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Modelling Earthquake's Inter-event Recurrence Intervals (IRIs) in Central India and Adjoining Regions using Weibull Probability Distribution Model – A Zone-Wise Approach

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Ranjeet Joshi^α, Sudhir S. Bhadauria^σ & Suresh S. Kushwah^ρ

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Keywords: conditional probability · weibull · madhya pradesh · earthquake recurrence · seismic hazard.

I. INTRODUCTION

Just like all natural events, earthquakes are random in occurrence. This randomness makes the use of statistics and probabilistic theory extremely suitable for analyzing earthquakes inter-event recurrence intervals (IRIs). Many studies have been conducted in India and around the world to substantiate the suitability of various distribution models for fairly assessing the conditional probabilities of earthquake recurrences. All such studies investigated the distribution of recurrence interval using established probabilistic models and analyzing their best fit employing various goodness-of-fit tests.

In India, extensive work has been done by researchers towards assessing earthquake inter-event recurrence intervals in various regions including western and northwestern parts Kachch (Tripathi and Nath (2001), Rajendran and Rajendran (2003)), north-eastern regions (Yadav et al. (2010)) and Himalayan region (Bungum et al. (2017)). These studies are conducted considering various probabilistic models like Lognormal,

Gamma, Weibull, Exponential, Brownian Passage Time (BPT), and Poisson model with parameter estimation using maximum likelihood method and validating data fitting through Kolmogorov-Smirnov statistical method and Anderson-Darling method.

Similarly, a considerable amount of work has been done globally, like the one done by Yilmaz et al. Bayrak et al. (2015) for north Anatolian fault zone in Turkey using Weibull, lognormal, exponential and gamma models with Kolmogorov-Smirnov test; Kinasih et al. Kinasih et al. (2014) for the Lesser Sunda Islands using Weibull distribution over different categories of earthquake magnitudes (low, medium and high) and the most recent one by the Coban et. Coban and Sayil (2019) et al., towards evaluating the earthquake recurrence in western Anatolia using five different probabilistic models with an estimation of model parameters using the maximum likelihood method.

Most of these studies concluded Weibull as the best approximation model for earthquake IRI estimation. Hardly any research has been conducted for central India to analyze the probabilities of recurrence of earthquakes, especially for earthquakes with a magnitude greater than 4 in the region. Present study attempts to analyze the pattern of recurrence of earthquakes in the region by analyzing IRIs using the Weibull distribution model.

II. METHODOLOGY

a) Study Region for this research

Although higher magnitude earthquakes are infrequent in central India, the catalog for central India suggests a notable frequency of earthquakes with magnitude ranging from 3 to 5. One of the most significant and damaging earthquakes (Mw 5.8) ever experienced in this region is the one that struck on 21st May 1997 in the city of Jabalpur, which lies on the Central Indian Tectonic Zone (CITZ). The central part of the Indian subcontinent mainly consists of four tectonic regimes i.e., the Bundelkhand Craton, the Satpura Mobile Belt, Kotri-Dongargarh Mobile Belt, and the Bastar Craton. Besides, the Narmada-Son Lineament and Central Indian Suture (CIS) are also critical tectonic

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elements of this regime. The faults and lineaments considered under this study are taken from the Seismotectonic Atlas of India and its Environs published by Geological Survey of India. The records have been digitized and using GIS application QGIS in different

layers along with historical seismic records over the map of the study region. Based on the cluster of sources and historical seismicity, the study region is divided into four zones as potential seismic sources to study the earthquake recurrence pattern as shown in Figure 1.

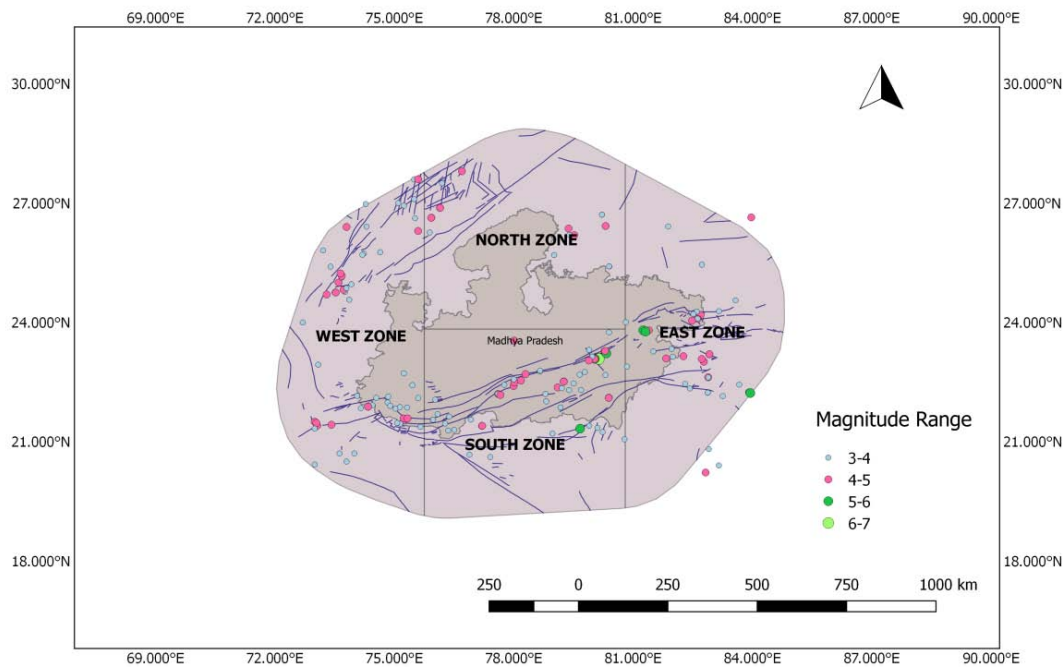


Figure 1: Figure highlights various zones within the study region, classified based on of shared clusters of seismogenic features such as faults and historical seismicity

b) Catalog Preparation

In this study, a new earthquake catalog for the study region has been compiled using various national and international resources with an aim to perform consistent seismic hazard assessment. A total of 187 seismic events are considered in earthquake data from 1995. The catalog is uniformly harmonized in terms of Mw. In the absence of any dedicated conversion formula for the study region, the global conversion formulae proposed by E. M. Scordilis (2006) have been used for magnitude conversion. After zone-wise distribution of seismic events, for each zone, the catalog

has been de-clusterized in order to remove the foreshocks and aftershock events. In order to the catalog, an algorithm proposed by Reasenber (1985) has been used using ZMAP software. The algorithm assumes the inter-connectivity of seismic events both in terms of space and time. The algorithm correctly filtered all foreshocks and aftershocks from events. The region is divided into four zones (*South, West, North, and East*), and these four zones are further analyzed by clustering earthquakes into two categories of magnitudes, as shown in Tables 1, 2, 3, and 4.

Table 1: Earthquake catalog for South (a) & (b) category in Madhya Pradesh and adjoining regions

S. No.	Longitude	Latitude	Year	Month	Day	Magnitude	Depth	Hour	Minute
South (a) category Earthquake Catalog									
1	77.60	22.20	1996	1	10	3.90	33	10	37
2	78.00	22.57	1998	7	19	3.80	33	0	57
3	76.09	21.69	1998	10	20	3.10	2	0	5
4	76.23	21.62	1998	10	24	3.00	1	0	48
5	76.38	21.63	1998	11	5	3.50	10.8	0	42
6	77.19	22.12	1999	5	11	3.00	5	0	56

7	79.18	21.86	2000	6	30	3.60	15	0	57
8	79.51	22.47	2001	1	3	3.20	33	0	45
9	74.78	20.63	2002	2	6	3.00	5	0	15
10	79.21	22.35	2002	3	6	3.20	45.7	0	24
11	75.66	21.37	2002	8	31	3.20	10	0	42
12	80.79	21.06	2002	9	21	3.20	10	0	7
13	76.36	21.28	2002	11	2	3.30	10	0	57
14	77.41	20.61	2003	1	19	3.10	7.7	0	48
15	80.24	21.24	2003	11	29	3.20	13.3	0	5
16	76.89	20.67	2003	12	26	3.20	13.2	0	37
17	75.80	21.69	2004	3	1	3.00	10	0	38
18	78.98	21.20	2004	5	12	3.20	4	0	29
19	76.28	21.46	2005	4	1	3.30	17.1	0	40
20	77.77	22.43	2006	3	7	3.20	15	0	39
21	79.39	22.30	2006	8	5	3.40	10	0	57
22	78.66	22.77	2007	6	6	3.40	8.2	0	15
23	78.67	22.79	2008	1	10	3.40	10	0	48
24	79.70	22.30	2009	8	1	3.50	10	0	49
25	76.93	21.56	2010	1	25	3.30	10	0	0
26	78.82	22.01	2012	6	12	3.40	35	0	9
27	76.51	21.30	2012	9	12	3.20	20	0	34
28	79.90	21.40	2015	7	23	3.90	10	14	36
29	77.20	19.50	2017	8	16	3.00	10	6	35
South (b) category Earthquake Catalog									
1	78.30	22.70	1995	5	2	4.30	33	0	46
2	77.67	22.17	1996	1	10	4.40	10	10	37
3	78.19	22.54	1998	3	9	4.50	20.6	0	41
4	79.26	22.51	1998	3	29	4.30	33	0	54
5	78.01	23.54	1999	4	3	4.20	30	0	38
6	79.11	22.37	2000	9	12	4.10	8.9	0	46
7	79.67	21.33	2001	7	26	5.30	10	0	5
8	77.21	21.40	2003	3	10	4.30	22.7	22	45
9	75.97	21.55	2003	11	22	4.00	10.5	0	18
10	80.11	21.35	2015	7	23	4.00	10	14	36

Table 2: Earthquake catalog for West (a) & (b) category in Madhya Pradesh and adjoining regions

S. No.	Longitude	Latitude	Year	Month	Day	Magnitude	Depth	Hour	Minute
West (a) category Earthquake Catalog									
1	75.46	22.42	1998	9	13	3.30	15	0	42
2	73.76	24.76	1998	12	26	3.40	5	0	14

3	75.15	21.45	1999	3	3	3.30	20	0	43
4	74.16	21.84	1999	7	17	3.40	5	0	48
5	74.45	21.92	2000	4	14	3.40	10	0	41
6	75.03	21.83	2000	7	10	3.50	20	0	6
7	74.85	22.13	2000	7	24	3.30	15	0	19
8	75.24	22.72	2001	1	12	3.40	2.9	0	36
9	73.09	22.94	2002	1	23	3.20	19.8	0	11
10	75.07	21.47	2002	5	19	3.90	30.9	0	25
11	73.87	24.57	2002	9	13	3.40	10	0	35
12	73.62	20.71	2002	12	1	3.10	1.6	0	33
13	74.55	22.10	2003	12	23	3.70	5	0	9
14	74.07	22.15	2003	12	24	3.10	40.6	0	47
15	75.32	21.86	2004	10	28	3.20	13.4	0	41
16	73.92	24.96	2005	6	1	3.60	33	0	28
17	73.68	25.12	2005	11	28	3.20	3.5	0	27
18	73.00	21.33	2008	5	2	3.80	12	0	53
19	73.80	24.86	2008	6	27	3.60	10	0	53
20	74.65	25.77	2008	7	5	3.60	17.2	0	59
21	74.30	26.41	2010	8	15	3.80	10	0	8
22	76.03	22.06	2012	11	20	3.40	15	0	15
23	74.83	21.99	2013	6	30	3.40	19.1	0	44
24	74.00	20.71	2014	1	7	3.30	15	0	50
25	75.14	21.87	2014	8	20	3.60	6.5	1	29
26	72.70	24.00	2015	3	19	3.50	5	9	41
27	73.00	20.43	2015	11	2	3.20	18.1	0	39
28	73.21	25.81	2016	3	18	3.60	7.7	0	37
29	74.24	25.73	2016	12	26	3.40	10	0	17
West (b) category Earthquake Catalog									
1	73.30	24.70	1996	1	4	4.20	33	7	30
2	73.04	21.47	1996	11	17	4.60	10	18	12
3	73.60	25.00	1997	7	29	4.50	33	9	43
4	75.25	21.55	1997	11	13	4.70	8	20	17
5	73.73	24.82	2002	1	22	4.10	1.9	0	28
6	74.34	21.88	2003	7	27	4.20	20	0	35
7	73.53	24.75	2004	6	17	4.10	10	0	41
8	75.24	21.59	2009	1	4	4.40	8.4	0	20
9	73.65	25.23	2010	11	9	4.90	13.5	22	46
10	75.60	26.30	2013	2	24	4.10	5	0	57
11	73.42	21.43	2014	6	21	4.20	35	0	59
12	73.80	26.40	2017	11	18	4.20	10	9	51

Table 3: Earthquake catalog for North (a) & (b) category in Madhya Pradesh and adjoining regions

S. No.	Longitude	Latitude	Year	Month	Day	Magnitude	Depth	Hour	Minute
North (a) category Earthquake Catalog									
1	76.45	26.40	1999	7	3	3.00	10	0	59
2	79.02	25.69	2000	10	7	3.40	33	0	32
3	76.20	27.50	2012	12	20	3.60	5	13	0
4	75.00	27.20	2013	3	31	2.30	5	14	43
5	75.52	26.62	2013	9	5	3.20	11.1	0	29
6	79.40	26.20	2013	9	23	3.50	5	13	26
7	75.50	27.60	2014	4	27	3.40	5	9	14
8	75.50	27.10	2016	1	28	3.80	10	22	47
9	75.25	26.94	2016	4	7	3.40	10	0	3
North (b) category Earthquake Catalog									
1	80.31	26.42	1999	10	13	4.10	15	6	56
2	80.22	26.71	2001	1	8	4.00	33	0	44
3	79.38	26.36	2005	1	14	4.20	33	5	16
4	75.93	26.63	2006	12	23	4.30	1.2	22	43
5	75.89	26.26	2013	2	24	4.00	35	0	57
6	79.52	26.20	2013	9	23	4.50	10	0	26
7	75.60	27.60	2015	9	3	4.40	10	17	57
8	76.70	27.80	2016	11	16	4.40	10	22	58

Table 4: Earthquake catalog for East (a) & (b) category in Madhya Pradesh and adjoining regions

S. No.	Longitude	Latitude	Year	Month	Day	Magnitude	Depth	Hour	Minute
East (a) category Earthquake Catalog									
1	75.46	22.42	1998	9	13	3.30	15	0	42
2	73.76	24.76	1998	12	26	3.40	5	0	14
3	75.15	21.45	1999	3	3	3.30	20	0	43
4	74.16	21.84	1999	7	17	3.40	5	0	48
5	74.45	21.92	2000	4	14	3.40	10	0	41
6	75.03	21.83	2000	7	10	3.50	20	0	6
7	74.85	22.13	2000	7	24	3.30	15	0	19
8	75.24	22.72	2001	1	12	3.40	2.9	0	36
9	73.09	22.94	2002	1	23	3.20	19.8	0	11
10	75.07	21.47	2002	5	19	3.90	30.9	0	25
11	73.87	24.57	2002	9	13	3.40	10	0	35
12	73.62	20.71	2002	12	1	3.10	1.6	0	33
13	74.55	22.10	2003	12	23	3.70	5	0	9
14	74.07	22.15	2003	12	24	3.10	40.6	0	47

15	75.32	21.86	2004	10	28	3.20	13.4	0	41
16	73.92	24.96	2005	6	1	3.60	33	0	28
17	73.68	25.12	2005	11	28	3.20	3.5	0	27
18	73.00	21.33	2008	5	2	3.80	12	0	53
19	73.80	24.86	2008	6	27	3.60	10	0	53
20	74.65	25.77	2008	7	5	3.60	17.2	0	59
21	74.30	26.41	2010	8	15	3.80	10	0	8
22	76.03	22.06	2012	11	20	3.40	15	0	15
23	74.83	21.99	2013	6	30	3.40	19.1	0	44
24	74.00	20.71	2014	1	7	3.30	15	0	50
25	75.14	21.87	2014	8	20	3.60	6.5	1	29
26	72.70	24.00	2015	3	19	3.50	5	9	41
27	73.00	20.43	2015	11	2	3.20	18.1	0	39
28	73.21	25.81	2016	3	18	3.60	7.7	0	37
29	74.24	25.73	2016	12	26	3.40	10	0	17

East (b) category Earthquake Catalog

1	82.70	24.19	1995	12	10	4.30	33	8	24
2	82.62	24.09	1996	1	18	4.10	33	8	5
3	82.89	22.62	1996	2	12	4.20	33	20	39
4	80.14	23.08	1997	5	21	5.80	36	22	51
5	80.04	23.08	1997	6	4	4.30	31.4	19	29
6	80.39	22.10	1997	11	23	4.30	33	0	34
7	82.88	22.23	2000	2	27	4.00	33	11	42
8	82.31	22.46	2000	4	6	4.00	11.7	0	34
9	82.78	23.01	2000	10	10	4.50	17.6	0	11
10	80.29	23.27	2000	10	16	4.80	20.2	0	33
11	80.40	25.41	2001	2	12	4.00	15	0	16
12	82.92	23.20	2001	6	10	4.10	16.5	0	12
13	83.95	22.22	2001	6	12	5.10	33	12	41
14	82.48	24.04	2008	1	25	4.50	10	0	39
15	81.26	23.80	2012	10	18	5.30	35	0	33
16	79.89	23.04	2014	10	22	4.10	10	0	18
17	81.83	23.09	2015	2	24	4.10	35	0	28
18	82.00	23.14	2015	4	9	4.00	10	0	0
19	80.85	22.89	2016	7	17	4.00	0	0	1
20	82.27	23.15	2017	8	29	4.10	0	0	21

Category I	$3 \leq M_w < 4$	South(a), West(a), North(a) and East (a)
Category II	$4 \leq M_w \leq 6$	South(b), West(b), North (b) and East (b)

A wide range of magnitudes are considered in the second category to compensate for the fewer events of higher magnitude, especially those with magnitude ≥ 5 .

c) Model Selection

Histograms plots are obtained for IRIs for different zones. All the plots thus obtained showed a

tendency to left-skew, as shown in figures 2, 3, 4, and 5. This skewness reflects their belonging to a skewed-distribution family such as exponential, lognormal, or Weibull.

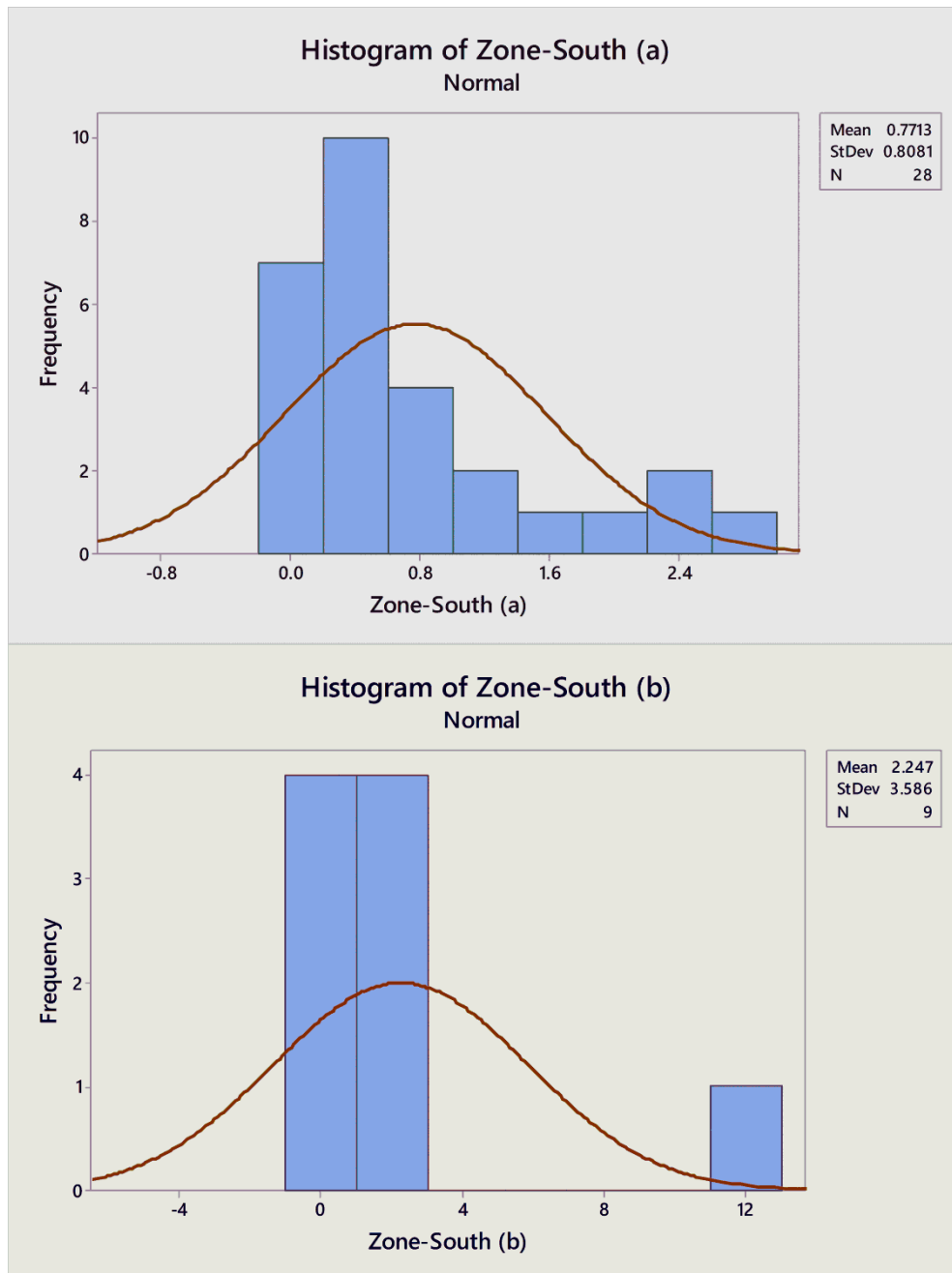


Figure 2: Histogram plots for South (a) & (b) category IRIs

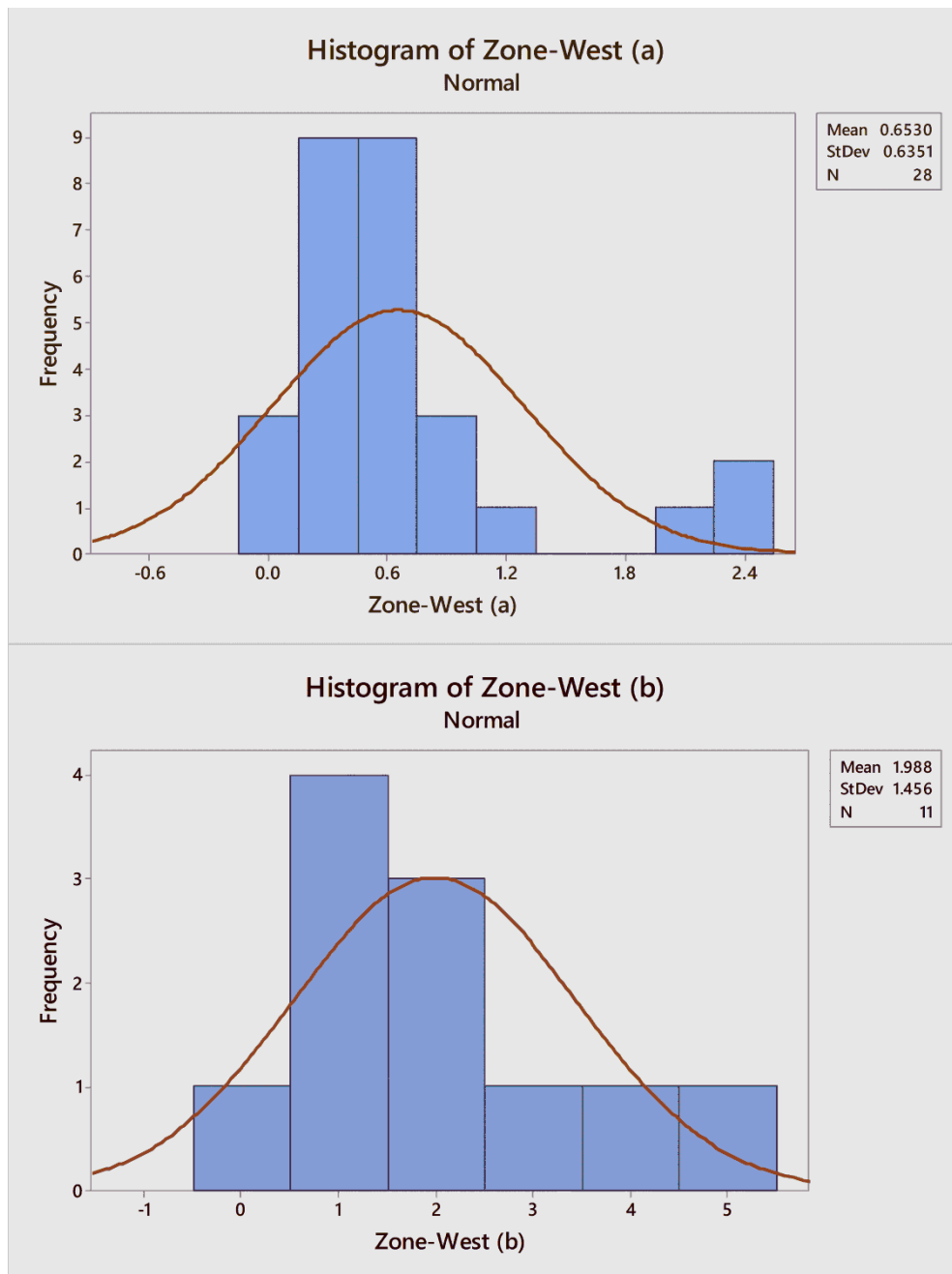


Figure 3: Histogram plots for West (a) & (b) category IRIs

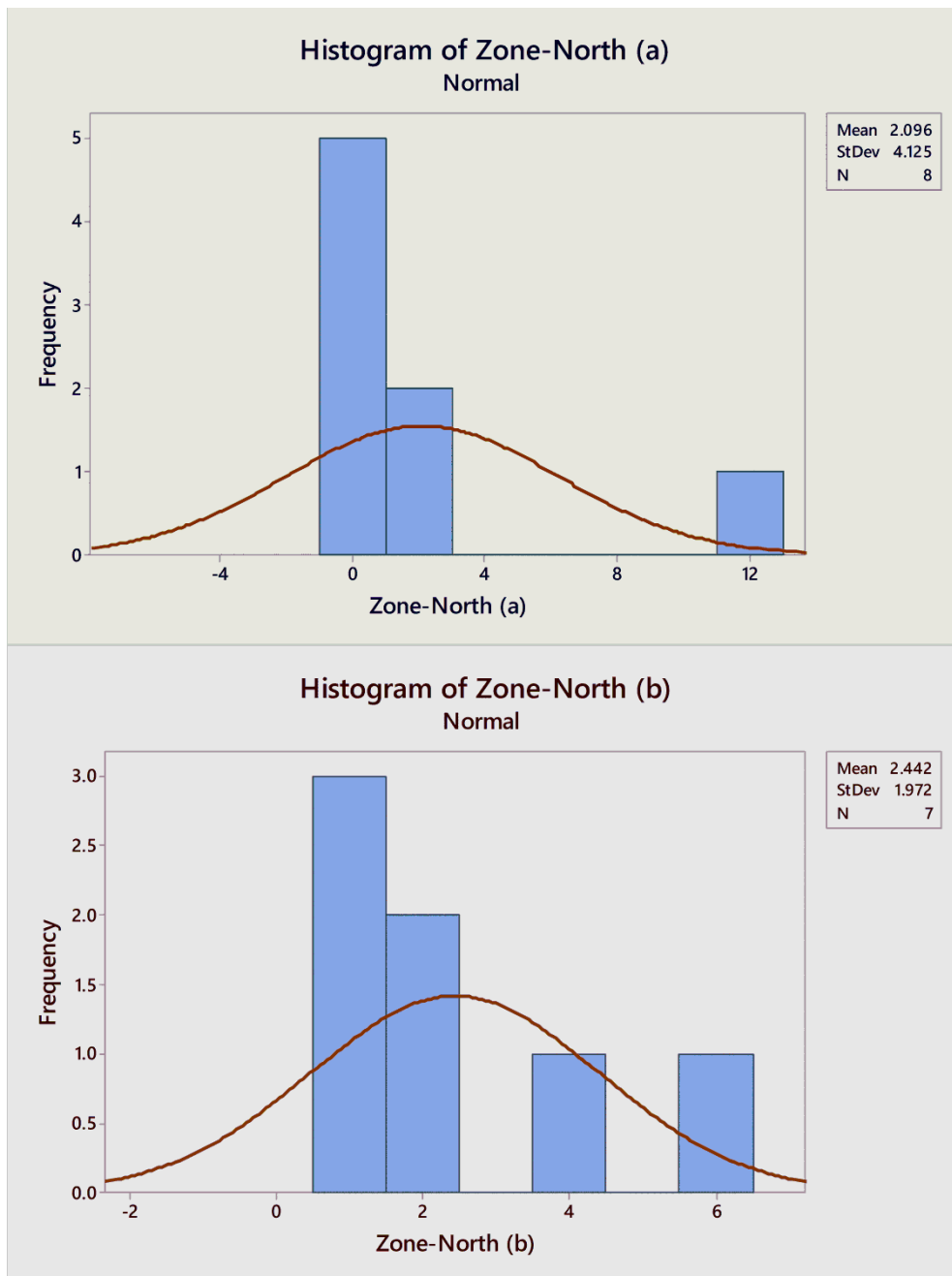


Figure 4: Histogram plots for North (a) & (b) category IRIs

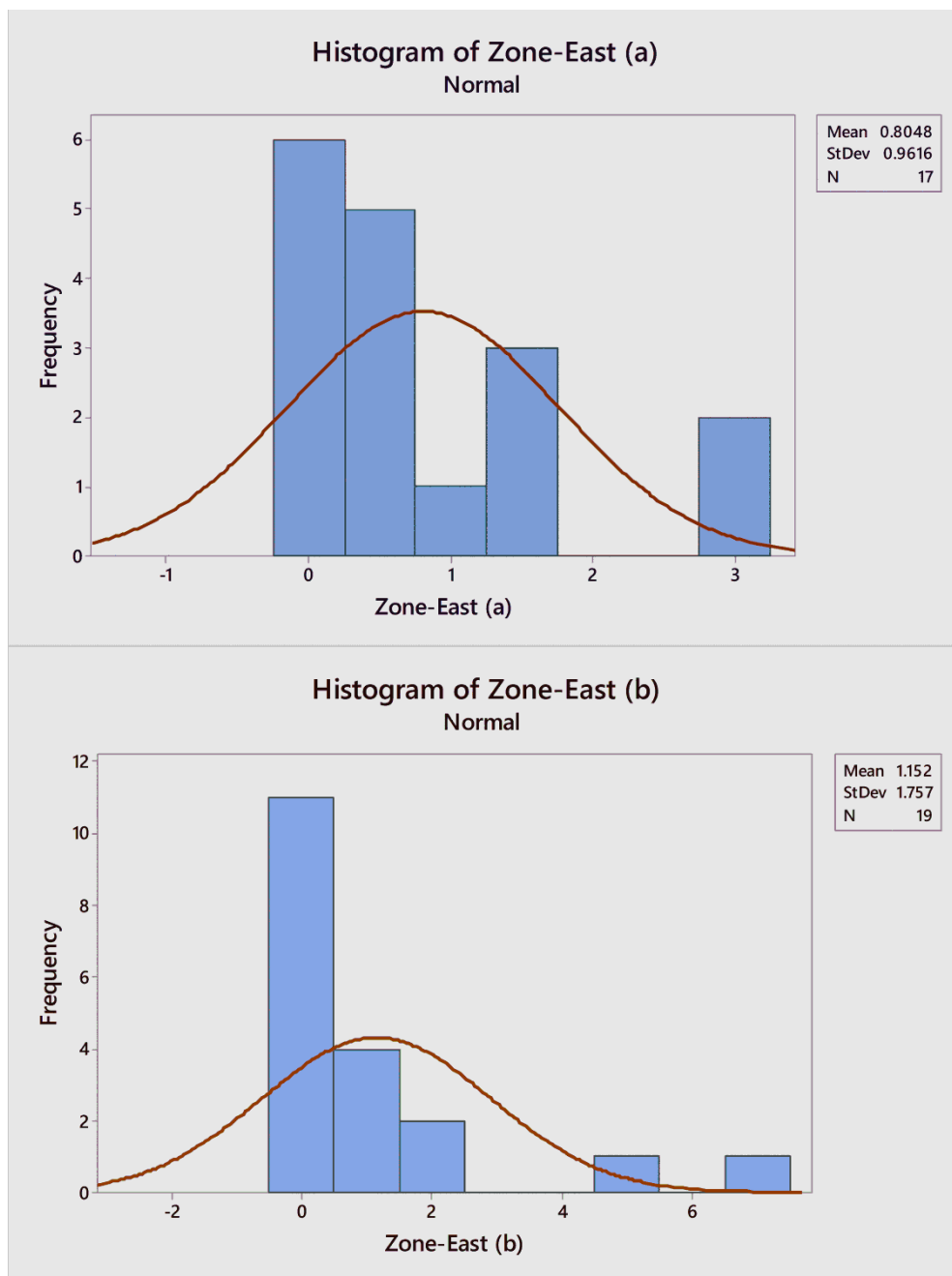


Figure 5: Histogram plots for Zone East (a) & (b) IRIs

In the next step, probability plots are obtained for the zone-wise IRIs for different categories of magnitudes. The distribution of data across reference lines of different models is visually inspected and the Anderson-Darling co-efficient is obtained. The values of Anderson-Darling co-efficient thus obtained are least for Weibull or Lognormal Distributions, thus confirming them to be the best choices for recurrence interval modeling for data fitting.

d) Weibull Distribution Model

Many stochastic function represents data distribution of natural processes like the occurrence of earthquakes. These functions help in formulating an

empirical model for the given process. Choosing the best function among many necessitates understanding the properties of different functions suitable for modeling the data. More than one functions can adequately represent the given seismic data, but then comparison and robustness of one over another is judged based on evaluated model parameters for different distribution functions. Earthquake IRIs data for various zones are fitted on four major probability distribution models, including Weibull, Lognormal, Exponential, and Normal, and it is found that the data fitted best either in case of Weibull or Lognormal with the least values of Anderson Darling in only these cases (Figure 6 to 9). Based on

these results and also recent work in this area where Weibull distribution is concluded to be the best option to model inter-event pattern, it is decided to do the modeling and analysis using the Weibull distribution

function. The Weibull distributions are used as a generalized exponential distributions with additional model parameters to accommodate data variability and range.

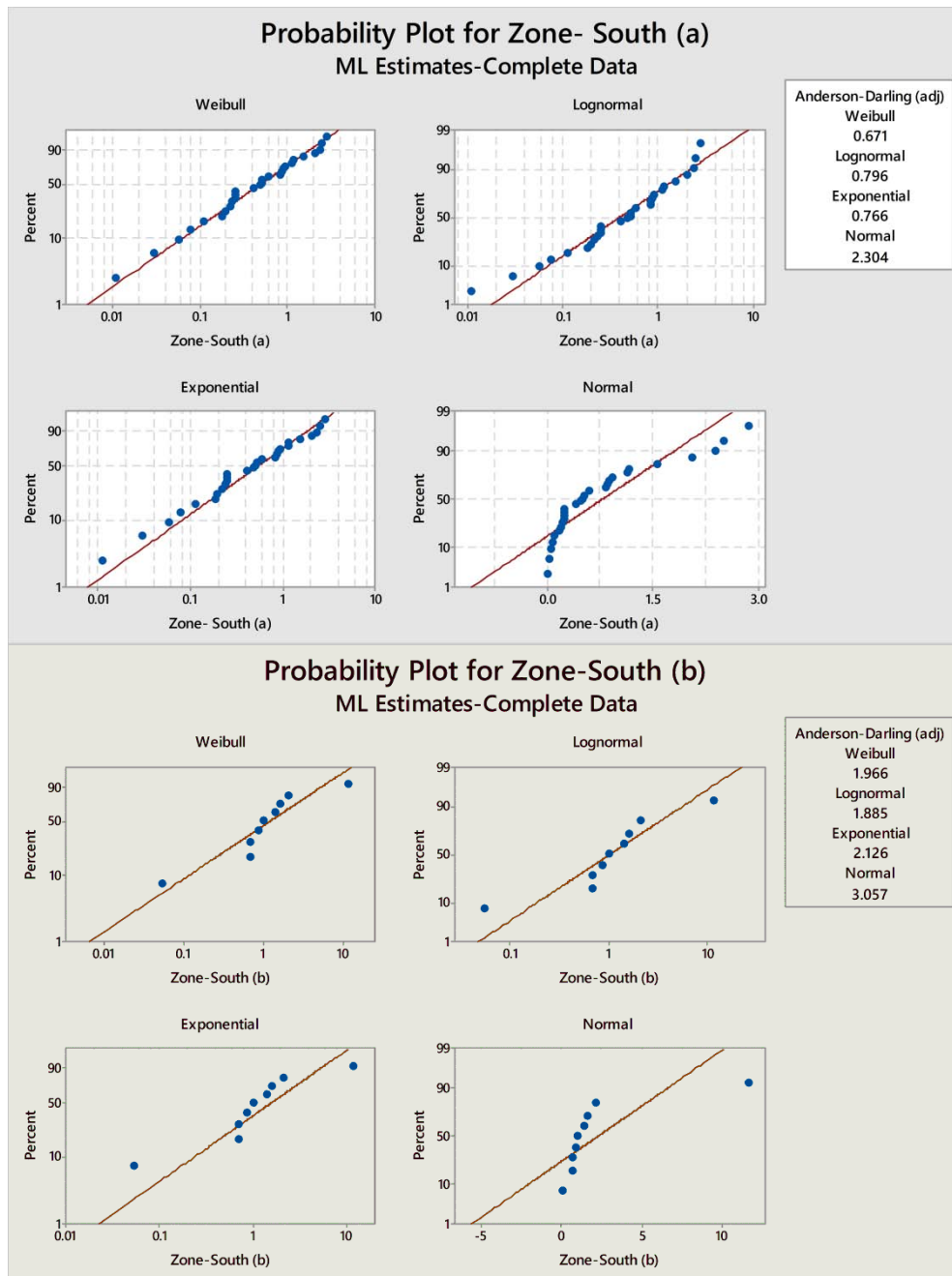


Figure 6: Probability plot of IRI for South (a) & (b) category. This plot shows IRI data falls near the Weibull reference line

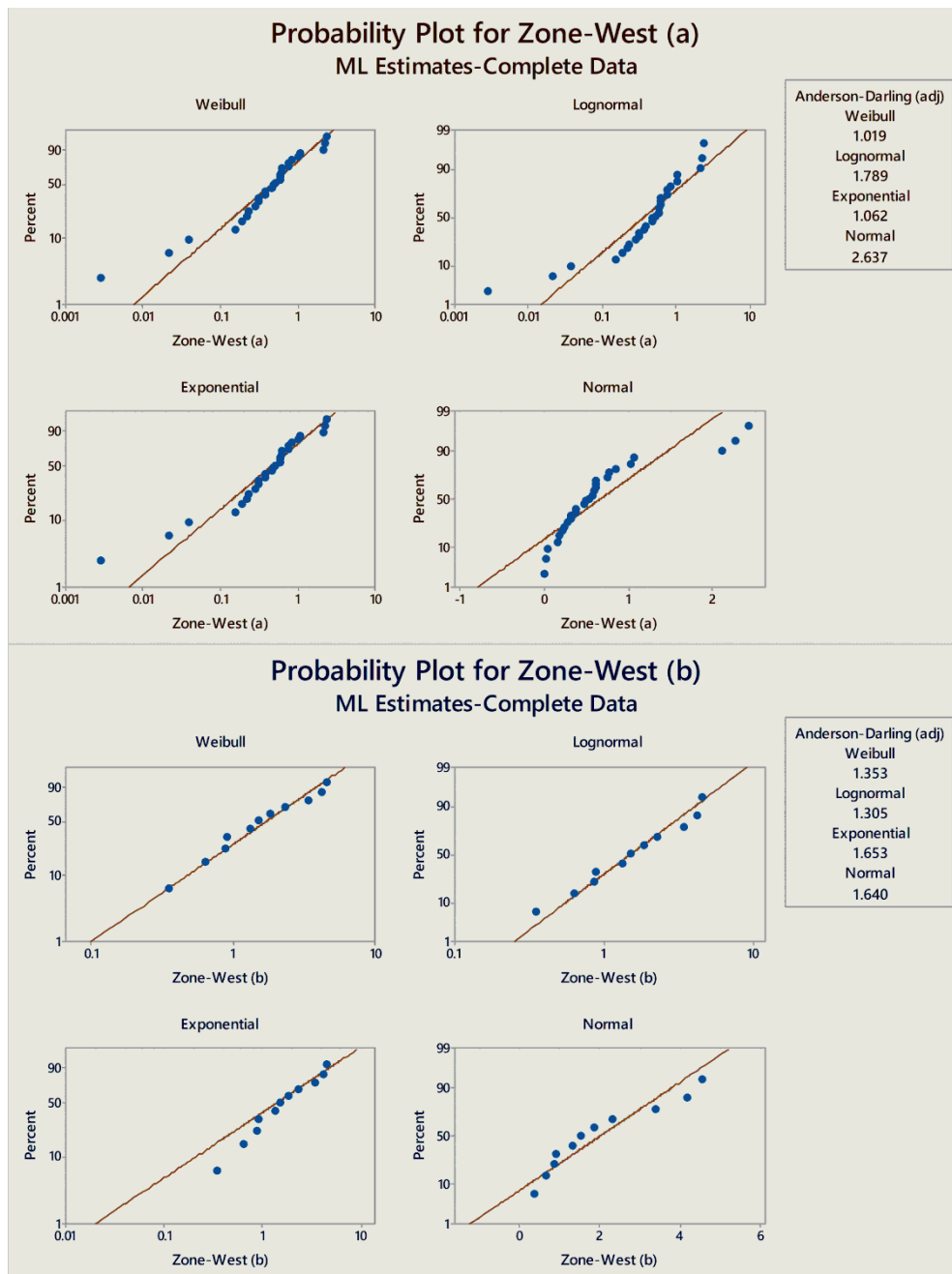


Figure 7: Probability plot of IRI for West (a) & (b) category. This plot shows IRI data falls near the Weibull reference line

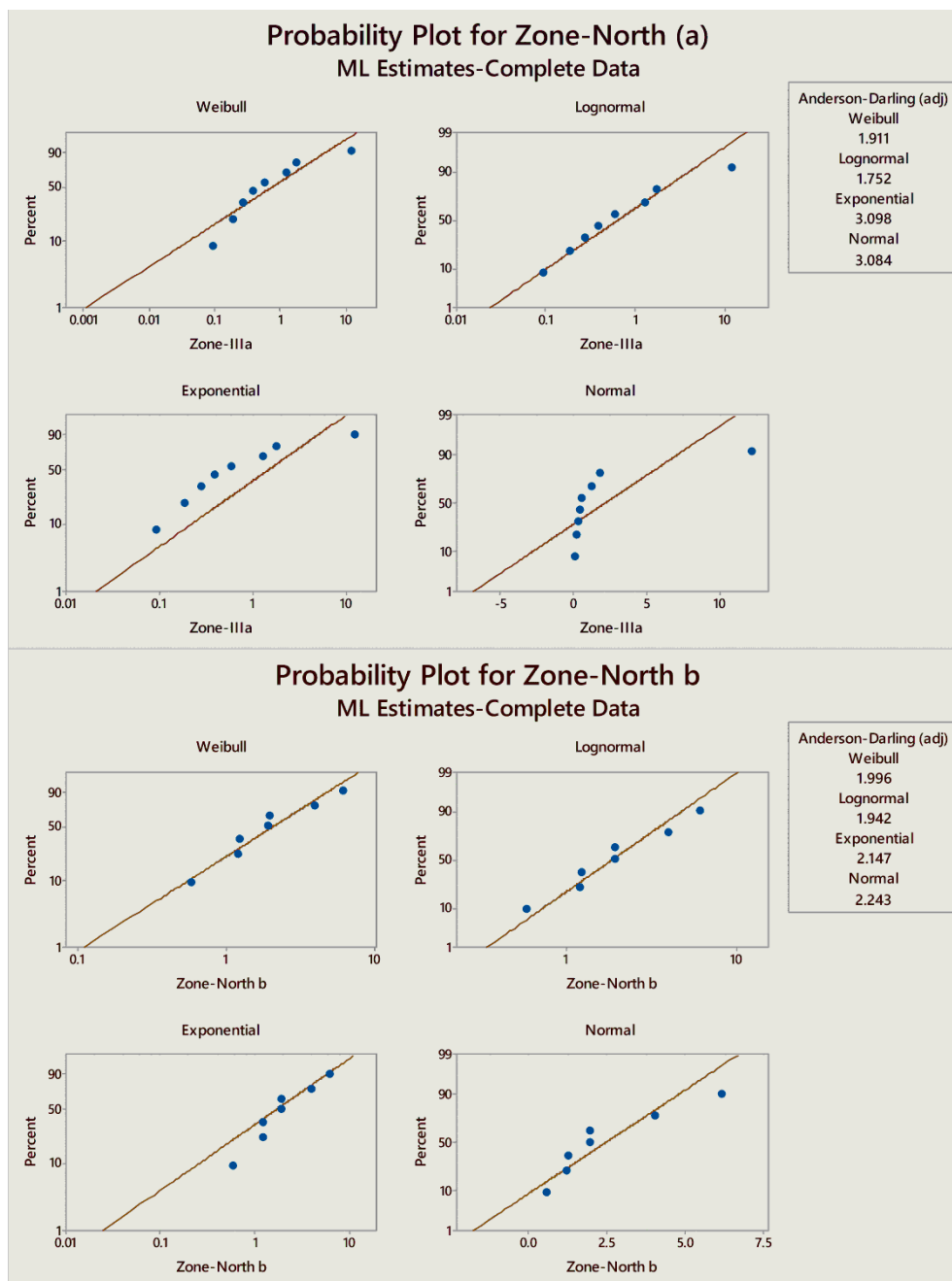


Figure 8: Probability plot of IRI for North (a) & (b) category. This plot shows IRI data falls near the Weibull reference line

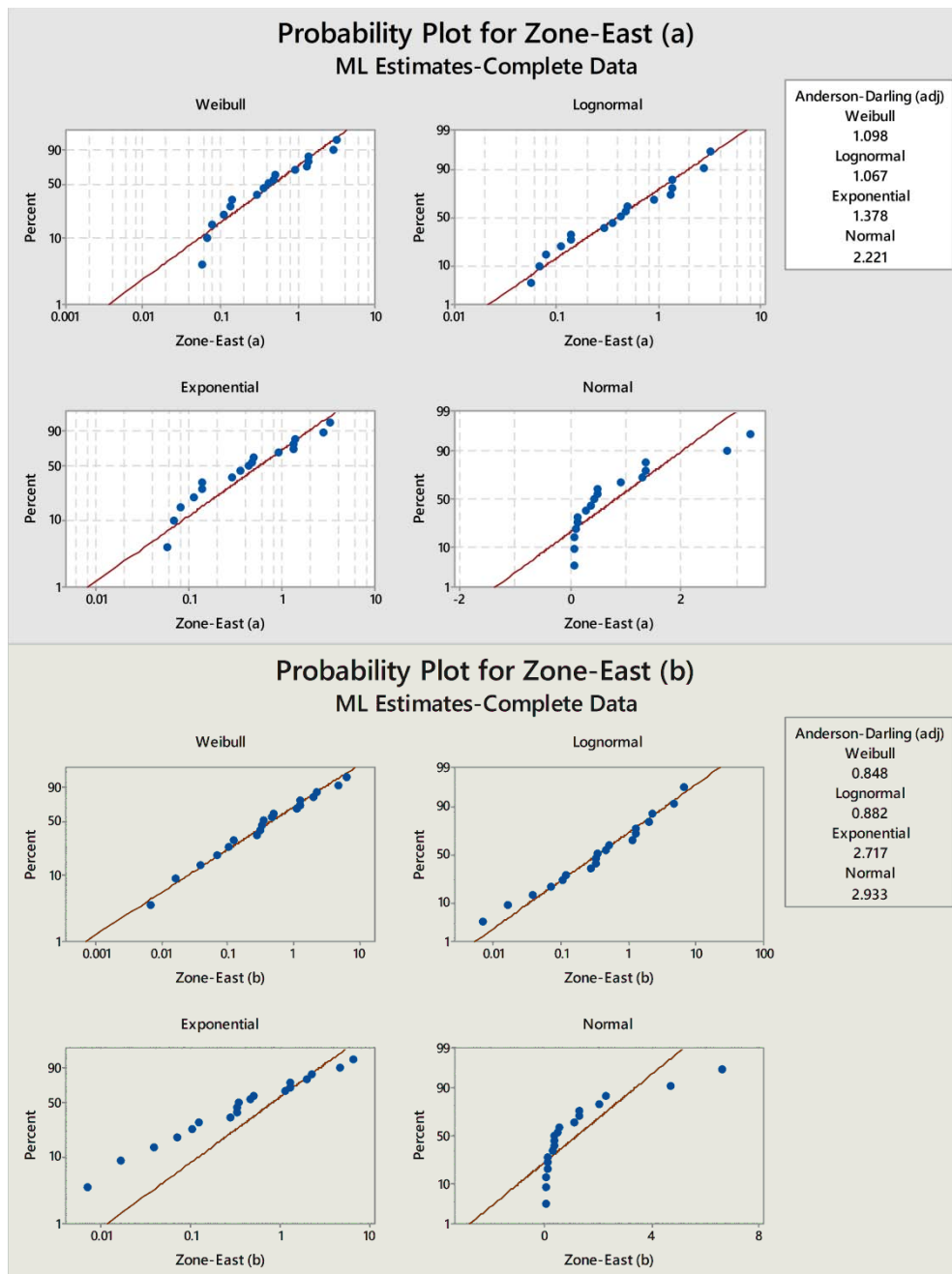


Figure 9: Probability plot of IRI for East (a) & (b) category. This plot shows IRI data falls near the Weibull reference line

If t is the time interval in years between successive events, α and β are the scale and shape parameters respectively for the Weibull distribution then, Probability Distribution Function (PDF): $f(t) = \alpha\beta t^{\beta-1}e^{-\alpha t^\beta}$

Where, $\alpha > 0$; $\beta > 0$

Cumulative Distribution Function (CDF): $\varphi(t) = e^{-\alpha t^\beta}$

Where $\varphi(t)$ is the cumulative probability of the next earthquake that will occur at a time later than t , and t is the time measured in years from the time of the last earthquake.

If (τ/t) is the conditional probability that the next earthquake will occur during the time interval between t and τ , then it is given as

Weibull Conditional Probability: $p(\tau/t) = (1 - e^{-[\beta*((t+\tau)^\alpha - t^\alpha)])}$

τ for Maximum Conditional Probability as proposed by Sergio G Ferraes (2003):

$$\tau = \frac{1}{\alpha\beta t^{\beta-1}}$$

III. PROBABILISTIC ANALYSIS METHOD

a) Parameters Estimation for earthquake IRIs

Variability in data and extremities in values are the significant reasons for selecting Weibull as a suitable model for analyzing earthquake recurrence intervals. The two-parameter Weibull distribution is the predominant distribution in reliability and lifetime data analysis used to model extreme value data. The two-parameter Weibull distribution has shown effective results for assessing earthquake recurrence intervals and is commonly used in modeling such data (Ram Bichar Singh Yadav et al. (2008), Şeyda Yilmaz et al. (2016), Sumanta Pasari et al. (2018), Sumanta Pasari et al. (2015)). The classical approach for estimating the scale and shape parameters employs the maximum likelihood estimation (MLE) method. The hazard function of Weibull is time-dependent with hazard increasing with time when the shape factor is greater than one and decreasing when it is less than one. When the shape factor equals one, the Weibull hazard function becomes constant or equivalent to the exponential function. The estimated parameters are tested to fit the distribution using the Anderson-Darling test.

b) Zone-wise probability calculation

i. Zone South

Zone South has 48 earthquakes recorded from the year 1995 to 20017 with maximum magnitude 2.9 and minimum magnitude 5.3, minimum depth as 0, and maximum as 45.7. Declustering is done by using the declustering function of ZMAP software which evaluated total five clusters in the zone with a total of 10 events as aftershocks, foreshocks, or dependent events out of total 48 events. The zone is further grouped into two categories based on earthquake magnitudes.

For South (a) category, the maximum recorded earthquake is of magnitude 3.9 (1996), whereas the minimum recorded earthquake is of magnitude 3 (2017). The last earthquake for this zoning category is recorded in 2017.

Similarly, for South (b) category, the maximum recorded earthquake is of magnitude 5.3 (2001), whereas the minimum recorded earthquake is of magnitude 4 (2015). The last earthquake for this zoning category is recorded in 2015. The estimated model parameters (scale, shape) are listed in Table 5. The conditional probabilities as per the Weibull model are as given in Table 6.

ii. Zone West

Zone West has 55 earthquakes recorded from the year 1996 to 20017 with maximum magnitude 4.9 and minimum magnitude 2.8, minimum depth as 0 (not recorded) and maximum as 40.6. Declustering is done by using the declustering function of ZMAP software which evaluated total three clusters in the zone is a total of 7 events as aftershocks, foreshocks, or dependent events out of total 55 events.

For Zone West (a) category, the maximum recorded earthquake is of magnitude 3.9 (2002), whereas the minimum recorded earthquake is of magnitude 3.1 (2016). The last earthquake for this zoning category is recorded in 2016.

Similarly, for Zone West (b) category, the maximum recorded earthquake is of magnitude 4.9 (2010), whereas the minimum recorded earthquake is of magnitude 4.1 (2013). The last earthquake for this zoning category is recorded in 2017. The estimated model parameters (scale, shape) are listed in Table 5.

Table 5: Zone-wise estimated parameters for different groups of earthquake magnitudes for Weibull distribution model

	Zone South (a)	Zone South (b)	Zone West (a)	Zone West (b)	Zone North (a)	Zone North (b)	Zone East (a)	Zone East (b)
Shape Factor	0.924	0.809	1.03	1.482	0.642	1.436	0.863	0.647
Scale Factor	0.743	1.955	0.66	2.209	1.381	2.711	0.742	0.832
Log-Likelihood	-20.583	-15.529	-16.047	-17.397	-11.952	-12.58	-12.975	-17.97
Mean	0.771	2.25	0.653	1.988	2.1	2.442	0.805	1.152

Std. Deviation	0.808	3.59	0.635	1.456	4.12	1.972	0.962	1.757
Range	2.849	11.62	2.429	4.198	12.11	5.593	3.191	6.615

iii. Zone North

Zone North has 25 earthquakes recorded from the year 1999 to 2017 with maximum magnitude 2.2 and minimum magnitude 4.6, minimum depth as 1.2, and maximum as 35. Declustering is done by using the declustering function of ZMAP software which evaluated total four clusters in the zone with a total of 8 events as aftershocks, foreshocks or dependent events out of total 25 events.

For Zone North (a) category, the maximum recorded earthquake is of magnitude 3.8 (2016), whereas the minimum recorded earthquake is of magnitude 3.0 (1999). The last earthquake for this zoning category is recorded in 2016. Similarly, for Zone North (b) category, the maximum recorded earthquake is of magnitude 4.5 (2013), whereas minimum recorded earthquake is of magnitude 4.0 (2013). The last earthquake for this zoning category is recorded in 2016. The estimated model parameters (scale, shape) are listed in Table 5.

iv. Zone East

Zone East has 59 earthquakes recorded from the year 1995 to 2017 with maximum magnitude 2.8 and minimum magnitude 6.1, minimum depth as 0 and maximum as 82.9. Declustering is done by using declustering function of ZMAP software which evaluated total ten clusters in the zone with a total of 24 events as aftershocks, foreshocks, or dependent events out of total 59 events.

For Zone East (a) category, the maximum recorded earthquake is of magnitude 3.9 (2002), whereas minimum recorded earthquake is of magnitude 3.1 (2003). The last earthquake for this zoning category is recorded in 2016.

Similarly, for Zone East (b) category, the maximum recorded earthquake is of magnitude 6.1 (1997), whereas minimum recorded earthquake is of magnitude 4.0 (2016). The last earthquake for this zoning category is recorded in 2017. The estimated model parameters (scale, shape) are listed in Table 5.

IV. RESULTS & DISCUSSION

The stochastic methodology is applied to the earthquake inter-event recurrence intervals for earthquakes recorded in the past 100 years by classifying the whole region into four zones based on the clusters of seismogenic faults and historical seismicity. Similar studies have been done for other regions in India and around the world with many promising results in terms of conditional probabilities for

assessing future hazard scenarios. The generalized exponential behavior, memory-less-ness, best fitting in terms of data, and promising results in other similar studies became reasons for the use of Weibull probability distribution as a modeling function for the earthquake IRLs in this study. Zone-wise conditional probability for different groups of earthquake magnitudes are calculated using respective model parameters. The results cover all possible combinations of elapsed time (t) and remaining time (τ) with an incremental value of 3 years. The following results are observed in this study:

1. The mean Weibull IRI (τ_{mean}) for the next event in for category (a) of magnitudes ($3 \leq M_w < 4$) came out to be 1.68 years whereas for category (b) of magnitudes ($4 \leq M_w \leq 6$) it came out to be 0.98 years.
2. The average remaining time for category (b) earthquakes is found to be less than that of category (a) earthquakes.
3. The estimated elapsed time (t) since the last earthquake as per catalog is added to the Weibull occurrence year as estimated from the equation for the maximum suggested by Sergio G. Ferraes (2003), and the results are presented in Table 11.
4. Results show that the probability of occurrence of 4 to 5 magnitude earthquakes is higher for zone South in 2022, zone West, and North in 2021 and zone East in 2022.
5. Similarly, the probability of occurrence of 3 to 5 magnitude earthquakes is higher for all the zones in 2022.
6. The average IRI with maximum probability is found to be 3.25 years for earthquakes ranging from magnitude 3 to 6.
7. For category (a) magnitudes in all the zones, the average IRI with maximum probability is found to 4.17 years
8. For category (b) magnitudes in all the zones, it is found to be 1.59 years.
9. The standard deviation category (a) earthquakes IRI is found to be maximum as 5.08, whereas it is found to be least for category (b) earthquakes IRI as 0.83.
10. It is observed the probability of recurrence for category (a) earthquakes is higher as compared to that of category (b) earthquakes with exception in Zone North, where the probability of recurrence of category (b) earthquakes is found to be higher than category (a) earthquakes.

11. The log-likelihood is found to be least for zone North (a) & (b) categories, justifying the data pertaining to this zone to be the best-fit for the Weibull distribution model.

V. CONCLUSIONS

The following conclusions are drawn from this study:

1. For all zones, category (a) magnitude have a longer time duration between next earthquakes while category (b) magnitudes have a shorter duration for the earthquake to happen.
2. Years 2021 to 2023 are critical for the entire region as significant seismological activity is predicted. This time must be suitably utilized at least for projects under construction to assure sufficient detailing measures are undertaken.
3. As for existing structures that are of critical importance, their state of strength must be reassessed in case of a seismic event.
4. The results published in this study are going to be instrumental in future site-specific hazard studies and for the development of site-specific hazard curves for various regions across the state of Madhya Pradesh.
5. It is also recommended to use results of this study to perform PSHA as a non-Poissonian model and compare results with the ones obtained by PSHA done with a Poissonian recurrence model for the study region.

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Table 6: Conditional Probabilities using Weibull Method for Zone South (a) & (b) categories

Conditional Probabilities using Weibull Method for ZONE South (a) category											
Remaining Time (t)	Elapsed Time										
	0	3	6	9	12	15	18	21	24	27	30
3	0.871	0.841	0.829	0.821	0.816	0.811	0.807	0.803	0.8	0.797	0.795
6	0.98	0.973	0.97	0.967	0.965	0.963	0.962	0.961	0.96	0.958	0.958
9	0.997	0.995	0.994	0.994	0.993	0.993	0.992	0.992	0.992	0.991	0.991
12	0.999	0.999	0.999	0.999	0.999	0.999	0.998	0.998	0.998	0.998	0.998
15	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
Conditional Probabilities using Weibull Method for ZONE South (b) category											
3	0.991	0.972	0.961	0.952	0.944	0.938	0.932	0.927	0.922	0.918	0.914
6	1	0.999	0.998	0.997	0.997	0.996	0.995	0.994	0.994	0.993	0.992
9	1	1	1	1	1	1	1	1	0.999	0.999	0.999
12	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1	1

Table 7: Conditional Probabilities using Weibull Method for ZONE West (a) & (b) categories

Conditional Probabilities using Weibull Method for ZONE West (a) category											
Remaining Time	Elapsed Time										
	0	3	6	9	12	15	18	21	24	27	30
3	0.871	0.881	0.885	0.888	0.89	0.891	0.892	0.893	0.894	0.895	0.896
6	0.985	0.986	0.987	0.988	0.988	0.988	0.989	0.989	0.989	0.989	0.989
9	0.998	0.998	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999
12	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
Conditional Probabilities using Weibull Method for ZONE West (b) category											

3	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1

Table 8: Conditional Probabilities using Weibull Method for ZONE North (a) & (b) categories

Conditional Probabilities using Weibull Method for ZONE North (a) category											
Remaining Time (Years)	0	3	6	9	12	15	18	21	24	27	30
3	0.939	0.791	0.727	0.683	0.65	0.623	0.601	0.582	0.566	0.552	0.539
6	0.987	0.943	0.913	0.889	0.868	0.85	0.833	0.819	0.805	0.793	0.782
9	0.997	0.982	0.97	0.958	0.947	0.937	0.928	0.919	0.91	0.902	0.895
12	0.999	0.994	0.989	0.983	0.978	0.973	0.968	0.962	0.958	0.953	0.948
15	1	0.998	0.995	0.993	0.99	0.988	0.985	0.982	0.979	0.977	0.974
18	1	0.999	0.998	0.997	0.996	0.994	0.993	0.991	0.99	0.988	0.987
21	1	1	0.999	0.999	0.998	0.997	0.997	0.996	0.995	0.994	0.993
24	1	1	1	0.999	0.999	0.999	0.998	0.998	0.997	0.997	0.996
27	1	1	1	1	1	0.999	0.999	0.999	0.999	0.998	0.998
30	1	1	1	1	1	1	1	0.999	0.999	0.999	0.999
Conditional Probabilities using Weibull Method for ZONE North (b) category											
3	0.986	0.986	0.986	0.986	0.986	0.986	0.986	0.986	0.986	0.986	0.986
6	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1

Table 9: Conditional Probabilities using Weibull Method for ZONE East (a) & (b) categories

Conditional Probabilities using Weibull Method for ZONE East (a) category											
Remaining Time (Year)	0	3	6	9	12	15	18	21	24	27	30
3	0.853	0.792	0.768	0.752	0.74	0.73	0.722	0.715	0.709	0.703	0.698
6	0.969	0.952	0.942	0.935	0.93	0.925	0.921	0.917	0.913	0.91	0.907

9	0.993	0.988	0.985	0.983	0.98	0.979	0.977	0.975	0.974	0.973	0.971
12	0.998	0.997	0.996	0.995	0.994	0.994	0.993	0.993	0.992	0.991	0.991
15	1	0.999	0.999	0.999	0.998	0.998	0.998	0.998	0.998	0.997	0.997
18	1	1	1	1	1	0.999	0.999	0.999	0.999	0.999	0.999
21	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
Conditional Probabilities using Weibull Method for ZONE East (b) category											
3	0.816	0.617	0.549	0.506	0.475	0.452	0.432	0.416	0.402	0.39	0.38
6	0.929	0.827	0.777	0.741	0.712	0.689	0.669	0.651	0.636	0.622	0.61
9	0.968	0.915	0.883	0.858	0.837	0.818	0.802	0.787	0.774	0.762	0.751
12	0.984	0.955	0.936	0.919	0.905	0.891	0.879	0.868	0.858	0.848	0.839
15	0.992	0.975	0.964	0.953	0.943	0.934	0.925	0.917	0.909	0.902	0.895
18	0.995	0.986	0.979	0.972	0.965	0.959	0.953	0.947	0.941	0.936	0.931
21	0.997	0.992	0.987	0.983	0.978	0.974	0.97	0.966	0.962	0.958	0.954
24	0.999	0.995	0.992	0.989	0.986	0.984	0.981	0.978	0.975	0.972	0.969
27	0.999	0.997	0.995	0.993	0.991	0.989	0.987	0.985	0.983	0.981	0.979
30	0.999	0.998	0.997	0.996	0.994	0.993	0.992	0.99	0.989	0.987	0.986

Table 10: Zone-wise computation of year with the highest probability of occurrence of earthquakes of different categories of magnitudes (a & b) by Weibull occurrence time

ZONE	α (Scale)	β (Shape)	T	τ	T + τ	Last Event Year	Probable Year for Next Event
South (a)	0.743	0.924	3	1.58	5	2017	2022
South (b)	1.955	0.809	5	0.86	6	2015	2021
West (a)	0.66	1.03	4	1.41	6	2016	2022
West (b)	2.209	1.482	3	0.18	4	2017	2021
North (a)	1.381	0.642	4	1.85	6	2016	2022
North (b)	2.711	1.436	4	0.14	5	2016	2021
East (a)	0.742	0.863	4	1.89	6	2016	2022
East (b)	0.832	0.647	3	2.74	6	2017	2023

Table 11: Table shows zone-wise statistical parameters (mean, standard deviation etc.) for Weibull occurrence time

	Mean	Standard Deviation	Minimum	Maximum	Range
All Zones	1.33	0.89	0.14	2.74	2.6
Category (a)	1.68	0.22	1.41	1.89	0.48
Category (b)	0.98	1.21	0.14	2.74	2.6

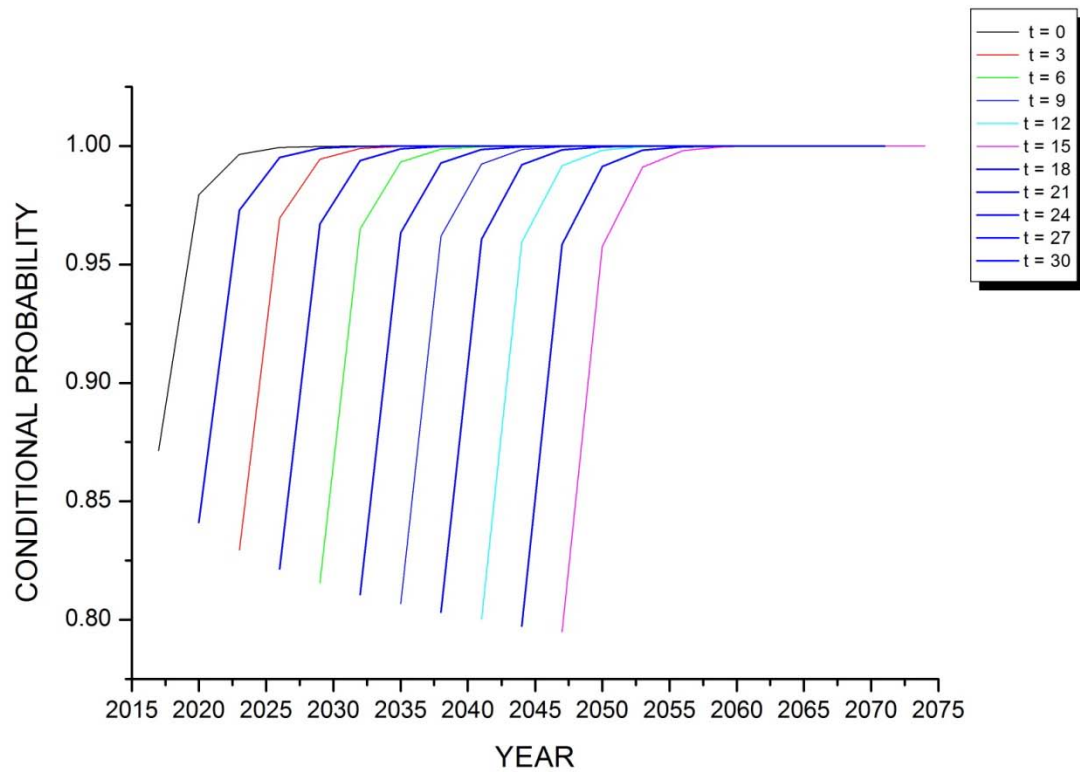


Figure 10: Conditional Probability Plot (Hazard Curve) for zone South (a) category. Elapsed time taken in an interval of 3 years up to 30 years

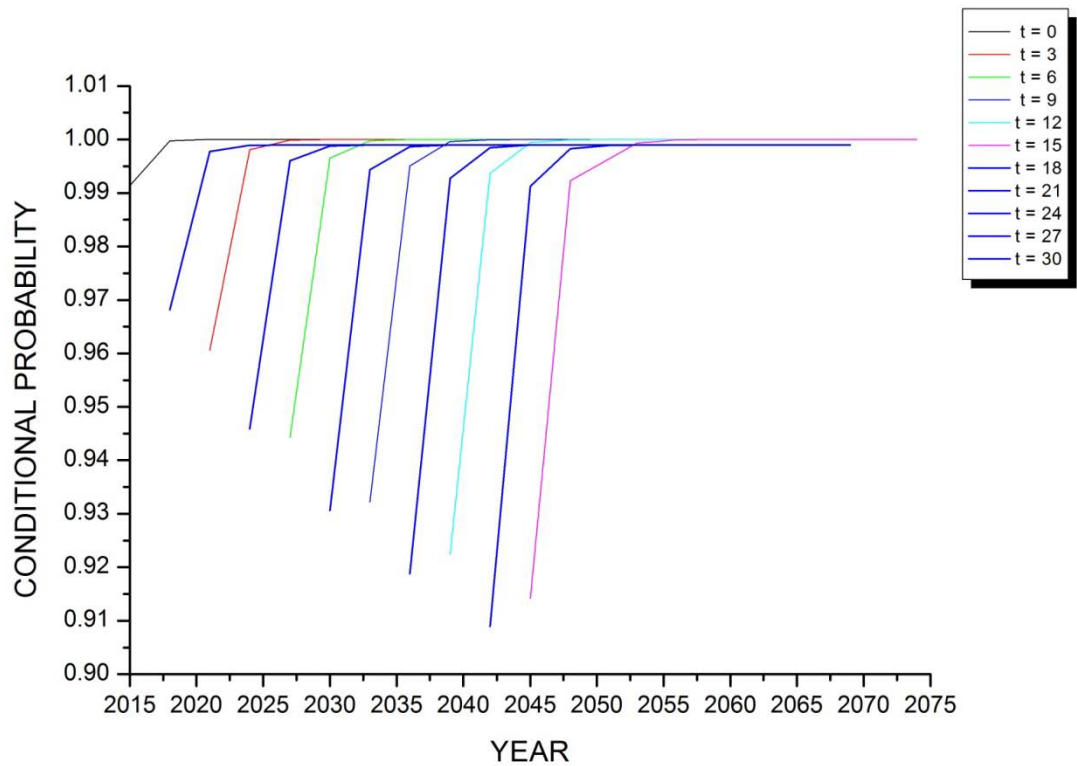


Figure 11: Conditional Probability Plot (Hazard Curve) for zone South (b) category. Elapsed time taken in an interval of 3 years up to 30 years

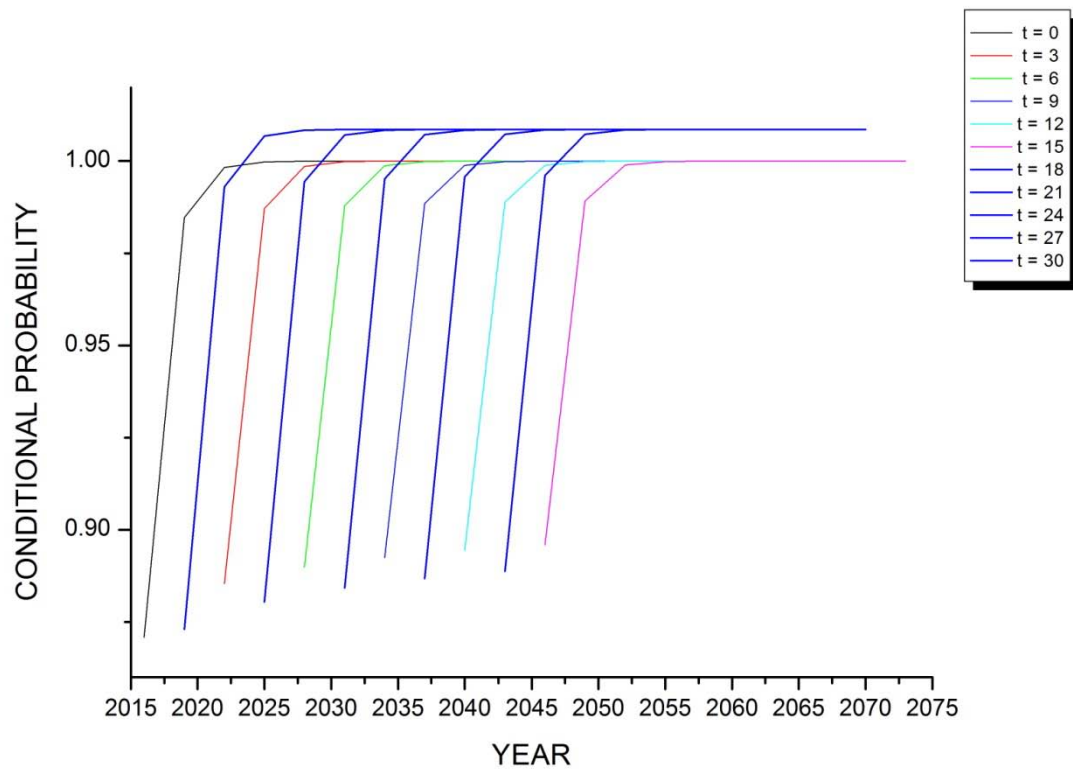


Figure 12: Conditional Probability Plot (Hazard Curve) for zone West (a) category. Elapsed time taken in an interval of 3 years up to 30 years

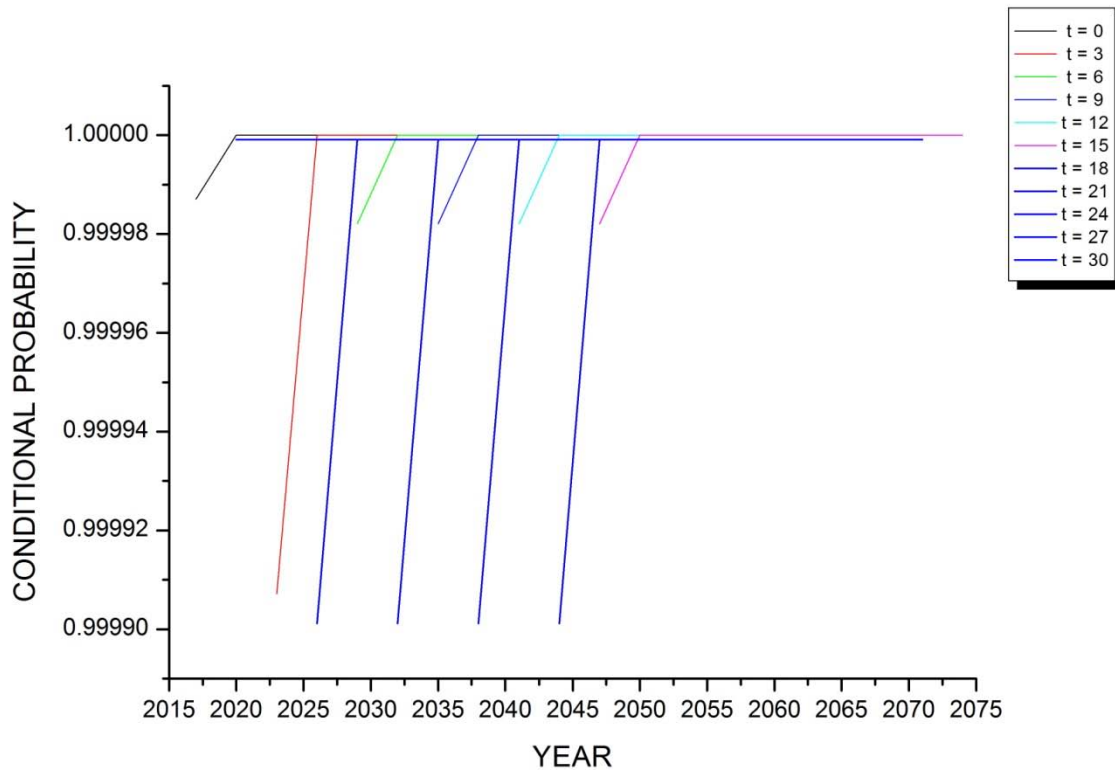


Figure 13: Conditional Probability Plot (Hazard Curve) for zone West (b) category. Elapsed time taken in an interval of 3 years up to 30 years

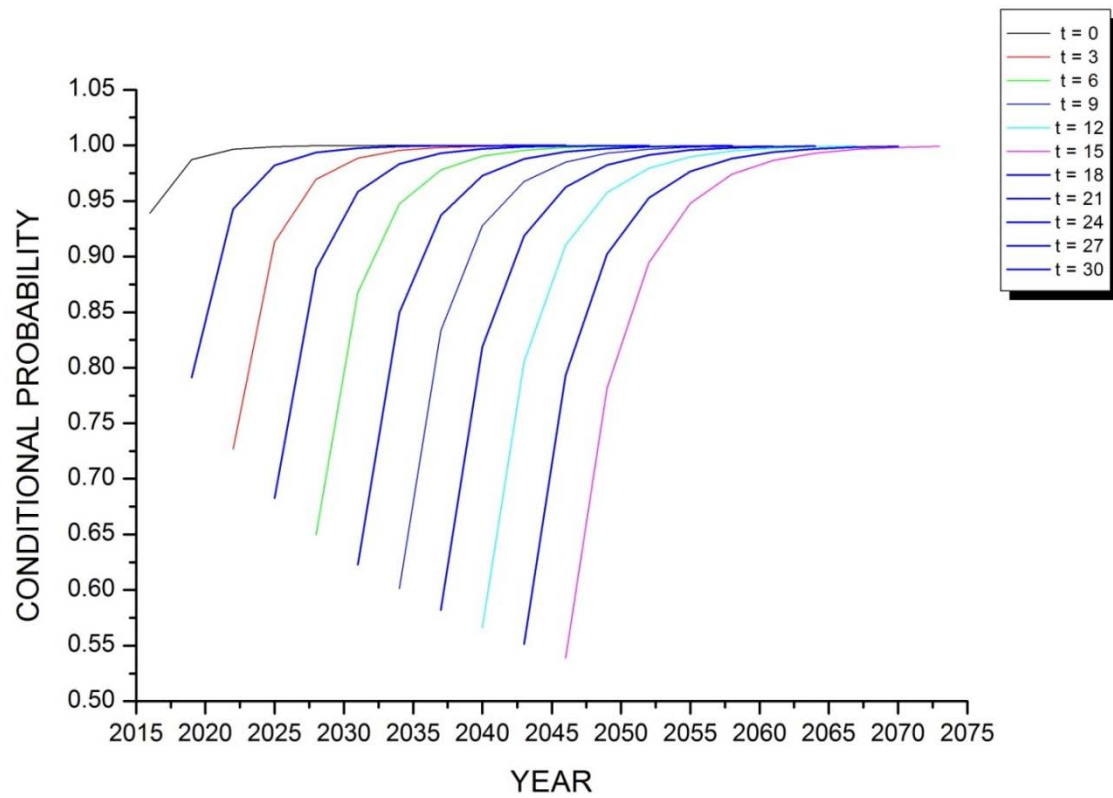


Figure 14: Conditional Probability Plot (Hazard Curve) for zone North (a) category. Elapsed time taken in an interval of 3 years up to 30 years

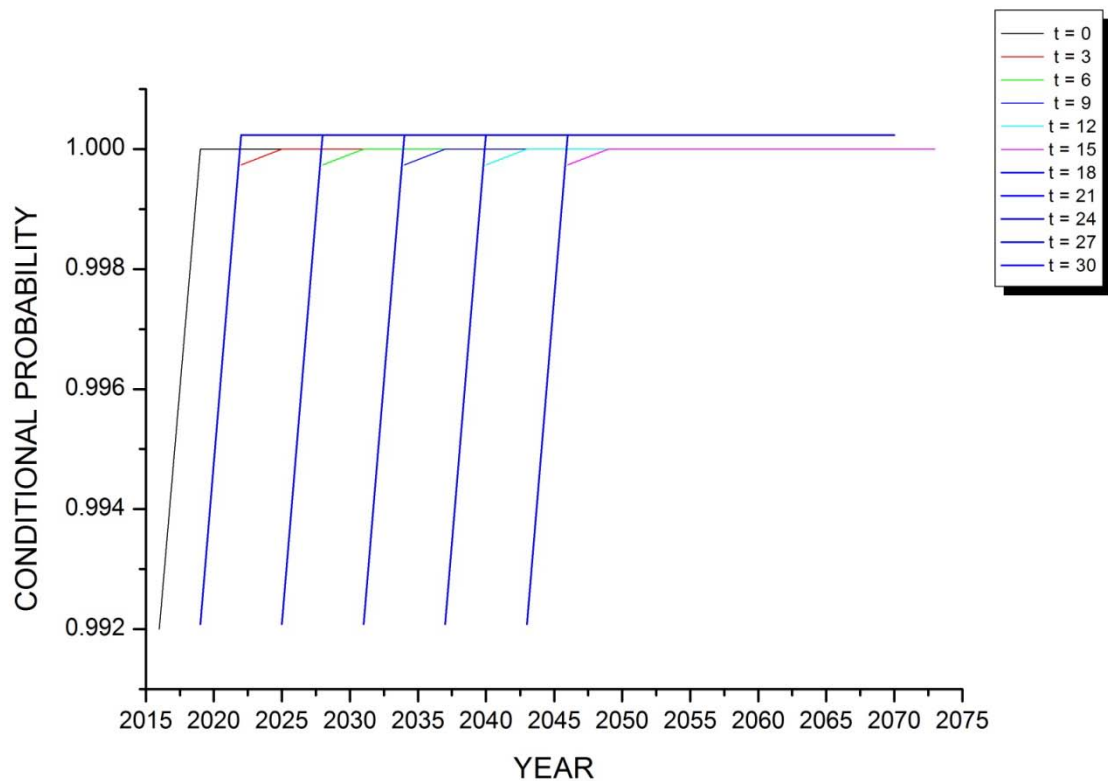


Figure 15: Conditional Probability Plot (Hazard Curve) for zone North (b) category. Elapsed time taken in an interval of 3 years up to 30 years

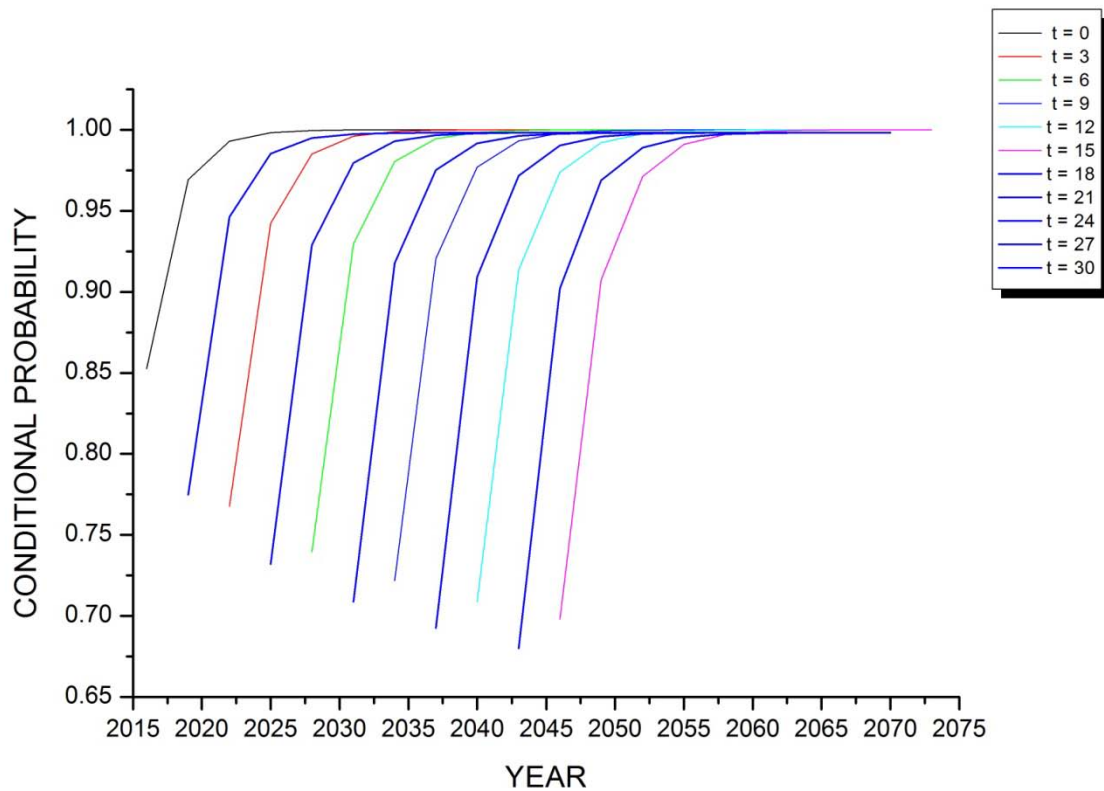


Figure 16: Conditional Probability Plot (Hazard Curve) for zone East (a) category. Elapsed time taken in an interval of 3 years up to 30 years

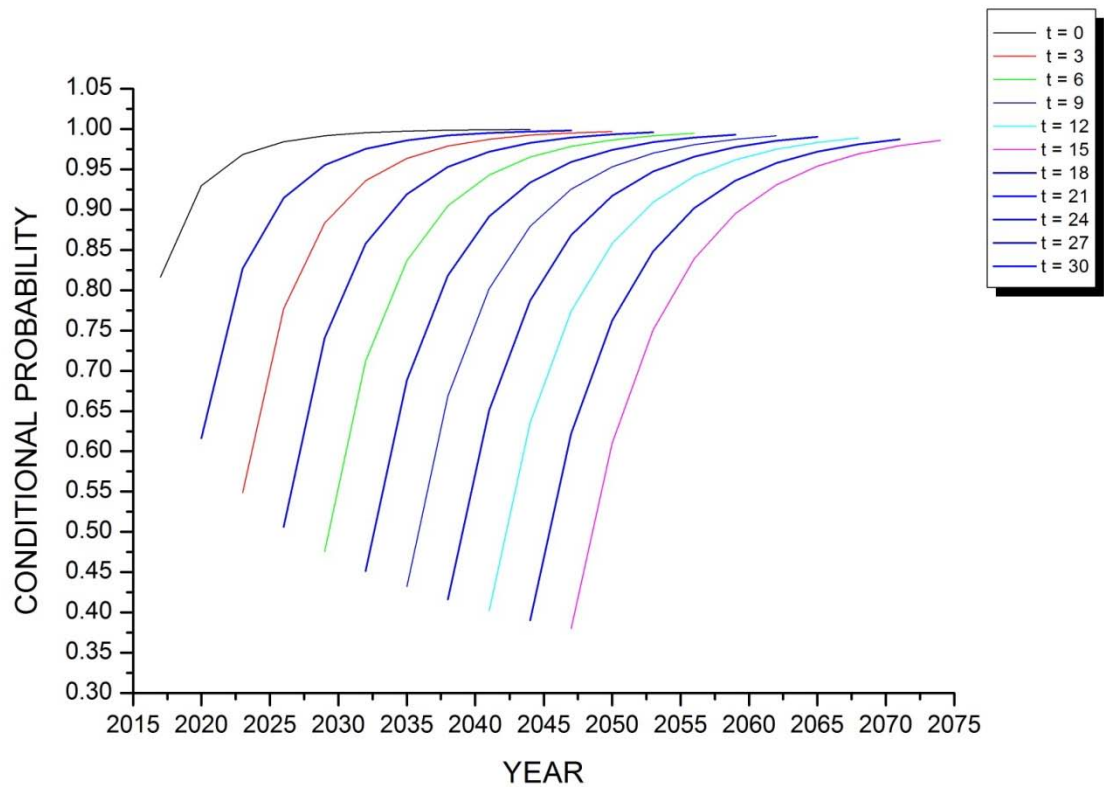


Figure 17: Conditional Probability Plot (Hazard Curve) for zone East (b) category. Elapsed time taken in an interval of 3 years up to 30 years