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Regional Flood Frequency Analysis using L-moments for Mahi and Sabarmati Subzone 3(a)

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Abstract : Estimation of flood frequencies and their magnitudes is needed for taking up various structural and non-structural measures of water resources planning, development and management. Regional flood frequency relationships are developed based on the L-moments approach. The annual maximum peak floods data are screened using the Discordancy measure (D_i) and homogeneity of the region is tested employing the L-moments based heterogeneity measure (H). For computing heterogeneity measure H, 500 simulations are performed using the Kappa distribution. Twelve frequency distributions namely Extreme value (EV1), Generalized 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) are employed. Based on the L-moments ratio diagram and $|Z_i^{dist}|$ -statistic criteria, PE3 is identified as the robust frequency distribution for the study area. For estimation of floods of various return periods for gauged catchments of the study area, the regional flood frequency relationship is developed using the L-moments based PE3 distribution. Also, for estimation of floods of various return periods for ungauged catchments, the regional flood frequency relationships developed for gauged catchments is coupled with the regional relationship between mean annual maximum peak flood and catchment area.

INTRODUCTION

Information on flood magnitudes and their frequencies is needed for design of various types of hydraulic structures such as dams, spillways, road and railway bridges, culverts, urban drainage systems; as well as for taking up non-structural measures such as 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), 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 catchments of Subzone 3 (a) of India.

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 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 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:

Probability Weighted Moments and L-Moments

$$\beta_r = E\left[x\{F(x)\}^r\right] \qquad (1)$$

which can be rewritten as:

$$\beta_r = \int_0^1 x(F)F^r\,dF \qquad (2)$$

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, b_0 is equal to the mean of the distribution ì = E[x].

For any distribution the r[th] L-moment l_r is related to the r[th] PWM (Hosking, 1990) through

$$\lambda_{r+1} = \sum_{k=0}^{r} \beta_k (-1)^{r-k} \binom{r}{k} \binom{r+k}{k} \tag{3}$$

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

$$l_1 = b_0 \tag{4}$$
$$l_2 = 2b_1 - b_0 \tag{5}$$
$$l_3 = 6b_2 - 6b_1 + b_0 \tag{6}$$
$$l_4 = 20b_3 - 30b_2 + 12b_1 - b_0 \tag{7}$$

Hosking (1990) defined L-moment ratios as:

L-coefficient of variation, L-CV (t_2) = $_2 / l_1$ (8)
L-coefficient of skewness, L-skew (t_3)=l_3 / l_2 (9)
L-coefficient of kurtosis, L-kurtosis (t_4)=l_4 / l_2 (10)

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 t_2, t_3, and t_4, expressed in equations (8) to (10). T denotes transposition of a vector or matrix. Let

$$\bar{u} = N^{-1} \sum_{i=1}^{N} u_i \tag{11}$$

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

$$A_m = \sum_{i=1}^{N} (u_i - \bar{u})(u_i - \bar{u})^T \tag{12}$$

The Discordancy measure for site i is defined as:

$$D_i = \frac{1}{3} N (u_i - \bar{u})^T A_m^{-1} (u_i - \bar{u}) \tag{13}$$

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).

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 (m_v) and standard deviation (s_v) of the computed inter-site variation is obtained. Then, heterogeneity measure H is computed as:

$$H = \frac{V - \mu_V}{\sigma_V} \tag{14}$$

The criteria for assessing heterogeneity of a region are: if H < 1, the region is acceptably homogeneous; if 1 £ H < 2, the region is possibly heterogeneous; and If H ³ 2, the region is definitely heterogeneous.

Identification of Robust 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 best fit distribution 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). The goodness-of-fit measure for a distribution, – statistic defined by Hosking and Wallis (1993), is expressed as:

$$Z_i^{dist} = \frac{\left(\bar{\tau}_i^R - \tau_i^{dist}\right)}{\sigma_i^{dist}} \quad (15)$$

Where, is the weighted regional average of L-moment statistic i, and 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 ||–statistic is sufficiently close to zero, a reasonable criterion being || –statistic less than 1.64.

STUDY AREA AND DATA AVAILABILITY

The Subzone 3 (a) is traversed by the rivers Mahi, Sabarmati, Saraswati and a large number of coastal streams. The general elevation of this Subzone varies from 0 to 600 m above mean sea level. This Subzone lies in semi-arid region. Annual maximum peak flood data of 10 gauging sites lying in Subzone 3(a), varying over 11 to 33 years in record length are available for study.

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 Wake by (WAK). Screening of the data, testing of regional homogeneity, identification of the regional distribution and development of regional flood frequency relationship are described below.

Screening of Data Using Discordancy Measure Test

Values of Discordancy measure have been computed in terms of the L-moments for all the 10 gauging sites of Subzone 3 (a). It is observed that the D_i values for all the 10 sites vary from 0.36 to 1.89 and are less than the critical D_i value of 2.491. Hence, as per the Discordancy measure test, data of all the 10 sites may be utilised for carrying out the flood frequency analysis.

The details of catchment area and sample statistics for 10 sites are given in Table 1 along with Discordancy measure (D_i) values.

Test of Regional Homogeneity

The value of the heterogeneity measure (H) was computed for Subzone 3 (a) by carrying out 500 simulations using the Kappa distribution utilising the data of 10 gauging sites. Its value was computed as 0.46. As this value of H is less than 1; hence, the Subzone 3 (a) comprising of 10 stream flow gauging sites is found to be a homogenous region.

Identification of Robust Regional Frequency Distribution

The $|Z_i^{dist}|$ –statistic is used as the best fit criteria for identifying the robust distribution for the study area. The regional average values of L-skewness i.e. t_3 = 0.3268 and L-kurtosis i.e. t_4 = 0.1602 are obtained. The Z_i^{dist} –statistic for various three parameter distributions is given in Table 2. It is observed that the $|Z_i^{dist}|$ –statistic values are lower than 1.64 for the three distributions viz. PE (3), GPA and GNO. Further, the | |–statistic is found to be the lowest for PE (3) distribution i.e. 0.06; which is very close to 0.0. Thus, based on the || –statistic criteria, the PE (3) distribution is identified as the robust distribution for the Subzone 3 (a).The values of regional parameters

Table 1. Catchment area and sample statistics for 10 bridge sites of Subzone 3 (a)

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)
253	48.43	189.68	119.78	0.631	0.682	19	0.36
334	18.44	75.59	87.79	1.161	3.160	17	1.20
5	230.00	352.72	416.40	1.181	1.688	18	1.89
99	144.50	258.14	176.69	0.684	0.837	21	1.72
945	231.11	212.07	181.75	0.857	0.963	14	0.53
26	1094.00	448.65	328.27	0.732	0.931	20	0.53
11	98.16	164.67	150.89	0.916	2.606	18	0.47
141	73.19	108.94	81.80	0.751	0.502	17	0.90
8	30.14	74.00	72.31	0.977	1.828	25	1.46
46	580.00	352.95	309.26	0.876	0.898	22	0.93

for the various distributions which have ll –statistic value less than 1.64 are given in Table 3.

Development of Regional Flood Frequency Relationship for Gauged Catchments As PE (3) distribution has been identified as the robust distribution for the study area; hence, regional flood frequency relationships have been developed using this distribution.

Pearson type-III distribution (PE (3))

The inverse form of the PE (3) distribution is not explicitly defined. Hosking and Wallis (1997) mention that the Pearson type-III distribution combines Gamma distributions (which have positive skewness), reflected Gamma distributions (which have negative skewness) and the normal

Table 2. Z_i^{dist} -statistic for various distributions for Subzone 3 (a)

Sl. No.	Distribution	Z_i^{dist} -statistic
1	PE (3)	-0.06
2	GPA	-0.14
3	GNO	1.13
4	GEV	1.82
5	GLO	2.51

Table 3. Regional parameters for the various distributions for Subzone 3 (a)

Distribution	Parameters of the distribution		
PE (3)	$\mu = 1.000$	$\sigma = 0.890$	$\gamma = 1.961$
GPA	$\xi = 0.099$	$\alpha = 0.914$	$k = 0.015$
GNO	$\xi = 0.748$	$\alpha = 0.651$	$k = -0.686$

distribution (which has zero skewness). The authors parameterize the Pearson type-III distribution by its first three conventional moments viz. mean m, the standard deviation s, and the skewness g. The relationship between these parameters and those of the Gamma distribution is as follows. Let X be a random variable with a Pearson type-III distribution with parameters m, s and g. If g > 0, then X - m + 2 s/g has a Gamma distribution with parameters $a = 4/g^2$, = s g/2. If g = 0, then X has normal distribution with mean m and standard deviation, s. If g < 0, then -X + m - 2 s/g has a Gamma distribution with parameters a = $4/g^2$, = ç g/2ç. If g ¹ 0, let a = $4/g^2$, b = çs g/2ç, and x = m - 2s/g and G (.) is Gamma function. If g > 0, then the range of x is x £ x < µ and the cumulative distribution function is:

$$F(x) = G\left(\alpha, \frac{x-\xi}{\beta}\right) \Big/ \Gamma(\alpha\alpha \tag{16}$$

If g < 0, then the range of x is -µ < x £ x and the cumulative distribution function is:

$$F(x) = 1 - G\left(\alpha, \frac{\xi - x}{\beta}\right) \Big/ \Gamma(\alpha) \tag{17}$$

By substituting regional values of the PE (3) distribution the growth factors given in Table 4 are computed. For estimation of floods of desired return periods (Q_T) for a small to moderate size gauged catchment of Subzone 3 (a), the mean annual peak flood of the catchment ($\overline{Q}$) may be multiplied by the corresponding value of growth factors(Q_T/).

Regional Flood Frequency Relationship for Ungauged Catchments

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 cannot 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. Fig. 1 shows variation of mean annual peak flood with catchment area for the study area. The regional relationship developed for the region in log domain using least squares approach based on the data of 10 gauging sites is given below.

$$\overline{Q} = 20.818\,(A)^{0.457} \tag{18}$$

Where, A is the catchment area, in km^2 and $\overline{Q}$ is the mean annual peak flood in m^3/s. For Eq. (18), the coefficient of determination is, $r^2 = 0.917$.

The values of floods of various return periods for ungauged catchments of the study area may be estimated using the following equation, which has been developed by coupling the regional flood frequency relationship of estimation of floods of various return periods for gauged catchments with the regional relationship between mean annual peak flood and catchment area (eq. 18).

$$Q_T = C_T\,(A)^{0.457} \tag{19}$$

Where, Q_T is the flood estimate for T year return period, C_T is the regional coefficient for T year return period and A is the area of ungauged catchment.

Floods of various return periods for ungauged catchments may also be estimated using the equation (19) and values of "C_T" and "b" given in Table 5.

Table 4. Values of growth factors ($Q_T/\overline{Q}$) for various distributions for Subzone 3 (a)

Distribution	Return period (Years)								
	2	5	10	25	50	100	200	500	1000
	Growth factors								
PE3	0.731	1.446	1.788	2.200	2.493	4.191	4.800	5.905	6.213

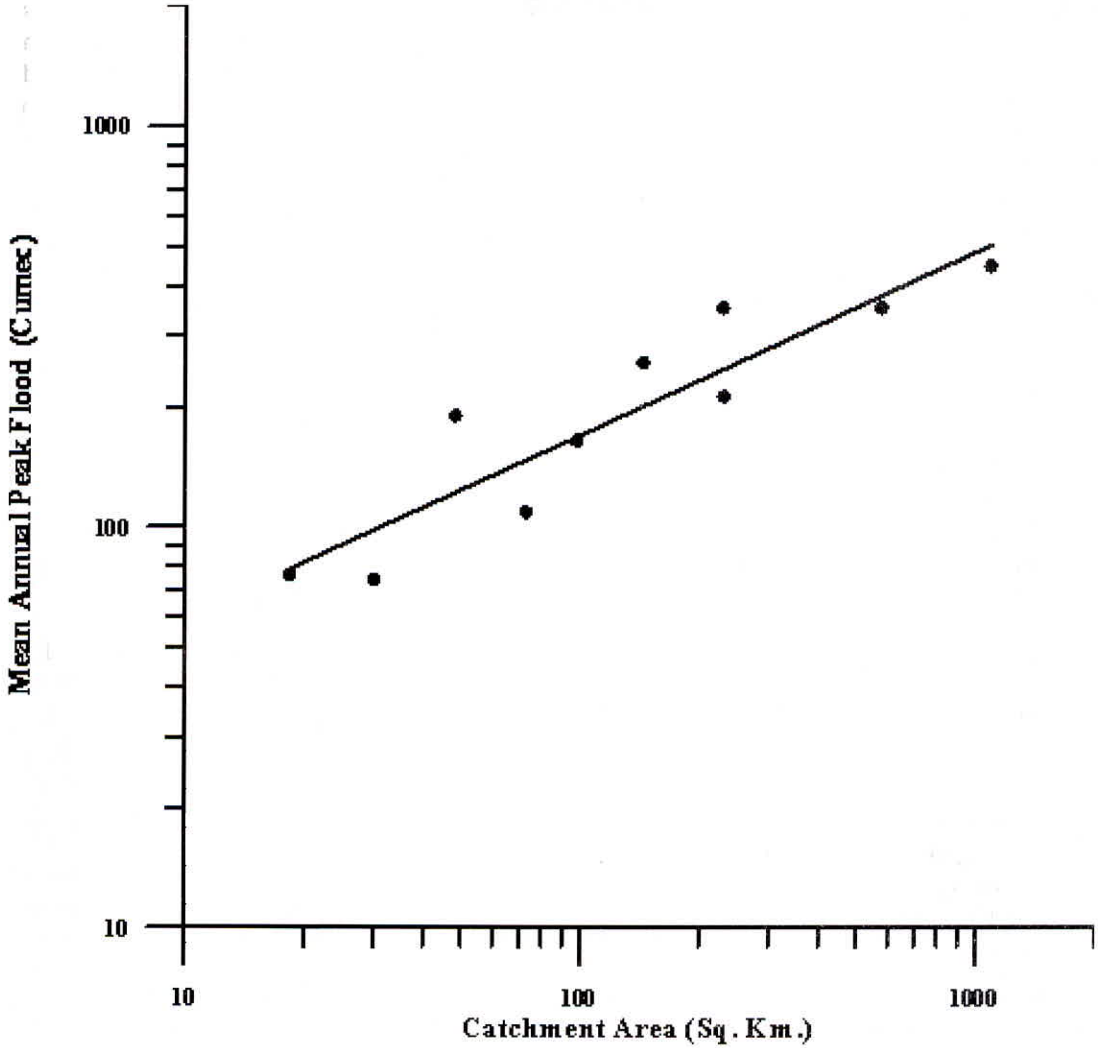

Fig. 1. Variation of mean annual peak flood with catchment area for Subzone 3 (a)

Table 5. Values of regional coefficients 'b' and 'C_T' for Subzone 3(a)

Coeff. 'b'	Return Period (Years)							
	2	10	25	50	100	200	500	1000
	Values of C_T							
0.457	15.218	37.223	45.800	51.899	87.248	99.926	122.930	129.342

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 3 (a) employing the Discordancy measure (D_i) test reveals that data of all the 10 gauging sites are suitable for regional flood frequency analysis. The L-moment based heterogeneity measure, 'H' shows that the data of all the 10 sites constitute a homogeneous region.

ii. Various distributions viz. EV1, GEV, LOS, GLO, UNF, PE (3), 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 $|Z_i^{dist}|$–statistic criteria; PE (3) distribution has been identified as the robust distribution for the study area.

iii. The developed regional flood frequency relationships are especially useful for estimation of floods of various return periods for the catchments having inadequate or short record length data.

iv. For estimation of floods of various return periods for gauged catchments of the study area the mean annual peak flood of the catchment may be multiplied by corresponding values of the growth factors, computed using the PE (3) distribution.

v. For estimation of floods of various return periods for ungauged catchments of the study area the regional relationship developed for the study area may be used.

vi. As the regional flood frequency relationships have been developed using the data of catchments varying from 18.44 km^2 to 1094.00 km^2 in area; hence, these relationships are be expected to provide estimates of floods of various return periods for catchments of the Subzone 3 (a), lying nearly in the same range of areal extent, as those of the input data.

vii. For the regional relationship between mean annual peak flood and catchment area the value of coefficient of determination is obtained as 0.917. Hence, this relationship is able to explain a variance of 91.7% and the flood frequency estimates of the ungauged catchments are subject to the error explained by this relationship.

viii. 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.

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