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Comparison of Estimators of Probability Distributions for Selection of Best Fit for Estimation of Extreme Rainfall

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ABSTRACT

Extreme Value Analysis (EVA) of rainfall is considered as one of the important aspects to arrive at a design value for planning, design and management of civil and hydraulic structures. This can be achieved by fitting Probability Distribution (PDs) to the series of observed annual 1-day maximum rainfall data wherein the parameters of PDs are determined by method of moments and L-Moments (LMO). In this paper, a study on comparison of Extreme Value Type-1 (EV1), Extreme Value Type-2, Generalized Extreme Value (GEV) and Generalized Pareto distributions adopted in EVA of rainfall for Anakapalli, Atchutapuram, Kasimkota and Parvada sites is carried out. The selection of best fit PD for EVA of rainfall is made through quantitative assessment by using Goodness-of-Fit (viz., Chi-square and Kolmogorov-Smirnov) and diagnostic (viz., root mean squared error) tests; and qualitative assessment by using the fitted curves of the estimated rainfall. On the basis of evaluation of EVA results through quantitative and qualitative assessments, the study indicates the extreme rainfall given by EV1 (LMO) distribution could be used for the purpose of economical design. The study also indicates the extreme rainfall obtained from GEV (LMO) distribution may be considered for the design of civil and hydraulic structure with little risk involvement.

Keywords: Chi-square, Extreme value analysis, Extreme Value Type-1, Kolmogorov-Smirnov, L-Moments, Method of moments, Rainfall, Root mean squared error

INTRODUCTION

For planning, design and management of civil and hydraulic structures, Extreme Value Analysis (EVA) of rainfall is generally considered as one of the important aspects to arrive at a design value. This can be achieved by fitting Probability Distributions (PDs) to the series of observed rainfall data. Depending on the size and the design-life of the structure, the estimated extreme rainfall corresponding to a desired return period is used (Mujere, 2011).

A number of PDs related to the families of normal, gamma and Extreme Value Distributions (EVD) are generally adopted in EVA of rainfall. Out of which, the Generalized Extreme Value (GEV), Extreme Value Type-1 (EV1), Extreme Value Type-2 (EV2) and Generalized Pareto (GPA) distributions are the members of EVD (Rao and Hamed, 2000). Generally, Method of Moments (MoM) is used in determining the parameters of PDs. Sometimes, it is difficult to assess the exact information about the shape of a distribution that is conveyed by its third and higher order moments. Also, when the sample size is small, the numerical values of sample moments can be very different from those of PD from which the sample was drawn. It is also reported that the estimated parameters of PDs fitted by MoM are often less accurate than those obtained by other parameter estimation procedures viz., maximum likelihood method, method of least squares and probability weighted moments (Acar et al., 2008). To address these shortcomings, the application of alternative approach, namely L-Moments (LMO) is used for EVA (Hosking, 1990). Number of studies has been carried out by different researchers showed that there is no unique distribution is available for EVA of rainfall for a region or country (Bhuyan et al., 2010; Malekinezhad et al., 2011; Olumide et al., 2013; Haberlandt and Radtke, 2014). AlHassoun (2011) carried out a study on developing empirical formula to estimate rainfall intensity in Riyadh region using EV1 (commonly known as Gumbel), LN2 and LP3. He concluded that the LP3 distribution gives better accuracy amongst three distributions studied in estimation of rainfall intensity. Baratti et al. (2012) carried out flood frequency analysis on seasonal and annual time scales for the Blue Nile River adopting Gumbel distribution. Esteves (2013) applied Gumbel distribution to estimate the extreme rainfall depths at different rain-gauge stations in southeast United

Kingdom. Rasel and Hossain (2015) applied Gumbel distribution for development of intensity-duration-frequency curves for seven divisions in Bangladesh. Afungang and Bateira (2016) applied Gumbel distribution to estimate the maximum amount of rainfall for different periods in the Bamenda mountain region, Cameroon. Studies carried out by Sasireka et al. (2019) indicated that the extreme rainfall for various return periods obtained from Gumbel distribution could be used for design purposes by considering the risk involved in the operation and management of hydraulic structures in Tiruchirappalli region. However, when number of PDs adopted in EVA of rainfall, a common problem that arises is how to determine which distribution model fits best for a given set of data. This possibly could be answered by quantitative and qualitative assessments; and the results are also reliable. In this paper, a study on comparison of MoM and MLM of estimators of probability distributions for selection of best fit for estimation of extreme rainfall is carried out. The selection of best fit PD is made through quantitative assessment by using Goodness-of-Fit (GoF) (viz., Chi-square (χ^2) and Kolmogorov-Smirnov (KS)) and diagnostic (viz., Root Mean Squared Error (RMSE)) tests and qualitative assessment through the fitted curves of the estimated rainfall. This paper details the procedures adopted in EVD for EVA of rainfall with illustrative example and the results obtained thereof.

MATERIAL AND METHODS

The aim of the study is to select the best fit PD for EVA of rainfall. Thus, it is required to process and validate the data for application such as (i) select the PDs (viz., GEV, EV1, EV2 and GPA); (ii) select parameter estimation methods (viz., MoM and MLM); and (iii) conduct EVA of rainfall and analyse the results obtained thereof. The Cumulative Distribution Function (CDF), quantile estimator and parameters of GEV, EV1, EV2 and GPA distributions adopted in EVA of rainfall is presented in Table 1.

Table 1. CDF, Quantile estimator and parameters of PDs

Distri-bution	CDF	Quantile estimator (R_T)	Parameters of PDs	
			MoM	**LMO**
GEV	$F(r)=e^{-\left(1-\frac{k(r-\xi)}{\alpha}\right)^{1/k}}$	$R_T=\xi+\frac{\alpha[1-(-\ln(F))^k]}{k}$	$\overline{R}=\xi+\frac{\alpha(1-\Gamma(1+k))}{k}$ $S_R=\frac{\alpha}{k}\left(\Gamma(1+2k)-\Gamma(1+k)^2\right)^{1/2}$ $\psi=(\text{sign } k)\frac{\Gamma(1+3k)+3\Gamma(1+k)(1+2k)-2\Gamma^3(1+k)}{\left\{\Gamma(1+k)-\Gamma^2(1+k)^2\right\}^{1/2}}$	$z=(2/(3+\tau_3)-(\ln(2)/\ln(3))$ $\tau_3=(2(1-3^{-k})/(1-2^{-k}))-3$ $k=7.817740z+2.930462z^2+13.641492z^3+17.206675z^4$ $\alpha=\lambda_2 k/(1-2^{-k})\Gamma(1+k)$ $\xi=\lambda_1+(\alpha(\Gamma(1+k)-1)/k)$
EV1	$F(r)=e^{-e^{-\left(\frac{r-\xi}{\alpha}\right)}}$	$R_T=\xi+\alpha[-\ln(-\ln(F))]$	$\xi=\overline{R}-(0.5772157)\alpha$ $\alpha=\left(\frac{\sqrt{6}}{\pi}\right)S_R$	$\xi=\lambda_1-(0.5772157)\alpha$ $\alpha=\frac{\lambda_2}{\ln(2)}$
EV2	$F(r)=e^{-\left(\frac{r}{\alpha}\right)^{-k}}$	$R_T=\alpha e^{[-\ln(-\ln(F)]/k}$	By using the logarithmic transformation of the observed data, parameters of EV1 are initially obtained by MoM and LMO; and are used to determine the parameters of EV2 from α=exp(ξ) and k=1/(scale parameter of EV1).	
GPA	$F(r)=1-\left(1-\frac{k(r-\xi)}{\alpha}\right)^{1/k}$	$R_T=\xi+\frac{\alpha(1-(1-F)^k)}{k}$	$\overline{R}=\xi+(\alpha/(1+k))$ $\sigma_R^2=\alpha^2/(1+2k)(1+k)^2$ $C_S=2(1-k)(1+2k)^{1/2}/(1+3k)$	$\xi=\lambda_1-(\alpha/(1+k))$ $k=(1-3\tau_3)/(\tau_3+1)$ $\alpha=(1+k)(2+k)\lambda_2$

In Table 1, ξ, α, k are the location, scale and shape parameters, respectively; μ (or $\overline{R}$), σ (or S_R) and C_S (or ψ) are the average, standard deviation and Coefficient of Skewness respectively; F(r) (or F) is the CDF of r (i.e., AMR); ϕ^{-1} is the inverse of the standard normal distribution function and $\phi^{-1}=(P^{0.135}-(1-P)^{0.135})/0.1975$ wherein P is the probability of exceedance; sign(k) is plus or minus 1 depending on the sign of k ; λ_1, λ_2 and λ_3 are the first, second and third L-moments respectively; L-Skewness is a measure of the lack of symmetry in a distribution and given by $\tau_3=\lambda_3/\lambda_2$; R_T is the estimated extreme rainfall for a return period (T). A relation F, P and T is defined by $F(r) = 1-P(R_T \geq r) = 1-P = 1-1/T$.

Goodness-of-Fit (GoF) tests

GoF tests are applied for checking the adequacy on fitting PDs to the observed rainfall data. Out of a number GoF tests available, the widely accepted GoF tests are χ^2 and KS, which are used in the study. Theoretical descriptions of GoF tests statistic are given as below:

χ^2test statistic is defined by:

$$\chi^2 = \sum_{j=1}^{NC} \frac{\left(O_j(r) - E_j(r)\right)^2}{E_j(r)} \quad \ldots (1)$$

where, $O_j(r)$ is the observed frequency value of r for j^{th}class, $E_j(r)$ is the expected frequency value of r for j^{th}class and NC is the number of frequency classes.The rejection region of χ^2 statistic at the desired significance level (η) is given by $\chi_C^2 \geq \chi_{1-\eta,NC-m-1}^2$ (Zhang, 2002). Here, m denotes the number of parameters of the distribution and χ_C^2 is the computed value of χ^2 statistic by PDs.

KS test statistic is defined by:

$$KS = \underset{i=1}{\overset{N}{Max}}\left(F_e(r_i) - F_D(r_i)\right) \quad \ldots (2)$$

where, $F_e(r_i)$=M/(N+1) is the empirical CDF of r_i and $F_D(r_i)$ is the computed CDF of r_i.Here, M denotes the rank assigned to the observed values arranged in ascending order and N is the number of sample values.

Test criteria: If the computed values of GoF tests statistic given by PD are less than that of the theoretical values at the desired significance level, then the PD is found to be acceptable for EVA.

Diagnostic test

A selection of suitable PD for EVA of rainfall is carried out through RMSE, which is defined as:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(r_i - r_i^*\right)^2\right]^{1/2} \quad \ldots (3)$$

Here, r_i and r_i^* are the observed and corresponding estimated extreme values by EVD. The distribution with minimum RMSE is considered as better suited distribution in comparison with the other PDs adopted in EVA (US Water Resources Council, 1975).

Application

In this paper, a study on evaluation of GEV, EV1, EV2 and GPA distributions through quantitative and qualitative assessments for EVA of rainfall is carried out. The daily rainfall data (with some gaps) observed at Anakapalli for the period 1970 to 2017, Atchutapuram for the period 1989 to 2017, Kasimkota for the period 1989 to 2017 and Parvada for the period 1992 to 2017 was used. Table 2 gives the descriptive statistics of AMR for the sites considered in the study. From the scrutiny of the daily rainfall data, it was observed that the data for the intermittent period for Anakapalli (2004), Kasimkota (1990, 1991 and 2013) and Parvada (1994, 1995 and 2013) are missing. However, the data for the missing years were not considered in EVA of rainfall. For estimation of extreme (i.e., 1-day maximum) rainfall, the Annual 1-day Maximum Rainfall (AMR) series of each site was extracted from the corresponding daily rainfall data series and also used.

Table 2. Descriptive statistics of AMR

Site	Average (mm)	SD (mm)	CS	CK	Max. (mm)	Min. (mm)
Anakapalli	107.8	53.0	1.539	2.707	36.8	280.0
Atchutapuram	115.1	66.9	2.588	8.485	34.4	378.2
Kasimkota	101.2	41.2	1.270	1.556	35.7	211.8
Parvada	98.8	41.7	0.260	-0.870	31.2	179.0

SD: Standard Deviation; CS: Coefficient of Skewness; CK: Coefficient of Kurtosis; Max: Maximum; Min: Minimum

RESULTS AND DISCUSSION

By applying the procedures of EVA, as described above, the parameters of GEV, EV1, EV2 and GPA distributions were determined by MoM and LMO; and are used for estimation of extreme rainfall. The EVA results of Anakapalli, Atchutapuram, Kasimkota and Parvada sites are presented in Tables 3 to 6 while the plots are shown in Figure 1. For EVA results, it is noted that the estimated extreme rainfall by EV2 (LMO) was higher than the corresponding values of EV1, GEV and GPA distributions for the return periods from 50-year and above.

Analysis based on GoF tests

In the present study, GoF tests statistic values of GEV, EV1, EV2 and GPA distributions were computed and are presented in Table 7. Based on GoF tests results, it is noted that:

i) χ^2test supported the use of GEV, EV1, EV2, and GPA distributions for EVA of rainfall for Anakapalli, Atchutapuram, Kasimkota and Parvada.
ii) KS test confirmed the applicability of GEV, EV1 and EV2 distributions for EVA of rainfall for Anakapalli, Atchutapuram and Kasimkota.
iii) For Parvada, KS test results indicated that the PDs considered in the study are acceptable for EVA of rainfall while determining the parameters by MoM and LMO.

Table 3. Estimated 1-day maximum rainfall (mm) by MoM and MLM of EVD for Anakapalli

Return period (year)	GEV		EV1		EV2		GPA	
	MoM	LMO	MoM	LMO	MoM	LMO	MoM	LMO
2	97.6	94.6	99.1	99.4	94.6	90.3	92.5	92.9
5	143.1	138.7	145.9	144.5	129.3	131.1	144.4	145.1
10	174.9	172.9	176.9	174.4	159.0	167.8	180.8	181.1
20	206.8	209.9	206.6	203.0	193.9	212.6	215.0	214.2
25	217.2	222.7	216.1	212.1	206.5	229.2	225.5	224.3
50	250.1	265.2	245.1	240.1	250.6	288.8	256.8	254.0
100	284.1	312.7	274.0	267.9	303.8	363.3	286.1	281.4
200	319.5	365.9	302.7	295.6	368.0	456.6	313.6	306.7
500	368.3	446.3	340.6	332.1	474.0	617.3	347.2	337.1
1000	407.0	515.9	369.3	359.7	573.8	775.3	370.8	357.9

Table 4. Estimated 1-day maximum rainfall (mm) by MoM and MLM of EVD for Atchutapuram

Return period (year)	GEV		EV1		EV2		GPA	
	MoM	LMO	MoM	LMO	MoM	LMO	MoM	LMO
2	99.8	96.8	104.1	105.6	98.5	94.9	94.0	94.8
5	152.9	144.4	163.3	156.7	139.3	140.5	150.8	150.6
10	193.5	185.3	202.4	190.5	175.3	182.1	196.6	195.0
20	237.0	233.5	240.0	222.9	218.4	233.7	244.9	241.5
25	251.9	251.0	251.9	233.2	234.2	252.9	261.0	256.9
50	301.1	312.3	288.6	264.9	290.4	322.6	312.9	306.2
100	355.5	386.4	325.1	296.3	359.5	410.8	367.7	357.8
200	415.9	476.1	361.4	327.7	444.8	522.7	425.5	411.7
500	506.1	624.6	409.2	369.0	588.9	718.1	507.0	486.8
1000	583.2	765.0	445.4	400.3	728.0	913.0	572.6	546.6

Table 5. Estimated 1-day maximum rainfall (mm) by MoM and MLM of EVD for Kasimkota

Return period (year)	GEV		EV1		EV2		GPA	
	MoM	LMO	MoM	LMO	MoM	LMO	MoM	LMO
2	94.1	91.4	94.5	94.6	91.0	88.4	90.1	90.0
5	130.1	126.6	130.9	130.3	119.8	121.7	132.1	131.9
10	154.5	153.2	155.0	154.0	143.7	150.3	159.8	159.5
20	178.2	181.5	178.1	176.7	171.1	184.2	184.5	184.2
25	185.8	191.1	185.4	183.9	180.9	196.4	191.8	191.6
50	209.4	222.6	208.0	206.1	214.5	239.5	212.8	212.8
100	233.2	257.2	230.4	228.1	254.1	291.6	231.5	231.7
200	257.3	295.2	252.7	250.1	300.8	354.9	248.1	248.6
500	289.6	351.4	282.2	279.0	375.7	459.7	267.3	268.1
1000	314.4	398.9	304.5	300.9	444.5	559.0	279.9	281.0

Table 6. Estimated 1-day maximum rainfall (mm) by MoM and MLM of EVD for Parvada

Return period (year)	GEV		EV1		EV2		GPA	
	MoM	LMO	MoM	LMO	MoM	LMO	MoM	LMO
2	96.6	95.4	92.0	91.5	88.5	83.7	95.1	94.8
5	134.0	134.4	128.8	131.2	117.3	119.9	140.6	141.1
10	154.4	156.7	153.2	157.5	141.4	152.1	159.5	160.5
20	171.4	175.8	176.6	182.7	169.1	191.1	170.8	172.2
25	176.3	181.4	184.0	190.7	178.9	205.5	173.4	174.9
50	190.1	197.6	206.9	215.3	213.1	256.8	179.2	181.0
100	202.0	212.0	229.6	239.8	253.6	320.5	182.7	184.6
200	212.3	224.9	252.2	264.2	301.4	399.5	184.8	186.8
500	223.9	239.9	282.0	296.4	378.7	534.4	186.3	188.5
1000	231.3	249.9	304.6	320.7	450.0	665.9	186.9	189.2

Table 7. Theoretical and computed values of GoF tests statistic by MoM and MLM of EVD

Rain-gauge station	Computed value								Theoretical value				
	MoM				LMO				χ^2				KS
	GEV	EV1	EV2	GPA	GEV	EV1	EV2	GPA	GEV	EV1	EV2	GPA	
χ^2 test statistic													
Anakapalli	3.936	3.936	6.489	5.212	2.660	3.936	0.872	5.212	7.82	7.82	7.82	5.99	-
Atchutapuram	1.172	3.759	3.241	2.552	1.862	3.241	2.552	1.517	5.99	5.99	5.99	3.84	-
Kasimkota	4.000	2.846	1.692	2.846	2.846	3.615	1.308	2.846	5.99	5.99	5.99	3.84	-
Parvada	2.000	1.130	5.843	2.870	2.000	1.130	3.739	2.870	5.99	5.99	5.99	3.84	-
KS test statistic													
Anakapalli	0.083	0.098	0.105	0.252	0.072	0.099	0.099	0.231	-	-	-	-	0.184
Atchutapuram	0.085	0.125	0.102	0.446	0.078	0.104	0.098	0.471	-	-	-	-	0.228
Kasimkota	0.100	0.106	0.088	0.403	0.069	0.105	0.082	0.416	-	-	-	-	0.240
Parvada	0.100	0.116	0.167	0.069	0.095	0.103	0.145	0.065	-	-	-	-	0.253

Table 8. RMSE values given by MoM and MLM of EVD

Rain-gauge station	GEV		EV1		EV2		GPA	
	MoM	LMO	MoM	LMO	MoM	LMO	MoM	LMO
Anakapalli	11.861	10.647	12.736	13.280	16.368	11.793	10.806	11.026
Achutapuram	24.310	23.612	27.407	29.044	27.679	23.225	22.792	23.506
Kasimkota	10.290	9.731	10.388	10.643	13.614	10.476	9.689	9.712
Parvada	6.123	5.634	8.714	7.507	16.698	15.053	4.785	4.873

Analysis Based on Diagnostic Test

For the selection of suitable PD for EVA of rainfall, RMSE values were computed by EVD and the results are presented in Table 8. From the diagnostic test results, it is observed that:

i) RMSE of GPA (MoM) for Atchutapuram, Kasimkota and Parvada while GEV (LMO) for Anakapalli was found as minimum.

ii) For Atchutapuram site, it is noted that the RMSE of GEV (LMO) is the second minimum next to RMSE of GPA (MoM).

iii) For Kasimkota and Parvada, it is noted that RMSE of GPA (LMO) and GEV (LMO) are the second and third minimum next to RMSE of GPA (MoM).

Selection of Probability Distribution

Based on EVA results obtained from quantitative assessment by using GoF and diagnostic tests, it was observed that the analysis offered diverging inferences and thus called for qualitative assessment using plots of the estimated extreme rainfall (Figure 1). Hence, the best fit for rainfall estimation was re-assessed through fitted curves of the estimated extreme rainfall together with RMSE values; and accordingly final selection was made.

i) Diagnostic test results indicated that GPA (MoM) for Atchutapuram, Kasimkota and Parvada while GEV (LMO) for Anakapalli could be used for EVA.

ii) But, the rainfall estimates given by MoM are less accurate when compared to LMO because of the characteristics of moment estimators.

iii) Alternatively, GEV (LMO) for Atchutapuram while GPA (LMO) for Kasimkota and Parvada is found as second best choice for rainfall estimation.

iv) However, for Kasimkota and Parvada sites, it is noted that the most of the observed data are lying below the fitted lines of the estimated extreme rainfall by GPA (LMO); and hence GPA (LMO) is not adjudged as better suited for EVA. In light of the above, it is found that GEV (LMO) is the best choice for EVA for Kasimkota and Parvada.

v) By considering the uncertainty involved in rainfall estimation for higher order return periods, the study suggested that:

   a) For the case of economical design of civil and hydraulic structures, extreme rainfall obtained from EV1 (LMO) distribution may be considered even though the RMSE of EV1 (LMO) was higher than the corresponding values of other PDs for Anakapalli, Atchutapuram, Kasimkota and Parvada sites.

   b) For the case of little risk involved in the operation and management of civil and hydraulic structures, extreme rainfall obtained from GEV (LMO) distribution may be used for design purposes.

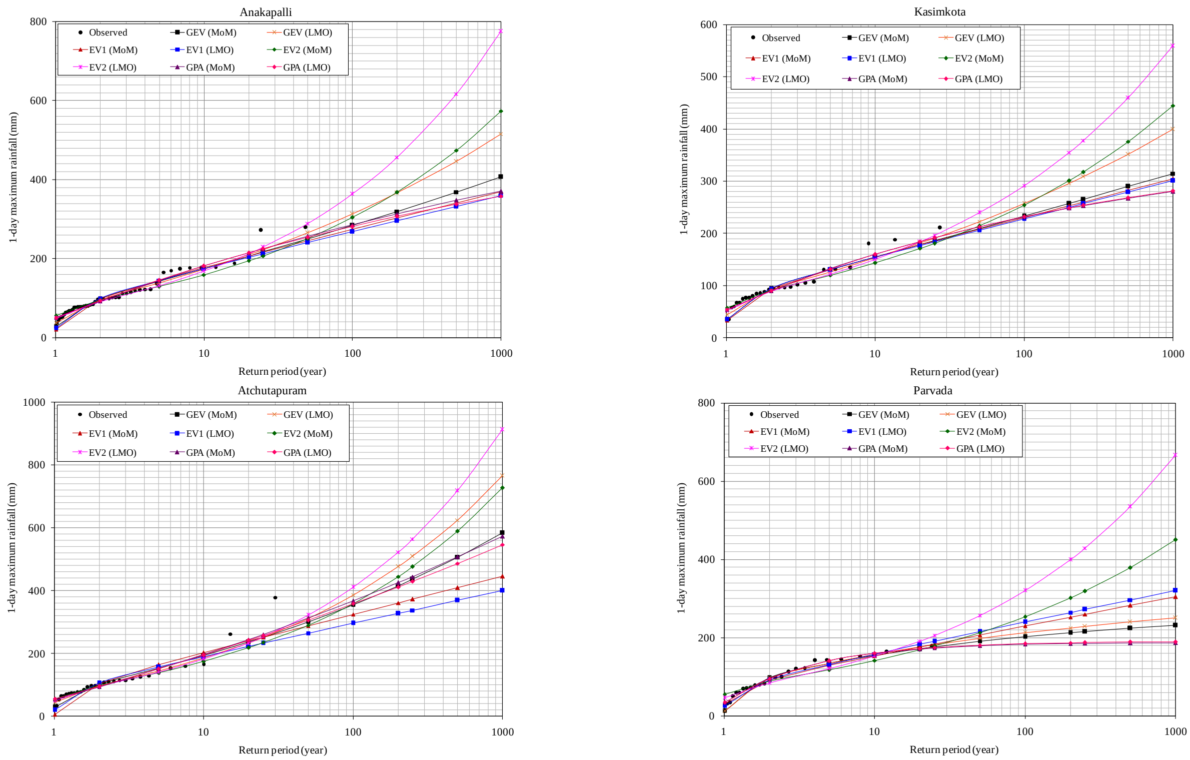

Figure 1. Plots of estimated extreme rainfall by GEV, EV1, EV2 and GPA distributions with observed data

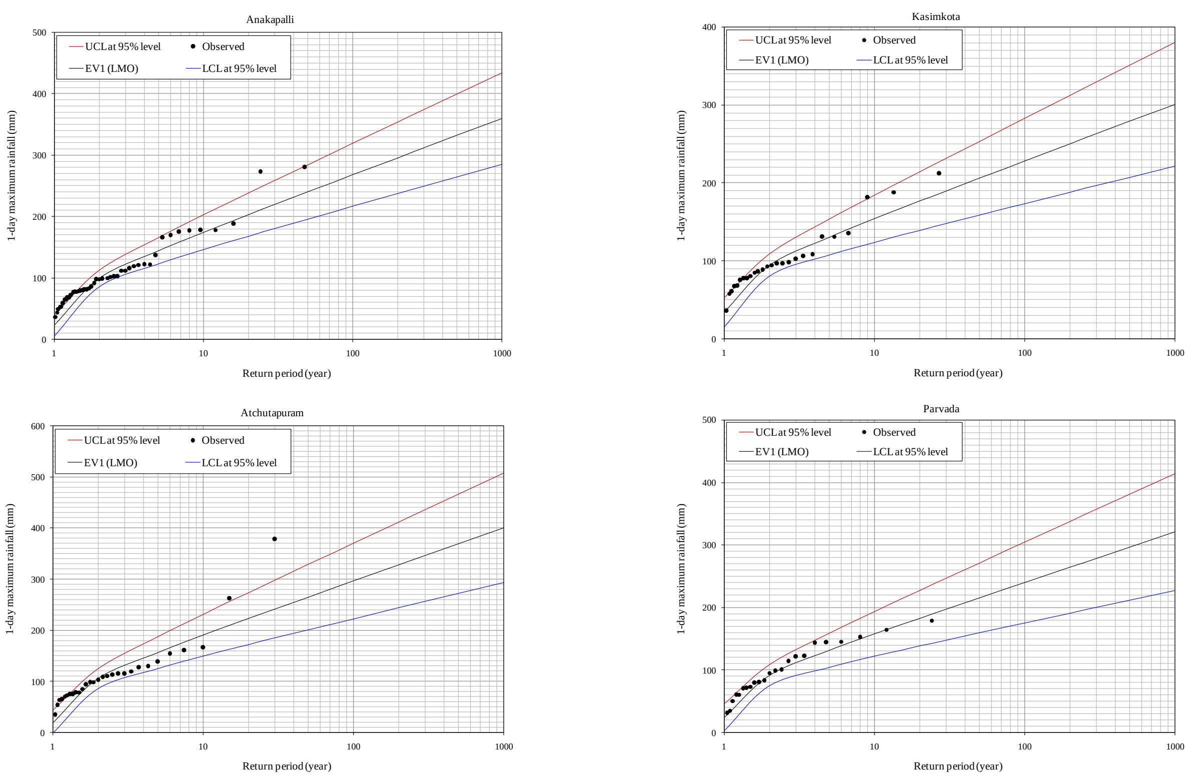

Figure 2. Plots of estimated extreme rainfall by EV1 (LMO) distribution with confidence limits and observed data

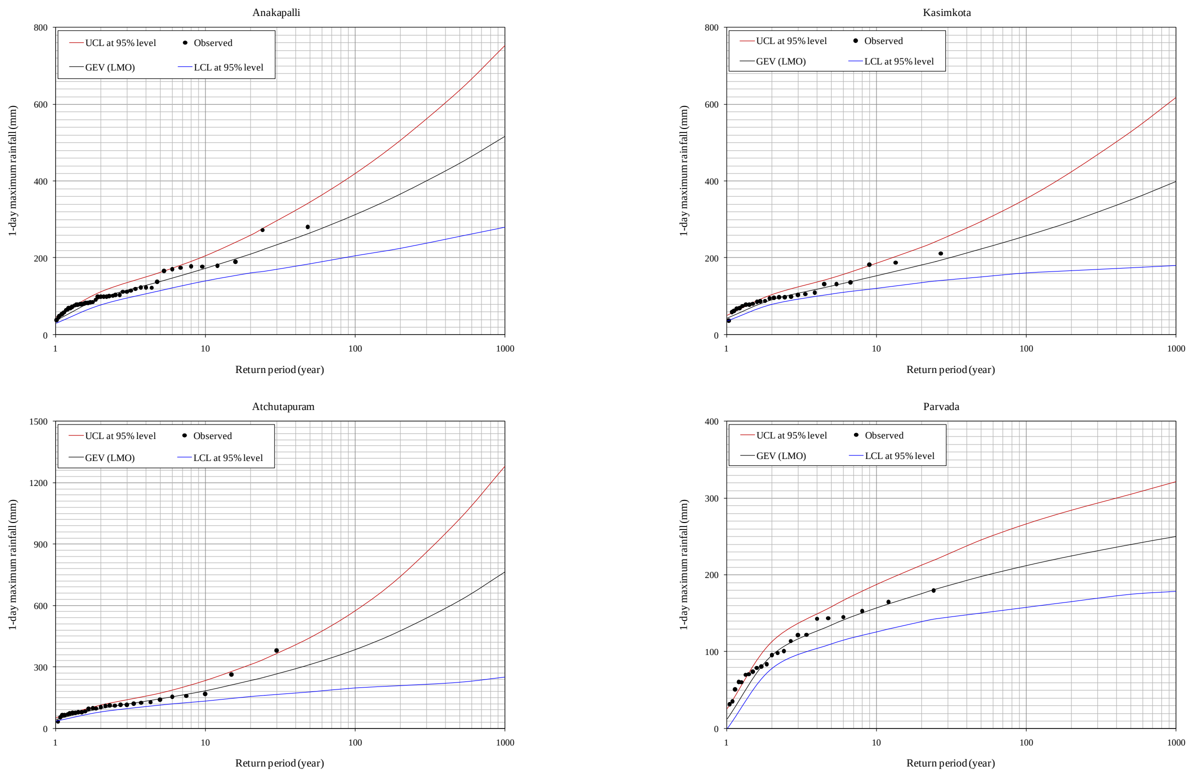

Figure 3. Plots of estimated extreme rainfall by GEV (LMO) distribution with confidence limits and observed data

Figures 2 and 3 present the plots of estimated extreme rainfall by EV1 (LMO) and GEV (LMO) distributions with 95% confidence limits and observed data for Anakapalli, Atchutapuram, Kasimkota and Parvada sites. From Figures 2 and 3, it is noted that about 80% of the observed AMR data iscovered by the confidence limits of the estimated rainfall by EV1 (LMO) and GEV (LMO) distributions for Anakapalli, Atchutapuramand Kasimkota. Likewise, for Parvada, it can be seen that the observed data covered by the confidence limits of the estimated rainfall using EV1 (LMO) and GEV (LMO) are 100% and 85%, respectively.

CONCLUSIONS

The paper describes the study carried out on comparison of MoM and LMO estimators of probability distributions adopted in EVA for selection of best fit for estimation of extreme rainfall for Anakapalli, Atchutapuram, Kasimkota and Parvada sites through qualitative (viz., GoF and diagnostic tests) and qualitative (viz., plots of the estimated rainfall) assessments. On the basis of evaluation of EVA results, the following conclusions were drawn from the study:

a) The estimated extreme rainfall by EV2 (LMO) was consistently higher than the corresponding values of GEV, EV1 and GPA distributions for the return periods from 50-year and above.

b) χ^2 test results confirmed the applicability of GEV, EV1, EV2 and GPA distributions for EVA of rainfall for Anakapalli, Atchutapuram, Kasimkota and Parvada.

c) KS test results indicated that GEV, EV1, and EV2 distributions are acceptable for EVA of rainfall for Anakapalli, Atchutapuram and Kasimkota sites.

d) From KS test results, it was found that GEV, EV1, EV2 and GPA are acceptable for EVA of rainfall for Parvada.

e) Qualitative assessment of the outcomes was weighed together with RMSE values and fitted curves of the estimated extreme rainfall. Accordingly, GEV (LMO) is considered as the best choice for rainfall estimation for all four sites considered in the study.

f) For the case of economical design of civil and hydraulic structures, the extreme rainfall obtained from EV1 (LMO) distribution could be used for design purposes.

g) For the case of little risk involved in the operation and management of civil and hydraulic structures, extreme rainfall obtained from GEV (LMO) distribution could be used for design purposes.

However, by considering the data length of rainfall (i.e., 47 years for Anakapalli, 29 years for Atchutapuram, 26 years for Kasimkota and 23 years for Parvada) used in EVA, the study suggested that the extreme rainfall for return period beyond 100-year may be cautiously used due to uncertainty in the higher order return periods.

DECLARATIONS

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Competing interests

The author declares that he has no competing interests.

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