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DEVELOPMENT OF REGIONAL FLOOD FREQUENCY RELATIONSHIPS USING L-MOMENTS FOR SOUTH BIHAR/JHARKHAND

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PREFACE

Estimation of magnitudes of likely occurrence of floods is of immense importance for solution of a variety of water resources problems such as design of various hydraulic structures, urban drainage systems, flood plain zoning and economic evaluation of flood protection works etc. 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 flood estimates directly. In such a situation, the regional flood frequency relationships or the flood formulae developed for the region are one of the alternative methods which may be adopted for estimation of design flood specially for small catchments. Most of the flood formulae developed for different regions of the country are empirical in nature and do not provide flood estimates for the desired return periods. Hence, there is a need for developing the regional flood formulae for estimation of floods of desired return periods for different regions of the country, based on recently developed improved and efficient techniques of flood frequency analysis.

Regional frequency analysis basically involves substitution of "space for time" where data from different sites in a region are used to compensate for short records at a site and provides an alternative method for estimation of flood frequency estimates for ungauged catchments lying in the region . In this study, based on the recently introduced goodness of fit approaches viz. L-moment ratio diagram and Z^{Dist} statistics criteria; Pearson Type-III (PT-III) distribution has been identified as the robust distribution among the commonly used frequency distributions. For estimation of floods of desired return periods for the small to medium size gauged catchments, the regional flood frequency relationships have been developed using the L–moment based PT-III distribution for small to medium size catchments of South Bihar/Jharkhand. The L-moment based regional flood frequency curves derived for the PT-III distribution have also been coupled with the relationship between mean annual peak flood and the catchment area and the regional flood formula has been developed for estimation of floods of desired return periods for ungauged catchments of the study area.

The study has been carried out by Shri Rakesh Kumar, Dr. C. Chatterjee, Dr. Sanjay Kumar, Shri A. K. Lohani and Shri R.D. Singh Scientists of the Institute. Technical assistance has been provided by Shri Atm Prakash, R.A. and Shri A. K. Sivadas, Technician. It is expected that the regional flood frequency relationship developed for South Bihar/Jharkhand region, together with at-site mean annual peak floods will provide rational flood frequency estimates for gauged catchments of South Bihar/Jharkhand, while for computing the floods of desired return periods for the ungauged catchments of South Bihar/Jharkhand the developed regional flood formula may serve as an useful alternative.

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ABSTRACT

For planning and design of various types of water resources projects, estimation of flood magnitudes and their frequencies has been engaging attention of the engineers the world over since time immemorial. 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 flood frequency estimates directly. In such a situation, the regional flood frequency relationships or the flood formulae developed for the region are one of the alternative methods which provide estimates of design floods especially for small to moderate size catchments.

In this study, annual maximum peak flood data of 22 gauging sites lying in the states of Bihar/Jharkhand have been used. The states of Bihar/Jharkhand comprises of alluvial plains of Indo-Gangetic basin and Kaimur-Chotanagpur Santhal Pargana plateau. Catchment areas of these sites vary from 11.7 to 3171 square kilometers. Mean annual peak floods of these sites vary from 29.15 cumec to 1293.20 cumec. Comparative regional flood frequency analysis studies have been carried out using some of the commonly used frequency distributions viz. Extreme Value (EV1), General Extreme Value (GEV), Normal, Log Normal, Pearson Type-III (PT-III), Generalized Logistic (GLO), Exponential, Generalized Pareto (GPA), and Wakeby, based on L-moments approach. L-moments of a random variable were first introduced by Hosking (1986). They are analogous to conventional moments, but are estimated as linear combinations of order statistics. Hosking (1986, 1990) defined L-moments as linear combinations of the PWMs. In a wide range of hydrologic applications, L-moments provide simple and efficient estimators of characteristics of hydrologic data and of a distribution's parameters (Stedinger et al., 1992). Based on the L-moment ratio diagram and Z^{Dist} statistics criteria, Pearson Type-III (PT-III) distribution has been identified as the robust distribution for the study area. For estimation of floods of various return periods for the gauged catchments of the study area, the regional flood frequency relationship has been developed using the Pearson Type-III (PT-III) distribution based regional flood frequency curves derived by utilising the L-moments approach. For estimation of floods of desired return periods for the ungauged catchments, the regional flood formula has been developed by coupling the regional flood frequency curves of the L-moments based Pearson Type-III distribution and regional relationship between annual maximum peak flood and catchment area. Thus, for estimation of floods of various return periods for the gauged catchments, the derived regional flood frequency relationship may be employed; whereas, the developed regional flood formula or its graphical representation may be used for estimation of floods of desired return periods for the ungauged catchments of study area.

1.0 INTRODUCTION

Information on flood magnitudes and their frequencies is often 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. 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 flood estimates directly. In such a situation, flood formulae developed for the region are one of the alternative methods for estimation of design floods, especially for small to medium size catchments. The conventional flood formulae developed for different regions of India are empirical in nature and do not provide estimates for desired return period. A number of studies have been carried out for estimation of design floods for various structures by different Indian organizations. Prominent among these include the studies carried out 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 USGS and pooled curve methods (e.g. RDSO, 1991) for various hydrometeorological subzones of India.

Use of a Generalised Extreme Value (GEV) distribution as a regional flood frequency model with an index flood approach has received considerable attention (Chowdhury et al., (1991). Some of the recent studies based on index flood approach include Wallis and Wood (1985), Hosking et al. (1985), Hosking and Wallis (1986), Lettenmaier et al. (1987), Landwehr et al. (1987), Hosking and Wallis (1988), Wallis (1988), Boes et al. (1989), Jin and Stedinger (1989), Potter and Lettenmaier (1990), Farquharson et al. (1992) etc. Based on some of the comparative flood frequency studies involving use of probability weighted moment (PWM) based at-site, at-site and regional and regional methods as well as USGS method, carried out for some of the typical regions of India (Kumar et al., 1992; NIH, 1995-96) in general, PWM based at-site and regional GEV method is found to be robust. Farquharson et al. (1992) state that GEV distribution was selected for use in the Flood Studies Report (NERC, 1975) and has been found in other studies to be flexible and generally applicable. Karim and Chowdhary(1995) mention that both goodness-of-fit analysis and L-moment ratio diagram analysis indicated that the three-parameter GEV distribution is suitable for flood frequency analysis in Bangladesh while the two-parameter Gumbel distribution is not.

L-moments of a random variable were first introduced by Hosking(1986). They are analogous to conventional moments, but are estimated as linear combinations of order statistics.

Hosking (1986, 1990) defined L-moments as linear combinations of the PWMs. 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). The regional flood frequency curves derived by using the L-moment approach have been coupled with the relationship between annual maximum peak floods and catchment area for development of regional flood frequency relationships and flood formulas for the seven subzones of India (Kumar et al., 1999).

In this study, annual maximum peak flood data of the 22 stream gauging sites of South Bihar/Jharkhand have been utilised for developing the regional flood frequency relationship using the L-moment based Pearson Type-III (PT-III) distribution for estimation of floods of various return periods for the small to medium size gauged cathments of South Bihar/Jharkhand. Regional flood formula has also been developed for estimation of floods of desired return periods for the ungauged catchments of the region.

2.0 REVIEW OF LITERATURE

Statistical flood frequency analysis has been one of the most active areas of research since the last thirty to forty years. However, the questions such as (i) which parent distribution the data may follow? (ii) what should be the most suitable parameter estimation technique? (iii) how to account for sampling variability while identifying the distributions? (iv) what should be the suitable measures for selecting the best fit distribution? (v) what criteria one should adopt for testing the regional homogeneity? and many others remain unresolved. The scope of frequency analysis would have been widened if the parameters of the distribution could have been related with the physical process governing floods. Such relationships, if established, would have been much useful for studying the effects of non-stationarity and man made changes in the physical process on frequency analysis. Unfortunately, this has not been yet possible and the solution of identifying the parent distribution still remains empirical based on the principle of the best fit to the data. However, development of geomorphological unit hydrograph seems to be a good effort towards the physically based flood frequency analysis. Inspite of many drawbacks and limitations, the statistical flood frequency analysis remains the most important means of quantifying floods in systematic manner.

As such there are essentially two types of models adopted in flood frequency analysis literature: (i) annual flood series (AFS) models and (ii) partial duration series models (PDS). Maximum amount of efforts have been made for modelling of the annual flood series as compared to the partial duration series. In the majority of research projects attention has been confined to the AFS models. The main modelling problem is the selection of the probability distribution for the flood magnitudes coupled with the choice of estimation procedure. A large number of statistical distributions are available in literature. Among these the Normal, Log Normal, Gumbel, General Extreme Value, Pearson Type III, Log Pearson Type III, Generalized Pearson, Logistic, Generalized Logistic and Wakeby distributions have been commonly used in most of the flood frequency studies. For the estimation of the parameters of the various distributions the graphical method, method of least squares, method of moments, method of maximum likelihood, method based on principle of maximum entropy, method of probability weighted moment and method of L-moment are some of the methods which have been most commonly used by many investigators in frequency analysis literature. Once the parameters are estimated accurately for the assumed distribution, goodness of fit procedures then test whether or not the data do indeed fit the assumed distribution with a specified degree of confidence. Various goodness of fit criteria have been adopted by many investigators while selecting the best fit distribution from the various distributions fitted with the historical data. However, most of the goodness of fit criteria are conventional and found to be inappropriate for selecting a best fit distribution which may provide an accurate design flood estimate corresponding to the desired recurrence interval.

2.1 Methods of Regional Flood Frequency Analysis

Cunnane (1988) mentions twelve different regional flood frequency analysis (RFFA) methods. Out of these methods the some of the commonly methods, namely, (i) Dalrymple's Index Flood method, (ii) N.E.R.C. method, (iii) United States Water Resources Council (USWRC) method, (iv) Bayesian method, and (v) Regional Regression based methods as described in literature are briefly described here under.

2.1.1 U.S.G.S. method or Darlymple's index flood method

This method is known as the United States Geological Survey (U.S.G.S.) or Darlymple's index flood method. It was proposed by Dalrymple (1960). It is a graphical regional averaging index flood method, which uses unregulated flood records of equal length N, from each of the rivers considered. The homogeneity test of this method is applied at the 10-year return period level and is based on an assumed underlying EV1 population. For each site, a probability plot is prepared and the following steps are performed:

(i) A smooth, eye-judgement curve is used to estimate the Q-T (Quantile-Return Period) relation at each site;

(ii) The quantile value of return period 2.33 years is read off each graph, corresponding to each site;

(iii) The quantile values for the return periods, T=2, 5, 10, 25, 50, 100 years are read off from each graph, corresponding to each station;

(iv) The quantile values obtained in step (iii) are standardised by dividing by the $Q_{2.33}$ value obtained in step (ii), for the respective sites;

(v) The median of the standardised values from all sites in the region (X_T) is computed for each return period considered;

(vi) X_T is plotted against T on EVl (Gumbel) probabilty paper,

(vii) A smooth, eye-guided curve gives the Q-T relationship, which is assumed to hold at every site in the region;

(viii) The estimate of Q_T at any site is obtained from : $Q_T = X_T * \overline{Q}$ where $\overline{Q}$ is the mean estimated from flood data available at any site or estimated from catchment characteristics, if flood data are not available.

The USGS method for regional flood frequency analysis as given by Dalrymple (1960) and modified to accommodate unequal length of records consists of following sequential steps.

(i) Select gauged catchment within the region having more or less similar hydrological characteristics.

(ii) Estimate the parameters of EV1 distribution using method of moments.

(iii) Estimate the mean annual flood $\overline{Q}$ at each station.

(iv) Test homogeneity of data using homogeneity test as explained in (NIH, 1995-96).

(v) Establish the relationship between mean annual flood and catchment characteristics.

(vi) Obtain the ratio $Q_T/\overline{Q}$ for different return periods for each site

(vii) Compute mean ratio for each of the selected return period.

(viii) Fit a Gumbel distribution between these mean ratio and return periods or reduced variates either analytically or plotting mean of $Q_T/\overline{Q}$ against return priod (reduced variate) on Gumbel probability paper.

The end result of above sequential steps is a regional flood frequency curve which can be used for quantile estimation of ungauged catchments. For ungauged sites mean annual flood is computed using the relationship established at step (v).

In the above method as compared to original USGS methods, the modification are in terms of (i) estimation of mean annual flood (ii) the replacement of median ratio by the mean ratio $Q_T/\overline{Q}$ (iii) Variable length of data instead of fixed length of data (iv) parameter estimation by method of moments instead of method of least squares.

2.1.2 N.E.R.C. method

This method described in the Flood Studies Report, Natural Environmemtal Research Council (NERC, 1975) involves the following steps of computation and is based on similar general principles of U.S.G.S. method.

(i) Select the gauged catchments in a more or less hydrologically similar region.

(ii) Compute the mean of annual flood for each station of the region, where short records are available, suitably augment the record by regression.

(iii) Establish relationship between mean annual flood and catchment characteristics.

(iv) For each station in the region plot the ranked annual maximum series $Q_i/\overline{Q}$ against reduced variate y_i.

(v) Select intervals on Y scale (reduced variate scale) like (2.0 to - 1.5), (-1.15 to 1.0), ..., (3.5 to 4.0) and for each interval compute mean on all E $(Y_{(i)})$ and mean of Q_i/Q and plot them as a smooth mean curve.

(vi) Use this curve as the regional curve for quantile estimation of ungauged catchments.

2.1.3 United States Water Resources Council (USWRC) method

A uniform approach for determining flood flow frequencies was recommended for use by U.S. federal agencies in 1967, which consisted of fitting Log Pearson type - 3 (LP-3) distribution to describe the flood data. This procedure was extended in 1976 to fitting LP-3 distribution with a regional estimator of the log-space skew coefficient and this was released as Bulletin 17 by US Water Resources Council (USWRC). Bulletins 17A and 17B were released subsequently, in 1977 and 1981, respectively. These procedures of the USWRC were widely followed in USA and a few other countries. Because of the variability of at-site sample skew coefficient with a generalized skew coefficient, which is a regional estimate of the log-space skewness. The other notable features of this procedure are treatment of outliers and conditional probability adjustments. Though this procedure attempts to combine regional and at-site flood frequency information, the flood quantiles obtained using this method are quite inferior to those obtained from index flood procedures. This is because, in the USWRC method, regional smoothing is effected only in skewness. In addition to being poor in quantile productive ability, the USWRC method is also found to be lacking in roubstness as both at-site and regional estimators.

2.1.4 Bayesian methods

The use of Bayes' Theorem for combining prior and sample flood information was introduced by Bernier (1967). Cunnane and Nash (1971) showed how it could be used to combine regional estimates of $\overline{Q}$ and C_v obtained from catchment characteristics, using bivariate lognormal distribution for $\overline{Q}$ and C_v and site data assumed to be EV1 distributed to give a posterior distribution for Q_T. This method involves considerable amount of numerical integration. The Bayesian methods do not have to assume perfect regional homogeneity. In fact, specifying a prior distribution itself, acknowledges heterogeneity. The Bayesian method, in given a posterior distribution of parameters, allows legitimate subjective probability statement to be made about parameters and quantiles and this holds even if a non-informative prior distribution (one which is not based on regional flood information, in this context) is used. This is one of its major advantages (Cunnane, 1987). However, Bayesian flood estimation studies which have used informative prior distributions based on regional regression models (which express the parameters in terms of catchment characteristics), have not been successful, since the regression models are quite imprecise. Nash and Shaw (1965) showed that $\bar{Q}$ estimated from catchment characteristics is only as good as $\bar{Q}$ obtained from one year of at-site flood record or less. This result holds for a catchment located at the centroid of the catchment characteristic space. For other catchments, the result is much worse (Hebson and Cunnane, 1986).

2.1.5 Regional regression based methods

Regression can be used to derive equations to predict the values of various hydrologic statistics such as means, standard deviations, quantiles and normalized flood quantiles, as a function of physiographic characteristics and other parameters. Such relationships are useful for estimating flood quantiles at various sites in a region, when little or no flood data are available at or near a site. The prediction errors for regression models of flood flows are normally high. Regional regression models have long been used to predict flood quantiles at ungauged sites, and these predictions compare well with the more complex rainfall-runoff methods.

Consider the traditional log-linear model which is to be estimated by using watershed characteristics such as drainage area and slope.

$$y_t = \alpha + \beta_1 \log(\text{Area}) + \beta_2 \log(\text{slope}) + \ldots + \varepsilon$$

. A challenge in analyzing this model and estimating its parameters with available records is that it is possible to obtain sample estimates, denoted by y_i of the hydrologic statistics y_i. Thus, the observed error ε is a combination of: (i) the sampling error in sample estimators of y_i (these errors at different sites can be cross-correlated if the records are concurrent) and (ii) underlying model error (lack of fit) due to failure of the model to exactly predict the true value of the y_i's at every site. Often, these problems have been ignored and standard ordinary least squares (OLS) regression has been employed. (Thomas, and Benson, 1970). Stedinger and Tasker (1985, 1986a, 1986b) have developed a specialized Generalized Least Squares (GLS) regression methodology to address these issues. Advantages of the GLS procedure include more efficient parameter estimaes when some sites have short records, an unbiased model-error estimator, and a better description of the relationship between hydrologic data and information for hydrologic network analysis and design (Stedinger and Tasker, 1985; Tasker and Stedinger, 1989). Example are provided by Potter and Faulkner (1987), Vogel and Kroll (1989) and Tasker and Driver (1988). Potter and Faulkner (1987) have used catchment response time as a predictor of flood quantiles.

The use of this information reduces the standard errors of regression estimates from regional regression equations. Application of this approach requires estimation of catchment response time at an ungauged site. The cost-effectiveness of this approach remains to be investigated.

2.1.6 Improvised index-flood algorithms

The index-flood algorithm originally suggested by Dalrymple (1960) to derive the regional flood frequency curve, was once adopted by the U.S. Geological Survey for flood quantile estimation. Subsequently, it was discontinued, since the coefficient of variation of floods was found to vary with drainage area and other basin characteristics (Stedinger, 1983). However, the index-flood methods came into limelight, once again, in the wake of the new estimation algorithm, Probability Weighted Moments (PWMs), proposed by Greenwood et al. (1979), which helped in reducing the uncertainty in estimating the flood quantiles. The graphical method of Dalrymple (1960) was subsequently improvised by Wallis (1980). The improvised algorithm of Wallis (1980) was an objective numerical method, based on regionally averaged, standardised PWMs. Kuczera (1982a,b) adopted lognormal empirical Bayes estimators, which incorporate the index-flood concept. In Kuczera's work, the log-space mean was estimated using only at-site data, while the log-space variance (denoting the shape parameter that determines the coefficient of variation and coefficient of skew of a longnormal distribution), was assigned a weighted average of at-site and regional estimators. Here, the logarithmic transformation is used to effect normalisation, by means of a simple subtraction of the log space mean, this avoiding the division by an index-flood estimator in real space (Stedinger, 1983).

Greis and Wood (1981) presented an initial evaluation of the index-flood approach, which did not reflect the uncertainties in flood quantile estimators, resulting from scaling the regional flood frequency estimates by the at-site means. This is a critical source of uncertainty especially for regions with a large mean CV (Lettenmaier et al., 1987). Hosking et al. (1985b) has given a PWM estimation procedure for the Generalised Extreme Value (GEV) Distribution of Jenkinson (1955). Further, Hosking et al. (1985a) have presented an apprisal of the regional flood frequency procedure followed by the UK Flood Studies Report (FSR)(NERC, 1975), in which they have pointed out that FSR algorithm, at times, can lead to unrealistic upper flood quantile estimates. In fact, the Monte-Carlo simulation studies conducted by Hosking et al. (1985a), indicate that the FSR algorithm may result in high degree of overestimation of flood quantile estimates. The advantages of PWM estimators have been brought out by Landwehr et al. (1979), Hosking et al. (1985a), Wallis and (1988) and Hosking (1990). The use of L-moments in selection of regional frequency distribution have been dealt with in Chowdhury et al. (1991), Wallis (1993), Hosking and Wallis (1993), Vogel and Fennessey (1993), and Cong et al. (1993). Further, the unbiasedness of the L-Moment estimators have been well utilized in both regional homogeneity tests and Goodness of Fit test (Lu and Stedinger, 1992; Hosking and Wallis, 1993; Zrinji and Burn, 1994) which are prerequisites in regional frequency analysis. Hosking and Wallis (1988) have studied the impact of cross-correlation among concurrent flows at different sites, on regional index-flood methods. They have concluded that regional analysis is preferable to at-site analysis, even in case of regions with mild heterogeneity and moderate inter-site cross correlation. Also, Hosking et al. (1985a) show the impact of historical information on the precision of computed regional growth curves, in case of regions with large number of gauging stations.

Further, Wallis and Wood (1985) and Potter and Lettenmaier (1990) have found the regional-PWM index-flood estimators to be superior to the variations of the USWRC procedure (USWRC, 1982). Lettenmaier et al. (1987) investigated the performance of eight different GEV-PWM index flood estimators and the effect of regional heterogeneity in a detailed manner. GEV-PWM index flood quantile estimator was found to be robust and had the least RMSE, when compared with all other at-site as well as regional quantile estimators, for mildly heterogeneous regions. Further, with the increase in the degree of regional heterogeneity or the sample size, a two parameter quantile estimator with a regional shape parameter was found to perform the best.

2.2 Some of the Flood Frequency Studies Carried Out in India

A number of studies have been carried out in the area of regional flood frequency analysis in India. Goswami(1972), Thiru Vengadachari et al.(1975), Seth and Goswami (1979), Jhakade et al.(1984), Venkataraman and Gupta (1986), Venkataraman et al(1986), Thirumalai and Sinha(1986), Mehta and Sharma (1986), James et al., Gupta(1987) and many others have conducted regional flood frequency analysis for some typical regions in India. In most of the regional flood frequency studies the conventional methods such as U.S.G.S. Method, regression based methods and Chow's method have been used. Some attempts have been made by Perumal and Seth (1985), Singh and Seth (1985), Huq et al. (1986), Seth and Singh (1987) and others to study the applications of new approaches of regional flood frequency analysis for some of the typical regions of India for which the conventional methods have been already applied. The Bridges and Structures Directorate of the Research, Designs and Standards Organization, Lucknow has carried out studies for design flood estimation based on regional flood frequency approach for various hydrometeorological sub-zones of India.

A comparative study has been carried out for the 7 hydrometeorological subzones of zone-3 of India using the EV1 distribution by fitting the probability weighted moment (PWM) as well as following the modified U.S.G.S. method, General Extreme Value (GEV) and Wakeby distribution based on PWMs. The mean annual peak flood data of 2 bridge catchments for each subzone which were excluded while developing the regional flood frequency curves and these are utilized to compute the at site mean annual peak floods. These at site mean values together with the regional frequency curves of the respective subzones were used to compute the floods of various return periods for those 2 test catchments in each sub-zone. The descriptive ability as well as predictive ability of the various methods viz. (i) at site methods, (ii) at site and regional methods, and (iii) regional methods has been tested in order to identify the robust flood frequency method. At site and regional methods viz. SRGEV and SRWAKE have been found to estimate floods of various return periods with relatively less Bias and comparable root mean square error as well as coefficient of variation. The regional parameters of the GEV distribution have been adopted for development of the regional flood frequency curves. Floods for these test catchments are also estimated using the combined regional flood frequency curves and respective at site mean annual peak floods. Flood frequency curves developed by fitting the PWM based GEV distribution have been coupled with the relationships between mean annual peak flood and catchment area for developing regional flood formulae for each of the seven hydrometeorologically homogeneous subzones of India. A regional flood formula has also been developed for zone 3 considering data of all the 7 subzones in combined form. Applicability of this flood formula over those developed for each of the sub-zones is examined by comparing the flood estimates of different return periods obtained by the developed regional flood formulae for the various subzones and the regional flood formula for combined zone 3 (NIH, 1995-96).

For the above mentioned study area, regional flood frequency relationships developed based on PWM approach have been revised based on the method of L moments (NIH, 1997-98) as briefly summarised below. Regional flood frequency curves are developed by fitting L-moment based GEV distribution to annual maximum peak flood data of small to medium size catchments of the seven hydrometeorological subzones of zone 3 and combined zone 3 of India. These seven subzones cover an area of about 10,41,661 km^2. Effect of regional heterogeneity is studied by comparing the growth factors of various subzones and combined zone 3. The flood frequency curves based on probability weighted moment (PWM) approach have been compared with the flood frequency curves based on L Moment approach. Relationships developed between mean annual peak flood and catchment area are coupled with the respective regional flood frequency curves for development of the regional flood formulae.

Sankarasubramanian (1995) investigated the sampling properties of L-moments for both unbiased and biased estimators for five of the commonly used distributions. Based on the simulation results, regression equations have been fitted for the bias and the variance in L-skewness for the five distributions. The sampling properties of L moments have been compared with those of conventional moments and the results of the comparison have been presented for both the biased and unbiased estimators. The performance of evaluation in terms of "Relative-RMSE in third moment ratio" reveals that conventional moments are preferable at lower skewness, while L-moments are preferable at higher skewness. The improvised index-flood procedure suggested by Hosking and Wallis (1993) has been used in the study to find an appropriate regional flood frequency distribution and to obtain the regional growth curve for a selected region from U.K. Based on the study, generalized logistic distribution has been prescribed as the regional flood frequency distribution for the region considered. Index-flood based regional model performed the best when compared to all other models considered in predicting flood quantiles at sites with short record length, which is very vital in any regional study.

Upadhyay and Kumar (1999) applied L-moments approach for regional flood frequency analysis for flood estimation at an ungauged site. The study concludes that at gauged sites, regional flood estimates were found to be more accurate than at-site estimates as is clear from root mean square error and standard error of regional estimates as compared to at-site estimates. However, for the sites having sufficiently long records, the difference in accuracy of the at-site and regional estimates is very small. The authors recommended that alongside the discharge data collection at gauging sites, emphasis should be given collection of detailed data about the physiographic and hydrological characteristics of the catchment. This will improve the reliability and accuracy of regional flood estimates not only at ungauged sites but also at gauged sites having short record lengths and facilitate reliable and economically viable design of the hydraulic structures.

Parmesraran et al. (1999) developed a flood estimating model for individual catchment and for the region as a whole using the data of fifteen gauging sites of Upper Godavari Basins of Maharashtra. Seven probability distributions have been used in the study. Based on the goodness of fit tests log normal distribution is reported to be the best fit distribution. A regional relationship between mean annual peak flood and catchment area has been developed for estimation of mean annual peak flood for ungauged catchments and regional relationship for maximum discharge of a known recurrence interval for the ungauged catchments.

2.3 Current Status

Various issues involved in regional flood frequency analysis are testing regional homogeneity, development of frequency curves and derivation of relationship between MAF and the catchment characteristics. Inspite of a large number of existing regionalisation techniques, very few studies have been carried out with somewhat limited scope to test the comparative performance of various methods. Some of the comparative studies have been conducted by Kuczera (1983), Gries and Wood (1983), Lettenmaier and potter (1985) and Singh (1989). A procedure for estimating flood magnitudes for return period of T years Q_T is robust if it yields estimates of Q_T which are good (low bias and high efficiency) even if the procedure is based on an assumption which is not true (Cunnane, 1989).

Some of the recent studies based on index flood approach include Wallis and Wood (1985), Hosking et al. (1985), Hosking and Wallis (1986), Lettenmaier et al. (1987), Landwehr et al. (1987), Hosking and Wallis (1988), Wallis (1988), Boes et al. (1989), Jin and Stedinger (1989), Potter and Lettenmaier (1990), Farquharson et al. (1992) etc. Farquharson et al. (1992) state that GEV distribution was selected for use in the Flood Studies Report (NERC, 1975) and has been found in other studies to be flexible and generally applicable. Use of a generalized extreme value (GEV) distribution as a regional flood frequency model with an index flood approach has received considerable attention (Chowdhary et al., 1991). Karim and Chowdhary (1995) mention that both goodness-of-fit analysis and L-moment ratio diagram analysis indicated that the three-parameter GEV distribution is suitable for flood frequency analysis in Bangladesh while the two-parameter Gumbel distribution is not. L-moments of a random variable were first introduced by Hosking(1986). They are analogous to conventional moments, but are estimated as linear combinations of order statistics. Hosking (1986, 1990) defined L-moments as linear combinations of the PWMs. 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).

Lu and Stedinger (1992) presented sampling variance of normalized GEV(PWM) quantile estimators and a regional homogeneity test. The authors state that for a three-parameter GEV distribution the asymptotic variance of probability weighted moments (PWM) quantile estimators have been derived previously. Their study extended the results to obtain the asymptotic variance of normalized GEV(PWM) estimators, which are at-site quantile estimators divided by the sample mean. Monte Carlo simulations provided correction factors for use with small samples. Normalized 10-year flood quattile estimators and their sample variances have been used to construct a regional homogeneity test for GEV(PWM) index flood analysis. The new test performed better than the R-statistic test proposed before.

Wang (1996) derived the direct estimators of L moments thus eliminating the need for using probability weighted moments. In another study, Wang (1996) mentioned that the estimation of floods of large return periods from lower bound censored samples may often be advantageous because interpolation and extrapolation are made by exploring the trend of larger floods in each of the records. The method of partial probability weighted moments (partial PWMs) is an useful technique for fitting distributions to censored samples. The author redefined partial PWMs. The expression for partial PWMs is derived for the extreme values type I distribution. Combined with those for the extreme value II and III distributions, an unified expression for partial PWMs is presented for for the GEV distribution. The equations for solving the distribution parameters are provided. Monte Carlo simulation shows that lower bound censoring at a moderate level does not unduely reduce the efficiency of high-quantile estimation even if the samples have come from a true GEV distribution.

Rao and Hamed (1997) used regional flood frequency analysis to estimate flood quantiles in Wabash river basin. The parent distribution is identified by analyzing the data from number of stations within the basin. L-moments are used to investigate the feasibility of regional frequency analysis in the basin. Basin is shown to be hydrologically heterogeneous. Basin is divided into smaller sub-regions by using L-moments diagrams. The generalized extreme value distribution is recommended to be the regional parent distribution.

Zafirakou – Koulouris et.al. (1998) introduced L moments diagrams for the evaluation of goodness of fit for censored data (data containing values above or below the analytical threshold of measuring equipment's).

Whitley and Hromadka (1999) presented approximate confidence intervals for design floods for a single site using a neural network. The authors mention that a basic problem in hydrology is the computation of confidence levels for the value of the T-year flood when it is obtained from a log Pearson III distribution using the estimated mean, standard deviation and skewness. The authors gave a practical method for finding approximate one-sided or two-sided confidence intervals for the 100-year flood based on data from a single site. The confidence interval are generally accurate to within a percent or two, as tested by simulations, and are obtained by use of neural network.

Iacobellis and Fiorentino (2000) presented a new rationale, which incorporates the climatic control for deriving the probability distribution of floods which based on the assumption that the peak direct streamflow is a product of two random variates, namely, the average runoff per unit area and the peak contributing area. The probability density function of peak direct streamflow can thus be found as the integral over total basin area, of that peak contributing area times the density function of average runoff per unit area. The model was applied to the annual flood series of eight gauged basins in Basilicata (Southern Italy) with catchment area ranging from 40 to 1600 km^2. The results showed that the parameter tended to assume values in good agreement with geomorphologic knowledge and suggest a new key to understand the climatic control of the probability distribution of floods.

Martins and Stedinger (2000) mention that the three-parameter extreme-value (GEV) distribution has found wide application for describing annual floods, rainfall, wind speeds, wave heights, snow depths and other maxima. Previous studies show that small-sample maximum-likelihood estimators (MLE) of parameters are unstable and recommend L moment estimators. More recent research shows that method of moments quantile estimators have for $-0.25 < k < 0.30$ smaller root mean square error than L moments and MLEs. Examination of the behaviour of MLEs in small samples demonstrates that absurd values the GEV-shape parameter k can be generated. Use of a Bayesian prior distribution to restrict k values to a statistically/physically reasonable range in a generalized maximum likelihood (GML) analysis eliminates this problem.

2.4 General Methodology

The main issues involved in regional flood frequency analysis and its generalised approach are mentioned here under:

(i) Regional homogeneity

(ii) Degree of heterogeneity and its effects on flood frequency estimates

(iii) Development of a relationship between mean annual peak flood and catchment characteristics for estimation of floods for the ungauged catchments

(iv) Estimation of parameters of the adopted frequency distributions by efficient parameter estimation approach

(v) Identification of a robust flood frequency analysis method based on descriptive ability or predictive ability criteria

Based on data availability and record length of the available data the following approaches may be adopted for developing the flood frequency relationships:

a. At-site flood frequency analysis
b. At-site and regional flood frequency analysis
c. Regional flood frequency analysis

The basic steps of the above approaches are mentioned below.

2.4.1 At-site flood frequency analysis

(i) Fit various frequency distributions to the at-site annual maximum peak flood data,
(ii) Select the best fit distribution based on descriptive and predictive ability criteria, and
(iii) Use the best fit distribution for estimation of T-year flood.

2.4.2 At-site and regional flood frequency analysis

(i) Test the regional homogeneity,
(ii) Develop flood frequency relationships for the region considering various frequency distributions,
(iii) Select the best fit distribution based on descriptive and predictive ability criteria,
(iv) Estimate the at-site mean annual peak flood, and
(v) Use the best fit regional flood frequency relationship for estimation of T-year flood.

2.4.3 Regional flood frequency analysis

(i) Test the regional homogeneity,
(ii) Develop flood frequency relationships for the region considering various frequency distributions,
(iii) Select the best fit distribution based on descriptive and predictive ability criteria,
(iv) Develop a regional relationship between mean annual peak flood and catchment as well as climatic characteristics for the region,
(v) Estimate the mean annual peak flood using the developed relationship, and
(vi) Use the best fit regional flood frequency relationship for estimation of T-year flood.

Regional Flood Frequency (RFFA) provides a approach of utilizing the obvious spatial coherence of hydrological variables, as one would do in preparing a rainfall map, and thus all available relevant information is incorporated in the flood estimate. It provides at-site regional flood quantile estimates which are superior to the pure at-site estimates, even if the region is moderately heterogeneous. RFFA can be considered a necessity when one considers the case against complete reliance on at-site estimates alone. Two-parameter distributions are not sufficiently flexible to be able to model all plausible flood-parent distributions. Their parsimony in parameters leads to quantile estimates whose standard errors are not excessively large, but whose bias may be excessively so. Three-parameter distributions, on the other hand, are sufficiently flexible to be relatively unbiased, but this is accompanied by unacceptably large standard error. These facts are true both in the case of homogeneous regions and mildly heterogeneous regions. The gains obtained by RFFA in such cases have been documented by Hosking et al. (1985a). Lettenmaier and Potter (1985), Wallis and Wood (1985), Lettenmaier et al. (1987) and have been reviewed by Lettenmaier (1985). Thus, regionalisation seems to be the most viable way of improving flood quantile estimation. The performance of Probability Weighted Moments (PWM)-based regional index flood procedure, in particular, is so superior to the currently used institutional methods that no viable argument for the continuation of current practice is evident. Particularly, where the flexibility of using a three-parameter distribution is required, the reduction in the variability of flood quantile estimates achieved by proper regionalization is so large that at-site estimators should not be seriously considered.

Hosking (1990) has defined L-Moments which are analogous to conventional Moments and can be expressed as linear functions of probability weighted moments (PWMs). The basic advantages offered by L-Moments over conventional moments in Hypothesis Testing, and identification of distributions, have opened new vistas in the field of regional flood frequency analysis. In this regard, a very recent and significant contribution is that of Hosking and Wallis (1993 and 1997), which can be regarded as the state-of-the-art method for regional flood frequency analysis.

2.5 Effect of Regional Heterogeneity on Quantile Estimates

Cunnane (1989) mentions that regional flood estimation methods are bsed on the premise that standardized flood variate, such as $X = Q/E(Q)$ has the same distribution at every site in the chosen region. Serious departures from such assumptions could lead to biased flood estimates at some sites. Those catchments whose C_v and C_s values happen to coincide with the regional mean values would not suffer such a bias. If the degree of heterigeneity present is not too great its negative effect may be more than compensated for by the larger sample of sites contributing to parameter estimates. Thus X_T estimated from M sites, which are slightly heterogeneous may be more reliable than X_T estimated from a smaller number, say M/3, more homogeneous sites, especially if flow records are short. Hosking et al. (1985a) studied the effect of regional heterogeneity on quantile estimates obtained by a regional index flood method. A heterogeneous region of 20 stations (j = 1, 2....20) is specified, whose flood populations are GEV distributed with parameters varying linearly, thus reflecting a transition from small to large catchments. This simulation study has shown that the regional algorithms give relatively more stable quantile estimates, compared to at-site estimators. Further, Lettenmaier (1985), using heterogeneous GEV data bases (qualitatively similar to those of Hosking et al., 1985a), as compared the two parameter Gumbel at-site estimator with a variety of regional estimators. The clear conclusion from this study is that if record lengths at individual sites are <30 years, at-site quantile estimates are less reliable than regional estimates, even when the regional heterogeneity is found to be moderate. Lettenmaier and Potter (1985) have used a regional flood distribution at each site depend on the logarithm of the catchment area. This offers the advantage of a controlled simulation study, that has been used to impose heterogeneity on the flood generating populations. They have compared the performance of eight estimators, out of which at-site estimators are two and remaining are regional estimators. They found that the index-flood regional estimators had lower root mean square error than the at-site estimators, even under conditions of moderate heterogeneity.

Stedinger and Lu (1995) examined the performance of at-site and regional GEV(PWM) quantile estimators with various hydrologically realistic GEV distributions, degrees of regional heterogeneity, and record lengths. The main importance of this study is that, it evaluates the performance of the above-mentioned estimators, for different possible hydrologic regions, assuming realistic parameters. They have concluded that the index-flood quantile estimators perform better than other estimators, when regional heterogeneity is small to moderate and n<T (Cv <0.4). Further, they conclude that, for sites with sufficient record length, with significant lack of fit, the shape parameter estimator is preferable. For estimating quantiles at sites with long record length (n>T), the use of at-site GEV (PWM) estimator is suggested from their study.

Hence, on the basis of the studies carried out recently, it may be concluded that dividing the catchment data set into various parts, for obtaining more internal homogeneity of regions is not necessary or quite useful. On the other hand, more reliable flood frequency estimates may be obtained by considering a few larger and slightly heterogeneous regions, comprising of the larger number of catchments, than many homogenous regions, each with only a smaller number of catchments.

2.6 Application of L-Moments as a Parameter Estimator in Flood Frequency Analysis

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 maximum likelihood
(iv) Method of probability weighted moments

(v) Method based on principle of maximum entropy
(vi) Method based on L-moments

The method of moments has been one of the simplest and conventional parameter estimation techniques used in statistical literature. In this method, while fitting a probability distribution to a sample, the parameters are estimated by equating the sample moments to these of the theoretical moments of the distribution. Even though this method is conceptually simple, and the computations are straight-forward, it is found that the numerical values of the sample moments can be very different from those of the population from which the sample has been drawn, especially when the sample size is small and/or the skewness of the sample is considerable. Further, the estimated parameters of the distributions fitted by method of moments, are not very accurate.

Sankarasubramanian (1995) mentions that there have been quite a number of attempts in literature to develop unbiased estimates of skewness for various distributions. However, these attempts do not yield exactly unbiased estimates. In addition, the variance of these estimates is found to increase. Further, a notable drawback with conventional moment ratios such as skewness and coefficient of variation is that, for finite samples, they are bounded, and will not be able to attain the full range of values available to population moment ratios (Kirby, 1974). Wallis et al. (1974) have been shown that the sample estimates of conventional moments are highly biased for small samples and the same results have been extended by Vogel and Fennessey (1993) for large samples (n>1000) for highly skewed distributions.

Hosking (1990) has defined L-moments, which are analogous to conventional moments, and can be expressed in terms of linear combinations of order statistics, i.e., L-statistics. L-moments are capable of characterising a wider range of distributions, compared to the conventional moements. A distribution may be specified by its L-moments, even if some of its conventional moments do not exist (Hosking, 1990). For example, in case of the generalised pareto distribution, the conventional skewness is underfind beyond a value of 155, (shape parameter = 1/3), while the L-skewness can be defined, even beyond that value. Further, L-moments are more robust to outliers in data than conventional moments (Vogel and Fennessey, 1993) and enable more reliable inferences to be made from small samples about an underlying probability distribution. The advantages offered by L-moments over conventional moments in hypothesis testing, boundedness of moment ratios and identification of distributions have been discussed in detail by Hosking (1986). Stedinger et al. (1993) have described the theoretical properties of the various distributions commonly used in hydrology, and have summarised the relationships between the parameters and the L-moments. The expressions to compute the biased and the unbiased sample estimates of L-moments and their relevance with respect to hydrologic application have also been presented therein. Hosking (1990) has also introduced L-moment ratio diagrams, which are quite useful in selecting appropriate regional frequency distributions of hydrologic and meteorologic data. The advantages offered by L-moment ratio diagrams over conventional moment ratio diagrams are well elucidated by Vogel and Fennessey (1993).

Examples for the usage of L-moment ratio diagrams are found in the works of Wallis (1988, 1989), Hosking and Wallis (1987a, 1991), Vogel et al. (1993a).

Exact analytical forms of sampling properties of L-moments are extremely complex to obtain. Hosking (1986) has derived approximate analytical forms for the sampling properties of same probability distributions, using asymptotic theory. It is to be noted that even these approximate analytical forms are not available for some of the important distributions, ofthen used in water resources applications, such as generalised normal (Long normal-3 parameter) distribution and Pearson-3 (three parameter Gamma) distribution Further, the sampling properties obtained from the asymptotic theory using first order approximation, give reliable approximation to finite sample distributions, only when sample size is considerable (Hosking et al., 1985b; Hosking, 1986; Chowdhury etal., (1991). But, often, hydrologic records are available for only short periods. Hence, it is necessary to investigate the sampling properties of L-moments for sample size, for which Monte-Carlo simulation provides a viable alternative. In recent literature (Hosking, 1990; Vogel and Fennessey, 1993; Stedinger et al., 1993), it is stated that L-moment estimators in general, are almost unbiased. However, a detailed investigation of the sampling properties of L-moments has been attempted so far. It is to be noted that sample estimators of L-moments are always linear combinations of the ranked observations, while the conventional sample moment estimators such as s^2 and G require squaring and cubing the observations respectively, which in turn, increases the weightages to the observations away from the mean, thus resulting in considerable bias. However, a detailed comparison of the sampling properties between conventional moment estimators and L-moment estimators has not been attempted so far.

Utilising the desirable properties of the L-moments such as unbiasedness of the basic moments and normality of the asymptotic distributions of the sampling properties. Hosking and Wallis (1993) have defined a set of regional flood frequency measures namely,i) Discordancy measure ii) Heterogeneity measure and iii) Goodness of fit (GOF) measure. They have suitably incorporated these measures in the modified index flood algorithm suggested by Wallis (1980). This has resulted in a very versatile and efficient regional flood frequency procedure, which has been discussed in detail by Hosking and Wallis (1993). The tests suggested by them for regional heterogeneity and goodness of fit are the most powerful, out of the available tests.

The various regional flood frequency distributions coupled with PWM-based index flood procedure, the different at-site estimators (2-parameters and 3-parameter) and the regional shape parameter based models of various distributions together provide a wide range of choice for the selection of the most competitive flood frequency models for the region/site in question. In such situations, regional Monte-Carlo simulation technique will be very much useful in evaluating the performance efficiency of the different alternative models. A further advantage of adopting the Monte-Carlo simulation technique is that regional data can be easily generated according to the pattern of the real-world data of the region and in addition the true flood quantiles are also known, thus enabling the evaluation of the relative performance between the different models (estimators). A few such regional Monte-Carlo simulation exercises have been carried out in order to establish the performance of regional estimators under different conditions of heterogeneity. Littenmaier et al. (1987) consider GEV regional population, for a hypothetical region of 21 sites, with their CV, Skewness and length of record varying linearly across the sites. However, in a real world situation, these variations may not be linear as assumed. They considered regions with k=0.15 and an average coefficient of variation = 0.5, 1.0, 1.5 and 2.0. Out of the cases considered, only CV=0.5 represents the realistic regional flood frequency distributions, since the other cases of CV give rise to considerable percent of negative flows in the simulation study. Further, their assumption of mean = 1.0 for all sites creates a source of uncertainty in flood quantile estimates, particularly for regions, where the mean CV is large (Stedinger and Lu, 1994).

Pilon and Adamowski (1992) carried out a Monte-Carlo simulation study to show the value of information added to flood frequency analysis, by adopting a GEV regional shape parameter model over the at-site models using the observed data collected from the province of Nova Scotia (Canada). However, they assumed the at-site mean in all sites considered as 100.0 and they have generated the flood data directly from a GEV distribution (after selecting through L-Moment ratio diagram), whose parameters have been computed from the regional moments. This simulation does not correspond to the true regional Monto-Carlo simuiation of the region considered, even though it shows that additional information value is added by regional models. Further, their simulation does not incorporate the degree of heterogeneity present in the region.

Stedinger and Lu (1994) presented the performance of at-site and regional GEV (PWM) quantile estimators through a comprehensive Monte-Carlo simulation study using hydrologically realistic GEV distributions and varying degrees of heterogeneity, and record lengths. The authors evaluated the performance of these estimators for different possible hydrologic regions, using regional average standardised performance measures. Their Monte-Carlo analysis considers a wide range of realistic values of mean CV and coefficient of variation of CV to represent the different hydrologic regions and different degrees of heterogeneity, respectively.

3.0 PROBLEM DEFINITION

For design of various types of hydraulic structures such as road and railway bridges, culverts, weirs, barrages, cross drainage works etc. the information on flood magnitudes and their frequencies is needed. 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 flood estimates directly. In such a situation, the flood formulae developed for the region are the alternative method for estimation of design flood. Most of the flood formulae developed for different regions of the country are empirical in nature and do not provide flood estimates for the desired return period.

L-moments of a random variable were first introduced by Hosking(1986). They are analogous to conventional moments, but are estimated as linear combinations of order statistics. Hosking(1986, 1990) defined L-moments as linear combinations of the PWMs. In a wide range of hydrologic applications, L-moments provide simple and efficient estimators of characteristics of hydrologic data and of a distribution's parameters (Stedinger et al., 1992).

The objectives of this study are:

(a) To test the regional homogeneity of the study area.

(b) To identify the robust frequency distribution for the study area based on the L-moment ratio diagram and Z^{dist} statistics approaches.

(c) To develop regional flood frequency relationship for estimation of floods of various return periods for gauged catchments of the study area based on the L-moments approach.

(d) To develop regional relationship between mean annual peak floods and physiographic characteristics for estimating the mean annual peak floods for ungauged catchments of the study area.

(e) To develop the regional flood formula for estimation of floods of various return periods for ungauged catchments of the study area by coupling the relationship between mean annual peak flood and physiographic characteristics, with the L-moment based regional flood frequency curves.

4.0 DESCRIPTION OF THE STUDY AREA

The states of Bihar and Jharkand lie between latitudes 21°58'10"N and 27°31'15"N and longitudes 83°10'50"N and 80°17'40"N. The total geographical area of the two states is 1,73,877 sq. km. The states comprise alluvial plains of Indo-Gangetic basin and Kaimur-Chotanagpur-Santhal Pargana plateau. The alluvial plains is divided into two by the river Ganga flowing from west to east.

The study area comprises of various river basins, namely:

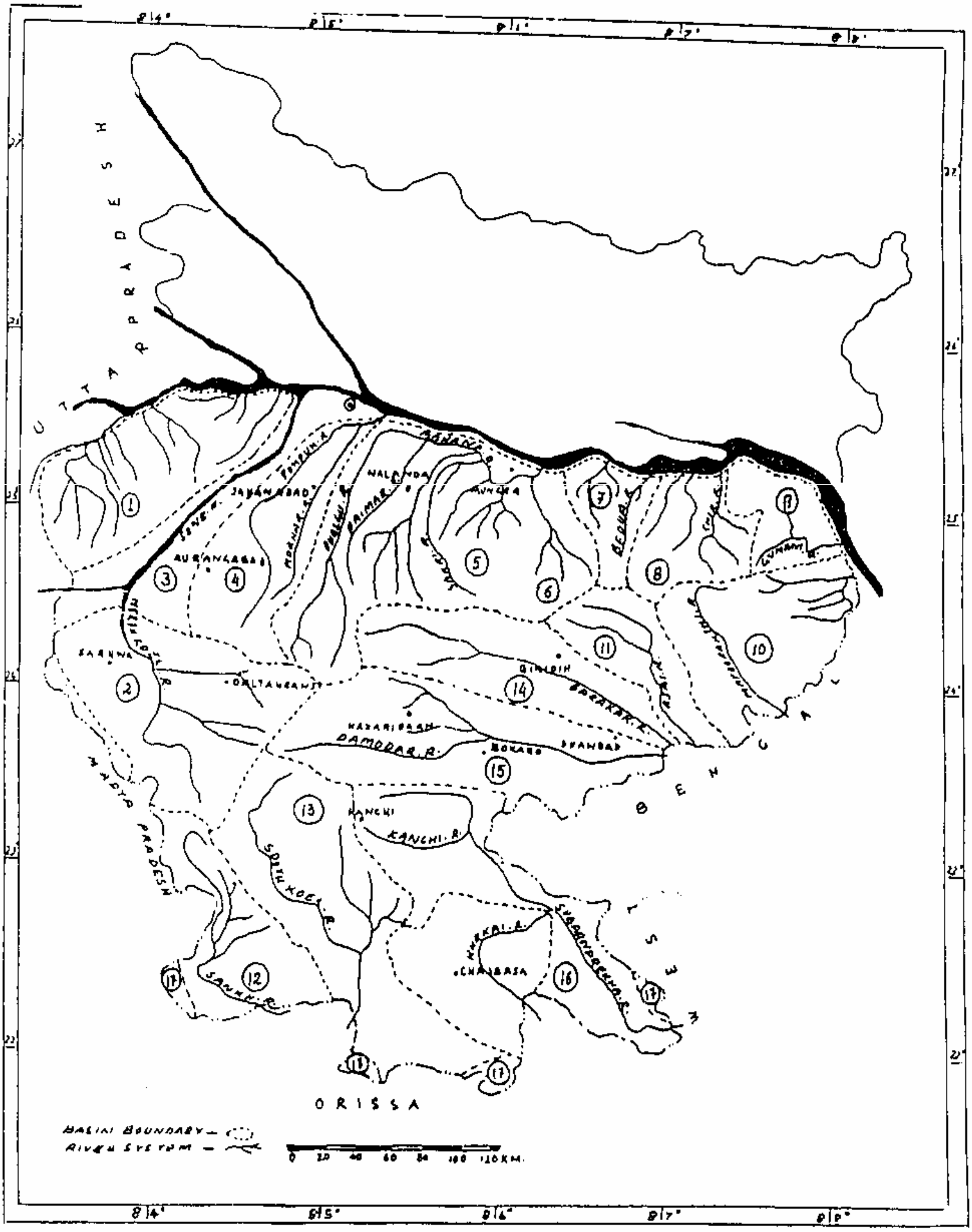
1. Karmnasa river basin
2. North Koel river basin
3. Sone-Kanhar and Kao Gangi river basin
4. Punpun river basin
5. Harohar river basin
6. Kiul river basin
7. Badua-Belharna river basin
8. Bilasi-Chandan-Chir river basin
9. Gumani and Koa-Bhena river basin
10. Mayurakshi and other adjoining streams
11. Ajay river basin
12. Sankh river basin
13. South Koel river basin
14. Barakar river basin
15. Damodar river basin
16. Subarnarekha-Kharkai river basin
17. Small streams draining independently outside the states

Fig. 1 shows the map of different river basins of South Bihar/Jharkhand. A brief description of the various river basins is given below.

The Karmnasa river basin is situated between latitudes 24°32' N and 25°31' N and longitudes 83°0' E and 84°5'E. The total geographical area of the basin is 5126.88 sq. km. The river Karmnasa rises at an elevation of 560 m above MSL in the eastern ridges of the plateau in the Kaimur hills about 29 km west of Rohtasgar in Rohtas district of Bihar.

The North Koel river basin is situated between latitudes 23° N and 24°30' N and longitudes 84°30' E and 85°E. The total geographical area of the basin is 10570 sq. km. The river North Koel originates from Chotanagpur hills (Bardih forest) at an altitude of about 910 m.

Fig. 1 Map Showing Different River Basins of South Bihar



1 Karmnasa Basin
2 North Koel Basin
3 Sone-Kanhar and Kao-Gangi Composite Basin
4 Punpun Basin
5 Harohar Basin
6 Kiul Basin
7 Badua-Belharna Basin
10 Basins of Mayurakshi and Other Adjoining Streams
11 Ajay Basin
12 Sankh Basin
13 South Koel Basin
14 Barakar Basin
15 Damodar Basin
16 Subarnrekha-Kharkai Basin

The Sone-Kanhar and Kao Gangi river basin comprises of three sub-basins namely: (a) Sone Stem, (b) Area draining in river Kanhar, and (c) Kao-Gangi (Ganga Stem). The total geographical area of the basin is 9374.71 sq. km. The river Sone rises together with the Narmada and the Mahanadi on the elevated plateau of Central India.

The Punpun river basin is situated between latitudes $24^0$6' N and $25^0$35' N and longitudes $84^0$0' E and $85^0$19' E. The total geographical area of the basin is 9025.75 sq. km. The river Punpun originates from Hariharganj block of Palamu district in the Chotanagpur plateau at an elevation of 442 m.

The Harohar river basin is situated between latitudes $24^0$10' N and $25^0$30' N and longitudes $84^0$40' E and $86^0$8' E. The total geographical area of the basin is 14296.18 sq. km. The river Harohar is the principal tributary of the river Kiul having its sub-tributaries like the *Dhadhar*, the *Sakri*, the *Kaurihari*, the *Panchane* and the *Phalgu*.

The Kiul river basin is situated between latitudes $24^0$27' N and $25^0$16' N and longitudes $85^0$58' E and $86^0$30' E. The total geographical area of the basin is 2927.32 sq. km. The river Kiul has its origin in the village Chauki (Khargdiha) of the district Giridih and flowing for about 28 km along the border of the district, it enters into the district of Munger.

The Badua-Belharna river basin is situated between latitudes $24^0$35' N and $25^0$25' N and longitudes $86^0$22' E and $86^0$55' E. The total geographical area of the basin is 2215 sq. km. The river Badua originates from the hills of Chakai block in Munger district.

The Badua-Belharna river basin is situated between latitudes $24^0$30' N and $25^0$17' N and longitudes $84^0$36' E and $87^0$27' E. The total geographical area of the basin is 4090 sq. km. The river Chandan originates from hills of Deoghar at an elevation of 274 m.

The Gumani river basin is situated between latitudes $24^0$40' N and $25^0$28' N and longitudes $87^0$31' E and $88^0$10' E while the Koa-Bhena river basin is situated between latitudes $25^0$0' N and $25^0$20' N and longitudes $86^0$58' E and $87^0$37' E. The total geographical area of Gumani basin is 2271.9 sq. km. The river Gumani originates from open mixed forest of hills of Damau-Rajmahal range near Tetaria at an elevation of 338 m.

The Mayurakshi and other adjoining streams river basin is situated between latitudes $23^0$48' N and $24^0$57' N and longitudes $86^0$45' E and $86^0$30' E. The total geographical area of the basin is 5710 sq. km. The river Mayurakshi originates from Trikuti hills in Deoghar district in Bihar at an altitude of 610 m above MSL and outfalls in Bhagirathi in West Bengal.

The Ajay river basin is situated between latitudes $24^0$6' N and $23^0$50' N and longitudes $86^0$16' E and $87^0$5' E. The total geographical area of the basin in Bihar/Jharkhand is 3553.65 sq. km. Ajay river originates from the hills in Chakai block of Munger district.

The Sankh river basin is situated between latitudes 22°0' N and 23°17' N and longitudes 83°55' E and 84°46' E. The total geographical area of the basin in Bihar/Jharkhand is 4027.43 sq. km. The river Sankh originates from hills of Chainpur block of Gumla district at an elevation of 1020 m.

The South Koel river basin is situated between latitudes 22°15' N and 22°32' N and longitudes 84°30' E and 85°45' E. The total geographical area of the basin in Bihar is 10588.56 sq. km. The river South Koel originates from Chotanagpur hills at an elevation of about 730 m near village Nagri, 16 km west of Ranchi township.

The Barakar river basin is situated between latitudes 23°43' N and 24°31' N and longitudes 85°7' E and 86°53' E. The total geographical area of the basin is 7026 sq. km. The Barakar river originates from the hills of Hazaribagh and runs almost parallel to river Damodar in about 200 km length in the eastern direction and joins the river Damodar near Dishergarh town.

The Damodar river basin is situated between latitudes 23°22' N and 24°8' N and longitudes 84°37' E and 86°50' E. The total geographical area of the basin is 9907.8 sq. km. The river Damodar originates from the hills of south-east corner of the Palamu district of Bihar at an elevation of 600 m and outfalls in the river Bhagirathi in West Bengal near Calcutta.

The Subarnerekha river basin is situated between latitudes 22°0' N and 23°31' N and longitudes 85°7' E and 86°46' E. The total geographical area of the basin is 8591.46 sq. km. The Subarnarekha river originates from village Bandhea 15 km south-west of Ranchi at an elevation of 720 m and falls in the Bay of Bengal after traversing through Bihar, West Bengal and Orissa.

The river basins of small streams draining independently outside the state lie on the fringe of Sankh, South Koel and Subernarekha river basins and is drained through small streams flowing to the neighbouring states namely Orissa and West Bengal. The total geographical area of the basins in Bihar is 1684.68 sq. km.

5.0 DATA AVAILABILITY FOR THE STUDY

Annual maximum peak flood data of 22 gauging sites of South Bihar/Jharkhand have been used. Catchment areas of these sites vary from 11.7 to 3171 square kilometers. Mean annual peak floods of these sites vary from 29.15 cumec to 1293.20 cumec. Most of the annual maximum peak floods used in this study are based on three hourly data. In some cases, the annual maximum peak flood have been chosen from the one hourly and six hourly data. The name of the rivers, respective gauging sites, record length, catchment area and mean annual peak flood are given in Table 1.

As shown in Table 1, out of 22 gauging sites, data are available only for a record length of 8 years or less than 8 years for 16 gauging sites. Thus, record length is more than 8 years for only 6 gauging sites out of the 22 sites. In all, total 200 values of annual maximum peak flood are available for the entire South Bihar/Jharkhand region. Thus the average record length per gauging site is only about 9 years.

Table 1: River name, gauging site, catchment area, mean annual maximum peak flood and record length, for the 22 gauging sites of South Bihar/Jharkhand

Sl. No.	Name of River	Name of Site	Catchment area (km^2)	Mean Flood (m^3/s)	Record length (years)
1	Darua	Gandhitanr	42.74	45.15	6
2	Ajay	Punasi	292.67	567.04	7
3	Ajay	Ghasko	673.40	829.82	10
4	Jam	Bhuiyadih	240.87	321.54	5
5	Dhanarji	Rajauli	194.25	194.23	6
6	Khuri	Akbarpur	150.22	78.67	8
7	Sakari	Gobindpur	1424.50	861.67	6
8	Tilayia	Phulwaria	194.25	234.19	6
9	Kiul	Lakhisarai	2619.00	628.41	24
10	Falgu	Gaya	3171.00	346.67	7
11	Jamuna	Vishnuganj	246.05	94.49	24
12	Dardha	Kolchak	715.00	185.18	33
13	Kharkai	Mahudilodha	2805.00	1293.2	5
14	Subarnarekha	Getalsood	828.80	732.85	7
15	Rajoya	Mero	42.22	87.89	5
16	Kao	Nawadih	176.12	247.21	5
17	Suru	Hurungda	62.16	51.99	5
18	Gopalraidih	Gopalraidih	11.66	29.15	6
19	Sindar	Dhanabindi	90.65	285.91	8
20	Tripta	Kharauni	104.43	279.67	7
21	Orhri	Belchar	150.89	172.13	5
22	Bunbuni	Kasoia	64.00	153.34	5

6.0 METHODOLOGY

The methodology for testing of regional homogeneity, description of L-moments and probability weighted moments (PWMs), frequency distributions and goodness of fit measures used in this study, development of regional flood frequency relationships for estimation of floods of various return periods for gauged catchments, development of relationship between mean annual peak flood and catchment area and development of regional flood formula for estimation of floods of different return periods for the ungauged catchments is described below.

6.1 Test of Regional Homogeneity

A test statistic H, termed as heterogeneity measure has been 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 LCV'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 or Wakeby distribution. The inter-site variation of each generated region is obtained and the mean (μ_v) and standard deviation (σ_v) of the computed inter-site variation is obtained. The heterogeneity measure (H) is then computed as.

$$H = \frac{V - \mu_v}{\sigma_v} \qquad (1)$$

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 $1 \le H < 2$	Region is possibly heterogeneous.
If $H \ge 2$	Region is definitely heterogeneous.

6.2 L-moments and Probability Weighted Moments (PWMs)

L-moments of a random variable were first introduced by Hosking (1986). 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).

6.2.1 Probability weighted moments (PWMs)

Probability weighted moments are defined by Greenwood et al. (1979) as:

$$M_{i,j,k} = \int_0^1 x(F)^i \; (F)^j \, (1-F)^k \, dF \tag{2}$$

where, $F = F(x) = \int_{-x}^{x} f(x)\,dx$ is the cumulative density function and x (F) is the inverse of it; i, j, k are the real numbers. The particularly useful special cases of the PWMs α_k and β_j. are:

$$\alpha_k = M_{1,0,k} = \int_0^1 x(F) \; (1-F)^k \, dF \tag{3}$$

$$\beta_j = M_{1,j,0} = \int_0^1 x(F) \; (F)^j \; dF \tag{4}$$

These equations are in contrast with the definition of the ordinary conventional moments, which may be written as:

$$E(X^r) = \int \{x(F)\}^r \, dF \tag{5}$$

The conventional moments or "*product moments*" involve higher powers of the quantile function x(F); whereas, PWMs involve successively higher powers of non-exceedance probability (F) or exceedance probability (1-F) and may be regarded as integrals of x(F) weighted by the polynomials F^r or $(1\text{-}F)^r$. As the quantile function x(F) is weighted by the probability F or (1-F), hence these are named as probability weighted moments. The PWMs have been used for estimation of parameters of probability distributions as described in Chapter2.

However, PWMs are difficult to interpret as measures of scale and shape of a probability distribution. This information is carried in certain linear combinations of the PWMs. These linear combinations arise naturally from integrals of x(F) weighted not by polynomials F^r or $(1\text{-}f)^r$ but by a set of orthogonal polynomials (Hosking and Wallis, 1997).

6.2.2 L-moments

Hosking (1990) defined L-moments as linear combination of probability weighted moments. In general, in terms of α_k and β_j, L-moments are defined as:

$$\lambda_{r+1} = (-1)^r \sum_{k=0}^{r} p^*_{r,k}\ \alpha_k = \sum_{k=0}^{r} p^*_{r,k}\ \beta_k \quad (6)$$

where, $p^r_{r,k}$ is an orthogonal polynomial (shifted Legender polynomial) expressed as:

$$p^*_{r,k} = (-1)^{r-k}\ {}^rC_k\ {}^{r+k}C_k = \frac{(-1)^{r-k}(r+k)!}{(k!)^2 (r-k)!} \quad (7)$$

L-moments are easily computed in terms of probability weighted moments (PWMs) as given below.

$$\lambda_1 = \alpha_0 \qquad = \beta_0 \quad (8)$$

$$\lambda_2 = \alpha_0 - 2\alpha_1 \qquad = 2\beta_1 - \beta_0 \quad (9)$$

$$\lambda_3 = \alpha_0 - 6\alpha_1 + 6\alpha_2 \qquad = 6\beta_2 - 6\beta_1 + \beta_0 \quad (10)$$

$$\lambda_4 = \alpha_0 - 12\alpha_1 + 30\alpha_2 - 20\,\alpha_3 \qquad = 20\beta_3 - 30\beta_2 + 12\beta_1 + \beta_0 \quad (11)$$

The procedure based on PWMs and L-moments are equivalent. However, L-moments are more convenient, as these are directly interpretable as measures of the scale and shape of probability distributions. Clearly λ_1, the mean, is a measure of location, λ_2 is a measure of scale or dispersion of random variable. It is often convenient to standardise the higher moments so that they are independent of units measurement.

$$\tau_r = \frac{\lambda_r}{\lambda_2} \quad \text{for} \quad r = 3, 4 \quad (12)$$

Analogous to conventional moment ratios, such as coefficient of skewness τ_3 is the L-skewness and reflects the degree of symmetry of a sample. Similarly τ_4 is a measure of peakedness and is referred to as L-kurtosis. These are defined as:

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

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

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

Symmetric distributions have $\tau_3 = 0$ and its values lie between -1 and +1. Although the theory and application of L-moments is parallel to that of conventional moments, L-moment have several important advantages. Since sample estimators of L-moments are always linear combination of ranked observations, they are subject to less bias than ordinary product moments. This is because ordinary product moments require squaring, cubing and so on of observations. This causes them to give greater weight to the observations far from the mean, resulting in substantial bias and variance.

6.3 Frequency Distributions Used

The following commonly adopted frequency distributions have been used in this study. The details about these distributions and relationships among parameters of these distributions and L-moments are available in literature (e.g. Hosking and Wallis, 1997).

6.3.1 Extreme value type-I distribution (EV1)

Extreme Value Type-I distribution (EV1) is a two parameter distribution and it is popularly known as Gumbel distribution. The quantile function or the inverse form of the distribution is expressed as:

$$x(F) = u - \alpha \ln(-\ln F) \quad (13)$$

Where, u and α are the location and scale parameters respectively, F is the non-exceedence probability viz. (1-1/T) and T is return period in years.

6.3.2 General extreme value distribution (GEV)

General Extreme Value distribution (GEV) is a generalized three parameter extreme value distribution. Its theory and practical applications are reviewed in the Flood Studies Report (NERC,1975). The quantile function or the inverse form of the distribution is expressed as:

$$x(F) = u + \alpha \{1-(-\ln F)^k\}/k; \qquad k \neq 0 \quad (14)$$

$$= x(F) = u - \alpha \ln(-\ln F) \qquad k = 0 \quad (15)$$

Where, u, α and k are location, scale and shape parameters of GEV distribution respectively. EV1 distribution is the special case of the GEV distribution, when k = 0.

6.3.3 Logistic distribution (LOGIS)

Inverse form of the Logistic distribution (LOGIS) is expressed as:

$$x(F) = u - \alpha \ln\{(1-F)/F\} \quad (16)$$

Where, u and α are location and scale parameters respectively.

6.3.4 Generalized logistic distribution (GLOGIS)

Inverse form of the Generalized Logistic distribution (GLOGIS) is expressed as:

$$x(F) = u + [\alpha [1 - \{(1-F)/F\}^k] / k; \qquad k \neq 0 \qquad (17)$$

$$x(F) = u - \alpha \ln \{(1-F)/F\}; \qquad k = 0 \qquad (18)$$

Where, u, α and k are location, scale and shape parameters respectively. Logistic distribution is the special case of the Generalized Logistic distribution, when k = 0.

6.3.5 Generalized Pareto distribution (GP)

Inverse form of the Generalized Pareto distribution (GP) is expressed as:

$$x(F) = u + \alpha \{1 - (1-F)^k\} / k; \qquad k \neq 0 \qquad (19)$$

$$x(F) = u - \alpha \ln(1-F) \qquad k = 0 \qquad (20)$$

Where, u, α and k are location, scale and shape parameters respectively. Exponential distribution is special case of Generalized Pareto distribution, when k = 0.

6.3.6 Pearson Type-III distribution (PT-III)

The inverse form of the Pearson type-III 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 distribution (which has zero skewness). The authors parameterize the Pearson type-III distribution by its first three conventional moments viz. mean μ, the standard deviation σ, and the skewness γ. 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 μ, σ and γ. If $\gamma > 0$, then $X - \mu + 2\sigma/\gamma$ has a Gamma distribution with parameters $\alpha = 4/\gamma^2$, $\beta = \sigma\gamma/2$. If $\gamma = 0$, then X has normal distribution with mean μ and standard deviation σ. If $\gamma < 0$, then $-X + \mu - 2\sigma/\gamma$ has a Gamma distribution with parameters $\alpha = 4/\gamma^2$, $\beta = |\sigma\gamma/2|$.

If $\gamma \neq 0$, let $\alpha = 4/\gamma^2$, $\beta = |\sigma\gamma/2|$, and $\xi = \mu - 2\sigma/\gamma$ and $\Gamma(.)$ is Gamma function. If $\gamma > 0$, then the range of x is $\xi \leq x < \infty$ and the cumulative distribution function is:

$$F(x) = G\left(\alpha, \frac{x-\xi}{\beta}\right) \Big/ \Gamma(\alpha) \qquad (21)$$

If $\gamma < 0$, then the range of x is $-\infty < x \leq \xi$ and the cumulative distribution function is:

$$F(x) = 1 - G\left(\alpha, \frac{\xi - x}{\beta}\right) \Big/ \Gamma(\alpha) \qquad (22)$$

6.3.7 Wakeby distribution

Inverse form of the five parameter Wakeby distribution is expressed as:

$$x(F) = \xi + \frac{\alpha}{\beta}\left\{1 - (1 - F)^{\beta}\right\} - \frac{\gamma}{\delta}\left\{1 - (1 - F) - \delta\right\} \tag{23}$$

Where, ξ, α, β, γ, and δ are the parameters of the Wakeby distribution.

6.4 Goodness of Fit Measures

In a realistically homogeneous region, all the sites follow the same frequency distribution. But as some heterogeneity is usually present in a region so no single distribution is expected to provide a true fit for all the sites of the region. In regional flood frequency analysis the aim is to identify a distribution which will yield reasonably accurate quantile estimates for each site of the homogeneous region. Assessment of validity of the candidate distribution may be made on the basis of how well the distribution fits the observed data. The goodness of fit measures assess the relative performance of various fitted distributions and help in identifying the robust viz. most appropriate distribution for the region. A number of methods are available for testing goodness of fit of the proposed flood frequency analysis models. These include Chi-square test, Kolmogorov-Smirnov test, descriptive ability tests and the predictive ability tests. Cunnane (1989) has brought out a comprehensive description of the descriptive ability tests and the predictive ability tests. Apart from the aforementioned tests the recently introduced L-moment ratio diagram based on the approximations given by Hosking (1991) and the goodness of fit or behavior analysis measure for a frequency distribution given by statistic Z_i^{dist} described below, are also used to identify the suitable frequency distribution.

6.4.1 L-moment ratio diagram

The L-moment statistics of a sample reflect every information about the data and provide a satisfactory approximation to the distribution of sample values. The L-moment ratio diagram can therefore be used to identify the underlying frequency distribution. The average L-moment statistics of the region is plotted on the L-moment ratio diagram and the distribution nearest to the plotted point is identified as the underlying frequency distribution. One big advantage of L-moment ratio diagram is that one can compare fit of several distributions using a single graphical instrument (Vogel and Fennessey, 1993).

6.4.2 Z_i^{dist} statistic as a goodness-of-fit measure

In this method also the objective is to identify a distribution which fits the observed data acceptably closely. The goodness of fit is judged 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. The goodness-of-fit measure for a distribution is given by statistic Z_i^{dist}.

$$Z_i^{dist} = \frac{\left(\bar{\tau}_i^R - \tau_i^{dist}\right)}{\sigma_i^{dist}} \quad (24)$$

where $\bar{\tau}_i^R$ - 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 for a given distribution.

The distribution giving the minimum $|Z^{dist}|$ value is considered as the best fit distribution. When all the three L-moment ratios are considered in the goodness-of-fit test, the distribution that gives the best overall fit when all the three statistics are consider together is selected as the underlying regional frequency distribution. According to Hosking (1993), distribution is considered to give good fit if $|Z^{dist}|$ is sufficiently close to zero, a reasonable criteria being $|Z^{dist}| \leq 1.64$.

Let the homogeneous region has N_s sites with site i having record length n_i and sample L-moment ratios t_i, t_{3i} & t_{4i}. Steps involved in computation of statistic Z_i^{dist} are:

i. Compute the weighted regional average L-moment ratios.

$$t^R = \frac{\sum_{i=1}^{N_S} n_i t_i}{\sum_{i=1}^{N_S} n_i} \quad (25)$$

The values of t_3^R and t_4^R are computed similarly by replacing t_i by t_{3i} and t_{4i} respectively.

ii. Fit the candidate distribution to the regional average L-moment ratios t^R, t_3^R and t_4^R and mean = 1.

iii. Use the fitted distribution to simulate a number of regions, say 500, having same record length as the observed data.

iv. Repeat step 1 for each simulated region and the weighted regional average for the simulations are taken as t_1^R, t_2^R ... t_{500}^R and similarly for t_3^R & t_4^R.

v. Compute the mean $\left(\tau_i^{dist}\right)$ and standard deviation $\left(\sigma_i^{dist}\right)$ for the values computed in step 4 above for each L-moment statistic i.

vi. Goodness-of-fit measure Z_i^{dist} is computed as $Z_i^{dist} = \frac{\bar{\tau}_i^R - \tau_i^{dist}}{\sigma_i^{dist}}$ (26)

vii. Repeat the steps 2 to 6 for each of the distributions. Distribution giving the minimum $|Z_i^{dist}|$ value for the L-moment statistics is identified as the best fit distribution.

7.0 ANALYSIS AND DISCUSSION OF RESULTS

In this study, regional flood frequency analysis has been carried out for the South Bihar/Jharkhand region. A region is defined as a set of sites having similar frequency distributions. This step involves assigning the sites to particular groups to form a homogeneous region based on the observed site characteristics. Based on the geographical continuity, it is assumed that the 22 sites of South Bihar/Jharkhand form a homogeneous region.The annual maximum peak flood data of the 22 gauging sites have been considered for development of the regional flood frequency relationship and the regional flood formula for South Bihar/Jharkhand.

7.1 Test of Regional Homogeneity

Homogeneity of the region has been tested using the U.S.G.S. homogeneity test (N.I.H.-1990-91) as well as the measure of heterogeneity test (H) as discussed in Section 6.1. The homogeneity test graph of the USGS test is shown in Fig. 2. Data of all the 22 sites are found to be homogenous as per this test.

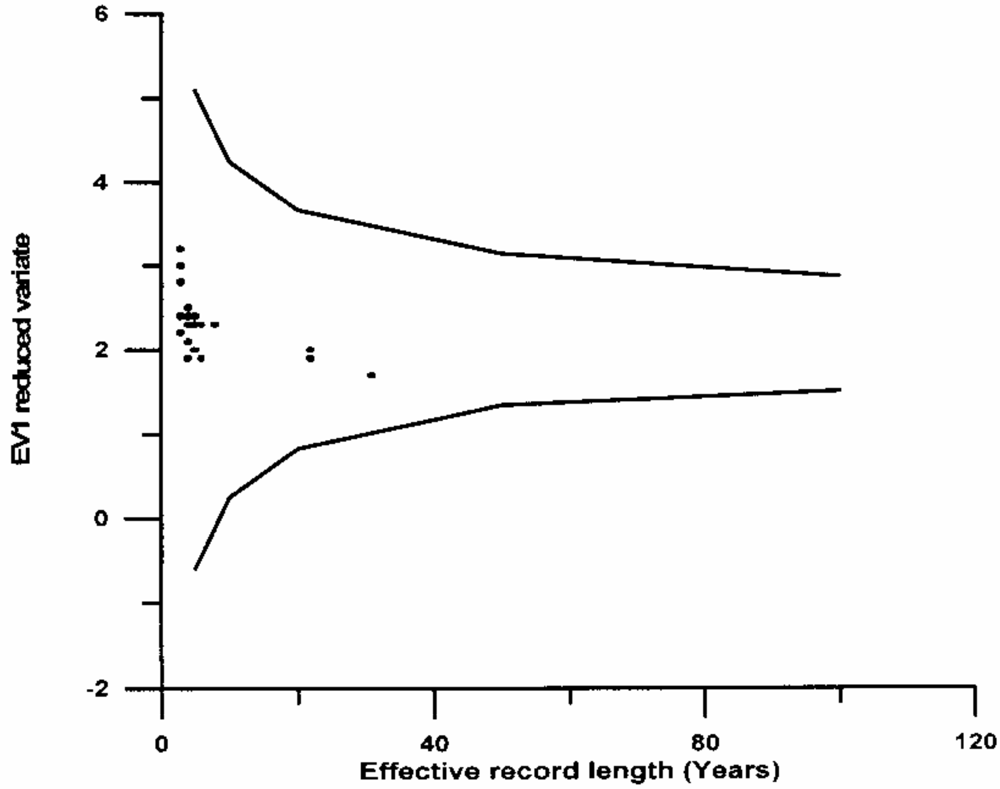


Fig. 2 Homogeneity test graph for South Bihar/Jharkhand

The test based on the heterogeneity measure 'H' takes into consideration that in a homogeneous region, all sites have same population L-moment ratios. But their sample L-moment ratios may differ at each site due to sampling variability. The intersite variation of L-Moment ratio is measured as the standard deviation of the at-site LCV's weighted proportionally to the record length at each site. To establish what would be the expected inter-site variation of L-Moment rations for a homogeneous region simulations are carried out. The heterogeneity measure for the South Bihar/Jharkhand region was found to be $H = 0.9975 < 1.0$ i.e. the region is acceptably homogeneous, as per this test also. The details of catchment area, sample size and sample statistics are given in Table 2.

7.2 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 aim of goodness-of-fit measure or the behaviour analysis is to identify a distribution that fits the observed data acceptably closely. The goodness of fit is judged 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. In this study, the L-moment ratio diagram and Z_i^{dist} have been used as goodness of fit measures for identifying the regional distribution. The regional averages of L-moment statistics for South Bihar/Jharkhand are given below.

The values of the regional L-moments for the study area are:

$\lambda_1 = 1.0000$

$\lambda_2 = 0.3503$

$\lambda_3 = 0.0620$, and

$\lambda_4 = 0.0367$.

The regional values of LC_v, LC_s, and LC_k are mentioned below.

Regional LC_v (τ) = 0.3503

Regional LC_s (τ_3) = 0.1770, and

Regional LC_k (τ_4) = 0.1049.

Table 2: Catchment area, sample statistics and sample size for the gauging sites of South Bihar/Jharkhand

S. No.	Name of River	Name of Site	Catchm-ent area (km^2)	Mean flood (m^3/s)	Standard deviation (m^3/s)	Coeff. of variation	Coeff. of skewness	Sam-ple size
1	Darua	Gandhitanr	42.74	45.15	19.02	.421	.386	6
2	Ajay	Punasi	292.67	567.04	159.99	.282	1.742	7
3	Ajay	Ghasko	673.40	829.82	499.60	.602	.416	10
4	Jam	Bhuiyadih	240.87	321.54	241.49	.751	1.843	5
5	**Dhanarji**	**Rajauli**	**194.25**	**194.23**	**76.91**	**.396**	**.465**	**6**
6	Khuri	Akbarpur	150.22	78.67	47.55	.604	-.197	8
7	Sakari	Gobindpur	1424.50	861.67	529.92	.615	1.309	6
8	Tilayia	Phulwaria	194.25	234.19	133.31	.569	-.443	6
9	Kiul	Lakhisarai	2619.00	628.41	409.55	.652	1.033	24
10	Falgu	Gaya	3171.00	346.67	190.70	.550	.419	7
11	Jamuna	Vishnuganj	246.05	94.49	55.79	.590	.360	24
12	Dardha	Kolchak	715.00	185.18	132.83	.717	.359	33
13	**Kharkai**	**Mahudilodha**	**2805.00**	**1293.2**	**824.79**	**.638**	**1.430**	**5**
14	Subarnarekha	Getalsood	828.80	732.85	377.95	.516	.834	7
15	**Rajoya**	**Mero**	**42.22**	**87.89**	**66.21**	**.753**	**.659**	**5**
16	Kao	Nawadih	176.12	247.21	113.24	.458	-.442	5
17	Suru	Hurungda	62.16	51.99	31.51	.606	.210	5
18	Gopalraidih	Gopalraidih	11.66	29.15	14.97	.514	.457	6
19	Sindar	Dhanabindi	90.65	285.91	165.03	.577	1.200	8
20	Tripta	Kharauni	104.43	279.67	175.40	.627	.746	7
21	Orhri	Belchar	150.89	172.13	59.36	.345	1.795	5
22	Bunbuni	Kasoia	64.00	153.34	37.87	.247	.858	5

The L-moment ratio diagram based on approximations provided by Hosking (1991) has been used to identify the suitable regional flood frequency distribution. As shown in Fig. 3, the PT-III distribution lies closest to the point defined by the regional average values of L-skewness i.e. τ_3 = 0.1770 and L-kurtosis i.e. τ_4 = 0.1049, and the same is identified as the regional distribution, as per this criteria.

In order to find out the robust regional flood frequency distribution, the behaviour analysis was also carried out for the South Bihar/Jharkhand region, and the Z_i^{dist} values are given in Table 3. Based on these values, the PT-III distribution has been identified as the underlying regional distribution for the South Bihar/Jharkhand region.

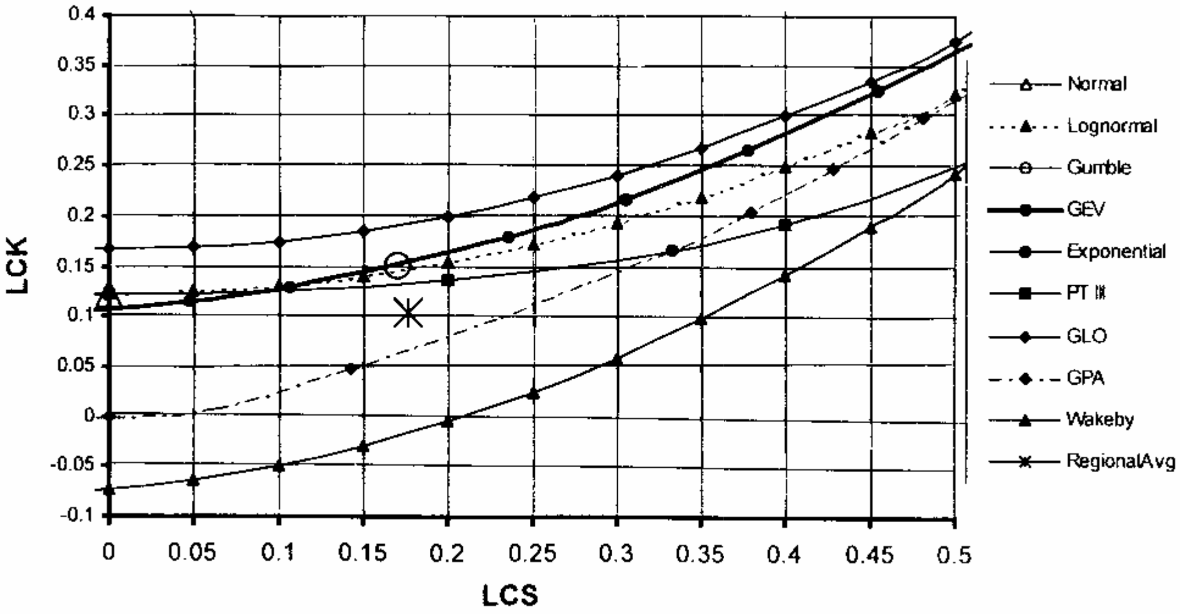


Fig. 3 L-moment ratio diagram for South Bihar/Jharkhand

Table 3 : Z_i^{dist} statistics values for the underlying regional distributions for South Bihar/Jharkhand

Distribution	Z_1 (LCV)	Z_2 (LCS)	Z_3(LCK)
PT-III	**0.21**	**1.54**	**0.01**
GEV	1.11	0.81	1.48
GPA	1.71	3.57	0.99
Wakeby	1.01	0.42	0.88
Exponential	1.49	2.12	1.91
EV1	0.87	1.87	0.62

7.3 Development of Regional Flood Frequency Relationship for Gauged Catchments of South Bihar/Jharkhand

Using the data of annual maximum peak floods of the 22 gauging sites, the regional parameters of the PT-III distribution have been estimated using the L-moments approach. The values of these parameters are mentioned below.

α = **0.3456** β = **3.4700** γ = **-0.1993**

Flood frequency estimates may also be obtained by multiplying the mean annual peak flood of the catchment ($\overline{Q}$) by the corresponding value of growth factor given in Table 4.

Table 4: Regional values of the growth factors based on PT-III distribution for various return periods

Return Period (Years)	2	5	10	20	25	50	100	200	500	1000
Growth Factor	0.906	1.494	1.859	2.194	2.297	2.607	2.906	3.195	3.568	3.844

7.4 Development of Regional Relationship between Mean Annual Peak Flood and Catchment Area

Figure 4 shows the variation of mean annual peak floods with catchment area for the 22 gauging sites of the study area.

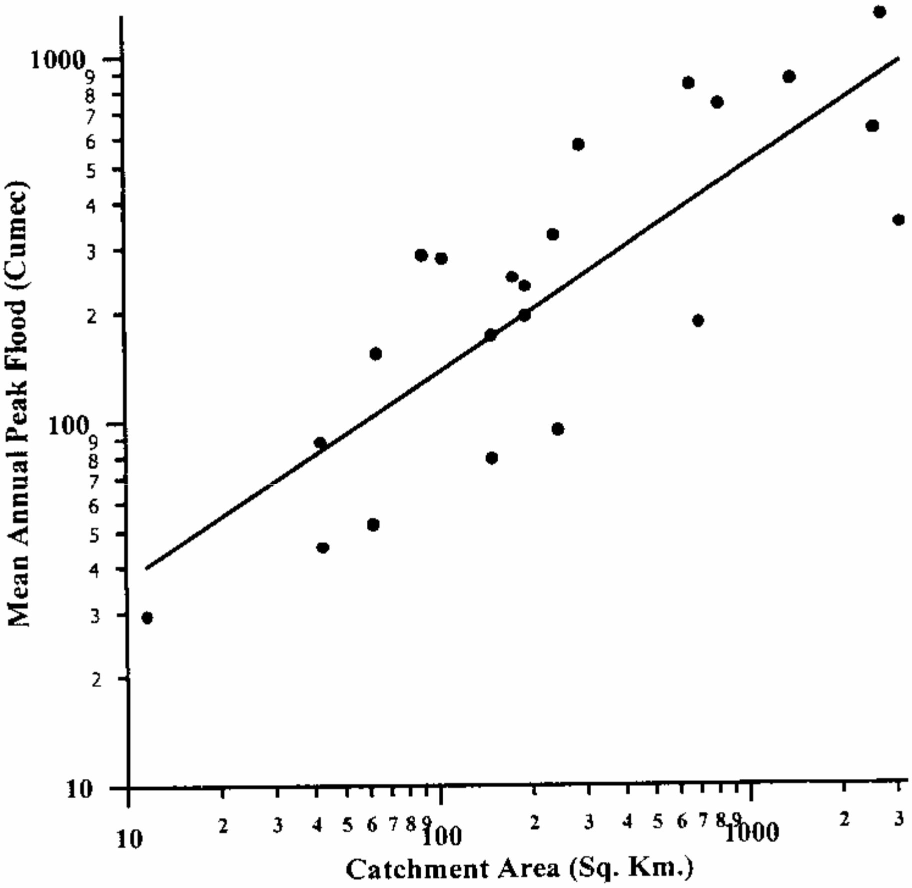


Fig. 4 Variation of mean annual peak flood with catchment area for South Bihar/Jharkhand

The regional relationship between $\bar{Q}$ (m^3/sec) and A (km^2) developed for the region in log domain using least squares approach is given below.

$$\bar{Q} = 10.012\ (A)^{0.567} \qquad (27)$$

for this relationship the correlation coefficient is, r = 0.819 and the standard error of the estimates is obtained as 0.605

7.5 Development of Regional Flood Formula for Ungauged Catchments of South Bihar/Jharkhand

The regional flood formula for estimation of floods of different return periods for the ungauged catchments for South Bihar/Jharkhand is mentioned below.

$$Q_T = C_T \ A^{0.5666} \quad (28)$$

Where, Q_T is the flood in m^3/s for T year return period for an ungauged catchment, C_T is the regional coefficient for T year return period and A is catchment area in km^2. The values of C_T for various return periods are given in Table 5.

Table 5. Values of regional coefficients C_T for different return periods

Sl. No.	Return period (years)	C_T
1	2	9.071
2	5	14.957
3	10	18.612
4	25	22.997
5	50	26.101
6	100	29.094
7	200	31.987
8	500	35.722
9	1000	38.485

The graphical representation of this regional flood formula is given in Fig. 5. This graphical representation may also be used for estimation of floods for various return periods for the ungauged catchments of South Bihar/Jharkhand.

The values of flood frequency estimates (Q_T) computed for various catchment areas are given in Table 6.

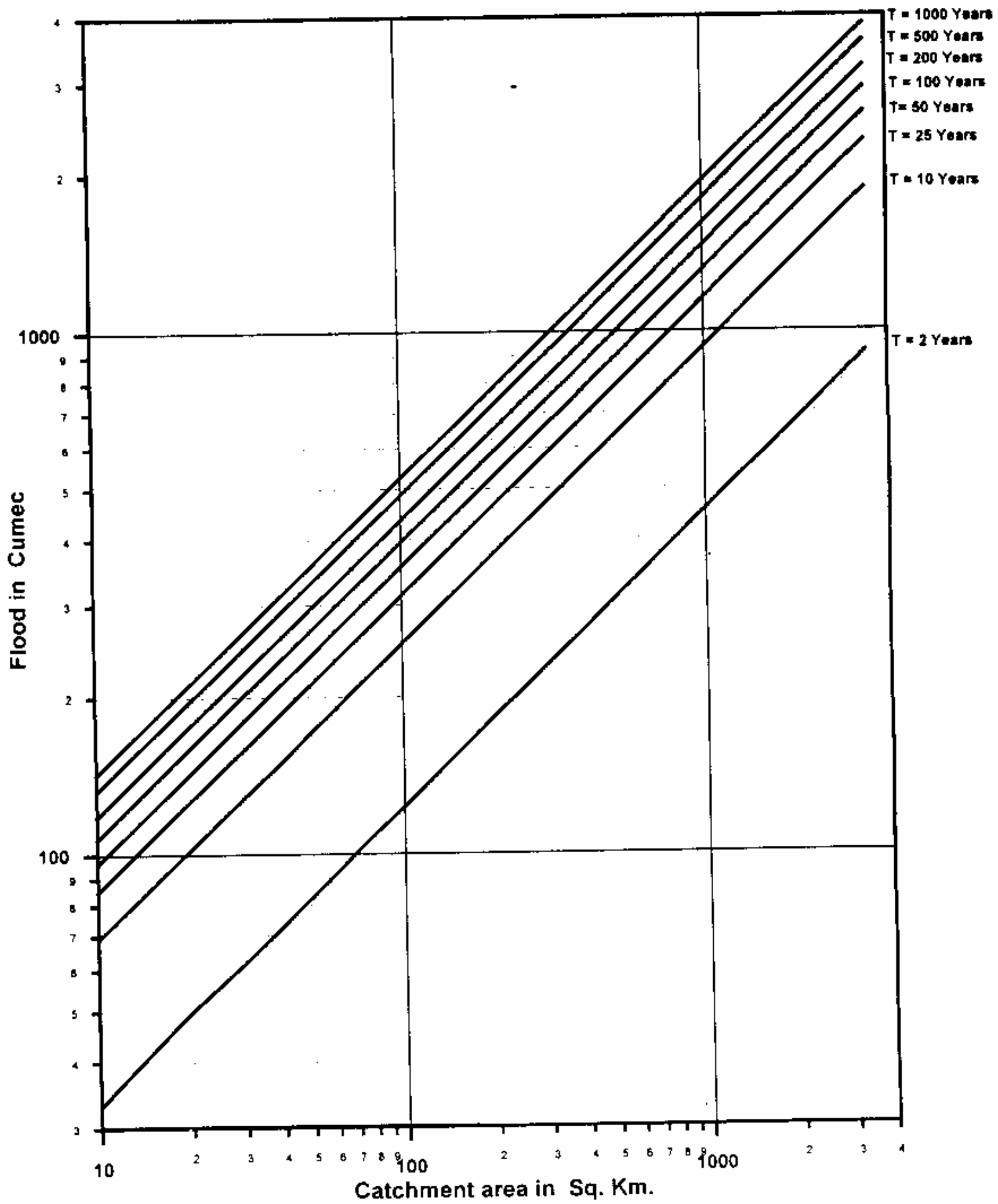


Fig. 5: Variation of floods of different return periods with catchment area for South Bihar/Jharkhand

Table 6: Variation of floods of various return periods with area for South Bihar/Jharkhand

Catchment Area (km^2)	Return periods (Years)								
	2	5	10	25	50	100	200	500	1000
	Floods of various return periods (m^3/s)								
10	33	55	69	85	96	107	118	132	142
20	50	82	102	126	142	159	175	195	210
30	62	103	128	158	179	200	220	245	264
40	73	121	150	186	211	235	259	289	311
50	83	137	171	211	239	267	294	328	353
60	92	152	189	234	266	296	325	363	392
70	101	166	207	255	290	323	355	397	427
80	109	179	223	275	313	348	383	428	461
90	116	191	238	294	334	372	409	457	493
100	123	203	253	313	355	395	435	485	523
150	155	256	318	393	446	497	547	611	658
200	183	301	375	463	525	586	644	719	775
250	207	342	425	525	596	664	731	816	879
300	230	379	471	582	661	737	810	905	975
350	251	413	514	636	721	804	884	987	1064
400	270	446	555	685	778	867	953	1065	1147
450	289	477	593	733	832	927	1019	1138	1226
500	307	506	630	778	883	984	1082	1208	1302
550	324	534	664	821	932	1039	1142	1275	1374
600	340	561	698	863	979	1091	1200	1340	1443
650	356	587	730	903	1024	1142	1255	1402	1510
700	371	612	762	941	1068	1191	1309	1462	1575
750	386	637	792	979	1111	1238	1361	1520	1638
800	400	660	822	1015	1152	1284	1412	1577	1699
850	414	683	850	1051	1192	1329	1461	1632	1758
900	428	706	878	1085	1232	1373	1510	1686	1816
950	441	728	906	1119	1270	1416	1557	1738	1873
1000	454	749	932	1152	1308	1457	1602	1790	1928
1200	504	831	1034	1277	1450	1616	1777	1984	2138
1400	550	907	1128	1394	1582	1764	1939	2165	2333
1600	593	978	1217	1504	1706	1902	2091	2336	2516
1800	634	1045	1301	1607	1824	2033	2236	2497	2690
2000	673	1110	1381	1706	1936	2159	2373	2650	2855
2200	710	1171	1457	1801	2044	2278	2505	2797	3014
2400	746	1231	1531	1892	2147	2393	2632	2939	3166
2600	781	1288	1602	1980	2247	2505	2754	3075	3313
2800	814	1343	1671	2065	2343	2612	2872	3207	3455
3000	847	1396	1737	2147	2437	2716	2986	3335	3593
3200	878	1448	1802	2227	2527	2817	3097	3459	3727
3400	909	1499	1865	2305	2616	2916	3206	3580	3857

7.6 Comparison of Flood Estimates for Different Return Periods for the Gauged and Ungauged Cases of the Test Catchments

With the objective of comparing the flood estimates computed for different return periods for the gauged and ungauged cases, the above described procedure was repeated using the annual maximum peak flood data and catchment area of 19 out of the 22 sites of the study area. The data of the 3 sites i.e. the second smallest, second largest and median size in catchment area (shown at S. Nos. 5, 13 and 15 in Table 2 in Section 7.2) were excluded as these were treated as the test catchments. The regional values of the L-moment based parameters of the PT-III distribution using the data of 19 sites are given below.

$\alpha = 0.4863$ $\qquad\beta = 2.3825$ $\qquad\gamma = -0.1586$

The regional relationship between mean annual peak flood and catchment area in log domain using data of 19 sites is given below.

$$\overline{Q} = 11.0475\,(A)^{0.5448} \tag{29}$$

for which correlation coefficient is, $r = 0.779$.

While considering the test catchments as gauged catchments, their mean annual maximum peak flood and the regional flood frequency relationship developed using the data of 19 catchments were used for computing the floods of various return periods.

When these test catchments are considered as ungauged catchments, the developed regional flood formula based on the data of 19 catchments has been used for estimation of floods of various return periods. In the regional flood formula, the catchment area of these three test catchments have been utilised.

Tables 7 and 8 show the comparison of flood estimates for different return periods for the gauged and ungauged cases of the three test catchments along with their percentage deviation. Figures 6, 7 and 8 show the comparison of floods for gauged and ungauged cases of three test catchments for 50, 100 and 200 year return periods respectively.

It is observed from tables 7 and 8 that the percentage deviation between the ungauged and gauged cases of the test catchment No. 1 is about –3.3%; while for the test catchment No. 2 and 3, the percentage deviation is about 0.3% and –35.4% respectively.

Table 7: Comparison of floods of 5, 10, 25 and 50 year return periods for gauged and ungauged cases of the test catchments of South Bihar/Jharkhand

Sl. No.	Catchment Area (km^2)	Return Period (Years)											
		5			10			25			50		
		Gauged	Ungauged	Deviation (%)	Gauged	Ungauged	Deviation (%)	Gauged	Ungauged	Deviation (%)	Gauged	Ungauged	Deviation (%)
1	42.22	137.3	133	-3.4	175	170	-3.4	222.3	215	-3.3	255.4	247	-3.3
2	194.25	304.4	306	0.5	388.8	390	0.3	491.2	493	0.31	564.4	567	0.4
3	2805.00	2026	1308	-35.4	2589	1672	-35.4	3270	2112	-35.4-6	3758	2427	-35.4

Table 8: Comparison of floods of 100, 200, 500 and 1000 year return periods for gauged and ungauged cases of the test catchments of South Bihar/Jharkhand

Sl. No.	Catchment Area (km^2)	Return Period (Years)											
		100			200			500			1000		
		Gauged	Ungauged	Deviation (%)	Gauged	Ungauged	Deviation (%)	Gauged	Ungauged	Deviation (%)	Gauged	Ungauged	Deviation (%)
1	42.22	287.4	278	-3.3	318.6	308	-3.3	358.9	347	-3.3	389.0	376	-3.3
2	194.25	635.1	638	0.4	704.1	707	0.4	793.2	796	0.3	859.7	863	0.3
3	2805.00	4228	2731	-35.4	4688	3027	-35.4	5281	3410	-35.4	5723	3696	-35.4

Fig. 6 Comparion of floods of various return periods for gauged and ungauged cases for test catchment No. 1

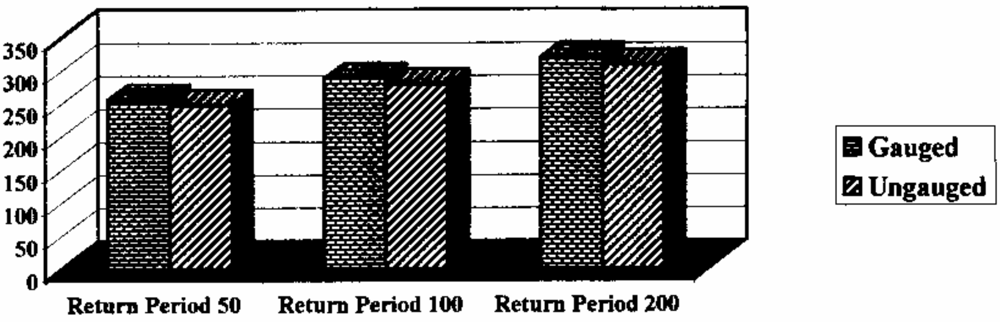


Fig. 7 Comparion of floods of various return periods for gauged and ungauged cases for test catchment No. 2

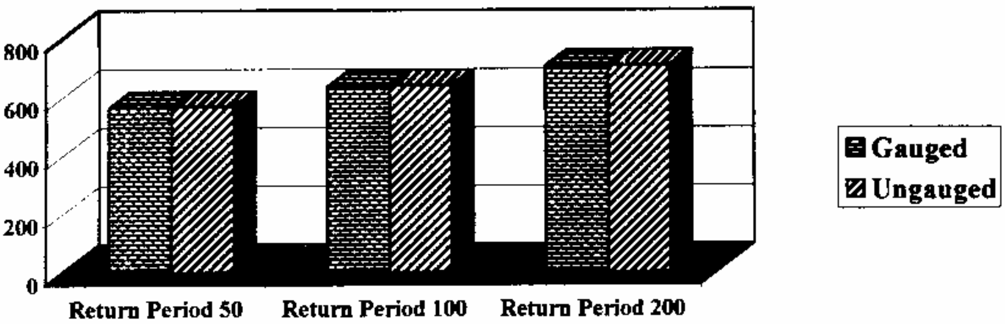
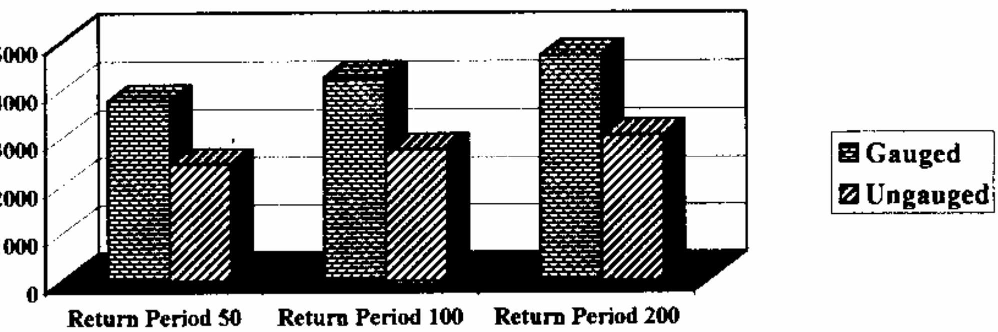


Fig. 8 Comparion of floods of various return periods for gauged and ungauged cases for test catchment No. 3



8.0 CONCLUSIONS

On the basis of this study following conclusions are drawn.

i. In this study, comparative regional flood frequency analysis has been carried out by employing some of the commonly used frequency distributions and utilizing the annual maximum peak flood data of the 22 small to moderate size catchments of South Bihar/Jharkhand. Homogeneity of the region has been tested using the L-moment based heterogeneity measure 'H' and the USGS homogeneity test.

ii. Based on the L-moment ratio diagram and the Z_i^{dist} statistics criteria, Pearson Type-III (PT-III) distribution has been identified as the robust distribution for the study area. Regional flood frequency relationship has been developed using the L–moment based PT-III distribution. For estimation of floods of different return periods for the small to moderate size gauged catchments of South Bihar/Jharkhand, the mean annual peak flood of the catchment may be multiplied by the corresponding growth factors.

iii. The L-moment based regional flood frequency curves derived for the PT-III distribution have been coupled with the relationship between mean annual peak flood and the catchment area and the regional flood formula has been developed for estimation of floods of desired return periods for ungauged catchments of South Bihar/Jharkhand. The developed regional flood formula or its graphical representation may be used for estimation of floods of desired return periods for small to moderate size ungauged catchments of South Bihar/Jharkhand. The conventional empirical flood formulae do not provide floods of various return periods. However, the regional flood formula developed in this study is capable of providing flood estimates for desired return periods.

iv. As the flood formula has been developed using the data of small to moderate size catchments ranging from 11.7 to 3171 km^2; therefore this formula may be used for estimation of reliable flood frequency estimates for catchments of about 10 to 3500 km^2 in areal extent for South Bihar/Jharkhand.

v. Based on the analysis carried out using the data of 19 sites for testing the regional flood formula for the three test catchments, it is observed that the percentage deviation between the ungauged and gauged cases of the test catchment No. 1 is about -3.3%; while for the test catchment No. 2 and 3, the percentage deviation is about 0.4% and -35.4% respectively.

vi. The form of the developed regional flood formula is very simple, as for estimation of flood of desired return period for an ungauged catchment, it requires only catchment area which is readily available. Hence, this formula may be used by the field engineers for estimation of floods of desired return periods.

vii. The relationship between mean annual peak flood and catchment area developed on the basis of available data of 22 catchments in log domain is able to explain 67% of initial variance (coefficient of determination, $R^2 = 0.67$). The standard error of the estimates is obtained as 0.605. However, if the physiographic and climatic characteristic other than catchment area are used, then it may further improve the regional flood formula.

viii. For most of the gauging sites, annual maximum peak flood data used in this study have been obtained from the three-hourly observed data. However, for some of the sites, the annual maximum peak floods have also been obtained from one-hourly and six-hourly data. Further, out of 22 gauging sites, data are available only for a record length of 8 years or less than 8 years for 16 gauging sites. In all, total 200 values of annual maximum peak flood are available for the entire South Bihar/Jharkhand region. Thus the average record length per gauging site is only about 9 years. As all the annual maximum peak flood values have not been obtained from the short interval observations like one hourly observations as well as the record length is also short, hence, the results of the study are subject to these limitations. However, the developed regional flood frequency relationships and the regional formula may be revised for obtaining more accurate flood frequency estimates, when the annual maximum peak flood data based upon one-hourly observations for a longer period become available.

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