0°–30.0°N and 88.5°–98.0°E; zone II between 25.0°–26.99°N and 89.7°–93.3°E, zone III between 21.0°–24.99°N and 90.7°–93.3°E, and zone IV between 20.2°–26.99°N and 93.31°–97.4°E. Figure 7 shows the cumulative distribution function estimated for the various zones. The mean occurrence period

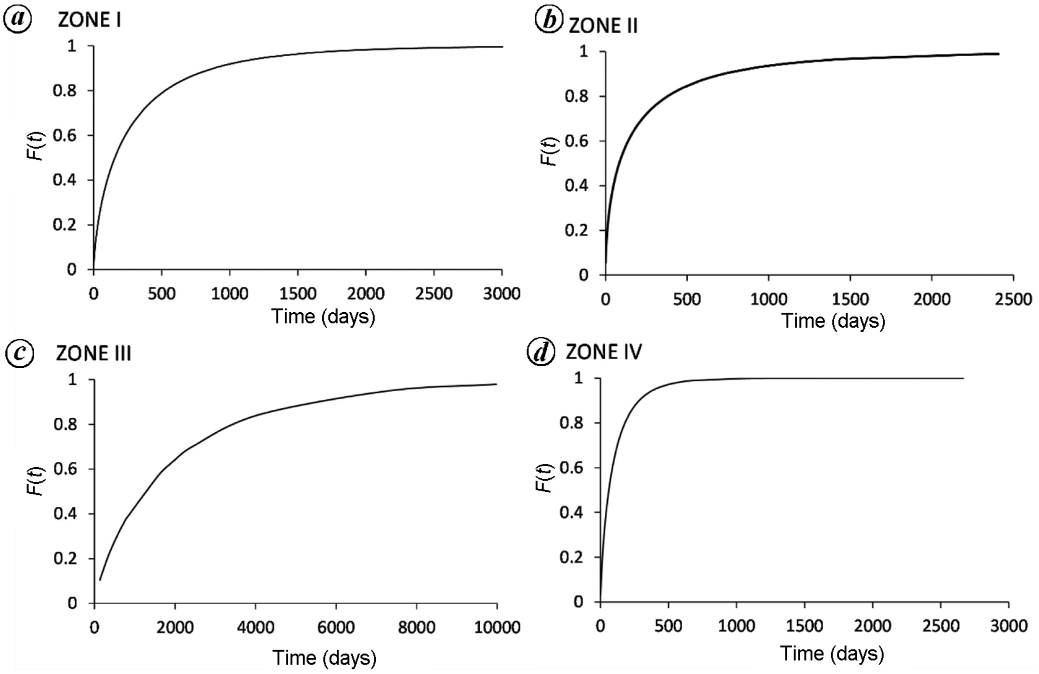

Figure 7. Cumulative probability function graph showing the occurrence risk of an earthquake with $M_w \geq 5$ in (***a***) zone I, (***b***) zone II, (***c***) zone III and (***d***) zone IV. Risk grading inside each zone shows that zone IV has the highest risk followed by zones II, I, III with zone III having the least risk.

$E(t)$ was estimated to be 337.98, 269.30, 1976.14 and 112.54 for zones I–IV respectively (Table 4). Zone IV was found to be more risky in the first 500 days, followed by zones II, I and III. Zone III was found to be the least risky relative to the other zones in the region. Figure 4 shows that the probability of occurrence of another earthquake of $M_w \geq 5.0$ with a recurrence time of 1 year (337–365 days approximately) in zones IV, II, I and III in the region is 93.84%, 78.68%, 71.39% and 21.06% respectively. Further, the risk of another earthquake of $M_w \geq 5.0$ with a recurrence time of 100–133 days in zones IV, II, I and III of the region is 63.85%, 53.61%, 40.86% and 10.34% respectively. In order to exemplify the probability of occurrence of earthquakes associated with each zone, it is concluded that zone IV indicates the highest probability, followed by zones II and I, while zone III indicate the least probability.

Conclusion

In this study, the probability of earthquake occurrence in NE India (20°–30°N and 86°–98°E) and its adjoining border region is analysed. The depth of the events (1918–2018) is mostly shallow (79.6%) to intermediate (20.4%), ranging from 4 km to 183 km. Earthquakes of magnitude $M_w \geq 5.0$ in the region are observed to have occurred at a fairly uniform interval with 83.49% of recurrence time within 100 days. It is also apparent that the seismic recurrence time series of $M_w \geq 5.0$ for the studied region portrays stationary condition, which improves the hypothetical standards or criteria for the synchronization of time series model for the required forecasting. The mean occurrence period $E(t)$ of an earthquake in the region has been estimated to be 74 days. The last earthquake of $M_w \geq 5.0$, on 12 September 2018, since 1918 used for the probabilistic analysis was followed by three more earthquakes of $M_w \geq 5.0$ in the region, and reflected an occurrence time period of 59, 18 and 29 days respectively, from the preceding earthquake. The occurrence time period is in the range of the estimated mean occurrence period $E(t)$. It is also observed that the probability of an earthquake ($M_w \geq 5.0$) to occur following the last earthquake in NE India with magnitude 5 or above within 140 days is 80%. The analysis concludes that the estimated cumulative probabilities indicate a similar recurrence period of about 15–25 years from the occurrence of the last earthquake for the forecast of large earthquakes ($M_w \geq 5$) in NE India and its vicinity. These observations are based on the output of statistical data analysis of earthquakes of $M_w \geq 5.0$ that occurred within 20°–30°N and 86°–98°E. In addition, the mean occurrence time period for $M_w \geq 5.0$ in the studied region is short and renders a higher probability of occurrence of an earthquake following the preceding one. Further, regarding the probability of time of occurrence associated to different zones, it is concluded that zone IV has the highest probability followed by zones II and I, while zone III is characterized by the least probability.

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ACKNOWLEDGEMENTS. We thank the Ministry of Earth Sciences, Government of India, for funds to CSIR-North East Institute of Technology, Jorhat to establish Multiparametric Geophysical Observatory for monitoring of earthquake precursors in Mikir Hills Plateau, Assam.

Received 2 April 2019; revised accepted 19 June 2019

doi: 10.18520/cs/v117/i7/1167-1173