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# DEVELOPMENT OF REGIONAL FOOD FREQUENCY RELATIONSHIPS USING L-MOMENTS AND A RELOOK ON HYDROLOGIC DESIGN CRITERIA UNDER CLIMATIC CHANGE

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## ABSTRACT

*L-moments are a recent development within statistics and offer significant advantages over ordinary product moments. Comparative regional flood frequency analysis studies are carried out using the L-moments approach employing the twelve frequency distributions. Based on the L-moments ratio diagram and $|Z_i^{dist}|$ -statistic criteria, Pearson Type-III (PE3) distribution is identified as the robust frequency distribution for the study area. Regional flood frequency relationships are developed for gauged catchments using the L-moments based robust identified PE3 frequency distribution. For estimation of floods of various return periods for ungauged catchments, a regional relationship between mean annual peak flood and catchment area is developed and the same is coupled with the regional flood frequency relationship derived for the gauged catchments. The percentage increases in flood frequency estimates are computed by comparing floods of various return periods with the floods of increased return periods, with a view to modify the hydrologic design criteria for various types of hydraulic structures for considering the impact of climate change.*

**Keywords**: *Regional flood frequency, L-moments, ungauged catchments, discordancy measure, regional homogeneity, hydrologic design criteria, climate change.*

## INTRODUCTION

Information on flood magnitudes and their frequencies is needed for design of various types of water resources projects/ hydraulic structures such as dams, spillways, road and railway bridges, culverts, urban drainage systems as well as for taking up various non-structural measures such as flood plain zoning, economic evaluation of flood protection projects etc. Since scientific hydrology began in the seventeenth century, one of the most difficult problems facing engineers and hydrologists is how to predict flow in basins with no records. Whenever rainfall or river flow records are not available at or near the site of interest, it is difficult for hydrologists or engineers to derive reliable design flood estimates directly. In such a situation, regional flood frequency relationships developed for the region are one of the alternative methods for prediction of design floods, especially for small to medium size catchments.

The approaches for design flood estimation may be broadly categorized as: (i) deterministic approach using design storm, and (ii) probabilistic approach involving flood frequency analysis. The deterministic and probabilistic methods, which have been used for design flood estimation, are: empirical methods, rational method, flood frequency analysis methods, unit hydrograph techniques, and watershed models. 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 state that hundreds of different methods have been used for estimating floods on small drainage basins, most involving arbitrary formulas. Regional flood frequency analysis resolves the problem of short data records or unavailability of data by "trading space for time"; as the data from several sites are used in estimating flood frequencies at any site (Hosking and Wallis, 1997). The choice of method primarily depends on design criteria applicable to the structure and availability of data.

Considering the importance of prediction in ungauged catchments, the International Association of Hydrological Sciences (IAHS) launched "Prediction of Ungauged Basins (PUBs)" as one of its initiatives and declared the current decade as "Decade of PUBs". As per the Bureau of Indian Standards (BIS) hydrologic 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. Most of the small size catchments are ungauged or sparsely gauged. Zafirakou-Koulouris et al. (1998) summarized the advantages of the L-moments. Kumar et al. (2003, 2005, 2015) applied L-moments approach for development of regional flood frequency relationships for some of the regions of India. Chang et al. (2016) presented a comparison of annual maximum and partial duration series for derivation of rainfall Intensity-Duration-Frequency relationships in Peninsular Malaysia. Basu and Srinivas (2016) evaluated the index-flood approach related regional frequency analysis procedures. To overcome the problems of prediction of floods of various return periods for ungauged and sparsely gauged catchments, a robust procedure of regional flood frequency estimation is required to be developed. In this study, regional flood frequency relationships are developed based on the L-moments approach for the gauged and ungauged catchments of Lower Godavari Subzone 3(f) in India.

## L-MOMENTS APPROACH

Some of the commonly used parameter estimation methods for most of the frequency distributions include: (i) method of least squares, (ii) method of moments, (iii) method of

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maximum likelihood, (iv) method of probability weighted moments, (v) method based on principle of maximum entropy, and (vi) method based on L-moments. 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). Like the 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).

Recently a number of regional flood frequency analysis studies have been carried out based on the L-moments approach. The 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). The L-moments offer significant advantages over ordinary product moments, especially for environmental data sets, because of the following (Zafirakou-Koulouris et al., 1998).

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).

**Probability Weighted Moments and L-Moments**

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

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

which, can be rewritten as:

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

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, …, is a nonnegative integer. When r = 0, $\beta_0$ is equal to the mean of the distribution $\mu = E[x]$.

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

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

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

$$\lambda_1 = \beta_0 \quad (4)$$

$$\lambda_2 = 2\beta_1 - \beta_0 \quad (5)$$

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

$$\lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \quad (7)$$

Hosking (1990) defined L-moment ratios as:

L-coefficient of variation, L-CV ($\tau_2$) = $\lambda_2 / \lambda_1$ (8)

L-coefficient of skewness, L-skew ($\tau_3$) = $\lambda_3 / \lambda_2$ (9)

L-coefficient of kurtosis, L-kurtosis ($\tau_4$) = $\lambda_4 / \lambda_2$ (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 $\tau_2$, $\tau_3$, and $\tau_4$, expressed in Eqs. (8) to (10). T denotes transposition of a vector or matrix. Let be the (unweighted) group average. The matrix of sums of squares and cross products is defined as:

$$\bar{u} = N^{-1}\sum_{i=1}^{N} u_i \quad (11)$$

The Discordancy measure for site i is defined as:

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

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

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 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 ($\mu_v$) and standard deviation ($\sigma_v$) of the computed inter-site variation is obtained. Then, heterogeneity measure H is computed as:

$$H = \frac{V - \mu_V}{\sigma_V} \quad (14)$$

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 ≥ 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 and Wallis, 1997). Further, the goodness-of-fit measure for a distribution, $Z_i^{dist}$ – statistic defined by Hosking and Wallis (1997) is expressed as:

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

Where, $\bar{\tau}_i^R$ is weighted regional average of L-moment statistic i, $\tau_i^{dist}$ and $\sigma_i^{dist}$ 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.

## STUDY AREA AND DATA AVAILABILITY

The Lower Godavari Subzone 3(f) lies between latitudes of $17^0$ to $23^0$ North and longitudes of $76^0$ to $83^0$ East. The Godavari river rises in the eastern side of the Western Ghats at an elevation of 1067 m. Lower Godavari Subzone 3 (f) is a sub-humid region with elevation varying from 150 meters to 1350 meters in its various portions. The Subzone receives about 75% to 80% rainfall of its annual rainfall from southwest monsoon during the period of June to October. The broad soil groups in the Subzone are red soils and black soils. The red soils are either classified into red sandy, red loamy and red yellow soils. Black soils are classified as deep black, medium black and shallow black soils. The black soils are clayey in texture and are derived from trap rocks. The texture of the red soils varies considerably from place to place and is derived from all groups. More than 50% of the area is covered by forests. Arable land is of the order of 25%. Annual maximum peak flood data of 19 stream flow gauging sites are available for carrying out the study. The catchment areas of these sites vary from 35 to 824 $km^2$ and their mean annual peak flood range from 77.75 to 1212.83 $m^3/s$. The sample size of data ranges from14 to 29 years.

## ANALYSIS AND DISCUSSION OF RESULTS

Regional flood frequency analysis was performed using the various frequency distributions: viz. 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). Screening of the data, testing of regional homogeneity, identification of the regional distribution and development of regional flood frequency relationships are described below.

**Screening of Data Using Discordancy Measure Test**

Values of discordancy statistic have been computed in terms of the L-moments for all the 19 gauging sites of the study area. It is observed that the $D_i$ values for all the 19 sites are lower than the critical value of $D_i$ i.e. 3.00 (Hosking and Wallis, 1997). The $D_i$ values for 16 sites, which are considered suitable for carrying out regional flood frequency analysis after conducting the regional homogeneity test as discussed in the following section vary from 0.0112 to 0.1157 and the same are given in Table 1, along with catchment area, mean annual peak flood, sample size, L-CV, L-skewness and L-kurtosis.

**Table 1: Catchment area, mean annual peak flood, sample size, sample statistics and discordancy statistic for Lower Godavari Subzone 3(f)**

| Stream Gauging Site | Catchment Area ($km^2$) | Mean Annual Peak Flood ($m^3/s$) | Sample Size (Years) | L-CV ($\tau_2$) | L-skew ($\tau_3$) | L-kurtosis ($\tau_4$) | Discordancy Statistic ($D_i$) |
|---|---|---|---|---|---|---|---|
| 184 | 364 | 344.483 | 29 | 0.3879 | 0.2106 | 0.1462 | 0.0366 |
| 57 | 163 | 189.393 | 28 | 0.2567 | 0.1229 | 0.1154 | 0.0675 |
| 973/1 | 362 | 505.036 | 28 | 0.3414 | 0.0600 | 0.0323 | 0.0713 |
| 912/1 | 137 | 404.862 | 29 | 0.4042 | 0.2779 | 0.1095 | 0.0163 |
| 20 | 60 | 204.714 | 28 | 0.3335 | 0.0219 | 0.0529 | 0.0954 |
| 4 | 35 | 77.750 | 24 | 0.2813 | 0.2460 | 0.2389 | 0.0710 |
| 214 | 87 | 206.680 | 25 | 0.2802 | 0.0747 | 0.1428 | 0.1367 |
| 51 | 824 | 1212.826 | 23 | 0.3730 | 0.1823 | 0.0663 | 0.1009 |
| 807/1 | 483 | 1075.273 | 22 | 0.3827 | 0.2806 | 0.1172 | 0.0112 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 228 | 459 | 854.913 | 23 | 0.3767 | 0.1968 | 0.1170 | 0.0261 |
| 15 | 158 | 307.783 | 23 | 0.2855 | 0.0763 | 0.0990 | 0.0973 |
| 881/1 | 751 | 778.095 | 21 | 0.4119 | 0.0773 | 0.0030 | 0.0942 |
| 875/1 | 53 | 93.882 | 17 | 0.2992 | 0.3648 | 0.2357 | 0.0937 |
| 36 | 139 | 170.800 | 15 | 0.4150 | 0.3185 | 0.2357 | 0.0883 |
| 224 | 750 | 687.357 | 14 | 0.4067 | 0.3365 | 0.2431 | 0.0638 |
| 65 | 731 | 725.133 | 15 | 0.4147 | 0.4224 | 0.2557 | 0.1157 |

**Table 2: Heterogeneity measures for Lower Godavari Subzone 3(f)**

| Sl. No. | Heterogeneity measures | Values |
|---|---|---|
| 1. | Heterogeneity measure H(1) | |
| | (a) Observed standard deviation of group L-CV | 0.0539 |
| | (b) Simulated mean of standard deviation of group L-CV | 0.0465 |
| | (c) Simulated standard deviation of standard deviation of group L-CV | 0.0084 |
| | **(d) Standardized test value H(1)** | **0.8800** |
| 2. | Heterogeneity measure H(2) | |
| | (a) Observed average of L-CV / L-Skewness distance | 0.1140 |
| | (b) Simulated mean of average L-CV / L-Skewness distance | 0.0911 |
| | (c) Simulated standard deviation of average L-CV / L-Skewness distance | 0.0143 |
| | **(d) Standardized test value H(2)** | **1.600** |
| 3. | Heterogeneity measure H(3) | |
| | (a) Observed average of L-Skewness/L-Kurtosis distance | 0.1193 |
| | (b) Simulated mean of average L-Skewness/L-Kurtosis distance | 0.1083 |
| | (c) Simulated standard deviation of average L-Skewness/L-Kurtosis distance | 0.0162 |
| | **(d) Standardized test value H(3)** | **0.6800** |

**Test of Regional Homogeneity**

The values of the heterogeneity measures H(1), H(2) and H(3) were computed utilising the data of 19 gauging sites by generating 500 regions using the fitted Kappa distribution. The data sample comprising of 16 gauging sites and yielding H(1), H(2) and H(3) values as 0.88, 1.60 and 0.68 is considered as homogeneous. The values of heterogeneity measures computed by carrying out 500 simulations using the Kappa distribution based on the data of 16 sites of the study area are given in Table 2.

The L-moment ratio diagram and $|Z_i^{dist}|$ –statistic are used as the best fit criteria for identifying the robust distribution for the study area. The regional average values of L-skewness i.e. $\tau_3$ = 0.1962 and L-kurtosis i.e. $\tau_4$ = .0918 are estimated for the study area. Figure 1 shows the L-moments ratio diagram for the study area. The $Z_i^{dist}$ –statistic for various three parameter distributions is given in Table 3. It is observed that the $|Z_i^{dist}|$ –statistic values are lower than 1.64 for the three distributions viz. PE3, GNO and GEV. Further, the $|Z_i^{dist}|$ –statistic value of 0.35 is found to be the lowest for the PE3. Thus, based on the L-moment ratio diagram and $|Z_i^{dist}|$ –statistic criteria, the PE3 distribution is identified as the robust distribution for the study area. The values of regional parameters for the various distributions which have $Z^{dist}$ –statistic value less than 1.64 (i.e. distributions accepted at the 90% confidence level) as well as the five parameter Wakeby distribution are given in Table 4. The regional parameters of the Wakeby distribution have been included in Table 4 because, the Wakeby distribution has five parameters, more than most of the common distributions and it 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. It is preferred to use Wakeby distribution for heterogeneous regions (Hosking and Wallis, 1997).

**Regional Flood Frequency Relationship for Gauged Catchments**

Floods of various return periods may be computed by multiplying mean annual peak flood of a catchment by the corresponding values of growth factors of PE3 distribution given in Table 5. The growth factor or site-specific scale factor ($Q_T$ / $\overline{Q}$) is computed by dividing flood quantile ($Q_T$) by the annual mean peak flood of a gauging site ($\overline{Q}$).

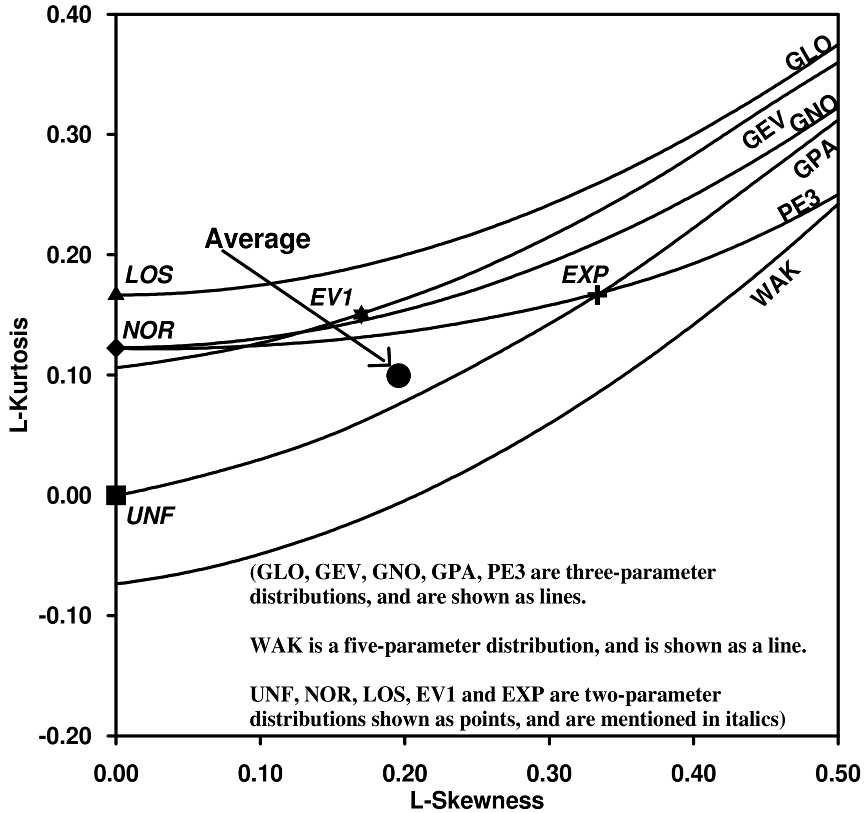


**Fig 1: L-moment Ratio Diagram for Lower Godavari Subzone 3(f)**

**Table 3: $Z_i^{dist}$ statistic for various distributions of Lower Godavari Subzone 3(f)**

| S. No. | Distribution | $Z_i^{dist}$ –statistic |
|---|---|---|
| 1. | **Pearson Type III (PE3)** | **0.35** |
| 2. | Generalized Normal (GNO) | 1.10 |
| 3. | Generalized Extreme Value (GEV) | 1.42 |
| 4. | Generalized Pareto (GPA) | 2.66 |
| 5. | Generalized logistic (GLO) | 3.24 |

**Table 4: Regional parameters for various distributions for Lower Godavari Subzone 3(f)**

| Distribution | Parameters of the Distributions | | | | |
|---|---|---|---|---|---|
| **PE3** | **$\mu$ = 1.000** | **$\sigma$ = .643** | **$\gamma$ = 1.131** | | |
| GNO | $\xi$ = .884 | $\alpha$ = .581 | k = -.385 | | |
| GEV | $\xi$ = .704 | $\alpha$ = .491 | k = -.026 | | |
| WAK | $\xi$ = .096 | $\alpha$ = 1.257 | $\beta$ = 2.591 | $\gamma$ = .573 | $\delta$ = -.034 |

**Regional Flood Frequency Relationship for Ungauged Catchments**

For ungauged catchments the at-site mean cannot be computed in absence of the observed flow data. Hence, 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. The regional relationship in the form of a power law ($Y = aX^b$) is developed for the region using the least squares approach on the data of 16 gauging sites and is given below.

$$\overline{Q} = 6.22\ A^{0.75} \quad (16)$$

Where, A is the catchment area, in $km^2$ and $\overline{Q}$ is the mean annual peak flood in $m^3/s$. For Eq. (16), the coefficient of determination is, $r^2 = 0.854$.

For development of regional flood frequency relationship for ungauged catchments, the regional flood frequency relationship developed for gauged catchments is coupled with regional relationship between mean annual peak flood and catchment area, given in Eq. (16) and following regional frequency relationship is developed.

$$Q_T = C_T * A^{0.75} \quad (17)$$

**Table 5: Values of growth factors ($Q_T / \overline{Q}$) for Lower Godavari Subzone 3 (f)**

| Distribution | Return period (Years) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 | 10 | 20 | 25 | 50 | 100 | 200 | 500 | 1000 |
| | Growth factors | | | | | | | | |
| **PE3** | **0.881** | **1.862** | **2.221** | **2.333** | **2.671** | **2.998** | **3.317** | **3.728** | **4.034** |
| GNO | 0.884 | 1.846 | 2.218 | 2.336 | 2.703 | 3.071 | 3.444 | 3.946 | 4.335 |
| GEV | 0.885 | 1.841 | 2.219 | 2.341 | 2.719 | 3.102 | 3.490 | 4.013 | 4.417 |
| WAK | 0.893 | 1.849 | 2.213 | 2.328 | 2.680 | 3.024 | 3.361 | 3.793 | 4.112 |

**Table 6: Values of regional coefficient $C_T$ for Lower Godavari Subzone 3 (f)**

| Distri-bution | Return period (Years) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2 | 10 | 25 | 50 | 100 | 200 | 1000 |
| | Values of Regional Coefficient $C_T$ | | | | | | |
| PE3 | 5.479 | 11.581 | 14.511 | 16.613 | 18.647 | 20.631 | 25.091 |

Where $Q_T$ is the flood estimate in $m^3/s$ for T year return period, and A is the catchment area of the ungauged catchment in $km^2$ and $C_T$ is a regional coefficient. Values of $C_T$ for some of the commonly used return periods are given in Table 6.

The above regional flood frequency relationship (Eq. 17) may be used for estimation of floods of desired return periods for ungauged catchments of the Lower Godavari Subzone 3 (f).

## COMPARISON OF FLOOD FREQUENCY ESTIMATES WITH INCREASED RETURN PERIODS DUE TO CLIMATE CHANGE

Now a day, it is generally felt that extreme flood events are likely to be affected due to impact of climate change. In this regard, the large flood events are expected to increase because of possibly increase in intensity of severe rainfall and urbanization of the catchments etc. Therefore, the hydrologic

**Table 7: Comparison of Flood Frequency Estimates with Increased Return Periods due to Climate Change**

| Cases | Existing Return Periods (Years) | Growth Factors for existing Return Periods | Return Periods Increased by 50% (Years) | Growth factors for 50% Increased Return Periods | Percentage Increase in Growth Factors |
|---|---|---|---|---|---|
| 1 | 10 | 1.862 | 15 | 2.019 | 8.43 |
| 2 | 20 | 2.221 | 30 | 2.363 | 6.40 |
| 3 | 25 | 2.333 | 37 | 2.467 | 5.74 |
| 4 | 50 | 2.671 | 75 | 2.818 | 5.50 |
| 5 | 100 | 2.998 | 150 | 3.1432 | 4.84 |
| 6 | 200 | 3.317 | 300 | 3.508 | 5.75 |
| 7 | 500 | 3.728 | 750 | 3.963 | 6.30 |
| 8 | 1000 | 4.034 | 1500 | 4.307 | 6.77 |

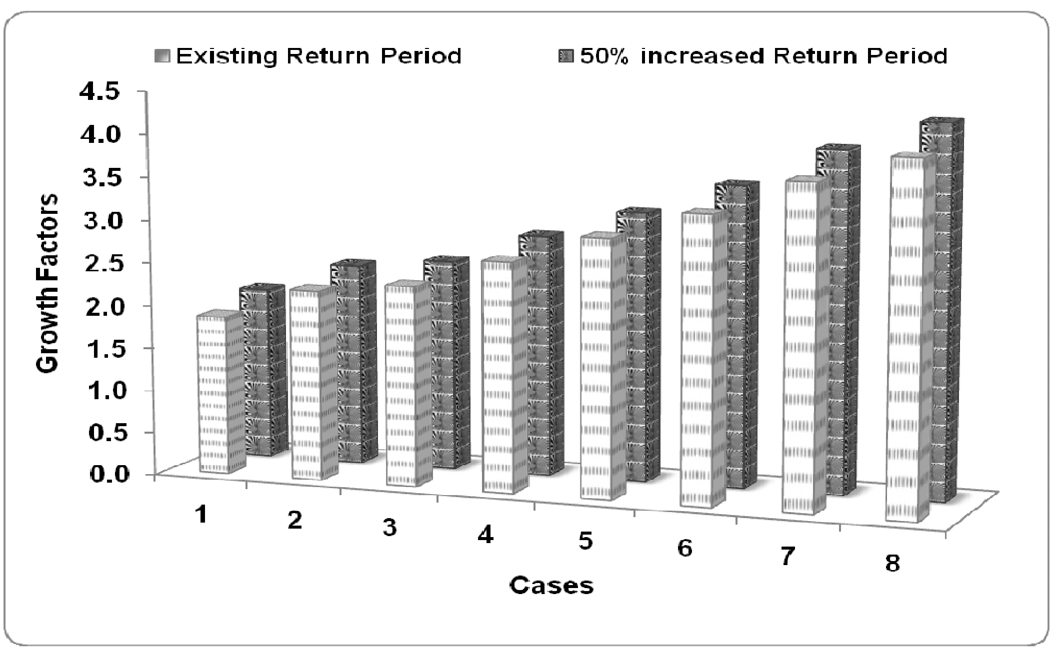


**Fig 2: Variation of growth factors with existing return periods and 50% increased return Periods**

design criteria for design of various types of hydraulic structures need to be re-looked. For analyzing this aspect, the flood frequency estimates are computed for 50% increased return periods and the resulting increase in the corresponding growth factors is given in Table 7. Fig.2 shows a comparison of growth factors of the existing return periods and the growth factors for the increased return periods.

## CONCLUSION

Screening of the data conducted using the annual maximum peak flood data of the Lower Godavari Subzone 3 (f) employing the discordancy measure ($D_i$) test reveals that the data of all the 19 stream flow gauging sites are suitable for regional flood frequency analysis. However, based on the heterogeneity measures, `H(j)'; the annual maximum peak flood data of 16 stream flow gauging sites are considered to constitute a homogeneous region and the same are used for regional flood frequency analysis. Various distributions viz. EV1, GEV, LOS, GLO, UNF, PE3, NOR, GNO, EXP, GPA, KAP and WAK are employed. Based on the L-moments ratio diagram and $|Z_i^{dist}|$ –statistic criteria, the PE3 distribution is identified as the robust distribution for the study area. Regional flood frequency relationship is developed for estimation of floods of various return periods for the gauged catchments using the PE3 distribution. For estimation of floods of various return periods for the ungauged catchments of the study area, the regional flood frequency relationship developed for estimation of floods of various return periods for the gauged catchments is coupled with the regional relationship developed between mean annual peak flood and the catchment area of the gauged catchments. A comparison of flood frequency estimates of the 50% increased return periods with the flood frequency estimates of the prevalent return periods shows that floods are increased by an average of about 6.22% for the study area.

As the regional flood frequency relationships are developed using the data of catchments varying from 35 to 824 $km^2$ in area; hence, these relationships are expected to provide estimates of floods of various return periods for catchments lying nearly in the same range of the areal extent. Further, the relationship between mean annual peak flood and catchment area is able to explain 85.4% of initial variance ($r^2 = 0.854$). Hence, in case of ungauged catchments 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.

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