Training Course

On

Hydrological Processes in an Ungauged Catchment

[July 25 – 29, 2011]

CHAPTER-5

Development of Regional Flood Frequency Relationships

By

Rakesh Kumar
Scientist-F

Organized under Hydrology Project - II

National Institute of Hydrology
Roorkee – 247667 (Uttrakhand)

DEVELOPMENT OF REGIONAL FLOOD FREQUENCY RELATIONSHIPS

Rakesh Kumar
Scientist-F, Head (Surface Water Div.)
National Institute of Hydrology, Roorkee–247 667

5.0 INTRODUCTION

Information on flood magnitudes and their frequencies is needed for design of hydraulic structures such as dams, spillways, road and railway bridges, culverts, urban drainage systems, flood plain zoning, economic evaluation of flood protection projects etc. Chow (1962) states that hundreds of different methods have been used for estimating floods on small drainage basins, most involving arbitrary formulas. Pilgrim and Cordery (1992) mention that estimation of peak flows on small to medium-sized rural drainage basins is probably the most common application of flood estimation as well as being of greatest overall economic importance. In almost all cases, no observed data are available at the design site, and little time can be spent on the estimate, precluding use of other data in the region. The authors further mention that the three most widely used types of methods are the rational method, the U.S. Soil Conservation Service method and regional flood frequency methods. The choice of method depends on the design criteria applicable to the structure and availability of data. As per Indian design criteria, frequency based floods find their applications in estimation of design floods for almost all the types of hydraulic structures viz. small size dams, barrages, weirs, road and railway bridges, cross drainage structures, flood control structures etc., excluding large and intermediate size dams. For design of large and intermediate size dams probable maximum flood and standard project flood are adopted, respectively (National Institute of Hydrology, 1992).

Some of the flood frequency analysis studies include Landwehr et al. (1979), Wallis and Wood (1985), Hosking and Wallis (1986), Hosking and Wallis (1988), Jin and Stedinger (1989), Potter and Lettenmaier (1990), Farquharson (1992), Iacobellis and Fiorentino (2000), Martins and Stedinger (2000), Peel et al. (2001) etc. The studies carried out in India include the studies performed jointly by Central Water Commission (CWC), Research Designs and Standards Organization (RDSO) and India Meteorological Department (IMD) using the method based on synthetic unit hydrograph and design rainfall considering physiographic and meteorological characteristics for estimation of design floods (e.g. CWC, 1985) and regional flood frequency studies carried out by RDSO using the United States Geological Survey (USGS) and pooled curve methods (e.g. RDSO, 1991). Regional flood frequency relationships were developed for some of the regions based on the comparative flood frequency studies using probability weighted moment (PWM) methods, and the USGS method (National Institute of Hydrology, 1996; Kumar et al., 1999). In the present study, regional flood frequency relationships have been developed based on the L-moments approach for estimation of floods of various return periods for the gauged and ungauged catchments of Subzone 1(f) of India.

5.1 L-MOMENTS APPROACH

L-moments are a recent development within statistics (Hosking, 1990). In a wide range of hydrologic applications, L-moments provide simple and reasonably efficient estimators of characteristics of hydrologic data and of a distribution's parameters (Stedinger et al., 1992). L-moment methods are demonstrably superior to those that have been used previously, and are now being adopted by many organizations worldwide (Hosking and Wallis, 1997). Zafirakou-

Koulouris et al. (1998) mention that like ordinary product moments, L- moments summarize the characteristics or shapes of theoretical probability distributions and observed samples. Both moment types offer measures of distributional location (mean), scale (variance), skewness (shape), and kurtosis (peakedness). The authors further mention that L-moments offer significant advantages over ordinary product moments, especially for environmental data sets, because of the following:

i. L-moment ratio estimators of location, scale and shape are nearly unbiased, regardless of the probability distribution from which the observations arise (Hosking, 1990).

ii. L-moment ratio estimators such as L-coefficient of variation, L-skewness, and L-kurtosis can exhibit lower bias than conventional product moment ratios, especially for highly skewed samples.

iii. The L-moment ratio estimators of L- coefficient of variation and L-skewness do not have bounds which depend on sample size as do the ordinary product moment ratio estimators of coefficient of variation and skewness.

iv. L-moment estimators are linear combinations of the observations and thus are less sensitive to the largest observations in a sample than product moment estimators, which square or cube the observations.

v. L-moment ratio diagrams are particularly good at identifying the distributional properties of highly skewed data, whereas ordinary product moment diagrams are almost useless for this task (Vogel and Fennessey, 1993).

Hosking and Wallis (1997) state that L-moments are an alternative system of describing the shapes of probability distributions. Historically they arose as modifications of the probability weighted moments (PWMs) of Greenwood et al. (1979). Probability weighted moments are defined as:

$$\beta_r = E\left[x\{F(x)\}^r\right] \tag{5.1}$$

which can be rewritten as:

$$\beta_r = \int_0^1 x(F)F^r dF \tag{5.2}$$

where $F = F(x)$ is the cumulative distribution function (CDF) for x, $x(F)$ is the inverse CDF of x evaluated at the probability F, and $r = 0, 1, 2, \ldots$, is a nonnegative integer. When $r = 0$, β_0 is equal to the mean of the distribution $\mu = E[x]$.

For any distribution the r^{th} L-moment λ_r is related to the r^{th} PWM (Hosking, 1990) through

$$\lambda_{r+1} = \sum_{k=0}^{r} \beta_k (-1)^{r-k} \binom{r}{k}\binom{r+k}{k} \tag{5.3}$$

For example, the first four L-moments are related to the PWMs using

$$\lambda_1 = \beta_0 \quad (5.4)$$

$$\lambda_2 = 2\beta_1 - \beta_0 \quad (5.5)$$

$$\lambda_3 = 6\beta_2 - 6\beta_1 + \beta_0 \quad (5.6)$$

$$\lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \quad (5.7)$$

Hosking (1990) defined L-moment ratios as:

L-coefficient of variation, L-CV (τ_2) $= \lambda_2 / \lambda_1$ (5.8)

L-coefficient of skewness, L-skew (τ_3) $= \lambda_3 / \lambda_2$ (5.9)

L-coefficient of kurtosis, L-kurtosis (τ_4) $= \lambda_4 / \lambda_2$ (5.10)

5.2 STUDY AREA AND DATA AVAILABILITY

The Middle Ganga Plains Subzone 1(f) lies between latitude 24^0 to 29^0 North and longitude 80^0 to 89^0 East. The total geographical area of Subzone 1(f) is 1,71,350 km^2. It covers parts of Uttar Pradesh, Bihar, Jharkhand and West Bengal. The major rivers flowing in this Subzone are Ganga, Yamuna, Gomti, Gandak, Ghagra, Rapti, Kosi including Kamla, Mahananda and others. Annual maximum peak flood data of 11 gauging sites lying in the Subzone 1(f) and varying over 11 to 33 years in record length are available for the study.

5.3 ANALYSIS AND DISCUSSION OF RESULTS

Regional flood frequency analysis was performed using the various frequency distributions: viz. Extreme value (EV1), General extreme value (GEV), Logistic (LOS), Generalized logistic (GLO), Normal (NOR), Generalized normal (GNO), Uniform (UNF), Pearson Type-III (PE3), Exponential (EXP), Generalized Pareto (GPA), Kappa (KAP), and five parameter Wakeby (WAK). Parameters of the distributions were estimated using the L-moments approach. Screening of the data, testing of regional homogeneity, identification of the regional distribution and development of regional flood frequency relationships for gauged and ungauged catchments are described below.

5.3.1 Screening of Data Using Discordancy Measure Test

The objective of screening of data is to check that the data are appropriate for performing the regional flood frequency analysis. In this study, screening of the data was performed using the L-moments based discordancy measure (D_i). Hosking and Wallis (1997) defined the discordancy measure (D_i) considering if there are N sites in the group. Let $u_i = [t_2^{(i)}\ t_3^{(i)}\ t_4^{(i)}]^T$ be a vector containing the sample L-moment ratios t_2, t_3 and t_4 values for site i, analogous to their regional values termed as τ_2, τ_3, and τ_4, expressed in equations (8) to (10). T denotes transposition of a vector or matrix. Let

$$\bar{u} = N^{-1} \sum_{i=1}^{N} u_i \quad (5.11)$$

be (unweighted) group average. The matrix of sums of squares and cross products is defined as:

$$A_m = \sum_{i=1}^{N}(u_i - \bar{u})(u_i - \bar{u})^T \quad (5.12)$$

The discordancy measure for site i is defined as:

$$D_i = \frac{1}{3} N (u_i - \bar{u})^T A_m^{-1} (u_i - \bar{u}) \quad (5.13)$$

The site i is declared to be discordant, if D_i is greater than the critical value of the discordancy statistic D_i given in a tabular form by Hosking and Wallis (1997).

Values of discordancy measure have been computed in terms of the L-moments for all the 11 bridge sites of Subzone 1(f). It is observed that the D_i values for all the 11 sites vary from 0.04 to 2.59 and are less than the critical D_i value of 2.757. Hence, as per the discordancy measure test, data of all the 11 sites may be utilised for carrying out the flood frequency analysis.

5.3.2 Test of Regional Homogeneity

For testing the regional homogeneity, a test statistic H, termed as heterogeneity measure was proposed by Hosking and Wallis (1993). It compares the inter-site variations in sample L-moments for the group of sites with what would be expected of a homogeneous region. The inter-site variation of L-moment ratio is measured as the standard deviation (V) of the at-site L-CV's weighted proportionally to the record length at each site. To establish what would be expected of a homogeneous region, simulations are used. A number of, say 500, data regions are generated based on the regional weighted average statistics using a four parameter distribution e.g. Kappa distribution. The inter-site variation of each generated region is computed and the mean (μ_v) and standard deviation (σ_v) of the computed inter-site variation is obtained. Then, heterogeneity measure H is computed as:

$$H = \frac{V - \mu_V}{\sigma_V} \quad (5.14)$$

The criteria established by Hosking and Wallis (1993) for assessing heterogeneity of a region is as follows.

If $H < 1$	Region is acceptably homogeneous.
If $1 \leq H < 2$	Region is possibly heterogeneous.
If $H \geq 2$	Region is definitely heterogeneous.

The heterogeneity measure for Subzone 1(f) using the data of 11 sites was computed and the same was found to be greater than 1.0. Based on the statistical properties one by one three sites of the region were excluded till H value less than 1.0 was obtained. Thus, the region comprising of 8 sites was identified as the homogenous region. The values of heterogeneity measure computed by carrying out 500 simulations using the Kappa distribution based on the data of 8 sites are given in Table 5.1. The details of catchment area, sample size and sample statistics for the 8 sites which form the homogeneous region are given in Table 5.2 along with the Discordancy measure (D_i) values. It is observed from Table II that the D_i values for the 8 sites vary from 0.08 to 2.08 and the same are less than the critical D_i value of 2.140 (Hosking and Wallis, 1997). Hence, data of these 8 sites have been used for development of regional flood frequency relationships for the Subzone 1(f).

Table 5.1 Heterogeneity measures for Subzone 1(f)

Sl. No.	Heterogeneity measures	Values
1.	Heterogeneity measure H	
	(a) Observed standard deviation of group L-CV	.0462
	(b) Simulated mean of standard deviation of group L-CV	.0385
	(c) Simulated standard deviation of standard deviation of group L-CV	.0108
	(d) Standardized test value H	0.71
2.	Heterogeneity measure H(2)	
	(a) Observed average of L-CV / L-Skewness distance	0.0976
	(b) Simulated mean of average L-CV / L-Skewness distance	0.0812
	(c) Simulated standard deviation of average L-CV / L-Skewness distance	0.0185
	(d) Standardized test value H(2)	0.89
3.	Heterogeneity measure H(3)	
	(a) Observed average of L-Skewness/L-Kurtosis distance	.1333
	(b) Simulated mean of average L-Skewness/L-Kurtosis distance	.0962
	(c) Simulated standard deviation of average L-Skewness/L-Kurtosis distance	.0211
	(d) Standardized test value H(3)	1.76

Table 5.2 Catchment area, sample statistics and sample size for the 8 bridge sites of Subzone 1(f)

Bridge number	Catchment area (km^2) (A)	Mean annual peak flood (m^3/s) ($\bar{Q}$)	Standard deviation (m^3/s) (V)	Coefficient of variation (CV)	Coefficient of skewness (CS)	Sample size (years) (SS)	Discordancy measure (D_i)
59	54.39	97.48	52.85	0.542	-0.233	33	1.63
30	447.76	490.5	277.93	0.567	0.322	30	1.24
160	150.4	70.31	37.68	0.536	0.861	32	0.28
3	32.89	24.29	16.99	0.699	0.915	31	0.89
60	130	140.56	73.16	0.52	3.503	27	2.08
24	69.75	59.31	33.99	0.573	0.441	26	0.08
141	59.83	79.39	47.04	0.593	0.682	23	0.55
104	234.19	555.21	422.62	0.761	2.542	29	1.26

5.3.3 Identification of Regional Frequency Distribution

The choice of an appropriate frequency distribution for a homogeneous region is made by comparing the moments of the distributions to the average moments statistics from regional data. The objective is to identify a distribution that best fits the observed data. The best fit is determined by how well the L-skewness and L-kurtosis of the fitted distribution match the regional average L-skewness and L-kurtosis of the observed data (Hosking, 1991). In this study, the L-moment ratio diagram and $|Z_i^{dist}|$–statistic are used as the best fit criteria for identifying the regional distribution. L-moment ratio diagrams compare sample estimates of the dimensionless L- moment ratios with their theoretical counterparts (Zafirakou-Koulouris et al., 1998). In the L-moment ratio diagram shown in Figure 1, the point defined by the regional average values of L-skewness i.e. $\tau_3 = 0.1637$ and L-kurtosis i.e. $\tau_4 = 0.1458$, lies closest to the GEV distribution.

The goodness-of-fit measure for a distribution, Z_i^{dist} –statistic defined by Hosking and Wallis (1993), is expressed as:

$$Z_i^{dist} = \frac{\left(\overline{\tau}_i^R - \tau_i^{dist}\right)}{\sigma_i^{dist}} \qquad (5.15)$$

Where, $\overline{\tau}_i^R$ is the weighted regional average of L-moment statistic i, τ_i^{dist} and σ_i^{dist} are the simulated regional average and standard deviation of L-moment statistics i, respectively, for a given distribution. The fit is considered to be adequate if $|Z_i^{dist}|$–statistic is sufficiently close to zero, a reasonable criterion being $|Z_i^{dist}|$ –statistic less than 1.64.

The Z_i^{dist} –statistic for the various three parameter distributions is given in Table III. It is observed that the $|Z_i^{dist}|$ –statistic values are lower than 1.64 for the four distributions viz. GEV, GNO, PE3 and GLO. Further, the $|Z_i^{dist}|$–statistic is found to be the lowest for GEV distribution i.e. 0.01; which is very close to 0.0. Thus, based on the L-moment ratio diagram as well as $|Z_i^{dist}|$ –statistic criteria, the GEV distribution is identified as the robust distribution for the Subzone 1(f).

Table 5.3 Z_i^{dist} -statistic for various distributions for Subzone 1(f)

Sl. No.	Distribution	Z_i^{dist} -statistic
1	GEV	0.01
2	GNO	-0.14
3	PE3	-0.62
4	GLO	1.58
5	GPA	3.40

The values of regional parameters for the various distributions which have $|Z_i^{dist}|$ – statistic value less than 1.64 as well as the five parameter Wakeby distribution are given in Table IV. As even for heterogeneous regions, it is important to use a distribution that is robust to moderate heterogeneity in the at-site frequency distribution. It is therefore preferred to use Wakeby distribution for heterogeneous regions. Further, the Wakeby distribution which has five parameters, more than most of the common distributions can attain a wider range of distributional shapes than can the common distributions. This makes the Wakeby distribution particularly useful for simulating artificial data for use in studying the robustness, under changes in distributional form of methods of data analysis (Hosking and Wallis, 1997).

Table 5.4 Regional parameters for the various distributions for Subzone 1(f)

Distribution	Parameters of the distribution				
GEV	$\xi = 0.734$	$\alpha = 0.468$	$k = 0.010$		
GNO	$\xi = 0.906$	$\alpha = 0.544$	$k = -0.337$		
PE3	$\mu = 1$	$\sigma = 0.588$	$\gamma = 0.994$		
GLO	$\xi = 0.915$	$\alpha = 0.308$	$k = -0.164$		
WAK	$\xi = 0.109$	$\alpha = 1.708$	$\beta = 2.525$	$\gamma = 0.362$	$\delta = 0.108$

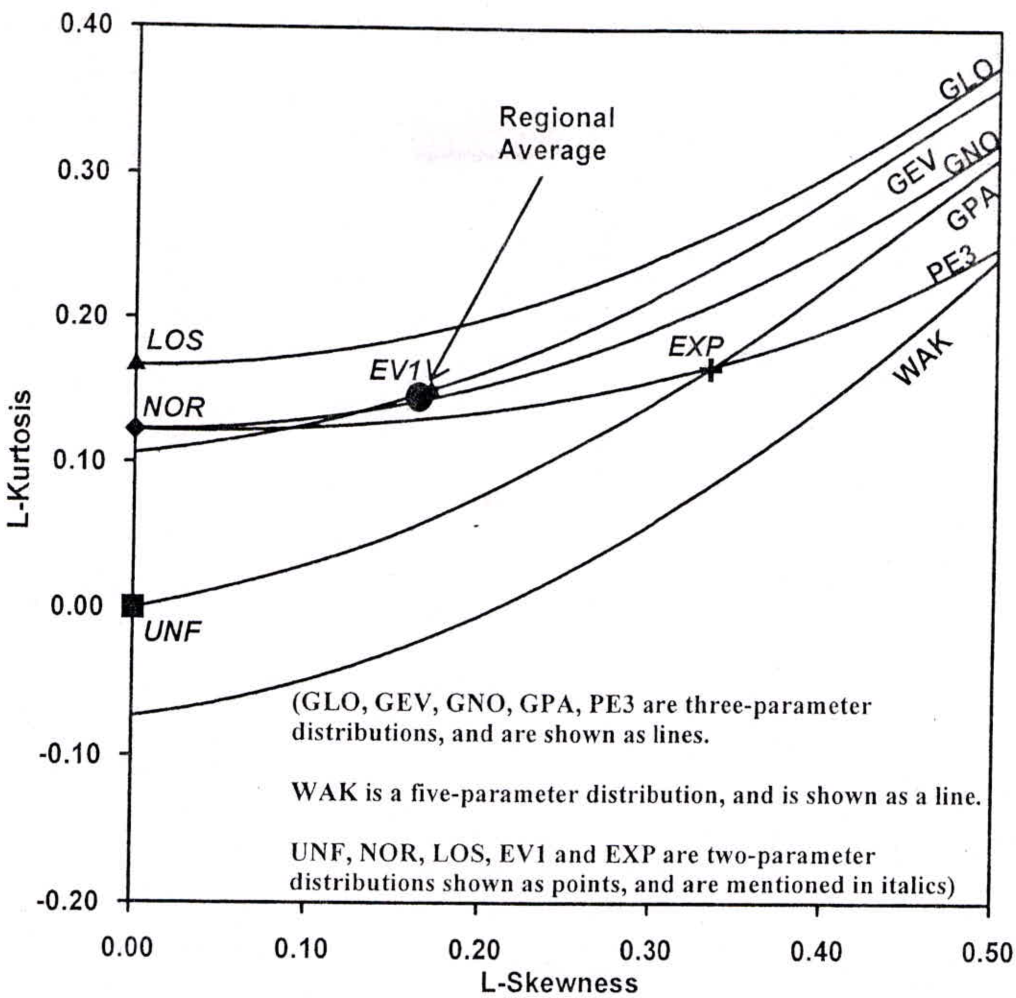

Figure 1. L-moment ratio diagram for Subzone 1(f)
Fig 5.1

5.3.4 Development of Regional Flood Frequency Relationship for Gauged Catchments

As GEV distribution has been identified as the robust distribution for the study area; hence, regional flood frequency relationships have been developed using this distribution. The form of the regional frequency relationship for GEV distribution is expressed as:

$$\frac{Q_T}{\overline{\overline{Q}}} = \xi + \alpha\, y_T \qquad (5.16)$$

Here, Q_T is T-year return period flood estimate, ξ and α are the parameters of the GEV distribution and y_T is GEV reduced variate corresponding to T-year return period i.e.

$$y_T = \left[1 - \left\{-\ln\left(1 - \frac{1}{T}\right)\right\}^k\right] \Big/ k \qquad (5.17)$$

The values of regional parameters of the GEV distribution for Subzone 1(f) are: $k = 0.010$, $\xi = 0.734$ and $\alpha = 0.468$. Substituting values of these regional parameters in equations (16) and (17), the regional flood frequency relationship for estimation of floods of various return periods for the gauged catchments of Subzone 1(f) is expressed as:

$$Q_T = \left[47.534 - 46.8 \left(-\ln\left(1-\frac{1}{T}\right)\right)^{0.01} \right] * \overline{Q} \qquad (5.18)$$

For estimation of flood of desired return period for a small to moderate size gauged catchment of Subzone 1(f), the above regional flood frequency relationship may be used. Alternatively, floods of various return periods may also be obtained by multiplying the mean annual peak flood of the catchment ($\overline{Q}$) by the corresponding value of growth factors given in Table V.

Table 5.5 Values of growth factors ($Q_T/\overline{Q}$) for various distributions for Subzone 1(f)

Distribution	Return period (Years)								
	2	5	10	25	50	100	200	500	1000
	Growth factors								
GEV	0.906	1.431	1.776	2.209	2.527	2.84	3.151	3.557	3.862
GNO	0.906	1.435	1.777	2.203	2.516	2.826	3.136	3.549	3.864
PE3	0.904	1.446	1.788	2.2	2.493	2.775	3.048	3.4	3.659
GLO	0.915	1.393	1.728	2.197	2.589	3.023	3.505	4.231	4.857
WAK	0.929	1.411	1.731	2.18	2.549	2.947	3.375	3.993	4.503

The variation of growth factors obtained for GEV, GNO, PE3, GLO and WAK distributions is shown in Figure 2. It is observed that growth factors of GLO and WAK distributions are higher and the growth factors of PE3 distribution are lower than that of GEV distribution; while the growth factors of GNO distribution are very close to that of the GEV distribution.

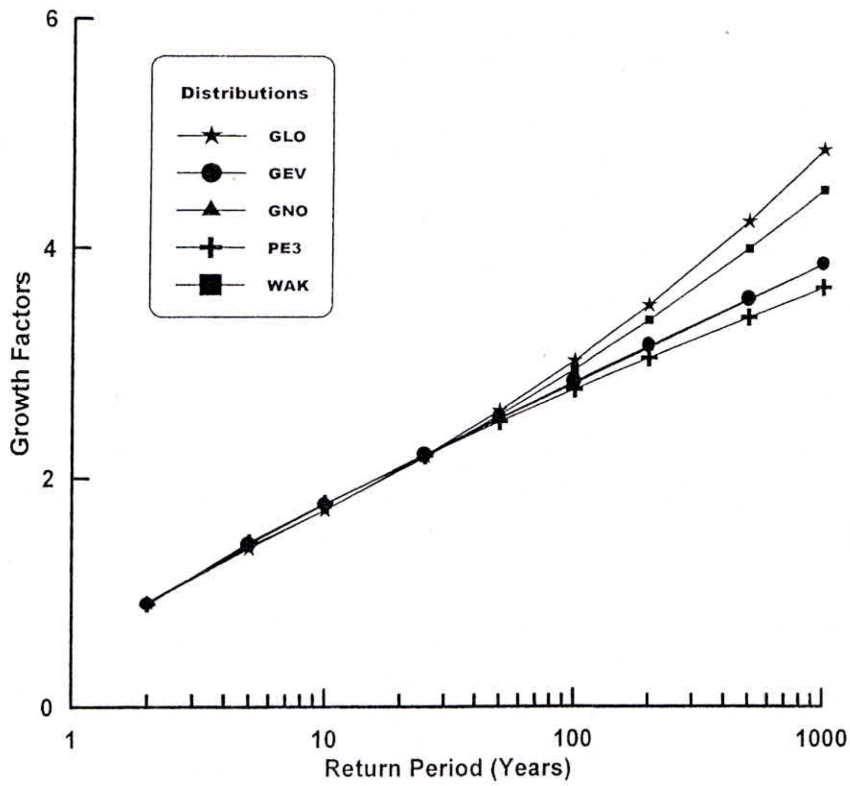

Figure 2. Variation of growth factors for various return periods for Subzone 1(f)

Fig. 5.2

5.3.5 Development of Regional Relationship Between Mean Annual Peak Flood and Catchment Area

For estimation of T-year return period flood at a site, the estimate for mean annual peak flood is required. For ungauged catchments at-site mean can not be computed in absence of the observed flow data. In such a situation, a relationship between the mean annual peak flood of gauged catchments in the region and their pertinent physiographic and climatic characteristics is needed for estimation of the mean annual peak flood. As catchment areas (A) of the various bridge sites were the only physiographic characteristics available; hence, a regional relationship has been developed in terms of catchment area for estimation of mean annual peak flood ($\overline{Q}$) for ungauged catchments. The regional relationship between $\overline{Q}$ and A developed for the region in log domain using least squares approach is given below.

$$\overline{Q} = 0.733\ (A)^{1.084} \qquad (5.19)$$

Where, A is the catchment area, in km^2 and $\overline{Q}$ is the mean annual peak flood in m^3/s. For this relationship, the correlation coefficient is, $r = 0.879$, and the standard error of the estimates is, SE = 0.545.

5.3.6 Development of Regional Flood Frequency Relationship for Ungauged Catchments

For development of regional flood frequency relationship for estimation of floods of various return periods for ungauged catchments, the regional flood frequency relationship given in equation (18) has been coupled with the regional relationship between mean annual peak flood and catchment area, given in equation (19) and following regional frequency relationship has been developed.

$$Q_T = \left[34.842 - 34.304 \left\{ - \ln \left(1 - \frac{1}{T} \right) \right\}^{0.01} \right] A^{1.084} \qquad (5.20)$$

Where, Q_T is flood estimate in m^3/s for T year return period, and A is catchment area in km^2.

5.3.7 Verification of the Regional Flood Frequency Relationship

With the objective of verifying the regional flood frequency estimates for the gauged catchments, regional flood frequency analysis was carried out for three cases of the test catchments, considering the data of 7 catchments and excluding the data of one of the test catchments in each case. For example, for Case I, the annual maximum peak flood data of the second smallest catchment (Bridge No. 59) were excluded and the parameters of the GEV distribution were computed using the data of the remaining 7 catchments. The regional values of parameters of the GEV distribution for Case I are obtained as: $k = -0.045$, $\xi = 0.721$ and $\alpha = 0.447$ and the growth factors were computed and are given in Table VI. Similarly, the analysis was repeated for Case II by excluding the data of medium size catchment (Bridge No. 60). For Case III, the analysis was repeated by excluding the data of the second largest catchment (Bridge No. 104). The regional values of parameters of the GEV distribution for Case II are obtained as: $k = 0.050$, $\xi = 0.732$ and $\alpha = 0.505$; and for Case III are obtained as: $k = 0.028$, $\xi = 0.743$ and $\alpha = 0.467$. The growth factors computed for the three test catchments were compared with the growth factors obtained for Subzone 1(f) using the data of 8 catchments as given in Table VI. It is observed from Table VI that the percentage deviations in growth factors for the three test catchments vary from 0.23% to 12.3%, 0.16% to 4.69%, and 0.14% to 4.79%, respectively for return periods of 2 to 1000 years. Further, the percentage deviations for commonly used return periods of 25, 50 and 100 years vary from 0.16% to 5.77% for the three test catchments.

Table 5.6 Percentage deviation of growth factors for the three test catchments

Return Period (Years)	Subzone 1(f)	Case I (Bridge No. 59)		Case II (Bridge No. 60)		Case III (Bridge No. 104)	
	Growth factors	Growth factors	Percent Deviation	Growth factors	Percent Deviation	Growth factors	Percent Deviation
2	0.906	0.887	-2.10	0.916	1.10	0.913	0.77
5	1.431	1.415	-1.12	1.462	2.17	1.429	-0.14
10	1.776	1.78	0.23	1.808	1.80	1.761	-0.84
25	2.209	2.258	2.22	2.225	0.72	2.172	-1.67
50	2.527	2.627	3.96	2.523	-0.16	2.469	-2.30
100	2.84	3.004	5.77	2.807	-1.16	2.759	-2.85
200	3.151	3.392	7.65	3.081	-2.22	3.042	-3.46
500	3.557	3.922	10.26	3.429	-3.60	3.407	-4.22
1000	3.862	4.337	12.30	3.681	-4.69	3.677	-4.79

5.4 CONCLUSIONS

On the basis of this study following conclusions are drawn.

i. Screening of the data carried out using the annual maximum peak flood data of the Subzone 1(f) employing the Discordancy measure (D_i) test reveals that data of all the 11 bridge sites are suitable for using in regional flood frequency analysis. The L-moment based homogeneity test viz. heterogeneity measure, 'H' shows that the data of 8 sites out of the 11 sites constitute a homogeneous region. Hence, the data of these 8 sites have been used for development of regional flood frequency relationships, in this study.

ii. Various distributions viz. EV1, GEV, LOS, GLO, UNF, PE3, NOR, GNO, EXP, GPA, KAP and WAK have been employed. Regional parameters of the distributions have been estimated using the L-moments approach. Based on the L-moment ratio diagram and $|Z_i^{dist}|$-statistic criteria; GEV distribution has been identified as the robust distribution for the study area.

iii. For estimation of floods of various return periods for gauged catchments of the study area, either the developed regional flood frequency relationship may be used or the mean annual peak flood of the catchment may be multiplied by corresponding values of the growth factors, computed using the GEV distribution.

iv. For estimation of floods of desired return periods for ungauged catchments of the study area, the regional flood frequency relationship developed for ungauged catchments may be used.

v. As the regional flood frequency relationship have been developed using the data of catchments varying from 32.89 km^2 to 447.76 km^2 in area; therefore, these relationships may be expected to provide estimates of floods of various return periods for the catchments of the Subzone 1 (f), lying nearly in the same range of areal extent, as those of the input data.

vi. The data of only 8 gauging sites, varying from 23 to 33 years have been used in this study. The relationship between mean annual peak flood and catchment area is able to explain 77.3% of initial variance ($r^2 = 0.773$) and the standard error of the estimates is obtained as 0.545. Hence, the results of the study are subject to these limitations. However, the regional flood frequency relationships may be refined for obtaining more accurate flood frequency estimates; when the data for some more gauging sites become available and physiographic characteristics other than catchment area as well as some of the pertinent climatic characteristics are also used for development of the regional flood frequency relationships.

vii. Verification of the developed regional flood frequency relationship for the gauged catchments shows that the percentage deviations of flood frequency estimates for the commonly used return periods of 25, 50 and 100 years vary from 0.16% to 5.77% for the three test catchments. Thus, the developed regional flood frequency relationship provides floods of various return periods with reasonable accuracy for comparatively small, medium and large size gauged catchments of the study area.

REFERENCES

Central Water Commission.: 1985, 'Flood estimation for Middle Ganga Plain Subzone 1(f)', Report No. GP/10/1984, *Directorate of Hydrology (Small Catchments)*, New Delhi.

Chow, V. T.: 1962, 'Hydrologic determination of waterway areas for the design of drainage structures in small drainage basins', *University of Illinois, Eng. Exp. Sta. Bull.*, 462.

Farquharson, J.R.: 1992, 'Regional flood frequency analysis in arid and semi arid areas', *J. Hydrol.*, **138**(3 & 4), 487-501.

Greenwood, J.A., Landwehr, J.M., Matalas, N.C. and Wallis, J.R.: 1979, 'Probability weighted moments: Definition and relation to parameters of several distributions expressible in inverse form', *Water Resour. Res.*, **15**(5), 1049-1054.

Hosking, J.R.M. and Wallis, J.R.: 1986, 'The value of historical data in flood frequency analysis', *Water Resour. Res.*, **22**(11), 1606-1612.

Hosking, J.R.M. and Wallis, J.R.: 1988, 'The effect of intersite dependence on regional flood frequency analysis', *Water Resour. Res.*, **24**(4), 588-600.

Hosking, J. R. M.: 1990, 'L-moments: Analysis and estimation of distributions using linear combinations of order statistics', *J. Royal Stat. Soc.*, Series B, **52**(2), 105-124.

Hosking, J. R. M.: 1991, 'Approximations for use in constructing L-moment ratio diagrams', *Res. Rep., RC-16635, 3,* IBM Res. Div., T.J., Watson Res. Cent., Yorktown Heights, New York.

Hosking, J.R.M. and Wallis, J.R.: 1993, 'Some statistics useful in regional frequency analysis', *Water Resour. Res.*, **29**(2), 271-281.

Hosking, J. R. M. and Wallis, J. R.: 1997, 'Regional frequency analysis-an approach based on L-moments', Cambridge University Press, New York.

Iacobellis V. and Fiorentino M.: 2000, 'Derived distribution of floods based on the concept of partial area coverage with a climatic appeal', *Water Resour. Res.*, **36**(2), 469 - 482.

Jin, M. and Stedinger, J.R.: 1989, 'Flood frequency analysis with regional and historical information', *Water Resour. Res.*, **25**(5), 925-936.

Kumar, R., Singh, R.D. and Seth, S.M.: 1999, 'Regional flood formulas for seven subzones of zone 3 of India', *J. of Hydrol. Eng.,* ASCE, **4**(3), 240-244.

Landwehr, J.M., Matalas, N.C. and Wallis, J.R.: 1979, 'Probablity weighted moments compared with some traditional techniques of estimating Gumbel parameters and quantiles', *Water Resour. Res.*, **15**(6), 1055-1064.

Martins E.S. and Stedinger, J.R.: 2000, 'Generalised maximum-likelihood generalised extreme-value quantile estimators for hydrologic data', *Water Resour. Res.*, **36**(3), 737 - 744.

National Institute of Hydrology.: 1992, 'Hydrologic design criteria', Course Material of *Regional*

Course on Project Hydrology, Roorkee.

National Institute of Hydrology.: 1996, 'Development of regional flood frequency relationships and flood formulae for various subzones of Zone 3 of India', *Technical Report*, TR(BR)-149, Roorkee.

Peel, M.C., Wang, Q. J., Vogel, R.M. and McMahon, T.A.: 2001, 'The utility of L-moment ratio diagrams for selecting a regional probability distribution', *Hydrol. Sci. J.*, **46**(1), 147-156.

Pilgrim, D. H. and Cordery, I.: 1992, 'Flood runoff', in *Handbook of Hydrology*, edited by D. R. Maidment, Chapter 9, Mc Graw-Hill, Inc., New York.

Potter K.W. and Lettenmaier D.P.: 1990, 'A comparison of regional flood frequency estimation methods using resampling method', *Water Resour. Res.*, **26**, 415-424.

Research Design and Standards Organization.: 1991, 'Estimation of design discharge based on regional flood frequency approach for Subzones 3 (a), 3 (b), 3 (c) and 3 (e)', *Bridges and Floods Wing Report No. 20*, Lucknow.

Stedinger, J. R., Vogel, R. M. and Foufoula-Georgiou, E.: 1992, 'Frequency analysis of extreme events', in *Handbook of Hydrology*, edited by D.R. Maidment, Chapter 18, Mc Graw-Hill, Inc., New York.

Vogel R. M. and Fennessey, N. M.: 1993, 'L-moments should replace product moments diagrams', *Water Resour. Res.*, **29**(6), 1745-1752.

Wallis J.R. and Wood E.F.: 1985, 'Relative accuracy of Log-Pearson III Procedures', *J. Hydraul. Eng.*, ASCE, **111**(7), 1043-56.

Zafirakou-Koulouris, A., Vogel, R. M., Craig, S.M. and Habermeier, J.: 1998, 'L moment diagrams for censored observations', *Water Resour. Res.*, **34**(5), 1241-1249.