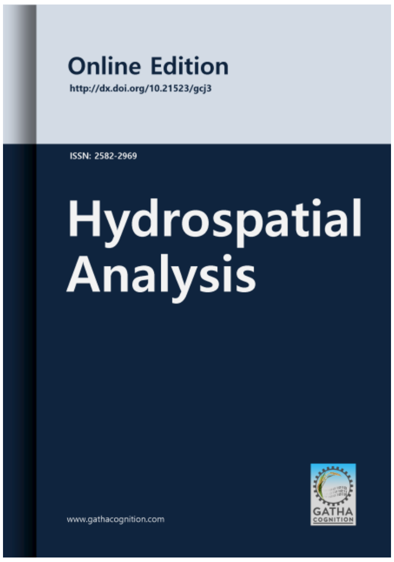

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Magnitude and Frequency Analyses of Floods on the Kaveri River of the Southern India by Using Gumbel Extreme Value Type-I Probability Distribution

Smita R. Pagare[1], Pramodkumar S. Hire[1], Archana D. Patil[2*]

1. Department of Geography, HPT Arts and RYK Science College, Nashik-422005 (India).
2. Department of Geography, RNC Arts, JDB Commerce and NSC Science College, Nashik Road, Nashik-422101 (India).

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Original Research Paper

Magnitude and Frequency Analyses of Floods on the Kaveri River of the Southern India by Using Gumbel Extreme Value Type-I Probability Distribution

Smita R. Pagare[1], Pramodkumar S. Hire[1], Archana D. Patil[2*]

1. Department of Geography, HPT Arts and RYK Science College, Nashik-422005 (India).
2. Department of Geography, RNC Arts, JDB Commerce and NSC Science College, Nashik Road, Nashik-422101 (India).

Abstract

The Gumbel Extreme Value Type-I (GEVI) probability distribution is applied to investigate magnitude and frequency of floods on the Kaveri River using Annual Maximum Series data for 17 to 47 years. The GEVI is used for future probabilities of occurrences of floods and to estimate the recurrence interval of average annual peak discharges ($\overline{Q}$), large floods (Qlf) and actually observed maximum annual peak discharges (Qmax). The discharges have been estimated for 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr and 1000-yr floods that range from 9 to 10408 m^3s^{-1}. As per GEVI, the $\overline{Q}$ has a recurrence interval of 2.33 years, Qlf has 6.93 years. However, recurrence interval of Qmax range between 36 and 636 years. The curves portrayed on GEVI probability paper provide dependable estimates of floods. The GEVI probability distribution, therefore, can be reliably and conveniently used to estimate the recurrence intervals for given magnitude and vice-versa.

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1 INTRODUCTION

Since pre-historic times, flooding, principally the destructive profusion of water (either freshwater or ocean), has been a key apprehension of people inhabiting the vicinity of rivers and water bodies (Kundzewicz and Schellnhuber, 2004). The United Nations Office for Disaster Risk Reduction (UNDRR) reported that over 2 billion people were affected by floods between 1998 and 2017 (Wallemacq and House, 2018). India, in particular, is extremely susceptible to the effects of flash floods, heavy rainfall events and tropical storms, that cause fatalities, damage to property and agricultural fields, and other undesirable effects on the environment, economy, and society (Kripalani *et al.*, 2003; Dube and Rao, 2005). According to Natural Disaster Management Authority of India, out of the total geographical area of India (3287263 km^2), more than ~ 400000 km^2 i.e. 13% area is flood prone. Therefore, reliable estimation of the magnitude and frequency of floods are vital for management of floodplains, estimates of flood insurance and the design of transportation and water carriage structures, for instance, dams, bridges, culverts, etc. Flood frequency analysis, based on a set of systematic data and historical floods, is commonly used to relate the magnitude of extreme runoff or river flow events to their frequency of occurrence through the use of probability distributions. Stochastic methods for hydrological flood analysis were seminally introduced by Fuller in 1914 (Fuller, 1914). His exposition on flood frequency incorporated the return period as a quantitative measure for the recurrence probability of floods of varying magnitudes. Subsequent advancements by Foster (1924), Hazen (1930), and Gumbel (1941) expanded this approach to include the application of theoretical probability distribution functions, thereby modelling the empirical frequency distributions of flood events. These methodologies have since become entrenched in contemporary practices of probabilistic flood frequency analysis, as codified by the U.S. Water Resources Council in 1981 (Hirschbock, 1988).

* Author address for correspondence
RNC Arts, JDB Commerce and NSC Science College, Nashik Road, Nashik 422101 (India).
Tel.: +917875075436
Emails: smitapagare2020@gmail.com (*S. Pagare*), pramodkumarhire@gmail.com (*P. Hire*), archanapatil.geo@gmail.com (*A. Patil* - Corresponding author)

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Numerous probability distributions, for instance, Gamma (Pearson type III), Log Normal (LN), Log Pearson type III (LP III), Gumbel Extreme Value Type-I (GEVI), etc. are indorsed in the hydrological literature to determine hydraulic frequency, however, none of these distributions are documented as a universal distribution that can precisely signify the flood frequency (Law and Tasker, 2003) at any gauging site. Nevertheless, the objective of the present work is not to find out the most appropriate probability distribution(s), but to estimate the recurrence interval of high magnitude flows. Therefore, in the current paper, flood frequency analysis of the Kaveri River and its tributaries has been carried out by applying the GEVI distribution. The GEVI, also known as the extreme value distribution, is used to model extreme values (Gumbel, 1958; Haan, 1977; Todorovic, 1978; Watt, 1989; Coles, 2001; Castillo *et al.*, 2005; Ferrari and Pinheiro, 2014). This distribution has been chosen primarily on the basis of its applicability to the monsoon-dominated Indian rivers (Hire, 2000; Hire and Patil, 2018; Patil, 2017; Pawar *et al.*, 2020; Anwat *et al.*, 2021). Besides, Garde and Kothyari (1990), on the basis of an investigation of long records available for 92 gauging stations, proposed the GEVI probability distribution for the Annual Maximum Series (AMS) data from Indian medium and large size catchments. Consequently, in view of the size of the Kaveri Basin and to understand the hydrological characteristics of floods in terms of magnitude and frequency, the GEVI probability distribution has been applied to the AMS data.

2 STUDY AREA

The Kaveri River originates at an elevation of 1341 m at Talakaveri in the Bhramagiri ranges of the Western

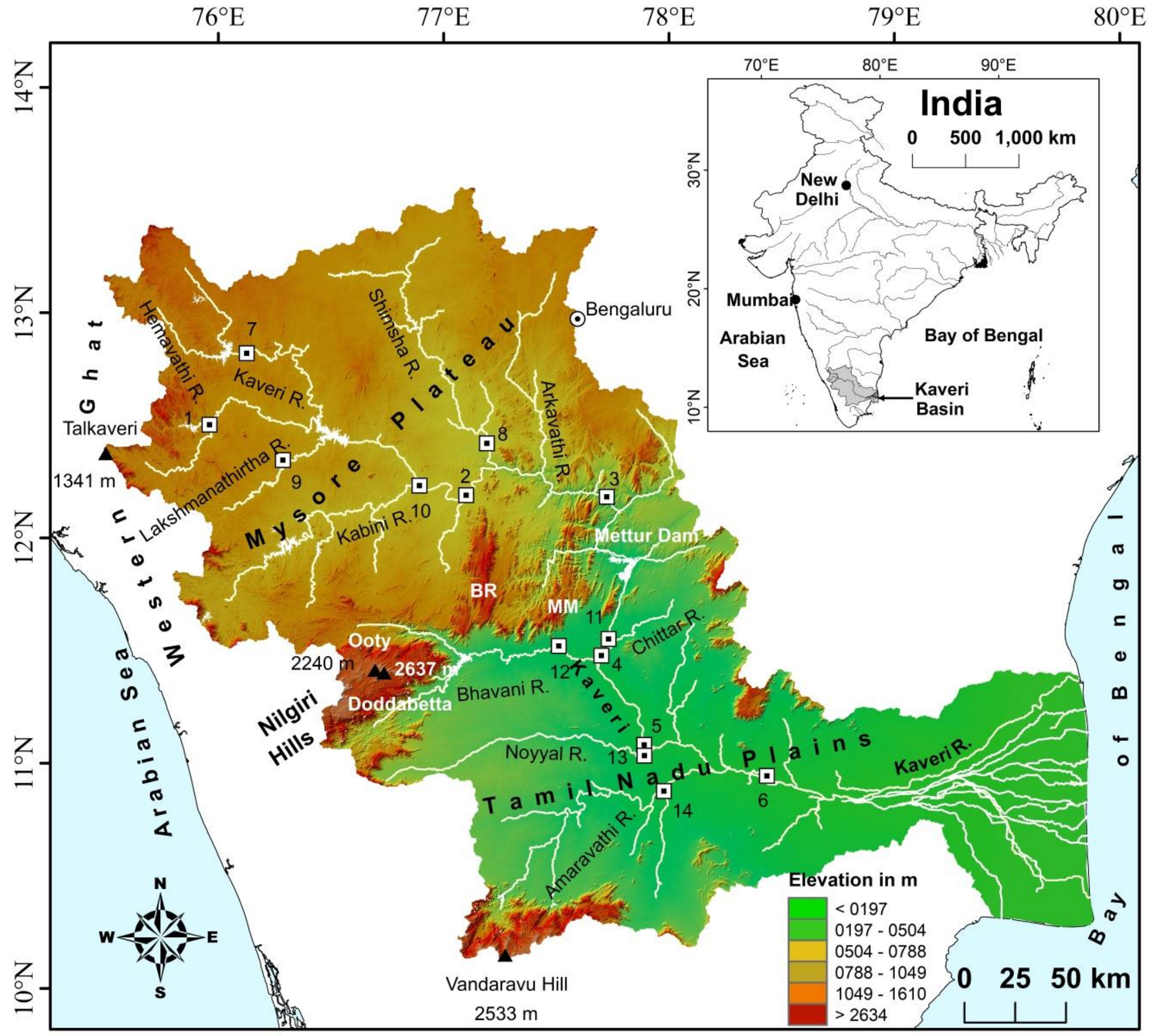

Figure 1. Physiography of the Kaveri Basin and locations of discharge gauging sites: 1 = Kudige, 2 = Kollegal, 3 = Biligundulu, 4 = Urachikottai, 5 = Kodumudi, 6 = Musiri, 7 = M.H. Halli, 8 = T. K. Halli, 9 = K. M. Vadi, 10 = T. Narasipur, 11 = Sevanur, 12 = Savandapur, 13 = E-Mangalam, 14 = Nallamaranpatty. BR = Biligirirangan Ranges; MM = Mahadeswaramalai Ranges.

Ghat in the Karnataka State (Figure 1). The river flows to south east direction over the Mysore Plateau and debouches in the Bay of Bengal. The length of the Kaveri River is 800 km and it drains 81155 km^2 area. The important tributaries of the river are the Hemavathi, Kabini, Shimsha, Arkavathi and Bhavani. The Kaveri Basin is flanked by the Western Ghat to the west, the Eastern Ghat to the east and south and to the north it is detached by the ridges separating from Krishna and Pennar Basins. The two major physiographic domains of the Kaveri Basin are the elevated Mysore Plateau characterised by broad valley and low gradient streams in the west and the fluvial-deltaic or Tamil Nadu Plains to the east (Kale *et al.*, 2014).

The Kaveri Basin is underlain primarily by Archaean-Proterozoic crystalline rocks, for instance gneisses, charnockites and granites (Sharma and Rajamani, 2001; Valdiya, 2001). In the eastern part of the basin, quaternary sediments are present mainly on the fluvial-deltaic plains of the Tamil Nadu state. Moreover, numerous north south and east west trending lineaments, faults and shear zones characterize the Kaveri as well as the adjacent basins (Vaidyanadhan, 1971; Valdiya, 2001; Ramasamy, 2006).

The basin is primarily influenced by southwest monsoon in the Karnataka and Kerala states and northeast monsoon in the Tamil Nadu state. The average annual rainfall of the Kaveri Basin is 1172 mm. It varies from >2500 mm in the headwaters i.e. Western Ghat to ~700 mm in the lower reaches (Kale *et al.*, 2014). More than three fourth of the annual rainfall and runoff of the basin arises during the southwest monsoon season and the wet season transports approximately 85% of the yearly sediment load (Vaithiyanathan *et al.*, 1992). The average annual runoff of the Kaveri Basin (~21.4 km^3) (Central Water Commission, 2020) is much less than other large rivers of the Peninsular India, for instance, the Godavari (111 km^3), the Krishna (78 km^3), the Mahanadi (67 km^3) and the Narmada (46 km^3). It, therefore, impels exceedingly low unit discharges and rates of erosion (Kale *et al.*, 2014).

3 DATA AND METHODOLOGY

The AMS data from 1971 to 2019 recorded at gauge and discharge (G/D) sites have been acquired from the water year book of 2018-19 published by Central Water Commission (2020) and were used to accomplish Flood Frequency Analysis of the Kaveri River and its tributaries. The record lengths of the data are from 17 to 47 years. The data were available for the Kudige, Kollegal, Biligundulu, Urachikottai, Kodumudi and Musiri sites on the Kaveri River and eight sites on its tributaries (Figure 1). In order to estimate discharges of a given return period, a frequency distribution is compiled from the data series of annual maximum events. The probable design flood discharges have been calculated for return periods of 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr and 1000-yr by means of the GEVI probability distribution. The distribution has also been employed for approximation of the recurrence interval of average annual peak discharge ($\overline{Q}$), large flood (Qlf) and actually observed maximum annual peak discharge (Qmax). A visual check of the fit of the frequency distribution is probably the best way in determining how satisfactory an individual distribution fits the AMS dataset or which distribution fits "best". Thus, flood frequency of all the sites of the Kaveri River and its tributaries are represented graphically (Figure 2, 3 and 4) which fairly represents the Kaveri Basin.

3.1 Gumbel Extreme Value Type-I (GEVI) Probability Distribution

The GEVI (Gumbel, 1941, 1958) probability distribution has been applied as a universal model of extreme flood events principally in the perspective of regionalization procedures and has been recognized as a rational approach to predict the flood recurrence interval (Al-Mashidani *et al.*, 1978; Hosking and Wallis, 1997). The GEVI probability distribution is expressed as;

$$QT = \overline{Q} + [K(T) * \sigma Q] \quad (1)$$

$$\overline{Q} = \frac{\Sigma Q}{N} \quad (2)$$

$$\sigma Q = \sqrt{\frac{\Sigma(Q-\overline{Q})^2}{n-1}} \quad (3)$$

where, QT = given return period's discharge; $\overline{Q}$ = average of annual peak discharge; K(T) = factor of frequency and is the return period's (T) function. K(T) values are obtained from the book 'Hydrology in Practice' (Shaw, 1988); σQ = AMS's standard deviation.

The return periods (T) were computed for average annual peak discharge ($\overline{Q}$), large flood (Qlf) and peak on record (Qmax) for all sites by using the formula given below.

$$\frac{1}{T} = 1 - F(X) = 1 - \exp[-e^{-b(X-a)}] \quad (4)$$

where, T = return period of a specified discharge; F(X) = probability density function (PDF) of an annual maximum series Q ≤ X; a and b = parameters allied to the moments of population of Q values. The parameters a and b are derived, as under, by equation (5) and (6).

$$b = \frac{\pi}{\sigma Q\sqrt{6}} \quad (5)$$

$$a = \overline{Q} - \frac{y}{b} \quad (6)$$

where, $\overline{Q}$ = average annual peak discharge; σQ = annual peak discharge's standard deviation; y = 0.5772.

3.2 Plotting Position and Frequency Curves

The plotting positions have been calculated using a variety of equations, nevertheless, Cunnane (1978) and Shaw (1988) argues that Gringorten's approach is pertinent as it fits outliers more closely than other plotting positions. Consequently, by using the following equations (Gringorten, 1963), F(X) values were determined.

$$P(X) = 1 - F(X) = \frac{r-0.44}{N+0.12} \quad (7)$$

where, P(X) = the probability of exceedance; r = rank of flood magnitude; N = the number of observations of AMS.

In the Gringorten plotting positions, by judgment, a line can be constructed to fit the scatter. Notwithstanding, drawing the line mathematically is more appropriate. Creating confidence limits about the fitted line and its association between the AMS and the linearized probability variable is also essential, since the majority of AMS data are only available for a short period of time (Shaw, 1988). In the present work, the procedure given by Shaw (1988) has been adopted to fit the line mathematically and to construct the confidence limits. The plotted graphs are represented in Figure 2, 3 and 4.

4 RESULTS AND DISCUSSION

A frequency distribution is amassed from a data series of AMS to estimate discharges of a given return period. Peak flows have been estimated for different return periods such as 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr and 1000-yr by using GEVI probability distribution and the estimated discharges are given in Table 1. Accordingly, the highest estimated discharge (10408 m^3s^{-1}) of 1000-yr return period was for the Musiri Site (Figure 1) on the Kaveri River in the Tamil Nadu state. Nevertheless, the peak discharge of 7690 m^3s^{-1} magnitude was observed on the Kaveri River at the Musiri Site in the year 2005 (Central Water Commission, 2020). The recurrence interval for this discharge is 135-yr (Table 2). Astonishingly, the estimated discharges of given return periods of the Kaveri River are remarkably low as compared to other Indian Peninsular Rivers (Hire, 2000; Hire and Patil, 2018; Patil, 2017; Pawar *et al.*, 2020; Anwat *et al.*, 2021).

Furthermore, an attempt has been made to find out the return periods of average annual peak discharge ($\bar{Q}$), large flood (Qlf) and actually observed maximum annual peak discharge (Qmax) by applying the GEVI distribution and result have been shown in Table 2. Unsurprisingly, as per GEVI distribution, the $\bar{Q}$ has the recurrence interval of 2.33-yr. The Qlf, which is well-defined as a flow that exceeds one standard deviation above the average annual peak discharge ($\bar{Q}$) (Hire, 2000), has the return period 6.93-yr. The analysis further confirms that the return period of the actually observed peak discharge (Qmax = 5571 m^3s^{-1}) on the Amaravati River at the Nallamaranpatty is 636-yr which is high. It is interesting to note here that the Amaravati is a tributary of the Kaveri River having drainage area of only 9080 km^2. Nonetheless, the Qmax of the river at the Nallamaranpatty is much higher. However, the recurrence interval of the Kaveri River at the Musiri site, the lowermost site just before the commencement of the Kaveri Delta, is 135-yr. This site has the upstream drainage area of 66243 km^2. Moreover, some discharge gauging sites have much less return period of the Qmax

Table 1. Estimated discharges in m^3s^{-1} for different return periods for fourteen sites on the Kaveri River and its tributaries (based on GEVI distribution)

SN	River	Site	Record Length	Return period (yr)							
				2	5	10	25	50	100	500	1000
1	Kaveri	Kudige	44	1132	1483	1715	2010	2237	2449	2968	3167
2	Kaveri	Kollegal	47	2264	3645	4555	5716	6610	7442	9481	10266
3	Kaveri	Biligundulu	46	2139	3315	4090	5078	5840	6548	8285	8953
4	Kaveri	Urachikottai	39	1235	2542	3404	4502	5349	6136	8066	8809
5	Kaveri	Kodumudi	46	1259	2501	3319	4363	5168	5916	7750	8455
6	Kaveri	Musiri	45	1570	3095	4100	5382	6370	7289	9542	10408
7	Hemavathi	M.H. Halli	36	476	933	1234	1618	1914	2189	2863	3123
8	Shimsha	T.K. Halli	39	334	559	707	895	1041	1176	1507	1635
9	Lakshmana-thirtha	K.M. Vadi	38	205	335	420	529	613	691	882	955
10	Kabini	T. Narasipur	47	1051	1497	1791	2166	2455	2724	3383	3637
11	Chittar	Sevanur	17	9	23	32	44	53	61	82	90
12	Bhavani	Savandapur	40	208	499	690	934	1122	1297	1726	1891
13	Noyyal	E-Mangalam	19	56	93	118	149	173	196	251	272
14	Amaravathi	Nallamaranpatty	40	408	1365	1996	2802	3422	3998	5413	5957

See Figure 1 for location of the sites; GEVI = Gumbel Extreme Value Type-I

Table 2. Return period of $\overline{Q}$, Qlf and Qmax for sites on the Kaveri River and its tributaries (based on GEVI distribution)

SN	River	Site	Record length	m^3s^{-1}	Return Period (Yr)
1	Kaveri	Kudige	44	$\overline{Q}$ = 1196	2.33
				Qlf= 1595	6.93
				Qmax= 2265	55.74
2	Kaveri	Kollegal	47	$\overline{Q}$ = 2515	2.33
				Qlf= 4084	6.93
				Qmax= 6414	43.56
3	Kaveri	Biligundulu	46	$\overline{Q}$ = 2352	2.33
				Qlf= 3689	6.93
				Qmax= 6688	114.55
4	Kaveri	Urachikottai	39	$\overline{Q}$ = 1473	2.33
				Qlf= 2958	6.93
				Qmax= 5855	78.74
5	Kaveri	Kodumudi	46	$\overline{Q}$ = 1485	2.33
				Qlf= 2896	6.93
				Qmax= 6585	183.70
6	Kaveri	Musiri	45	$\overline{Q}$ = 1847	2.33
				Qlf= 3580	6.93
				Qmax= 7690	134.69
7	Hemavathi	M.H. Halli	36	$\overline{Q}$ = 559	2.33
				Qlf= 1078	6.93
				Qmax= 2172	96.20
8	Shimsha	T.K. Halli	39	$\overline{Q}$ = 375	2.33
				Qlf= 630	6.93
				Qmax= 980	37.78
9	Lakshmanathirtha	K.M. Vadi	38	$\overline{Q}$ = 229	2.33
				Qlf= 376	6.93
				Qmax= 681	92.22
10	Kabini	T. Narasipur	47	$\overline{Q}$ = 1132	2.33
				Qlf= 1639	6.93
				Qmax= 2325	36.86
11	Chittar	Sevanur	17	$\overline{Q}$ = 11.27	2.33
				Qlf= 27.11	6.93
				Qmax= 58.40	81.25
12	Bhavani	Savandapur	40	$\overline{Q}$ = 261	2.33
				Qlf= 591	6.93
				Qmax= 1446	178.25
13	Noyyal	E-Mangalam	19	$\overline{Q}$ = 62	2.33
				Qlf= 105	6.93
				Qmax= 175	53.64
14	Amaravathi	Nallamaranpatty	40	$\overline{Q}$ = 582	2.33
				Qlf= 1670	6.93
				Qmax= 5571	636.58

$\overline{Q}$ = average annual peak discharge; Qlf = large flood; Qmax = maximum annual peak discharge; GEVI = Gumbel Extreme Value Type-I (Figure 1)

(2325 m^3s^{-1}) e.g. the Kabini River at T. Narasipur is merely 36-yr (Table 2). The observed annual peak discharges have been plotted against the return period or F(X) values (plotting positions) on the Gumbel graph paper, designed for the GEVI probability distribution. The magnitude-frequency graphs (Figure 2, 3 and 4) show that, the fitted lines are fairly near enough to the most of the data points and, consequently, can be reliably and expediently used to read the recurrence intervals for a given magnitude and vice versa. Remarkably, in plot of the GEVI distribution, the actually observed peak on record (Qmax) falls well in vicinity of the fitted line. This means the return period of Qmax(s) of all the sites projected by the GEVI

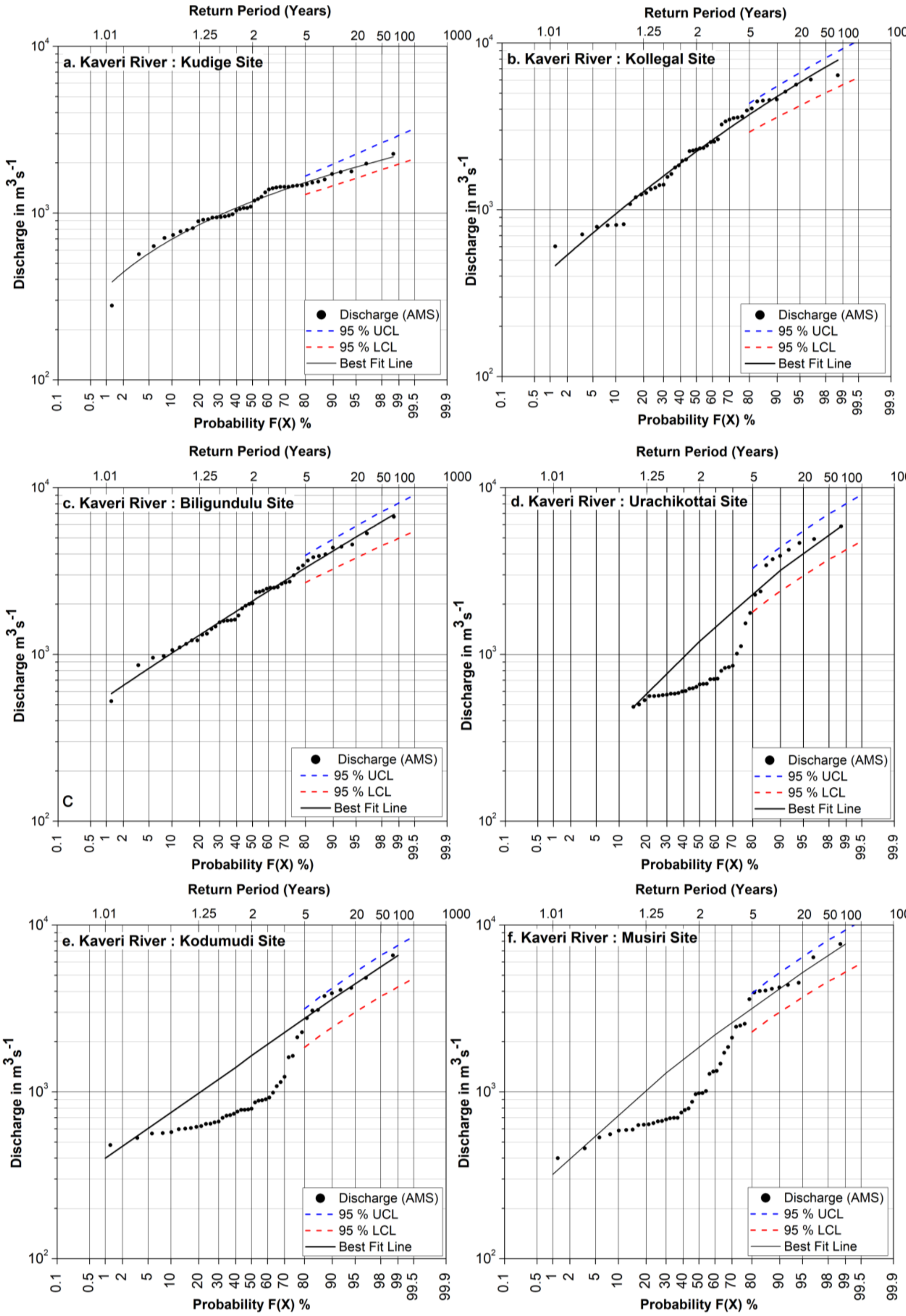

Figure 2. Magnitude-frequency curve for discharge gauging sites on the Kaveri River represented on the Gumbel Extreme Value Type-I (GEVI) probability graph paper. UCL = Upper Confidence Limit, LCL = Lower Confidence Limit.

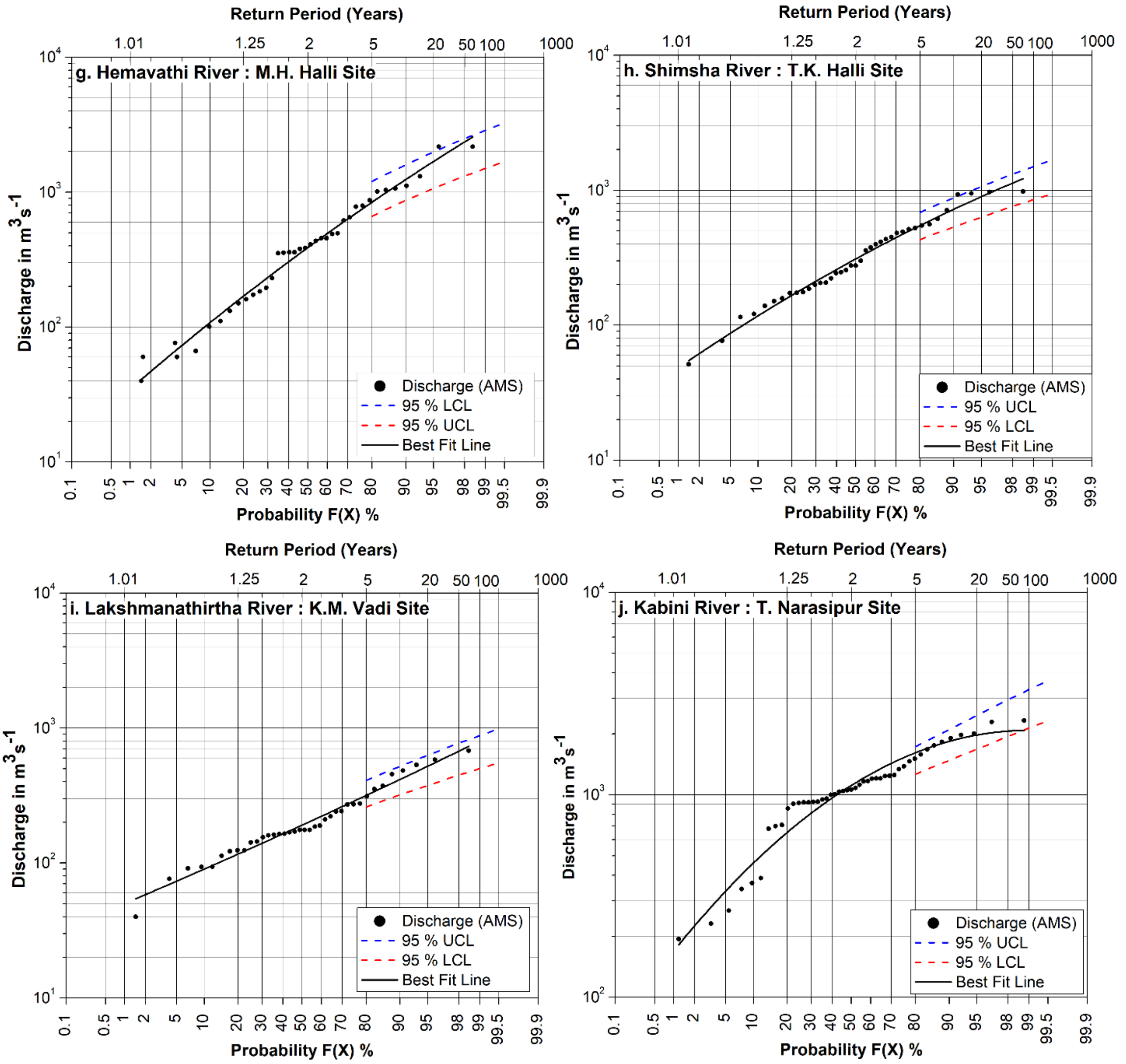

Figure 3. Magnitude–frequency curve for discharge gauging sites on the tributaries of the Kaveri River represented on the Gumbel Extreme Value Type-I (GEVI) probability graph paper. UCL = Upper Confidence Limit, LCL = Lower Confidence Limit.

probability distribution are likely to be quite reliable. Nevertheless, at three sites on the Kaveri River, viz. Urachikottai, Kodumudi and Musiri, the data points of lower magnitude floods are away from the fitted lines (Figure 2d, e, f). It may be attributed to controlled discharges as these sites are positioned downstream of the largest dam on the Kaveri River i.e. the Mettur Dam (Figure 1). Nonetheless, as stated earlier, the higher discharges are fairly close to the fitted lines (Figure 2d, e, f). Therefore, the GEVI probability distribution is an appropriate probability distribution for these sites too.

5 CONCLUSIONS

In order to estimate the long-term flow behavior of a river, flood frequency analysis is a rational approach. The present study has arisen with flood frequency approximations at fourteen sites in the Kaveri Basin with the help of broadly used GEVI probability distribution. The analysis confirms that the GEVI is the best-fit distribution model for the Kaveri River and its tributaries and therefore it is suitable for predicting discharge magnitudes for 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr and 1000-yr. return period. The magnitude-frequency graphs of the Kaveri River and its tributaries reveal that the fitted lines are fairly in vicinity of the most of the data points and therefore can be reliably and expediently applied to read the recurrence intervals for a given magnitude and vice-versa. Thus, modelling of magnitude and frequency of floods on the Kaveri River of the Peninsular India by using the Gumbel Extreme Value Type-I Probability Distribution is reliable and fallouts of this study are expected to be

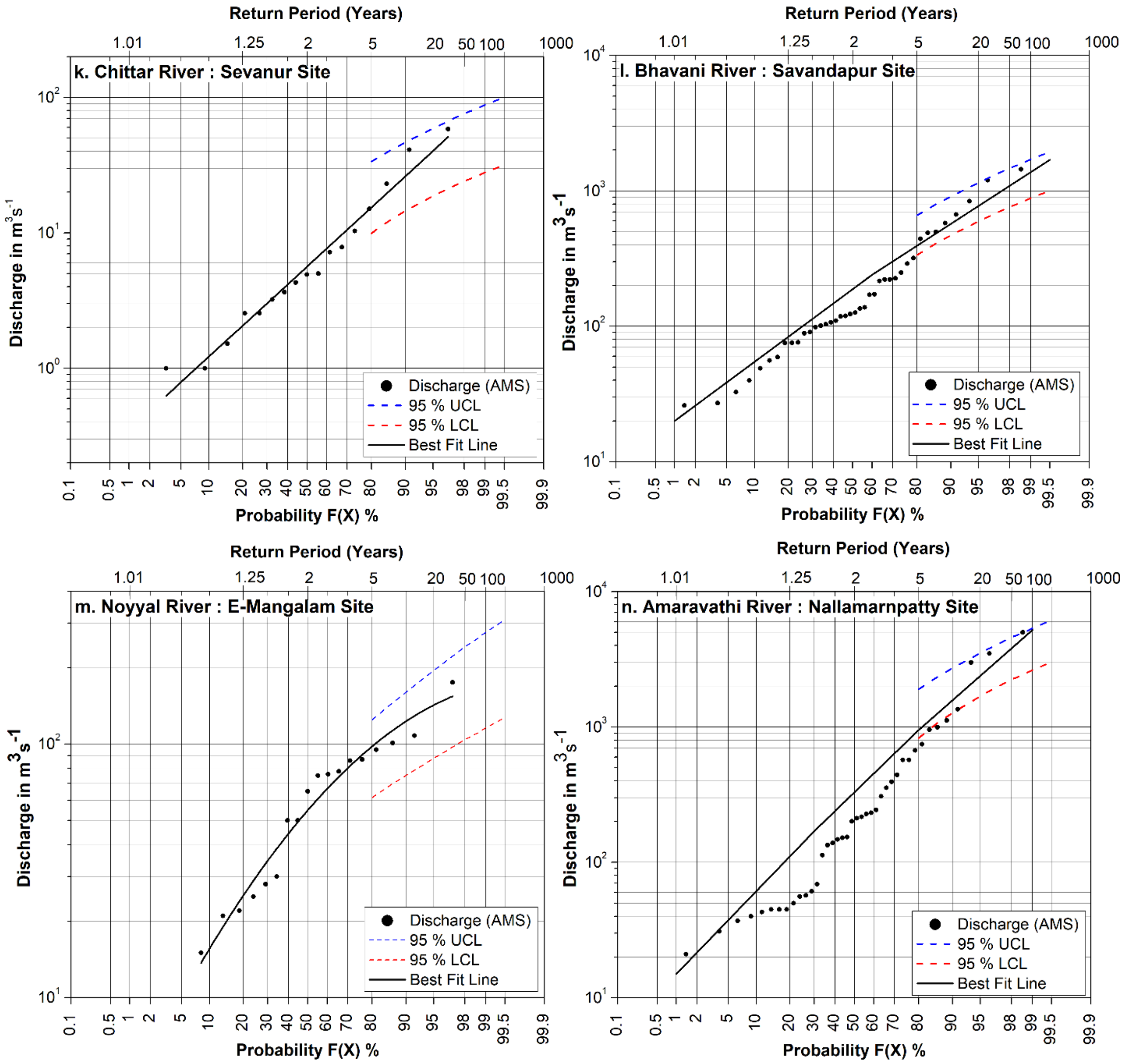

Figure 4. Magnitude-frequency curve for discharge gauging sites on the tributaries of the Kaveri River represented on the Gumbel Extreme Value Type-I (GEVI) probability graph paper. UCL = Upper Confidence Limit, LCL = Lower Confidence Limit.

useful for land use regulation, management of floodplains, estimates of flood insurance and the design of transportation and water carriage structures, for instance dams, bridges, culverts, etc. for the Kaveri Basin.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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