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REGIONAL FLOOD FREQUENCY MODELING FOR A BASIN OF CENTRAL INDIA

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ABSTRACT: Magnitude prediction of likely occurrence of flood is of a great importance for solution of variety of water resources problems for gauged, poorly gauged and ungauged catchments. Due to lack of robustness in at-site frequency analysis, the L-moments based regional flood frequency analysis (RFFA) has been found more applicable for flood analysis. In the present study, RFFA has been applied using less bias and more efficient standardized L-moments and probability weighted moments (PWM) for Parvati River in Central India. Different distributions including Wakeby-4, Wakeby-5, extreme value-I (EV-I), generalized extreme value (GEV), logistic (L), generalized logistic (GL), generalized pareto (GP), normal (NOR) and log normal (LNOR) have been applied in RFFA. Various tests attempted to detect randomness, trends and homogeneity indicated that Annual Flood Series (AFSs) of all three sites of Parvati basin used in analysis are distributed randomly having no trends and region may be considered as hydrologically homogeneous. From the analysis of L-moment based goodness of fit tests such as L-moment ratio diagram, L-kurtosis and Z-statistics, it has been observed that the GEV distribution with L-moments as parameter estimator is the most robust distribution for estimation of floods of different return periods for Parvati River system. The regional parameters of GEV distribution have been computed as $u = 0.751$, $\alpha = 0.334$ and $k = -0.148$. The regional equations developed in this study can be used for flood estimation in gauged and ungauged basins of the region. The performance of at-site regional approach has been compared with at-site approach with the help of D-index and it has been observed that at-site RFFA offers better results than at-site analysis for estimation of floods.

Keywords: Regional Flood Frequency Modeling, Annual Flood Series, Probability Weighted Moment, L-Moments, Generalized Extreme Value Distribution, Best-fit Distribution.

1. INTRODUCTION

Estimation of rational design flood is necessary for optimal design as well as avoiding excessive cost of construction due to overdesign and increased risk of failure due to under design of the water resources projects. As per Indian hydrologic design criteria, the deterministic approaches including probable maximum flood (PMF) for design of large dams (gross storages more than 60 MCM) and standard project flood (SPF) are used for design of medium dams (gross storages between 10 to 60 MCM). The flood frequency analysis (FFA) based probabilistic approach has been considered appropriate for design of hydraulic structures such as small dams (gross storages between 0.5 to 10 MCM), barrages, weirs, road and railway bridges, cross drainage structures, flood control structures, flood plain zoning and economic evaluation of flood protection schemes. In flood frequency analysis, the sample data (usually annual flood series) is used to fit frequency distributions, which in turn are used to extrapolate from record events to design events. The parameter estimation of different probability distributions is the first and foremost job in flood frequency analysis and the oldest and most widely used technique is the method of moment (MOM). In the later stage of research, the probability weighted moments (PWM) introduced by Greenwood *et al.* (1979) and developed by Hosking (1986) were found very useful in deriving expressions for the parameters of distributions whose inverse can be explicitly defined. Hosking (1986, 1990) suggested a new parameter estimation technique of L-moments which are analogous to conventional moments, but are estimated as a linear combination of order statistics and hence subjected to less bias.

The flood frequency modeling based on annual flood series (AFS) are carried out in three ways: i.e., at-site, at-site regional and regional only analysis. In the at-site analysis, the AFS of the site of interest is used for fitting the appropriate distribution and is suitable when sufficient lengths of records are available. The at-site frequency analysis may be subjected to large errors due to short length of data which can be eliminated by combining the data from many sites in regional analysis. In the at-site regional approach, the AFSs of several sites in a homogeneous region are grouped together for determination of regional parameters of different distributions and flood quantiles are estimated using regional parameters and mean annual flood obtained from observed AFS of the site under consideration. In the regional only approach, regional parameters of homogeneous region are used and the mean annual flood is computed by developing a relationship with catchment characteristics such as catchment area, drainage density, slope, soil types, etc. The regional flood frequency analysis (RFFA) is used to improve the accuracy and precision of the extreme flow estimates at a gauged site by pooling at-site information with information from hydrologically similar gauged sites and to estimate extreme flows at ungauged sites where no stream flow data are available. Dalrymple (1960) described an index flood technique (USGS method) to carry out RFFA. The National Environment Research Council (NERC, 1975) gave a method for RFFA based on order statistics (NERC method). Wallis (1980) recommended the method based on standardized PWMs for RFFA and the GEV distribution was recommended for U.K. conditions.

Parida *et al.* (1998) used index flood procedure of RFFA with L-moments in Mahi-Sabarmati basin (sub zone 3a) and suggested normal distribution for the region using flood data of 12 sites. Upadhyaya and Kumar (1999) found that regional flood estimates were more accurate than at-site estimates when the root mean square error (RMSE) and standard error (SE) of both the approaches were compared. Jaiswal (2000) conducted RFFA for Beas basin of Himalayan region and computed the bias and RMSE for at-site and at-site regional approaches. He concluded that at-site regional flood frequency estimates are less biased than at-site estimates. Kumar *et al.* (2003) applied L-moment based RFFA for computation of flood quantiles in gauged and ungauged basins in North Brahmputra river system and found the GEV is the most robust distribution for the region. Kumar (2007) used L-moments based approach for testing homogeneity, parameter estimation and determination of the best-fit regional distribution for estimation of floods and found that generalized normal (GN) is the robust distribution for lower Narmada and Tapi subzone (3b) of India. Kumar *et al.* (2007) applied a combination of deterministic approach using Clark model and L-moment based flood frequency approach for determination of design flood for Kashau dam site and observed that 478 years return period flood computed from generalized logistic (GL) distribution is equivalent to PMF at that site.

The L-moment based regional approach of frequency modeling can also be used in the analysis of rainfall, temperature, wind speed and other climatological data. Eslamian and Feizi (2007) used L-moment based regional frequency analysis for maximum monthly rainfall data of 18 sites in the Zayandehrood basin, Iran, and the GEV and Pearson type-III distributions have been selected as parent distributions. Yurekli *et al.* (2009) applied regional frequency modeling with L-moment for one day maximum rainfall of 17 stations in Cekerek watershed of Turkey and analyzed that three-parameter log normal distribution is the best regional distribution as it offered minimum value of Z-statistics. In the developing countries like India, where a large number of small to medium watershed are ungauged and old rational formulae are used for estimation of flood, the regional approach based on L-moments can be applied conveniently for computation of design flood in ungauged basins and basins with very little data because combination of RFFA with L-moment technique provide the better results even in case of small sets of data (Singh, 1995).

2. STUDY AREA AND DATA USED

The Parvati River is an important tributary of Yamuna river system originates in the Vindhyan mountains near Ashta village in Sehore district of Madhya Pradesh, India (Figure 1(a)). The

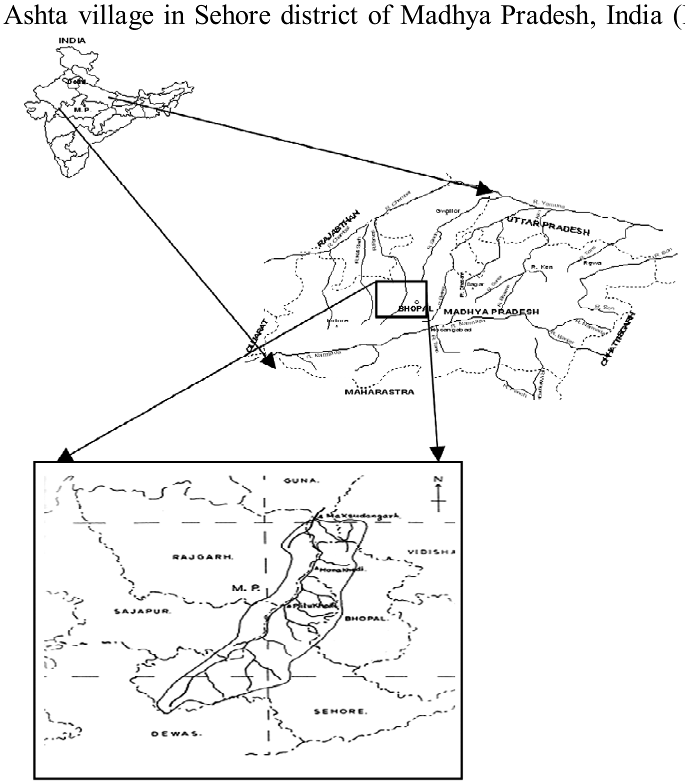

Figure 1(a): Location Map of River Parvati in Central India

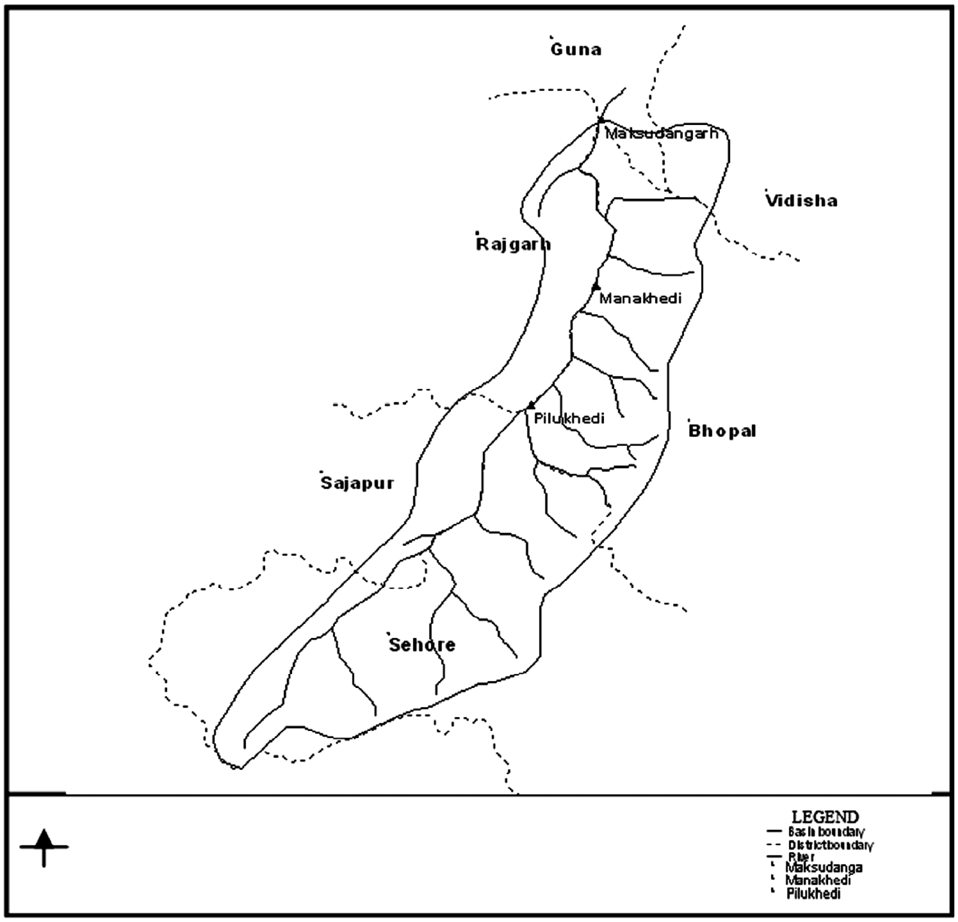

Figure 1(b): Drainage Map of Parvati River System

total catchment area of the river up to its confluence with river Chambal is about 15,670 km^2 out of which nearly 10,736 km^2 lies in Madhya Pradesh. The river Tem, Ahili, Parna, Ajnar and the Papras are the important tributaries of Parvati River. The river flows generally through high banks in the rainy seasons, while its discharge falls very low in winter month of January to March and becomes negligible during the summer months of April to June. The annual rainfall of the catchment varies from 515 to 1810 mm and nearly 90% of the total rainfall occurs in the monsoon season. A map showing Parvati River system and all gauging sites has been presented in Figure 1(b). The catchment area of Parvati River up to Pilukhedi, Manakhedi and Maksudangarh gauging sites are 2624, 3484 and 4876 km^2, respectively. Annual maximum peak flood data of 14 years at Pilukhedi stream flow gauging site and 10 years at Manakhedi and Maksudangarh gauging sites of Parvati River have been used. The statistical characteristics of AFS at Pilukhedi, Manakhedi and Maksudangarh gauging sites have been presented in Table 1.

Table 1
Statistical Information of Annual Flood Series (AFS)

S.N.	*Statistical Parameters*	*River Parvati at Pilukhedi*		*River Parvati at Manakhedi*		*Parvati River at Maksudangarh*	
		Original	*Log series*	*Original*	*Log series*	*Original*	*Log series*
1.	Mean in m^3/sec ($\bar{Q}$)	1421.82	7.091	1563.02	7.249	2964.63	7.943
2.	Standard deviation in m^3/sec (σ)	873.187	0.609	818.334	0.463	1045.63	0.326
3.	Maximum in m^3/sec	3550.28	8.18	3825.36	8.249	5511.41	8.615
4.	Minimum in m^3/sec	495.79	6.21	797.97	6.68	1856.71	7.527
5.	Coefficient of Skewness (C_{skew})	1.252	0.0009	1.679	0.599	1.255	0.527
6.	Coefficient of Kurtosis (C_{kurt})	1.641	-0.715	3.673	-0.229	1.619	-0.093
7.	Lag 1 correlation coefficient (C_{c1})	-0.444	-0.541	0.883	-0.229	0.852	-0.430
8.	Lag 2 correlation coefficient (C_{c2})	0.184	0.339	-0.263	0.316	-0.175	0.419
9.	Lag 3 correlation coefficient (C_{c3})	-0.177	-0.273	0.232	0.153	0.071	0.015

3. METHODOLOGY

In the present study, the standardized PWMs and L-moments based RFFA have been carried out to develop regional flood frequency formulae for Parvati basin in Central India region. The equations for computation of PWMs, L-moments and L-moment ratios have been presented in Annexure-I. The important prerequisites of RFFA are that AFSs should be independently distributed in time and space and region must be hydrologically homogeneous. Hence, before carrying out RFFA, turning point test and Anderson's test for randomness, Kendall's rank correlation test and linear regression test for trend analysis and a test suggested by Grubbs and Beck (1972) for determination of outliers in all of the AFSs were applied. The details of these tests can be seen from any standard book of hydrology. Another important prerequisite for RFFA is that the region under investigation must be hydrologically homogeneous. For judging the homogeneity of the region, the discordancy and heterogeneity measures (Hosking and Wallis, 1993) have been applied and discussed here.

3.1 Discordancy Measures

In this test, the L-moment ratios (L-C_v, L-$skew$, and L-$kurt$) of a site are used to describe that site in three-dimensional space. A group of homogeneous sites may form a cluster of such points. A point, which is far from the center of the cluster, can be discarded. Discordancy measure (D_i) of a site can be calculated as:

$$D_i = \frac{N}{3}(u_i - \bar{u})^T A^{-1}(u_i - \bar{u}) \tag{1}$$

where, $u_i = [t_2^{(i)}\ t_3^{(i)}\ t_4^{(i)}]$ is a vector containing the L-moment ratios for site i, $\bar{u}$ is the matrix of group average and can be expressed as $\bar{u} = \sum_{i=1}^{n} u_i \Big/ n$, A can be defined as $\sum_{i=1}^{n}(u_i - \bar{u})(u_i - \bar{u})^T$ and T denotes transposition of a vector or matrix. Generally any site with $D_i > 3$ can be regarded as discordant, but this criterion is subjective and no fixed limit has been determined so far.

3.2 Heterogeneity Measures (H)

In a homogeneous region, population L-moment ratios of all sites remain the same, but their sample L-moment ratios may differ due to sampling variability. The inter-site variation of L-moment ratios can be measured as the standard deviation of the generated L-moment ratio. Simulation procedure is used to determine expected variation of L-moment ratio and the standard deviation (V) of at-site $L\text{-}C_V$'s with regional average $L\text{-}C_v$ is computed using the following equation:

$$V = \left[\sum_{i=1}^{Ns} n_i (\tau_{2i} - \tau_2^{R})^2 \Big/ \sum_{i=1}^{Ns} n_i \right]^{1/2} \tag{2}$$

where, τ_{2i} is the $L\text{-}C_V$ of i^{th} site, τ_2^R is the regional $L\text{-}C_V$, n_i is the no. of years of data for i^{th} site and N_s is the total no. of stations used in regional analysis. In the test, by fitting a 4-parameter general distribution (Kappa or Wakeby), large number of regions say 1000 may be generated and $L\text{-}Cv$ for each generated sample is computed. Using, mean (μ_v) and standard deviation (σ_v) of $L\text{-}Cv$ series, the heterogeneity measures (H) can be determined with the help of following equation:

$$H = \frac{V - \mu_v}{\sigma_v} \tag{3}$$

The following may be the criteria used for assessing homogeneity of a region.

If	$H < 1$	region is acceptably homogeneous
If	$1 \le H < 2$	region is possibly heterogeneous
If	$H \ge 2$	region is heterogeneous

After confirming that the region under consideration is hydrologically homogeneous, a relation between mean annual flood and one or more catchment characteristics such as catchment area, storage, drainage density, overland and channel slope, soil type, rainfall is developed. In the present analysis, only catchment area has been considered for development of relationship in the following form:

$$\overline{Q} = mA^d \tag{4}$$

where, $\overline{Q}$ is the mean annual flood (m^3/s), A is the catchment area (km^2) and m and d are the region specific coefficient and exponent, respectively.

3.3 Regional Flood Frequency Modeling

In the regional flood frequency modeling, available peak flood data of different sites of a homogeneous region are required to be grouped for the estimation of regional parameters. The best-fit regional distribution is decided on the basis of goodness of fit tests such as D-index, L-moment ratio diagram and simulation experiments. The regional flood frequency modeling is generally preferred over at-site modeling because grouping of data of many sites may eliminate sampling error and the estimated parameters can be used for determination of probable flood at any ungauged site in the region.

3.4 Application of Standardized PWMs and L-moments

In the study, standardized PWMs and L-moments have been used for computation of regional parameters of various distributions. In this method, all the PWMs of a site are divided by at-site mean to get standardized values. Using these standardized PWMs, the standardized L-moment for each site is computed using Eq. 5 to 8 of Annexure-I. Averaging these standardized PWMs and L-moments across all sites in the ratio of record length, the regional standardized PWMs and L-moments can be computed. The regional parameters of different distribution including Wakeby-4, Wakeby-5, extreme value-I (EV-I), generalized extreme value (GEV), logistic (L), generalized logistic (GL), generalized pareto (GP), normal (NOR) and log normal (LNOR) and in turn the flood quantiles for different return periods may be computed. The flood quantile for any site (Q_{Ti}) of T year return period can be computed using following equation:

$$Q_{Ti} = Q_r * \overline{Q}_i \tag{5}$$

where Q_r = flood quantile calculated from regional parameters and

$\overline{Q}_i$ = Mean annual flood of i^{th} site.

3.5 Selection of Best-fit Distribution

The goodness of fit tests measure whether the data of a particular site are consistent with the fitted probability distribution or not. In case of RFFA, goodness of fit tests based on L-moment ratios and simulation experiments such as the L-moment ratio diagram, the measures based on L-kurtosis and Z-statistics have been identified as strong indicator for the selection of robust distribution.

3.5.1 L-moment Ratio Diagram

Hosking (1990) has constructed L-moment ratio diagram by plotting theoretical L-skewness (L-skew) and L-kurtosis (L-kurt) for different distributions. A significant advantage of L-moment ratio diagram is that the several distributions can be compared using a simple graphical instrument. The best-fit distribution is determined by plotting the regional L-skew and L-kurt with theoretically derived curves for different distributions.

3.5.2 Measure Based on L-kurtosis

The goodness of fit test based on L-moment ratio diagram is subjective to some extent. Hosking and Wallis (1993) proposed a convenient method for goodness of fit based on L-kurtosis in which the quality of fit is judged by determining the difference between the L-kurtosis of fitted distribution and the average L-kurtosis of the region. The good of fit measure of *GEV* distribution (Z^{GEV}) for a region can be expressed as:

$$Z^{GEV} = \frac{\tau_4 - \tau_4^{GEV}}{\sigma_4} \tag{6}$$

where τ_4 is the standardized regional *L-kurt*, τ_4^{GEV} is the theoretical value of L-kurt for GEV distribution and σ_4 is the standard deviation of *L-kurt* series obtained by repeated simulation of a homogeneous region with *GEV* distribution. For other distributions, simulation can be done with the parameter of that distribution and τ_4^{GEV} is replaced by the τ_4 of that distribution. The theoretical values of different distributions using scale parameter (k) as proposed by Hosking and Wallis (1993) are given below:

$$\tau_4^{GEV} = \frac{1.0 - 6*2^k + 10*3^{-k} - 5*4^{-k}}{(1-2^{-k})} \tag{7}$$

$$\tau_4^{EV-1} = 0.1504 \tag{8}$$

$$\tau_4^{EV-1} = \frac{1}{6} \tag{9}$$

$$\tau_4^{GLOG} = \frac{1+5k^2}{6.0} \tag{10}$$

$$\tau_4^{GPD} = \frac{(1-k)(2-k)}{(3+k)(4+k)} \tag{11}$$

$$\tau_4^{NOR} = 0.1226 \tag{12}$$

3.5.3 Z-statistics

Hosking (1993) proposed a technique of *Z*-statistics for selection of best-fit distribution. This goodness of fit statistics judged, how well the fitted distribution match with the regional

L-moment ratios. The goodness of fit measure for a distribution is given by statistics Z_i^{dist} (Z^{LCV}, Z^{LCK}, Z^{LCS}) and can be expressed as:

$$Z_i^{dist} = \frac{\overline{\tau}_i^R - \tau_i^{dist}}{\sigma_i^{dist}} \tag{13}$$

where, $\overline{\tau}_i^R$ is the weighted regional average of L-moment ratios and τ_i^{dist} and σ_i^{dist} are the simulated regional average and standard deviation of L-moment statistic, respectively. The distribution gives the minimum $\left|Z_i^{dist}\right|$ is considered the best fit for the region.

4. ANALYSIS AND RESULTS

The standardized PWMs and L-moments based RFFA have been applied for Parvati River basin using AFS of three gauging sites in the region. Before carrying out RFFA, the randomness of all AFSs was checked using turning point test and Anderson's test. The Kendal correlation and regression test were applied for identification of any significant trend in the series. The test statistics, their limits at 95% confidence level and the results of all the AFSs were presented in Table 2 and it has been observed that all the data point in AFSs were distributed randomly and no significant trend were observed at 95% confidence level. No outliers have been found in any of the AFSs.

Table 2
Results of Test for Randomness, Trends and Outliers

S.N.	*Particulars of tests*	*Parvati River at Pilukhedi*	*Parvati River at Manakhedi*	*Parvati River at Maksudangarh*
1.	Turning Point test			
	No. of turning point	10	7	5
	Test statistics $\|Z\|$	1.38	1.36	-0.27
	Limits at 5% significance level	±1.96	±1.96	±1.96
	Results	Random	Random	Random
2.	Kendal's rank correlation test			
	Test statistics p	53	29	44
	Test statistics $\|Z\|$	0.05	0.083	-0.16
	Limits at 5% significance level	±1.96	±1.96	±1.96
	Results	No trend	No trend	No trend
3.	Anderson's rank correlation test			
	Test statistics (r_1)	0.37	-0.40	-0.47
	Limits at 5% significance level	-0.58 to 0.42	-0.69 to 0.47	-0.69 to 0.47
	Results	Random	Random	Random

Table Contd…

Table 2 Contd…

4. Linear regression test			
S_b	60.24	56.00	130.11
$\lvert t_b \rvert$	0.07	0.45	0.79
Limits at 5% significance level	2.10	2.10	2.10
Results	Slope is not significant	Slope is not significant	Slope is not significant
5. Outlier's test (Values in m^3/sec)			
Higher limit (X_H)	9412.35	9935.52	13814.92
Lower limit (X_L)	-6624.78	-6717.31	-7092.51
Results	No outlier	No outlier	No outlier

The homogeneity of the region has been tested using discordancy and heterogeneity measures. In the discordancy measure test, the D_i value for Pilukhedi, Manakhedi and Maksudangarh gauging sites are 0.37, 0.11 and 0.52, respectively, which are less than 3.0 and hence the region may be considered as homogeneous. Similarly, the heterogeneity measures (H_{LCV}, H_{LCK} and H_{LCS}) have been worked out for the region by simulation of 1000 random samples using regional parameters. Values of different heterogeneity measures for the region were:

$$H_{LCV} = 0.56 \qquad H_{LCK} = 0.64 \qquad H_{LCS} = 0.87$$

As all values of H were less than 1.0, the region may be considered as homogeneous. For estimation of mean annual flood at any ungauged site in the Parvati basin, the following equation may be used to compute the mean annual flood $(\bar{Q})$ in m^3/s with the help of catchment area (A) in km^2:

$$\bar{Q} = 3.097A^{0.785} \tag{14}$$

The at-site PWMs, L-moments, L-moment ratios of each site in the study area have been computed and presented in Table 3. Using the at-site PWMs, the standardized PWMs, L-moments, L-moment ratios and in turn the regional parameters of different distributions were computed (Table 4). The L-moment based tests with simulation exercise have been used to select the best-fit distribution for river Parvati. The regional L-skew and L-kurt have been computed as 0.268 and 0.195, respectively and plotted on L-moment ratio diagram (Figure 2). From the analysis of L-moment ratio diagram, it is found that the GEV distribution may be the best fit distribution for the region. In the case of goodness of fit measure based on L-kurtosis, the Z-values for different distributions used in the regional flood frequency modeling have been computed using repeated simulation. The values of Z for different distributions are given in Table 5. Out of all the distributions used in analysis, the GEV which has given the minimum value of Z may be considered the best-fit distribution for the region. The Z-statistics for various distributions have been computed and the values of Z^{LCV}, Z^{LCK} and Z^{LCS} for each distribution have been calculated and presented in Table 6. The GEV distribution with the minimum overall *Z*-statistics can be considered the best-fit distribution for the region.

Table 3
At-site PWMs and L-moments for Different Gauging Sites in Parvati Basin

Parvati at Pilukhedi gauging site				
PWM				
M_{101}	M_{102}	M_{103}	M_{104}	M_{105}
1421.82	473.45	257.01	167.95	121.49
L-Moments				
λ_1	λ_2	λ_3	λ_4	
1421.82	474.92	123.17	91.57	
L-moment ratios				
	L-CV	*L-Skew*	*L-Kurt*	
	0.33	0.26	0.19	
Parvati at Manakhedi gauging site				
PWM				
M_{101}	M_{102}	M_{103}	M_{104}	M_{105}
1563.02	996.57	757.16	619.76	529.33
L-Moments				
λ_1	λ_2	λ_3	λ_4	
1563.01	430.12	126.58	76.11	
L-moment ratios				
	L-CV	*L-Skew*	*L-Kurt*	
	0.28	0.29	0.18	
Parvati at Maksudangarh gauging site				
PWM				
M_{101}	M_{102}	M_{103}	M_{104}	M_{105}
2964.63	1780.95	1311.35	1053.40	888.37
L-Moments				
λ_3	λ_3	λ_3	λ_4	
2964.63	597.27	147.03	134.26	
L-moment ratios				
	L-CV	*L-Skew*	*L-Kurt*	
	0.20	0.25	0.22	

Table 4
Regional Parameters of Various Distributions Computed in Regional Flood Frequency Modeling

		PWM		
M_{101}	M_{102}	M_{103}	M_{104}	M_{105}
1.00	0.365	0.210	0.144	0.108
		L-MOMENTS		
λ_1	λ_2	λ_3	λ_4	
1.00	0.27	0.072	0.053	
		L-MOMENT RATIOS		
	L-CV	*L-Skew*	*L-Kurt*	
	0.27	0.268	0.195	
		WAKEBY –5 (in Hosking's notation)		
Alpha	*Beta*	*Gama*	*Delta*	*XI*
0.914	1.279	0.139	0.408	0.364
		WAKEBY –5 (Landwehr et al. notation)		
A	*B*	*C*	*D*	*E*
0.714	1.279	0.342	0.408	0.364
		WAKEBY –4 (in Hosking's notation)		
Alpha	*Beta*	*Gama*	*Delta*	
16.347	32.501	0.515	-0.004	
		WAKEBY –4 (Landwehr et al. notation)		
A	*B*	*C*	*D*	
0.502	32.501	-129.664	-.004	
		EV-I DISTRIBUTION		
	u = 0.775	α = 0.389		
		GENERALISED EXTREME DISTRIBUTION		
	u = 0.751	α = 0.334	k = -0.148	
		LOGISTIC DISTRIBUTION		
	u = 1.00	α = 0.27		
		GENERALISED LOGISTIC DISTRIBUTION		
	u = 0.885	α = 0.239	k = -0.268	
		GENERALISED PARETO DISTRIBUTION		
	u = 0.418	α = 0.672	k = 0.155	
		NORMAL DISTRIBUTION		
	μ = 1.000	s = 0.479		
		LOG NORMAL DISTRIBUTION		
	μ = -0.28	s = 0.557	u = 0.118	

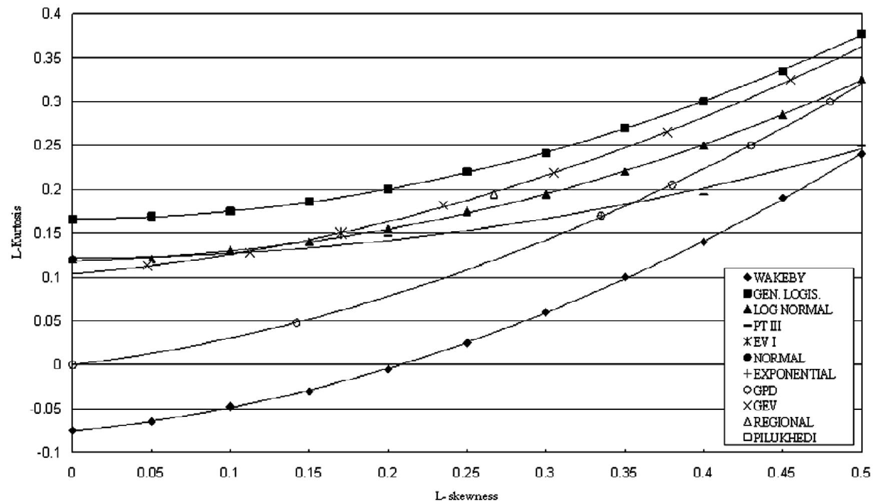

Figure 2: L-moment Ratio Diagram

Table 5
Results of Goodness of Fit Test Based on L-kurtosis

S.N.	*DISTRIBUTIONS*	*Z*
1.	EV-I	1.93
2.	GEV	**0.06**
3.	LOGISTIC	1.23
4.	GENERALISED LOGISTIC	1.33
5.	GENERALISED PARETO	3.27
6.	NORMAL	3.12
7.	LOG NORMAL	3.28

Table 6
Z-statistics for Different Distributions

S.N.	*DISTRIBUTION*	Z^{LCV}	Z^{LCK}	Z^{LCS}
1.	EV-I	0.867	0.956	0.954
2.	GEV	*0.632*	*0.821*	*0.524*
3.	WAKEBY-4	1.840	1.568	1.958
4.	WAKEBY-5	2.654	3.421	1.245
4.	LOGISTIC	1.984	2.658	2.564
5.	GEN. LOGISTIC	1.258	0.658	1.654
6.	GEN. PARETO	2.564	1.784	1.651
7.	NORMAL	3.145	1.548	2.417
8.	LOG NORMAL	1.598	3.564	1.487

All the results for selection of the best-fit distribution based on L-moments and D-index for PWMs show that the GEV distribution may be the best-fit distribution for the region. The regional parameters of GEV distribution computed are $u = 0.751$, $\alpha = 0.334$ and $k = -0.148$. The following regional equation may be used for estimation of flood quantile (Q_T) in m³/s at any gauged site in the region.

$$Q_T = \left[2.257 \left\{ -\ln\left(1 - \frac{1}{T}\right) \right\}^{-0.148} - 1.506 \right] \bar{Q} \tag{15}$$

where, $\bar{Q}$ is the mean annual flood in m³/s and T is the return period in years. In case of ungauged basins in Parvati River system, the following equation can be used for estimation of flood quantile (Q_T) in m³/s.

$$Q_T = \left[6.99 \left\{ -\ln\left(1 - \frac{1}{T}\right) \right\}^{-0.148} - 4.664 \right] A^{0.785} \tag{16}$$

where, A is the catchment area in km². The graphs for estimation of floods in gauged and ungauged basins in the region have been given in Figures 3 and 4. The performance of at-site and at-site regional FFA has been evaluated by comparing the D-index for different distributions (Table 7). From the analysis of Table, it has been observed that for most of the distributions, the values of D-index were less in at-site regional approach than at-site approach. Therefore, it may be concluded that the RFFA with L-moments as a parameter estimation technique is more appropriate technique for estimation of future floods.

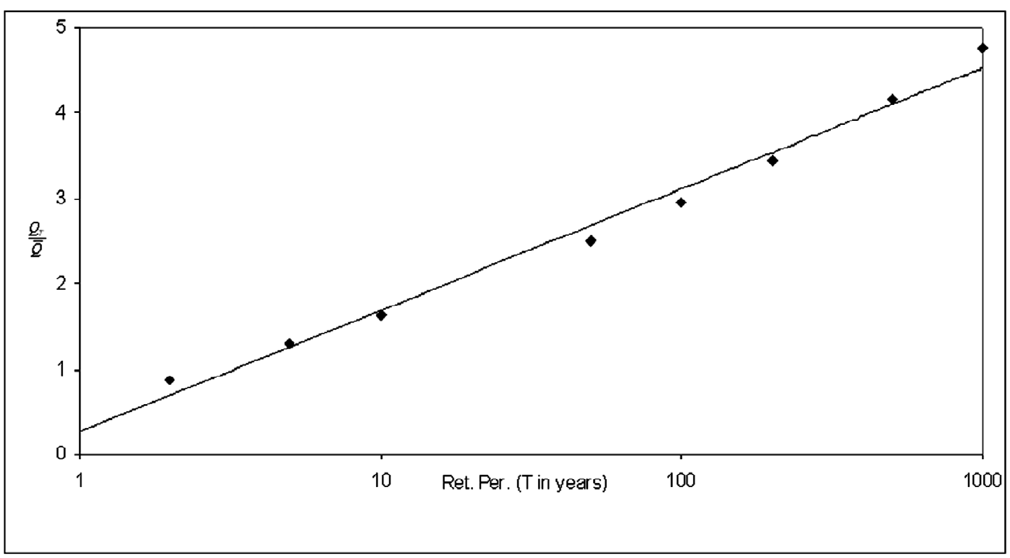

Figure 3: Graph for Estimation of Flood Quantile in Gauged Basins

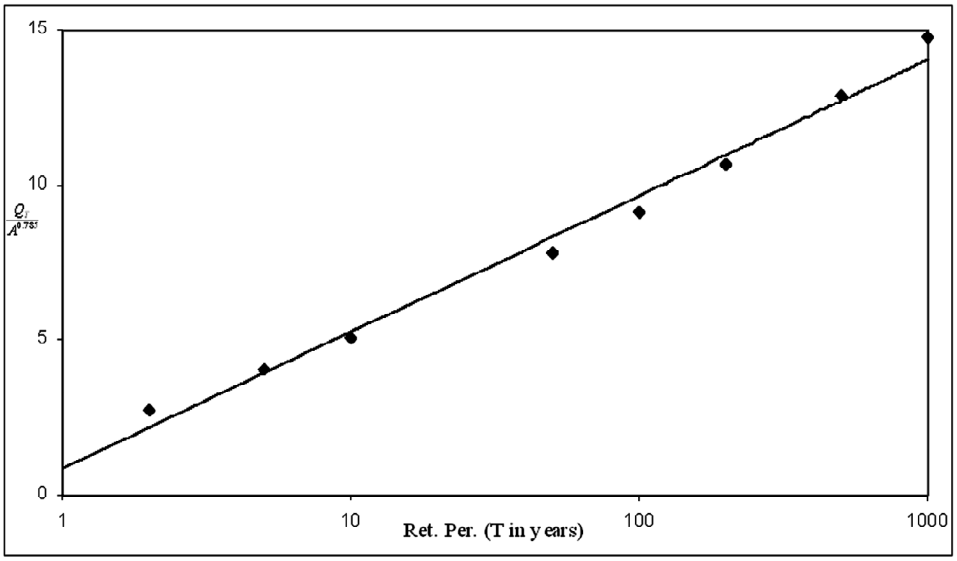

Figure 4: Graph for Estimation of Flood Quantile in Ungauged Basins

Table 7
The D-index Values for Different Distributions

S.N.	*Distributions*	*Parvati at Pilukhedi gauging site*		*Parvati at Manakhedi gauging site*		*Parvati at Maksudangarh gauging site*	
		At-site	*At-site regional*	*At-site*	*At-site regional*	*At-site*	*At-site regional*
1.	EV-I	0.95	0.87	1.01	1.01	1.39	1.02
2.	GEV	0.72	0.68	0.91	0.84	1.45	1.04
3.	WAKEBY-4	0.74	0.69	1.00	1.04	1.49	1.14
4.	WAKEBY-5	1.02	0.81	N.F.*	0.91	1.47	0.84
4.	LOGISTIC	1.19	1.30	1.07	1.07	1.63	0.91
5.	GEN. LOGISTIC	0.72	0.69	0.97	0.90	1.45	0.95
6.	GEN. PARETO	0.97	0.77	1.03	1.08	1.42	1.18
7.	NORMAL	1.34	1.02	1.56	1.16	1.72	0.96
8.	LOG NORMAL	0.71	0.70	0.99	0.97	1.45	1.07

• Not found suitable

5. CONCLUSIONS

Flood frequency modeling is one of the simplest and widely used applications of statistics in the field of hydrology. In the present study, the L-moment based RFFA has been applied for Pravati basin of Central India region using AFS of three gauging sites. Various tests attempted for determination of randomness, trends and outliers indicated that all AFSs are distributed randomly having no trends and free from outliers. The discordancy measures and heterogeneity measure tests employed for determination of homogeneity suggested that all the sites used in the analysis are homogeneous and RFFA can be performed for flood estimation. The regional PWMs, L-moments and the parameters of different distributions including Wakeby-4, Wakeby-5, EV-I, GEV, L, GL, GP, NOR and LNOR have been computed. The L-moments based tests including L-moment ratio diagram, L-kurtosis and Z-statistics have been used to identify the best-fit distribution for RFFA in the region. All the tests indicated that the *GEV* distribution with $u = 0.751$, $\alpha = 0.334$ and $k = -0.148$ may be considered the robust distribution for Parvati River system and can be used for flood estimation. In the analysis, two separate equations have been generated for computation of flood quantiles for gauged and ungauged catchments in Parvati basin. The performance of at-site and at-site regional FFA have been evaluated using D-index and it may be concluded that the results given by at-site regional FFA were less bias than the at-site analysis.

ANNEXURE I: PROBABILITY WEIGHTED MOMENTS (PWM) AND L-MOMENTS

Probability Weighted Moments (PWM)

The PWMs were first introduced by Greenwwod *et al.* (1979) and can be expressed as:

$$M_{ijk} = \int_0^1 x^i(F)F^j(1-F)^k\,dF \tag{1}$$

Where, i, j, k are the real numbers and $F(x)$ is the cumulative density function and quantile function $X(F)$ of variable x. The special case of expressing PWMs when $i = 1$ and either $j = 0$ or $k = 0$, M_{1j0} and M_{10k} are linear in x and are sufficient for parameters estimation. The sample estimates of M_{1j0} and M_{10k} as recommended by Landwehr *et al.* (1979a & b) can be expressed as:

$$M_{1j0} = \frac{1}{N}\sum_{i=1}^{N} F_{(i)}^{j} x_{(i)} \tag{2}$$

$$M_{10k} = \frac{1}{N}\sum_{i=1}^{N} \left[1 - F_{(i)}\right]^k x_{(i)} \tag{3}$$

Where, $x_{(i)}$, $I = 1, 2, 3, \ldots\ldots N$ are the ordered (ascending) N sample values and $F_{(i)}$ is the plotting position and can be computed as $F_{(i)} = \dfrac{i + A}{N + B}$ and usually, $A = -0.35$ and $B = 0.0$.

L-Moments

The simplest approach to describe L-moments is through PWMs. Let $x_{1:n} \le x_{2:n} \le \ldots\, x_{n:n}$ be the order statistics of a random sample of size n drawn from distribution of x. L-moments of x can be defined as:

$$\lambda_r = \frac{1}{r}\sum_{k=0}^{r-1}(-1)^k \begin{bmatrix} r-1 \\ k \end{bmatrix} EX_{r-k:r} \qquad r = 1,2 \tag{4}$$

The L-moments may also be defined as the linear functions of PWMs and the expressions for computation of L-moments (λ_1, λ_2, λ_3, λ_4) from PWMs are given below:

$$\lambda_1 = M_{100} \tag{5}$$

$$\lambda_2 = 2M_{110} - M_{100} \tag{6}$$

$$\lambda_3 = 6M_{120} - 6M_{110} + M_{100} \tag{7}$$

$$\lambda_4 = 20M_{130} - 30M_{120} + 12M_{110} - M_{100} \tag{8}$$

The L-moments can be used as a measure of scale and shape of probability distribution, clearly, λ_2 is a measure of scale or dispersion of distribution. It is often convenient to standardize the higher moments such as λ_r, $r \geq 3$, so that they are independent of unit of measurement of x. The L-moment ratios (τ_r) of x can be expressed as:

$$\tau_r = \frac{\lambda_r}{\lambda_2}, \qquad r = 3,4,\ldots \tag{9}$$

Analogous to conventional moment ratios, such as the coefficient of skewness (*L-skew* or τ_3) reflects the degree of symmetry of a sample and coefficient of kurtosis (*L-kurt* or τ_4) is a measure of peakedness. In addition, L-coefficient of variation (L-C_v or τ_2) is also a useful parameter and all these can be expressed as:

$$L-skew = \tau_3 = \frac{\lambda_3}{\lambda_2} \tag{10}$$

$$L-kurt = \tau_4 = \frac{\lambda_4}{\lambda_2} \tag{11}$$

$$L-C_v = \tau_2 = \frac{\lambda_2}{\lambda_1} \tag{12}$$

L-moments can be used to estimate parameter when fitting a distribution to a sample by equating the first p-sample L-moments to corresponding population.

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