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Regional Flood Frequency Analysis Using L Moments

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NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE - 247 667 (U.P.) INDIA

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ABSTRACT

Estimation of flood magnitudes and their frequencies for planning and design of water resources projects have 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 estimates directly. In such a situation, the regional flood frequency relationships or the flood formulae developed for the region are the alternative methods which provide estimates of design floods.

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 derivation of the regional flood formulae. The regional flood frequency curves developed for each subzone together with at site mean annual peak floods may be used for gauged catchments; while for ungauged catchments, regional flood formulae developed for the respective subzones may be adopted for obtaining rational flood estimates.

1.0 INTRODUCTION

Information on flood magnitudes and their frequencies is needed for design of hydraulic structures such as dams, spillways, road and railway bridges, culverts, urban drainage systems, flood plain zoning, economic evaluation of flood protection projects etc. 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, specially for small to medium 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, 1983) 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 generalized 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 distribuion 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). In this study, 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 formulae for the seven subzones of India.

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 in appropriate 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 EVI 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 EV1 (Gumbel) probabilty paper,

(vii) A smooth, eye-guided curve gives the X-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 : $Q_T = X_T Q$ where 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 freqency analysis as given by Dalrymple (1960) and modified to accomodate 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 Q at each station.

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

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

(vi) Obtain the ratio Q_T/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/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/Q (iii) Variable length of data instead of fixed length of data (iv) parameter estimation by method of moments instead of method of least square.

2.1.2 NERC 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, suitable 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/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 relelased 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. Becasue 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 prodictive 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 $\bar{Q}$ and C_v obtained from catchment characteristics, using bivariate lognormal distribution for $\bar{Q}$ and C_v and site data assumed to be EV1 distributed to give a posterior distribution for Q_T. This method invoilves 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 Q estimated from catchment characteristics is only as good as 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 for a statisticly which is to be estimated by using watershed characteristics such as drainage area and slope.

$$y_t = \alpha + \beta_1 \log(\text{Area}) + \beta_2 \log(\text{slope}) + \ldots + \epsilon \qquad (1)$$

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: (1) the sampling error in sample estimators of y_i (these errors at different sites can be cross-correlated if the records are concurrent) and (2) 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 (Sankarasubramanian, 1995).

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 longarithimc 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 exploited in both regional homogeneity tests and Goodness of Fig test (Lu and Stedinger, 1992a; Hosking and Wallis, 1993; Zrinji and Burn 1994) which are vital steps 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 mildheterogeneity and moderate inter-site cross correlations. Furthermore, Hosking et al. (1985a) illustrate the impact of historical informaion 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 more 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 reginal 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. Method based on standardised L oments is described below.

For regional estimation Wallis (1980) proposed that at sites values of PWMs be standardised by division by the at site mean M_{100} and the resulting standardised values be averaged across the sites in the region thus.

$$M_{(r)} = M_{1r0} / M_{100} \tag{2}$$

$$M_{(k)} = M_{0k} / M_{00} \qquad (3)$$

are caluculated for each site and then averaged across the m sites by

$$M_{(r)} = \sum_{i=1}^{m} M^{i}_{(r)}\, n_i / \sum_{i=1}^{m} n_i \qquad (4)$$

$$M_{(k)} = \sum_{i=1}^{m} M^{i}_{(k)}\, n_i / \sum_{i=1}^{m} n_i \qquad (5)$$

Where each site's contribution to the average is weighted in proportion to its record length.

It the similar fashion regional values of L-moments are computed. As L-moments are linear combinations of PWMs, above regional value of PWMs can be used a compute the regional L-moments.

These regional weighted average values of L-Moments can be used to estimate parameters of the distributions. Quantile of such distribution can be scaled by site mean to given a guantile estimate for any particular site.

2.2 Some of the Flood Frequency Studies Carried Out in India

There has been significant number of studies 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 sub-zone which are 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 sub-zones are 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 are coupled with the relationships between mean annual peak flood and catchment area for developing regional flood formulae for each of the seven hydrometeorologically homogeneous sub-zones of India. A regional flood formula is also developed for zone 3 considering data of all the 7 sub-zones 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 sub-zones and the regional flood formula for combined zone 3.

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 mean annual peak flood (MAF) and the catchment characteristics. Inspite of a large number of existing regionalisation techniques, very few studies have been carried out with some what 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). 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), which can be regarded as the state-of-the-art method for regional flood frequency analysis (RFFA).

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

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

(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

(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 and physiographic characteristics for the region

(v) Estimate the mean annual peak flood using the developed relationship

(vi) Use the best fit regional flood frequency relationship for estimation of T-year flood.

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), has 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 (1994) 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-said 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(Cv) <0.4). Further, they conclude that, for sites with sufficient record length, with significant lack of fit, the shape parameter estimator is perferable. 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 homogeous regions, each with only a smaller number of catchments.

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

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 likelyhood
(iv) Method of probability weighted moments
(v) Method based on principle of maximum entropy

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 exit (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 p[roperties 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 alternaive. 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 meansures namely,i) Discordancy meansure 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 choic for the selection of the most competitive flood frequency models for the region/site in question. In such situations, regional Monte-Carlo simularion technique will be very much usefull 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 elstimators 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 simulation 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 differen 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 histologists 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.

It has been observed in some of the comparative regional flood frequency analysis studies using the (i) at site data, (ii) at site and regional data and, (iii) regional data alone (NIH, 1995-96; NIH, 1994-1995), based on the descriptive ability and predictictive ability tests; probability weighted moment (PWM) based General Extreme Value (GEV) distribution in general estimates the flood frequency estimates with less bias and comparable root mean square error and coefficient of variation. 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 objectives of this study are:

(a) Development of regional flood frequency curves using the L moment based GEV distribution.

(b) Development of regional relationship between mean annual peak floods and physiographic characteristics for estimating the mean annual peak flood for the ungauged catchments for the various subzones of Zone 3.

(c) Comparison of the regional flood frequency curves based on probability weighted moment (PWM) approach and L moment approach.

(d) Coupling the relationship between mean annual peak flood and physiographic characteristics with the L moment based regional flood frequency curves of the General Extreme Value (GEV) distribution for developing the regional flood formulae for the seven subzones of Zone 3.

4.0 DESCRIPTION OF THE STUDY AREA

The country has been divided into 7 major zones, which are in turn sub-divided into 26 hydrometeorological subzones. The study area comprises of following 7 hydrometeorological sub-zones of zone 3 of India, namely:

(i) Mahi and Sabarmati subzone 3(a),
(ii) Lower Narmada and Tapi subzone 3(b),
(iii) Upper Narmada and Tapi subzone 3(c),
(iv) Mahanadi subzone 3(d),
(v) Upper Godavari subzone3(e),
(vi) Lower Godavari subzone 3(f), and
(vii) Krishna and Penner subzone 3(h)

The Indravati subzone 3(g) and Cauveri subzone 3(i) could not be included in the study, as data for these sub-zones were not available. The study area lies roughly between 13° 7′ to 25° north latitudes and 69° to 87° east longitudes. Location map of Zone-3 of India and its subzones is shown in Fig. 1. All the 7 sub-zones considered in the study receive about 75% to 80% of their annual rainfall from south-west monsoon during the period of June to October. The normal annual rainfall varies from 400 mm to 2000 mm in different parts of the study area. A brief description of these sub-zones is given below.

Mahi and Sabarmati subzone 3(a) is traversed by the rivers Mahi, Sabarmati, Saraswati and a large number of coastal streams. This sub-zone lies in semi-arid zone. The general elevation of this subzone varies from 0 to 600 meters above mean sea level. Lower Narmada and Tapi Sub-zone 3(b) is covered by the lower reaches of river Narmada and Tapi and their tributaries. It is a semi-arid region with elevation varying from 300 meters to 900 meters in its various parts. Upper Narmada and Tapi subzone 3(c) comprises of upper portions of Narmada and Tapi basins. Areas varying in height from 150 meters to 900 meters lie in its various portions. Mahanadi subzone 3(d) comprises of Mahanadi, Brahmani and Baitarani basins. About 50% of the area of this subzone is hilly varying from 300 meters to 1350 meters. Rest of the area lies in the elevation range of 0 to 300 meters. The Upper Godavari sub-zone 3(e) is traversed by the Upper Godavari and its tributaries. The elevation range of various portions of this sub-zone varies from 300 meters to 1350 meters. Lower Godavari subzone 3(f) is a sub-humid region with elevation varying from 150 meters to 1350 meters in its various portions. Krishna and Penner subzone 3(h) is traversed by the Krishna and Penner rivers excluding their deltaic strip along the eastern coast. The elevation range of its various parts varies from 150 meters to 600 meters.

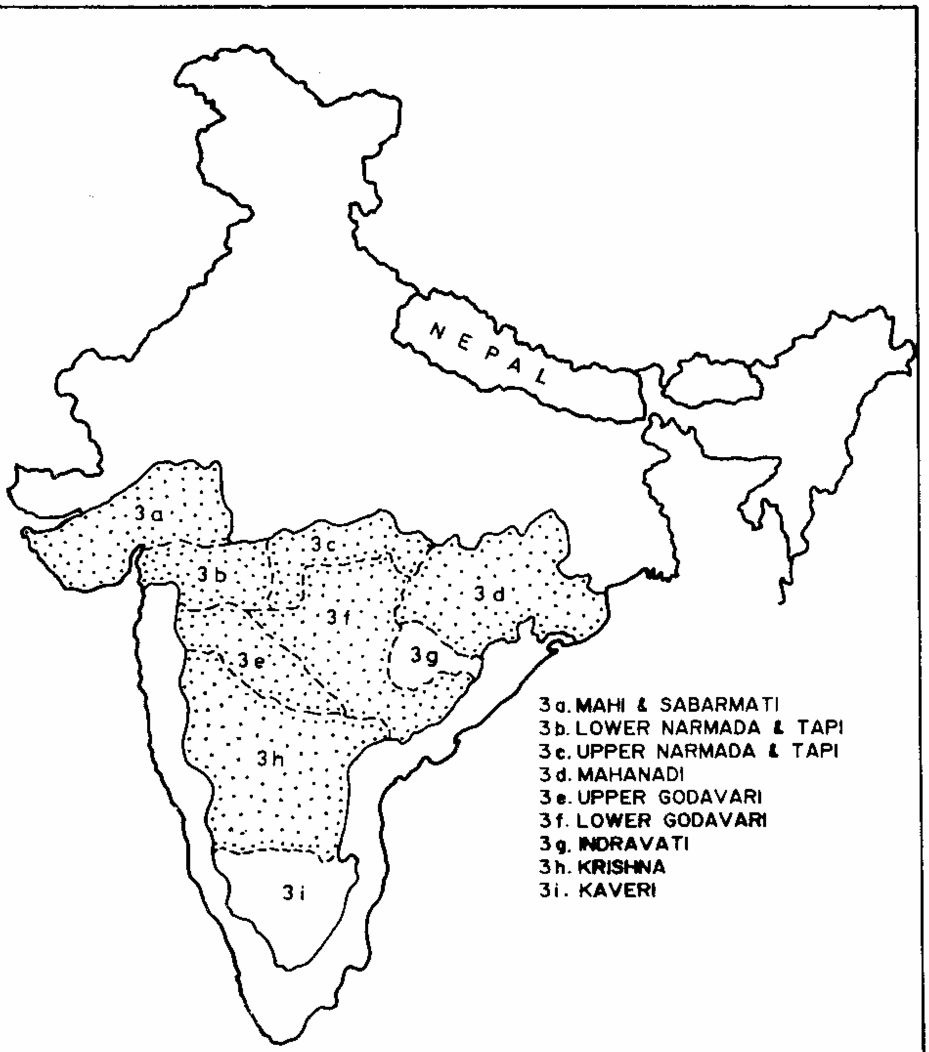

FIG. 1. LOCATION MAP OF HYDROMETEOROLOGICAL ZONE 3 OF INDIA AND ITS SUB-ZONES

5.0 DATA AVAILABILITY FOR THE STUDY

The annual peak flood series data varying over the period 1957 to 1989 for 115 bridge sites of the 7 hydrometeorologically homogeneous sub-zones of the zone 3 are available for the study(RDSO, 1991). The area of each sub-zone, number of bridge sites for which data are available, range of catchment area of the various bridge sites, range of mean annual peak flood and record length for various sub-zones are summarised in Table 1.

TABLE 1. Salient Features of Various Catchments of the Seven Subzones

Subzone (1)	Area of Subzone (km^2) (2)	No. of bridge sites in a subzone (3)	Range of catchment area of bridge sites (km^2) (4)	Range of mean annual peak flood (m^3) (5)	Range of record length (Years) (6)
3(a)	138400	10	18.44-1094.00	74.00-448.65	14-25
3(b)	77700	19	17.22-1017.00	34.95-558.29	12-28
3(c)	86353	15	41.80-2110.85	111.95-1730.53	14-30
3(d)	195256	22	19.00-1150.00	25.09-1071.95	11-31
3(e)	88870	12	31.31-2227.39	60.13-868.88	14-32
3(f)	174201	19	35.00-824.00	77.75-1212.83	14-29
3(h)	280881	18	31.72-1689.92	28.29-794.88	14-33

6.0 METHODOLOGY

The methodology used for development of regional flood frequency curves us L-moment based GEV distribution as well as regional relationship for the estimat of mean annual peak flood and developing the regional formulae is discussed l under.

6.1 Development of Regional Flood Frequency Curves

In order to develop the regional flood frequency curves a sample comprisir the station-year data of standardized values of annual maximum peak floods i.e. Z_T = values for various gauging sites of each subzone are considered for the analysis. F frequency analysis is performed with the sample of $\frac{Q_T}{\bar{Q}}$ values. In order to exa the effect of regional heterogeneity, regional flood frequency is also carried out the $\frac{Q_T}{\bar{Q}}$ values of all the catchments of the seven subzones in combined form.

The GEV distribution is a generalized three parameter extreme value distrit proposed by Jenkinson(1955). Its theory and practical applications are reviewed Flood Studies report prepared by Natural Environment Research Council (N 1975). The cumulative density function F(z) for GEV distribution is expressed

$$F(z) = e^{-\left[1-K\left(\frac{z-u}{\alpha}\right)\right]^{1/K}}$$

Here u, α and K are location, scale and shape parameters of the GEV distr respectively. It may be noted that the case of k=0 corresponds to the two pa Gumbel distribution, which has a constant skewness of 1.14. The parameters u, K of the GEV distribution are estimated using the method of L-moments.

This distribution gives the general mathematical form for extrem distributions for maxima. The GEV distribution's cdf may be written as :

$$f(x) = \alpha^{-1} e^{(1-k)y} e^{-e^{y}} \quad where\ y = \begin{cases} -k^{-1}\ln\{1-k(x-u)/\alpha\}, & k \neq 0 \\ (x-u)/alfa, & k \neq 0 \end{cases}$$

$$F(x) = e^{-e^{y}}$$

The form of the regional frequency relationship is expressed as:

$$Z_T = Q_T / \bar{Q} = u + \alpha Y_T \qquad (9)$$

Here, Z_T is T-year return period flood estimate, $\bar{Q}$ is the mean annual peak flood and Y_T is GEV reduced variate corresponding to T-year return period.

The GEV reduced variate (Y_T) can be expressed as a function of return period, T as:

$$Y_T = \left[1 - \left\{-\ln\left(1 - \frac{1}{T}\right)\right\}^K\right] / K \qquad (10$$

$$x(F) = \begin{cases} u + \alpha\{1 - (-\ln(F)^k\}/k, & k \neq 0 \\ u - \alpha \ln(-\ln F), & k \neq 0 \end{cases} \qquad (11)$$

6.2 L MOMENTS

L-moment of a random variable were first introduced by Hosking (1986). These are analogous to conventional moments, but are estimated as linear combination of order statistics. Let X be a real valued random variable with CDF F(X) and quantile function X(F) and let $X_{1:n} < X_{2:n} < \ldots < X_{n:n}$ be the order statics of a random sample of size n drawn from distribution of X, L-moments of X are quantities.

$$\lambda_r = \frac{1}{r} \sum_{k=0}^{r-1} (-1)^k \binom{r-1}{k} EX_{r-k:r} \qquad r = 1, 2 \ldots \qquad (12)$$

The experiment of an order statistics may be written as

$$EX_{j:r} = \frac{r!}{(j-1)!\,(r-j)!} \int_0^1 x\{F(x)\}^{j-1} \{1-F(x)\}^{r-j} \, dF(x) \qquad (13)$$

The L in `L-moment', emphasizes that λ_r is linear function of the expected order statistics. The first few L-moments are

$$\lambda_1 = EX = \int_0^1 x(F)\ dF \tag{14}$$

$$\lambda_2 = \int_0^1 x(F)\ (2F-1)\,dF \tag{15}$$

$$\lambda_3 = \int_0^1 x(F)\ (6F^2-6F+1)\,dF \tag{16}$$

$$\lambda_4 = \int_0^1 x(F)\ (20F^3-30F^2+12F-1)\,dF \tag{17}$$

The simplest approach to describe L-moments is through probability weighted moments because L-moments are linear functions of PWMs (Hosking 1986, 1990). as follows.

$$\lambda_1 = M_{100} \tag{18}$$

$$\lambda_2 = 2M_{110} - M_{100} \tag{19}$$

$$\lambda_3 = 6M_{120} - 6M_{110} + M_{100} \tag{20}$$

$$\lambda_4 = 20\, M_{30} - 30\, M_{20} + 12\, M_{10} + M_{00} \qquad (21)$$

So procedure based on PWMs and L-moments are equivalent. However, L-oments are more convenient, as there are directly interpretable as measures of the cale and shape of probability distributions. Clearly λ_1, the mean, is a measure of ction λ_2 is a measure of scale or dispersion of random variable. It is often convenient o standardise the higher moments so that they are independent of units measurement f X.

$$\tau_r = \frac{\lambda_2}{\lambda_r} \; for \; r = 3,4 \qquad (22)$$

Analogous to conventional moment ratios, such as the 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. In addition, the L-coefficient of variation, L-CV, is defined as,

$$\tau_2 = \frac{\lambda_2}{\lambda_1} \qquad (23)$$

Symmetric distributions have τ_3=0 and its values lie between -1 and +1. Although they theory and application of L-moments is parallel to that of conventional moments, L-moment have several importan 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.

The L-Moments may also be estimated as mentioned below.

$$rB_{r-1} = u + \alpha\{1 - r^{-k}\,\Gamma(1+k)\}/k, \qquad k > -1 \qquad (24)$$

The relationship between the parameters and the L-Moment estimates are :

$$k = 7.8590c + 2.9554\, c^2 \qquad (25)$$

$$c = \frac{(2B_i - B_o)\ \ln 2}{(3B_2 - B_o)\ \ln 3} \tag{26}$$

$$\lambda_2 = \alpha(1-2^{-k})\Gamma(1+k)/k \tag{27}$$

$$\lambda_1 = u+\alpha(1-2^{-k})\Gamma(1+k)/k \tag{28}$$

6.3 Estimation of T Year Flood Using At-Site Mean

Once, at site estimate of mean annual peak flood $(\bar{Q})$ is made for the gauged catchments the T year floods are estimated using the following relationship:

$$Q_T = \bar{Q} \,.\, z_T \tag{29}$$

6.4 Development of Relationship Between Mean Annual Peak Flood and Catchment Area

For estimation of T-year return period flood at a site, the estimate for mean annual peak flood is required. For gauged catchments, such estimates can be obtained based on the at-site mean of the annual maximum peak flood data. However, for ungauged catchments at-site mean can not be computed in absence of the flow data. In such a situation, a relationship between the mean annual peak flood of gauged catchments in the region and their pertinent physiographic and climatic characteristics is needed for estimation of the mean annual peak flood. Since, catchment area is considered to be one of the most prominent physiographic characteristics and is readily available, a relationship of the following form is developed in terms of catchment area for estimation of mean annual peak flood for ungauged catchments.

$$\bar{Q} = a\ A^b \tag{30}$$

Here, $\bar{Q}$ is the mean annual peak flood for a catchment, A is the catchment area and a and b are the coefficients to be estimated using the least squares approach.

6.5 Development of Regional Flood Formula

The various steps involved in the derivation of the regional flood formula are given below.

The form of the regional flood frequency relationship is:

$$\frac{Q_T}{\bar{Q}} = u + \alpha y_T \tag{31}$$

where,

$$y_T = \left[1 - \left(-\ln\left(1 - \frac{1}{T}\right)\right)^k\right] / k \tag{32}$$

The conventional Dicken's formula is:

$$Q = A^{0.75} \tag{33}$$

The form of the developed formula may be mentioned as:

$$Q_T = C_T A^b \tag{34}$$

The form of relationship between mean annual peak flood and catchment area is:

$$\bar{Q} = a A^b \tag{35}$$

Dividing equation (34) by equation (35):

$$\frac{Q_T}{\bar{Q}} = \frac{C_T}{a} \tag{36}$$

It may be expressed as:

$$C_T = \frac{Q_T}{\bar{Q}} a \tag{37}$$

Substituting the value of $\frac{Q_T}{Q}$ from equation (31):

$$C_T = (u + \alpha y_T)\, a \tag{38}$$

Substituting the value of C_T from equation (38) in equation (34) we get:

$$Q_T = (u + \alpha y_T)\, a\, A^b \tag{39}$$

or,

$$Q_T = [ua + a\alpha y_T]\, A^b \tag{40}$$

or,

$$Q_T = \left[ua + a\alpha[1 - \{-\ln(1 - \tfrac{1}{T})\}^k]/k\right] A^b \tag{41}$$

or,

$$Q_T = \left[ua + \frac{a\alpha}{k} - \frac{a\alpha}{k}\left\{-\ln(1 - \frac{1}{T})\right\}^k\right] A^b \tag{42}$$

or,

$$Q_T = \left[a(\frac{\alpha}{k} + u) - \frac{a\alpha}{k}\left\{-\ln(1 - \frac{1}{T})\right\}^k\right] A^b \tag{43}$$

or,

$$Q_T = \left[\beta + \gamma\left\{-\ln(1 - \frac{1}{T})\right\}^k\right] A^b \tag{44}$$

Where,

Where,

$$\beta = a(\alpha / k + u), \qquad ; \qquad \gamma = -\frac{\alpha}{k} a \tag{45}$$

Here, Q_T is the flood estimate for T year return period flood, C_T is a coefficient for the T year return period flood to be estimated from the regional flood frequency curve and a and b are coefficientsfor the regional relationship between mean annual peak flood and catchment area.

7.0 ANALYSIS AND DISCUSSION OF RESULTS

The annual maximum flood data of the various sites have been used for development of the regional flood frequency relationships and the regional flood formulae for each of the seven subzones of the Zone 3. The details of catchment area, sample size and sample statistics are given in Tables 2.1 to 2.7.

The form of regional flood formula developed for the various subzones as well as for the combined zone 3 based on the methodology as discussed earlier is:

$$Q_T = [\beta + \gamma\{-\ln(1-1/T)\}^K] A^b \qquad (46)$$

where,

Q_T is flood estimate in m^3/s for T-year return period,

$$\beta = a\,(\alpha/K + u), \qquad (47)$$

$$\gamma = -a\,\alpha/K, \qquad (48)$$

A is the catchment area in km^2, and a and b are the regional coefficients obtained from the relationship between mean annual peak flood $\bar{Q}$ and A.

Values of the L moment based regional flood frequency curves viz. K, u α and regional coefficients of the relationship between $\bar{Q}$ and A viz. a, b as well as correlation coefficient for relationship between $\bar{Q}$ and A viz. r and β, and γ for each of the seven subzones and combined zone 3 are given in Table 3.

Statistics of GEV reduced variate (Y) viz. its mean ($\bar{Y}$), median (Y_{med}), mode (Y_{mod}), standard deviation (σ_y), variance (σ^2_y), coefficient of variation (CV_y) and coefficient of skewness (g_y) computed using the regional values of K, u, and α are given in Table 4.

Table-2.1 Catchment area, sample statistics and sample size for Sub-Zone 3(a)

S.NO.	Br.No.	Catchment Area (Sq Km)	Mean Flood (Cumec)	Standard Deviation (Cumec)	Coff. of Variation	Coff. of Skewness	Sample Size (Years)
1	192/253	48.43	189.68	119.78	.631	.682	19
2	281/334	18.44	75.59	87.79	1.161	3.160	17
3	5	230.00	352.72	416.40	1.181	1.688	18
4	99	144.50	258.14	176.69	.684	.837	21
5	945	231.11	212.07	181.75	.857	.963	14
6	26	1094.00	448.65	328.27	.732	.831	20
7	11	98.16	164.67	150.89	.916	2.606	18
8	141	73.19	108.94	81.80	.751	.502	17
9	8	30.14	74.00	72.31	.977	1.828	25
10	46	580.00	352.95	309.26	.876	.898	22

Table-2.2 : Catchment area, sample statistics and sample size for Subzone 3(b)

S.NO.	Br.No.	Catchment Area (Sq Km)	Mean Flood (Cumec)	Standard Deviation (Cumec)	Coff. of Variation	Coff. of Skewness	Sample Size (Years)
1.	105	59.59	223.82	245.67	1.098	3.396	28
2.	502/3	105.07	234.15	150.32	.642	1.040	26
3.	200	27.18	34.95	30.24	.865	1.564	26
4.	162	17.22	69.27	48.25	.697	.985	21
5.	21(DEV)	378.04	492.53	651.98	1.324	2.805	22
6.	701	28.23	239.00	291.83	1.221	1.983	19
7.	374/1	225.84	316.10	351.56	1.112	1.550	18
8.	497/1	53.09	77.65	54.19	.698	.357	21
9.	21(KIM)	542.39	601.41	346.16	.576	.541	23
10.	50	193.73	352.05	355.42	1.010	2.564	17
11.	666	202.28	365.16	219.31	.601	1.380	19
12.	411/1	261.59	558.29	531.16	.951	1.735	19
13.	485/4	284.90	248.33	212.24	.855	1.153	21
14.	53	103.26	274.92	333.24	1.212	1.667	21
15.	561	1017.94	417.54	212.89	.510	-.486	19
16.	293/1	371.15	417.15	158.05	.379	-.403	12
17.	476/1	101.10	275.07	194.45	.707	.127	13
18.	110	18.90	116.65	84.77	.727	.695	13
19.	361/2	828.00	244.05	133.01	.545	.513	15

Table 2·3 Catchment area, sample statistics and sample size for subzone 3 (c)

S.NO.	Br.No.	Catchment Area (Sq Km)	Mean Flood (Cumec)	Standard Deviation (Cumec)	Coff. of Variation	Coff. of Skewness	Sample Size (Years)
1	731/6	115.90	252.87	130.05	.514	.603	30
2	294	518.67	919.60	561.88	.611	.635	30
3	897/1	341.88	856.46	665.22	.777	1.222	26
4	634/2	348.92	380.10	249.40	.656	1.661	29
5	813/1	70.18	211.79	112.87	.533	.274	24
6	863/1	2110.85	1687.27	1481.13	.878	1.404	22
7	253	114.22	216.90	135.35	.624	.417	20
8	584/1	139.08	248.78	203.32	.817	1.252	23
9	512/3	142.97	219.95	154.69	.703	1.066	22
10	710/1	41.80	111.95	122.69	1.096	1.152	21
11	776/1	179.90	572.78	279.18	.487	.826	18
12	625/1	535.40	1730.53	711.90	.411	-.617	19
13	787/2	321.16	811.79	854.59	1.053	2.876	14
14	831/1	53.68	209.17	97.51	.466	-.230	23
15	644/1	989.89	546.25	476.23	.872	1.512	20

Table 2.4 Catchment area, sample statistics and sample size for Sub-zone 3 (d)

S.NO.	Br.No.	Catchment Area (Sq Km)	Mean Flood (Cumec)	Standard Deviation (Cumec)	Coff. of Variation	Coff. of Skewness	Sample Size (Years)
1	66K	154	260.32	201.63	.775	1.611	28
2	48	109	103.90	79.68	.767	1.527	30
3	176	66	81.48	114.36	1.403	4.369	31
4	93K	74	153.07	75.26	.492	.735	28
5	59KGP	30	72.90	55.42	.760	1.262	29
6	308	19	41.22	25.42	.617	.819	27
7	332NGP	225	188.59	99.48	.527	1.158	22
8	59BSP	136	196.23	154.32	.786	1.560	22
9	698	113	247.00	198.48	.804	1.404	25
10	37	64	25.09	20.61	.822	1.054	23
11	121	1150	1003.86	466.53	.465	.521	19
12	385	194	115.40	70.67	.612	.387	21
13	332KGP	175	71.83	39.44	.549	.695	20
14	40K	115	260.67	165.51	.635	1.220	24
15	154	58	160.16	146.75	.916	2.405	21
16	42	49	53.50	20.36	.381	.028	19
17	69	173	238.89	147.75	.618	.916	21
18	90	190	130.73	80.74	.618	.458	20
19	195	615	963.77	385.71	.400	.335	19
20	235	312	176.14	96.65	.549	.764	11
21	325	26	50.00	42.81	.856	.953	13
22	489	823	1071.95	1171.58	1.093	2.003	14

Table-2·5 Catchment area, sample statistics and sample size for Sub-Zone 3(e)

S.NO.	Br.No.	Catchment Area (Sq Km)	Mean Flood (Cumec)	Standard Deviation (Cumec)	Coff. of Variation	Coff. of Skewness	Sample Size (Years)
1	139	93.60	163.34	116.99	.716	1.123	32
2	51	61.90	67.28	94.07	1.398	2.249	29
3	234	2227.39	868.88	648.13	.746	.700	24
4	346	64.88	203.70	128.07	.629	.341	23
5	295	77.70	90.86	46.74	.514	.731	22
6	55	31.31	66.24	84.13	1.270	1.998	21
7	368	136.75	206.29	139.58	.677	.336	21
8	66	157.55	134.56	175.19	1.302	1.547	16
9	44	152.33	214.64	215.27	1.003	1.562	14
10	289	458.00	263.80	138.87	.526	.132	15
11	79	35.22	60.13	48.75	.811	.567	23
12	76	1197.76	695.33	614.10	.883	.874	18

Table-2·6 Catchment area, sample statistics and sample size for Sub-Zone 3(f)

S.NO.	Br.No.	Catchment Area (Sq Km)	Mean Flood (Cumec)	Standard Deviation (Cumec)	Coff. of Variation	Coff. of Skewness	Sample Size (Years)
1	184	364	344.48	240.13	.697	.827	29
2	57	163	189.39	84.28	.445	.453	28
3	59TT	65	90.86	45.25	.498	1.450	29
4	973/1	362	505.04	297.74	.590	.103	28
5	912/1	137	404.86	299.45	.740	.995	29
6	20	60	204.71	118.51	.579	.025	28
7	214	35	77.75	40.43	.520	1.187	24
8	51	87	206.68	101.62	.492	.422	25
9	807/1	824	1212.83	811.09	.669	.827	23
10	228	483	1075.27	749.68	.697	.984	22
11	15	459	854.91	572.73	.670	.747	23
12	969/1	208	519.95	444.91	.856	1.810	21
13	881/1	158	307.78	151.44	.492	.285	23
14	161	53	93.88	53.75	.573	1.592	17
15	36	139	170.80	134.40	.787	1.430	15
16	224	750	687.36	536.59	.781	1.408	14
17	65	731	725.13	603.07	.832	1.872	15
18	4	50	237.97	116.68	.490	.414	29
19	875/1	751	778.10	557.87	.717	.110	21

Table-2.7 Catchment area, sample statistics and sample size for Sub-Zone 3(h)

S.NO.	Br.No.	Catchment Area (Sq Km)	Mean Flood (Cumec)	Standard Deviation (Cumec)	Coff. of Variation	Coff. of Skewness	Sample Size (Years)
1	642	326.08	283.47	205.47	.725	1.226	32
2	16	270.60	65.68	51.18	.779	.555	28
3	53(i)	102.45	78.52	64.80	.825	.383	29
4	378/3	79.00	89.77	64.30	.716	.571	22
5	53(ii)	1689.92	794.88	745.45	.938	1.796	26
6	215	167.32	44.31	40.59	.916	1.370	26
7	215(GTL)	139.08	88.04	66.34	.753	1.085	25
8	18	131.52	117.76	79.24	.673	1.050	25
9	322	31.72	50.92	27.72	.544	1.072	25
10	480/3	118.23	92.24	97.61	1.058	1.484	17
11	179	251.17	157.91	85.96	.544	1.776	22
12	449/3	230.87	177.56	279.73	1.575	2.304	16
13	601	398.60	280.24	245.29	.875	1.091	17
14	313	220.45	443.17	331.75	.749	1.357	18
15	66	70.84	28.29	33.06	1.168	1.221	17
16	98	348.40	125.36	121.17	.967	1.128	14
17	123	64.75	111.48	66.81	.599	.512	33
18	63	1357.15	403.37	262.96	.652	.511	19

TABLE 3. Regional Parameters for the Seven Subzones of India based on L Moment Approach

S. No. (1)	Subzone (2)	K (3)	u (4)	α (5)	a (6)	b (7)	r (8)	ß (9)	γ (10)
1.	3(a)	-0.247	0.558	0.493	20.91	0.46	0.77	-30.07	41.74
2.	3(b)	-0.200	0.591	0.500	24.53	0.46	0.92	-46.85	61.33
3.	3(c)	-0.109	0.665	0.481	11.82	0.67	0.87	-44.30	52.16
4.	3(d)	-0.180	0.649	0.443	3.29	0.79	0.84	-5.96	8.10
5.	3(e)	-0.194	0.563	0.539	8.33	0.61	0.94	-18.45	23.14
6.	3(f)	-0.042	0.704	0.477	7.24	0.73	0.90	-77.13	82.23
7.	3(h)	-0.150	0.597	0.537	3.60	0.68	0.78	-10.74	12.89
8.	Combined zone 3	-0.156	0.627	0.492	1.68	0.57	0.70	-4.25	5.30

TABLE 4. Statistics of GEV Reduced Variate

S. No. (1)	Subzone (2)	$\bar{Y}$ (3)	Y_{med} (4)	Y_{mod} (5)	σ_y (6)	σ^2_y (7)	CV_y (8)	g_y (9)
1.	3(a)	1.221	1.095	0.947	0.510	0.260	0.417	5.418
2.	3(b)	1.164	1.076	0.964	0.366	0.134	0.314	3.535
3.	3(c)	1.076	1.041	0.989	0.165	0.027	0.154	2.005
4.	3(d)	1.143	1.068	0.971	[illegible]	0.099	0.275	3.063
5.	3(e)	1.158	1.074	0.966	0.35	0.122	0.302	3.381
6.	3(f)	1.026	1.016	0.998	0.057	0.003	0.056	1.415
7.	3(h)	1.113	1.057	0.979	0.246	0.060	0.221	2.530
8.	Combined zone 3	1.118	1.059	0.978	0.259	0.067	0.232	2.624

The values of the regional parameters of the General Extreme Value (GEV) distribution for the seven subzones of India based on Probability Weighted Moment (PWM) approach are given in Table 5.

TABLE 5. Regional GEV Parameters for the Seven Subzones of India based on Probability Weighted Moment (PWM) Approach

S. No. (1)	Subzone (2)	K (3)	u (4)	α (5)
1.	3(a)	-0.213	0.575	0.506
2.	3(b)	-0.167	0.601	0.516
3.	3(c)	-0.083	0.671	0.494
4.	3(d)	-0.155	0.657	0.453
5.	3(e)	-0.167	0.567	0.560
6.	3(f)	-0.015	0.713	0.484
7.	3(h)	-0.105	0.611	0.561
8.	Combined zone 3	-0.117	0.637	0.513

The growth factors ($\frac{Q_T}{\bar{Q}}$) are computed for each of the subzones as well as for the combined zone 3.The growth factors for the seven subzones and combined zone 3 based on L moment approach are given in Table 6. The growth factors for the seven subzones and combined zone 3 based on Probability Weighted Moment (PWM) approach are given in Table 7. Fig. 2 shows the variation of the growth factors based on L moment approach with return period. Figs. 3.1 to 3.7 show comparison of the growth factors based on PWM and L moment approaches.

TABLE 6. Growth Factors ($\frac{Q_T}{Q}$) for the Seven Subzones and Combined Zone 3 based on L moment approach

S. No. (1)	Subzone (2)	Return Period							
		2 (3)	10 (4)	20 (5)	50 (6)	100 (7)	200 (8)	500 (9)	1000 (10)
1.	3(a)	o.747	2.042	2.719	3.795	4.780	5.946	7.826	9.558
2.	3(b)	0.780	2.009	2.615	3.540	4.335	5.289	6.736	8.021
3.	3(c)	0.844	1.892	2.352	3.004	3.538	4.112	4.939	5.621
4.	3(d)	0.817	1.879	2.391	3.159	3.826	4.578	5.730	6.734
5.	3(e)	0.767	2.082	2.726	3.705	4.563	5.543	7.055	8.390
6.	3(f)	0.880	1.830	2.213	2.726	3.124	3.533	4.090	4.526
7.	3(h)	0.780	2.035	2.608	3.447	4.157	4.942	6.112	7.110
8.	Combined Zone 3	0.812	1.953	2.486	3.272	3.940	4.682	5.793	6.746

TABLE 7. Growth Factors ($\frac{Q_T}{Q}$) for the Seven Subzones and Combined Zone 3 based on Probability Weighted Moment (PWM) approach

S. No. (1)	Subzone (2)	Return Period							
		2 (3)	10 (4)	20 (5)	50 (6)	100 (7)	200 (8)	500 (9)	1000 (10)
1.	3(a)	o.767	2.034	2.670	3.651	4.522	5.532	7.114	8.534
2.	3(b)	0.795	2.011	2.586	3.441	4.173	4.996	6.235	7.306
3.	3(c)	0.855	1.893	2.335	2.946	3.437	3.955	4.686	5.276
4.	3(d)	0.828	1.878	2.367	3.086	3.697	4.375	5.389	6.257
5.	3(e)	0.778	2.097	2.721	3.647	4.443	5.333	6.678	7.840
6.	3(f)	0.891	1.821	2.184	2.658	3.019	3.381	3.865	4.236
7.	3(h)	0.821	2.037	2.569	3.319	3.934	4.591	5.535	6.313
8.	Combined Zone 3	0.829	1.957	2.458	3.174	3.765	4.402	5.327	6.094

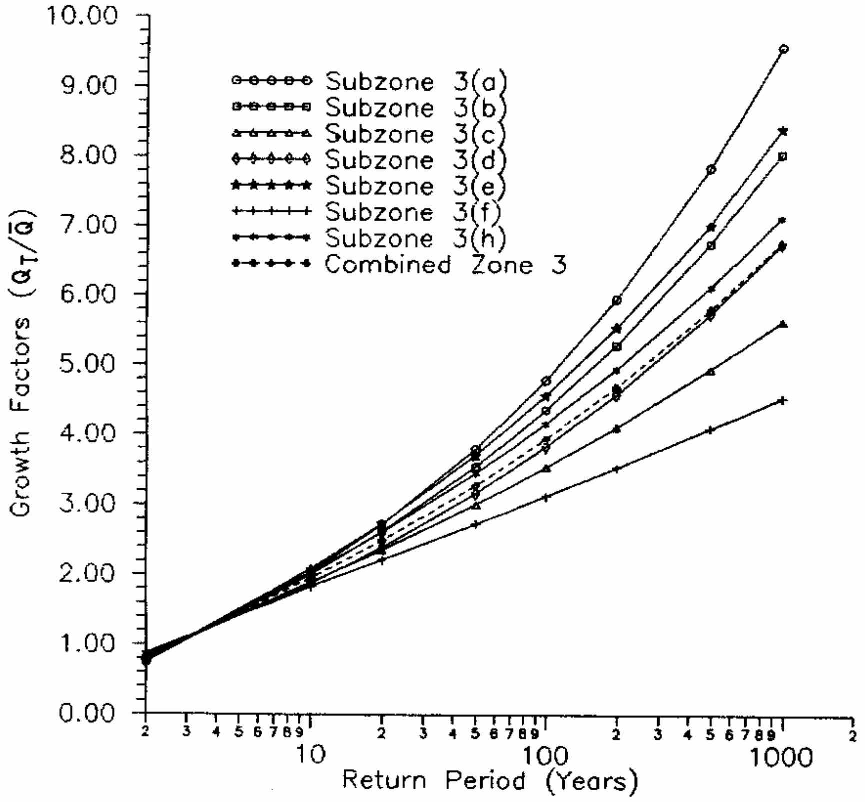

FIG. 2 Variation of Growth Factors ($Q_T/\bar{Q}$) with Return Period

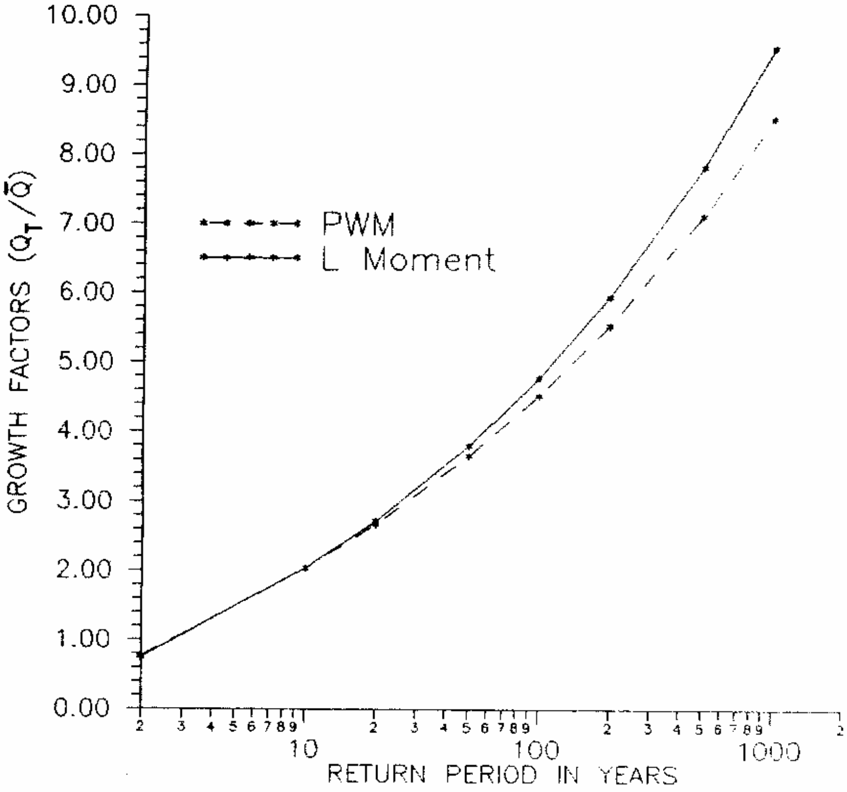

FIG.3·1 COMPARISON OF GROWTH FACTORS ($Q_T/\bar{Q}$) BASED ON PWM AND L MOMENT APPROACHES FOR SUBZONE 3 (a)

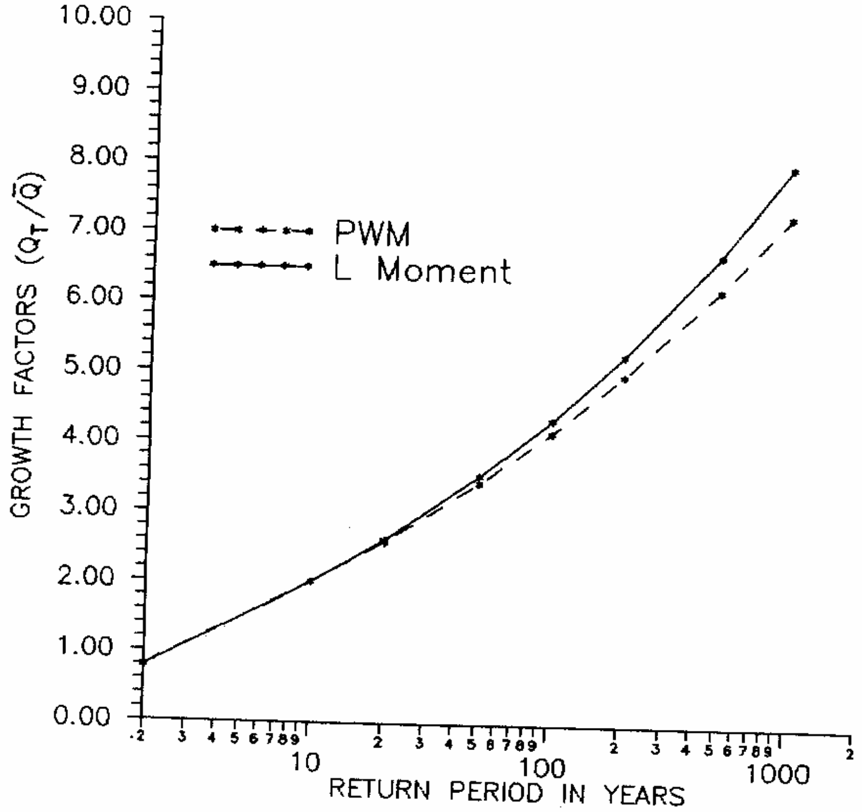

FIG. 3.2 COMPARISON OF GROWTH FACTORS $(Q_T/\bar{Q})$ BASED ON PWM AND L MOMENT APPROACHES FOR SUBZONE 3 (b)

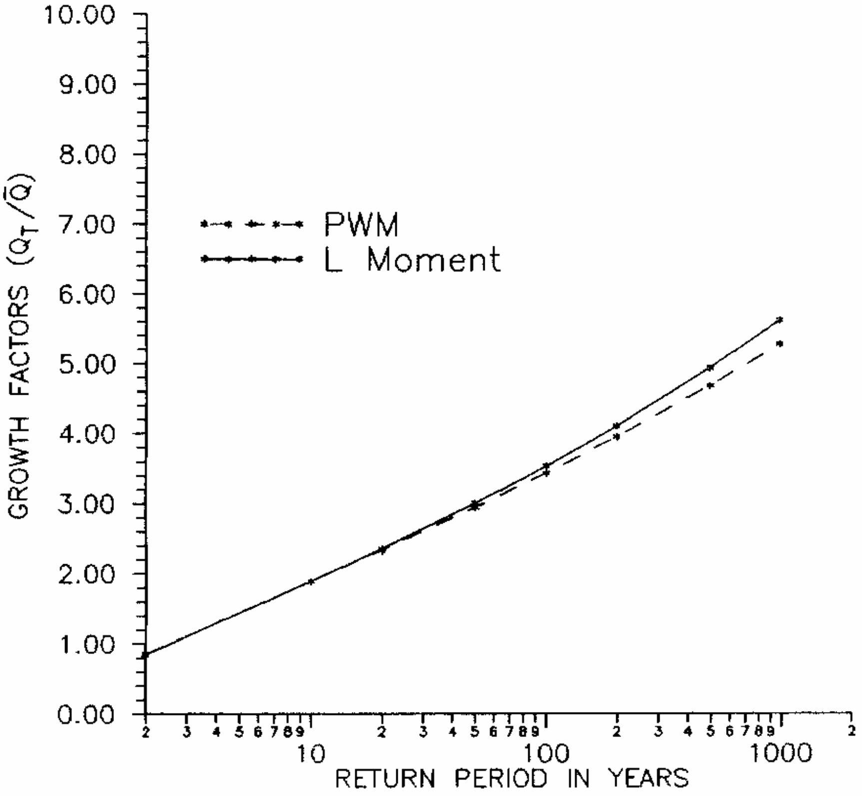

FIG.3.3 COMPARISON OF GROWTH FACTORS ($Q_T/\bar{Q}$) BASED ON PWM AND L MOMENT APPROACHES FOR SUBZONE 3 (c)

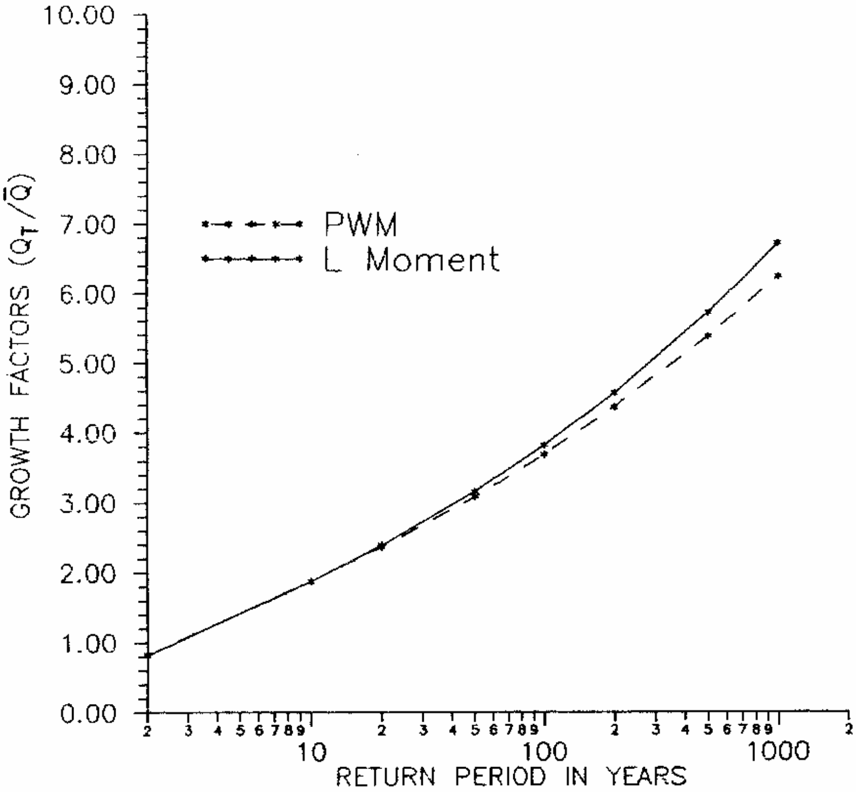

FIG. 3.4 COMPARISON OF GROWTH FACTORS ($Q_T/\bar{Q}$) BASED ON PWM AND L MOMENT APPROACHES FOR SUBZONE 3 (d)

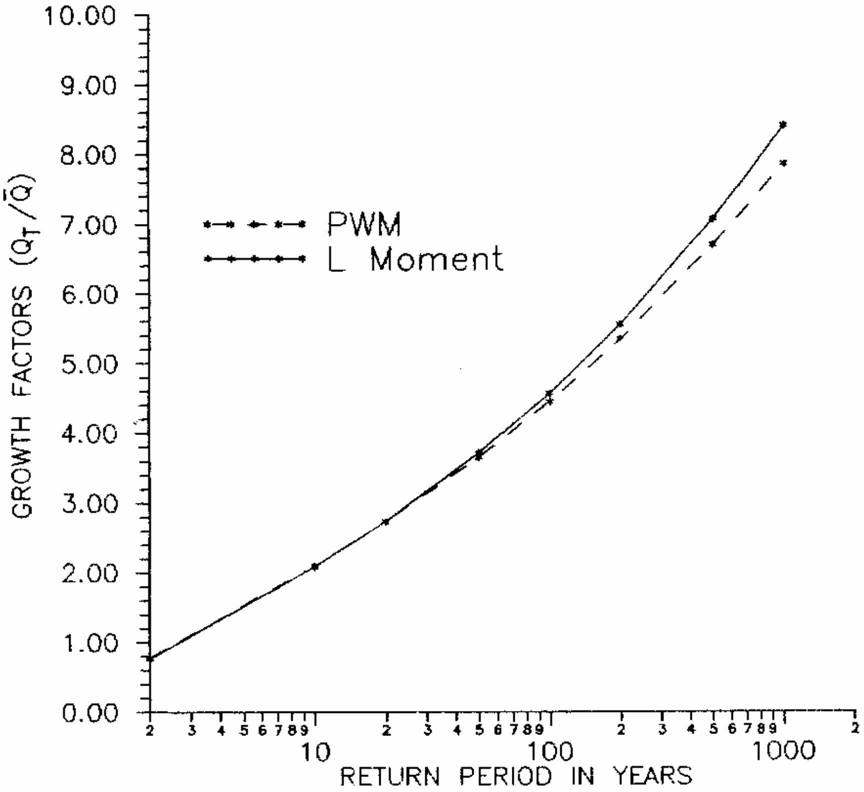

FIG.3.5 COMPARISON OF GROWTH FACTORS $(Q_T/\bar{Q})$ BASED ON PWM AND L MOMENT APPROACHES FOR SUBZONE 3 (e)

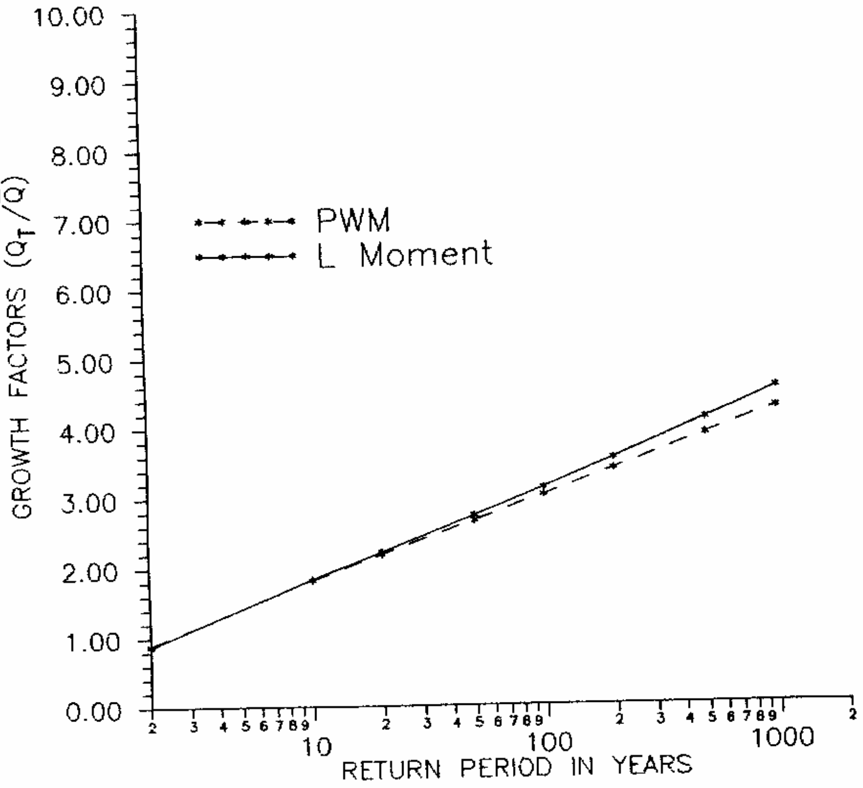

FIG. 3.6 COMPARISON OF GROWTH FACTORS ($Q_T/\bar{Q}$) BASED ON PWM AND L MOMENT APPROACHES FOR SUBZONE 3 (f)

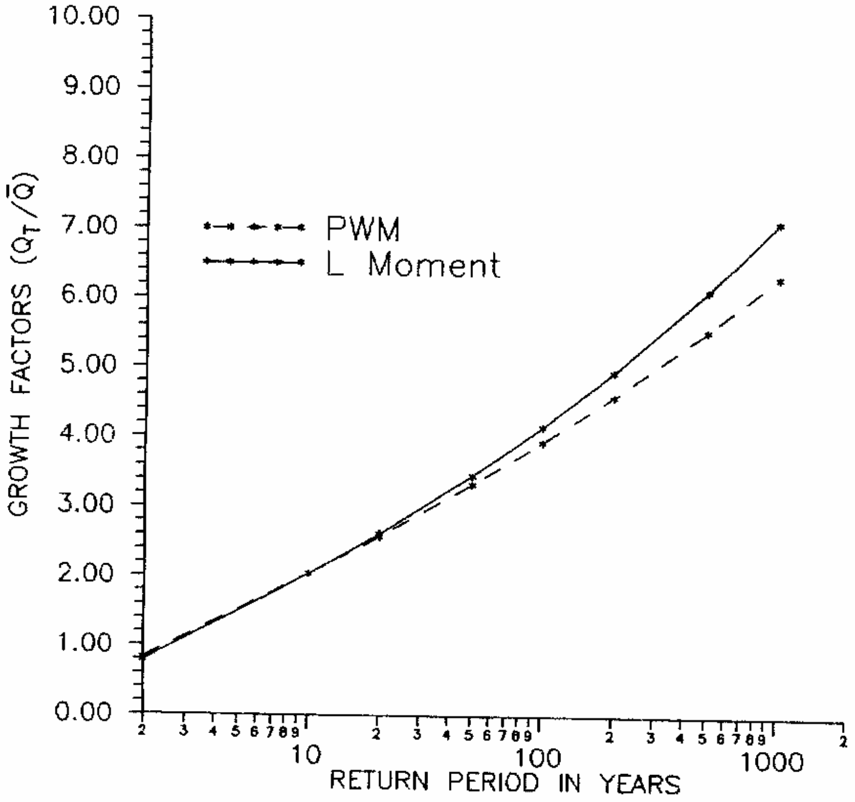

FIG.3·7 COMPARISON OF GROWTH FACTORS ($Q_T/\bar{Q}$) BASED ON PWM AND L MOMENT APPROACHES FOR SUBZONE 3 (h)

Table 8 shows percent deviations between the growth factors of each of the subzones and the growth factors of combined zone 3 based on L moment approach with return period for all the seven subzones. It is observed from the Table 8 that for lower return period, growth factors of the various subzones do not show much of variation. However, for higher return periods these growth factors show considerable variations.

The ratios of the flood frequency estimates computed by using the at-site and regional flood frequency analysis and the regional flood formulae of the respective subzone, would be same as the ratio between the respective regional mean and the at-site mean. Larger deviations between the flood frequency estimates computed by using the at-site and regional flood frequency analysis and the regional flood formulae of the respective subzones may be mainly attributed to the higher standard errors associated with the relationship between the mean annual peak flood and the catchment area.

TABLE 8. Percentage Deviation Between Growth Factors ($\frac{Q_T}{\bar{Q}}$) of Combined Zone 3 and the Respective Subzones

S. No. (1)	Subzone (2)	Return Period							
		2 (3)	10 (4)	20 (5)	50 (6)	100 (7)	200 (8)	500 (9)	1000 (10)
1.	3(a)	-8.7	4.4	8.6	13.8	17.6	21.3	26.0	29.4
2.	3(b)	-4.1	2.8	4.9	7.6	9.5	11.5	14.0	15.9
3.	3(c)	3.8	-3.2	-5.7	-8.9	-11.4	-13.9	-17.3	-20.0
4.	3(d)	0.6	-3.9	-4.0	-3.6	-3.0	-2.3	-1.1	-0.2
5.	3(e)	-5.9	6.2	8.8	11.7	13.7	15.5	17.9	19.6
6.	3(f)	7.7	-6.7	-12.3	-20.0	-26.1	-32.5	-41.3	-49.1
7.	3(h)	-4.1	4.0	4.7	5.1	5.2	5.3	5.2	5.1

Substituting values of the regional coefficients mentioned in Table 3, the regional flood formulae for the various subzones are expressed as:

$$\text{Subzone } 3(a),\quad Q_T = [41.7(-\ln(1-\frac{1}{T}))^{-0.25}-30.1]A^{0.46} \tag{40}$$

$$\text{Subzone } 3(b),\quad Q_T = [61.3(-\ln(1-\frac{1}{T}))^{-0.20}-46.9]A^{0.46} \tag{41}$$

$$\text{Subzone } 3(c),\quad Q_T = [52.2(-\ln(1-\frac{1}{T}))^{-0.11}-44.3]A^{0.67} \tag{42}$$

$$\text{Subzone } 3(d),\quad Q_T = [8.1(-\ln(1-\frac{1}{T}))^{-0.18}-6.0]A^{0.79} \tag{43}$$

$$\text{Subzone } 3(e),\quad Q_T = [23.1(-\ln(1-\frac{1}{T}))^{-0.19}-18.5]A^{0.61} \tag{44}$$

$$\text{Subzone } 3(f),\quad Q_T = [82.3(-\ln(1-\frac{1}{T}))^{-0.04}-77.1]A^{0.73} \tag{45}$$

$$\text{Subzone } 3(h),\quad Q_T = [12.9(-\ln(1-\frac{1}{T}))^{-0.15}-10.7]A^{0.68} \tag{46}$$

(Here, Q_T is flood in cumec for T year return period,
A is the catchment area in square kilometers).

Variation of flood frequency estimates with catchments area computed based on the developed regional flood formulae are given in Tables 9.1 to 9.7 and the same are shown in Figs. 4.1 to 4.7.

Table 9.1 Variation of flood frequency estimates with catchment area for subzone 3(a)

S.No.	Catchment Area (Sq.Km.)	Return Period							
		2	10	20	50	100	200	500	1000
1	10.	45.	123.	164.	229.	288.	359.	472.	576.
2	20.	62.	169.	226.	315.	396.	493.	649.	793.
3	30.	75.	204.	272.	379.	478.	594.	782.	955.
4	40.	85.	233.	310.	433.	545.	678.	893.	1090.
5	50.	94.	258.	344.	480.	604.	752.	989.	1208.
6	60.	103.	281.	374.	522.	657.	818.	1076.	1314.
7	70.	110.	301.	401.	560.	706.	878.	1155.	1411.
8	80.	117.	320.	427.	596.	750.	933.	1228.	1500.
9	90.	124.	338.	450.	629.	792.	985.	1297.	1583.
10	100.	130.	355.	473.	660.	831.	1034.	1361.	1662.
11	200.	179.	488.	650.	908.	1143.	1422.	1872.	2286.
12	300.	215.	589.	784.	1094.	1378.	1714.	2256.	2755.
13	400.	246.	672.	895.	1249.	1573.	1957.	2575.	3145.
14	500.	272.	745.	991.	1384.	1743.	2168.	2853.	3485.
15	600.	296.	810.	1078.	1505.	1895.	2358.	3103.	3790.
16	700.	318.	869.	1157.	1615.	2035.	2531.	3331.	4068.
17	800.	338.	924.	1231.	1718.	2164.	2691.	3542.	4326.
18	900.	357.	976.	1299.	1813.	2284.	2841.	3739.	4567.
19	1000.	375.	1024.	1364.	1903.	2398.	2982.	3925.	4794.
20	1100.	392.	1070.	1425.	1989.	2505.	3116.	4101.	5008.
21	1200.	408.	1114.	1483.	2070.	2607.	3243.	4268.	5213.
22	1300.	423.	1155.	1539.	2148.	2705.	3365.	4428.	5408.
23	1400.	437.	1196.	1592.	2222.	2799.	3482.	4582.	5596.
24	1500.	452.	1234.	1643.	2294.	2889.	3594.	4730.	5776.
25	1600.	465.	1271.	1693.	2363.	2976.	3702.	4872.	5951.
26	1700.	478.	1307.	1741.	2430.	3060.	3807.	5010.	6119.
27	1800.	491.	1342.	1787.	2494.	3142.	3908.	5144.	6282.
28	1900.	503.	1376.	1832.	2557.	3221.	4007.	5273.	6440.
29	2000.	515.	1409.	1876.	2618.	3298.	4102.	5399.	6594.

Table 9.2 Variation of flood frequency estimates with catchment area for subzone 3(b)

S.No.	Catchment Area (Sq.Km.)	Return Period							
		2	10	20	50	100	200	500	1000
1	10.	55.	142.	185.	251.	309.	375.	478.	569.
2	20.	76.	196.	255.	345.	425.	516.	657.	783.
3	30.	92.	236.	307.	416.	512.	622.	792.	943.
4	40.	105.	269.	351.	475.	584.	710.	904.	1077.
5	50.	116.	298.	389.	526.	647.	786.	1002.	1193.
6	60.	126.	325.	422.	572.	704.	855.	1089.	1297.
7	70.	135.	348.	454.	614.	756.	918.	1169.	1393.
8	80.	144.	370.	482.	653.	804.	976.	1244.	1481.
9	90.	152.	391.	509.	689.	848.	1030.	1313.	1563.
10	100.	159.	411.	534.	724.	890.	1082.	1378.	1641.
11	200.	219.	565.	735.	995.	1225.	1488.	1895.	2257.
12	300.	264.	680.	886.	1200.	1476.	1793.	2284.	2720.
13	400.	302.	777.	1011.	1369.	1685.	2046.	2607.	3105.
14	500.	334.	861.	1120.	1517.	1867.	2268.	2889.	3441.
15	600.	363.	936.	1218.	1650.	2030.	2466.	3142.	3742.
16	700.	390.	1005.	1308.	1771.	2180.	2647.	3373.	4016.
17	800.	415.	1068.	1391.	1883.	2318.	2815.	3586.	4271.
18	900.	438.	1128.	1468.	1988.	2447.	2972.	3786.	4509.
19	1000.	460.	1184.	1541.	2087.	2568.	3119.	3974.	4733.
20	1100.	480.	1237.	1610.	2181.	2683.	3259.	4152.	4945.
21	1200.	500.	1288.	1676.	2270.	2793.	3392.	4322.	5147.
22	1300.	519.	1336.	1739.	2355.	2898.	3519.	4484.	5340.
23	1400.	537.	1382.	1799.	2436.	2998.	3641.	4639.	5525.
24	1500.	554.	1427.	1857.	2515.	3095.	3759.	4789.	5703.
25	1600.	571.	1470.	1913.	2591.	3188.	3872.	4933.	5875.
26	1700.	587.	1511.	1967.	2664.	3278.	3982.	5073.	6041.
27	1800.	602.	1552.	2020.	2735.	3365.	4088.	5208.	6202.
28	1900.	618.	1591.	2071.	2804.	3450.	4191.	5339.	6358.
29	2000.	632.	1629.	2120.	2871.	3533.	4291.	5466.	6510.

Table 9.3 Variation of flood frequency estimates with catchment area for subzone 3(c)

S.No.	Catchment Area (Sq.Km.)	Return Period 2	10	20	50	100	200	500	1000
1	10.	47.	105.	130.	166.	196.	227.	273.	311.
2	20.	74.	166.	207.	264.	311.	362.	434.	494.
3	30.	98.	218.	271.	347.	408.	475.	570.	649.
4	40.	118.	265.	329.	420.	495.	576.	691.	787.
5	50.	137.	307.	382.	488.	575.	668.	803.	914.
6	60.	155.	347.	432.	552.	650.	755.	907.	1032.
7	70.	172.	385.	479.	612.	720.	837.	1006.	1145.
8	80.	188.	421.	524.	669.	788.	916.	1100.	1252.
9	90.	204.	456.	567.	724.	853.	991.	1190.	1355.
10	100.	218.	489.	608.	777.	915.	1063.	1277.	1454.
11	200.	348.	778.	968.	1236.	1456.	1692.	2032.	2313.
12	300.	456.	1021.	1270.	1622.	1910.	2220.	2666.	3035.
13	400.	553.	1238.	1540.	1967.	2316.	2692.	3233.	3680.
14	500.	642.	1438.	1788.	2284.	2690.	3126.	3755.	4273.
15	600.	726.	1625.	2020.	2580.	3039.	3532.	4242.	4828.
16	700.	805.	1802.	2240.	2861.	3370.	3916.	4704.	5354.
17	800.	880.	1970.	2450.	3129.	3685.	4283.	5144.	5855.
18	900.	952.	2132.	2651.	3386.	3988.	4635.	5567.	6336.
19	1000.	1022.	2288.	2845.	3634.	4279.	4974.	5974.	6799.
20	1100.	1089.	2439.	3032.	3873.	4562.	5302.	6368.	7247.
21	1200.	1155.	2585.	3215.	4106.	4835.	5620.	6750.	7682.
22	1300.	1218.	2728.	3392.	4332.	5102.	5929.	7122.	8106.
23	1400.	1280.	2867.	3564.	4552.	5361.	6231.	7484.	8518.
24	1500.	1341.	3002.	3733.	4768.	5615.	6526.	7838.	8921.
25	1600.	1400.	3135.	3898.	4978.	5863.	6814.	8185.	9316.
26	1700.	1458.	3265.	4059.	5185.	6106.	7097.	8524.	9702.
27	1800.	1515.	3392.	4218.	5387.	6345.	7374.	8857.	10080.
28	1900.	1571.	3518.	4373.	5586.	6579.	7646.	9184.	10452.
29	2000.	1626.	3641.	4526.	5781.	6809.	7913.	9505.	10818.

Table 9.4 Variation of flood frequency estimates with catchment area for subzone 3(d)

S.No.	Catchment Area (Sq.Km.)	Return Period							
		2	10	20	50	100	200	500	1000
1	10.	17.	38.	48.	64.	78.	93.	116.	136.
2	20.	29.	66.	84.	111.	134.	160.	201.	236.
3	30.	39.	91.	115.	152.	185.	221.	276.	325.
4	40.	50.	114.	145.	191.	232.	277.	347.	408.
5	50.	59.	136.	173.	228.	276.	331.	414.	486.
6	60.	68.	157.	200.	264.	319.	382.	478.	562.
7	70.	77.	177.	225.	298.	361.	431.	540.	634.
8	80.	86.	197.	250.	331.	401.	479.	600.	705.
9	90.	94.	216.	275.	363.	440.	526.	658.	774.
10	100.	102.	235.	299.	395.	478.	572.	715.	841.
11	200.	177.	406.	517.	682.	826.	989.	1237.	1454.
12	300.	243.	560.	712.	940.	1138.	1362.	1704.	2002.
13	400.	305.	702.	893.	1180.	1429.	1710.	2139.	2513.
14	500.	364.	838.	1065.	1408.	1704.	2039.	2551.	2998.
15	600.	421.	967.	1230.	1626.	1968.	2355.	2946.	3462.
16	700.	475.	1093.	1390.	1836.	2223.	2660.	3328.	3911.
17	800.	528.	1214.	1544.	2040.	2471.	2956.	3698.	4346.
18	900.	580.	1333.	1695.	2239.	2712.	3245.	4059.	4769.
19	1000.	630.	1448.	1842.	2434.	2947.	3526.	4411.	5183.
20	1100.	679.	1562.	1986.	2624.	3177.	3802.	4756.	5589.
21	1200.	728.	1673.	2128.	2811.	3403.	4073.	5094.	5986.
22	1300.	775.	1782.	2266.	2994.	3626.	4339.	5427.	6377.
23	1400.	822.	1890.	2403.	3175.	3844.	4600.	5754.	6762.
24	1500.	868.	1995.	2538.	3353.	4059.	4858.	6076.	7140.
25	1600.	913.	2100.	2670.	3528.	4272.	5112.	6394.	7514.
26	1700.	958.	2203.	2801.	3701.	4481.	5363.	6708.	7883.
27	1800.	1002.	2304.	2931.	3872.	4688.	5610.	7018.	8247.
28	1900.	1046.	2405.	3059.	4041.	4893.	5855.	7324.	8606.
29	2000.	1089.	2505.	3185.	4208.	5095.	6097.	7627.	8962.

Table 9.5 Variation of flood frequency estimates with catchment area for subzone 3(e)

S.No.	Catchment Area (Sq.Km.)	Return Period							
		2	10	20	50	100	200	500	1000
1	10.	26.	71.	93.	126.	155.	188.	240.	285.
2	20.	40.	108.	141.	192.	237.	287.	366.	435.
3	30.	51.	138.	181.	246.	303.	368.	468.	557.
4	40.	61.	165.	216.	293.	361.	438.	558.	664.
5	50.	70.	189.	247.	336.	414.	502.	639.	760.
6	60.	78.	211.	276.	375.	462.	562.	715.	850.
7	70.	85.	232.	303.	412.	508.	617.	785.	934.
8	80.	93.	251.	329.	447.	551.	669.	852.	1013.
9	90.	100.	270.	354.	481.	592.	719.	915.	1088.
10	100.	106.	288.	377.	513.	631.	767.	976.	1161.
11	200.	162.	440.	576.	782.	964.	1170.	1490.	1771.
12	300.	207.	563.	737.	1002.	1234.	1499.	1907.	2268.
13	400.	247.	671.	879.	1194.	1471.	1786.	2273.	2704.
14	500.	283.	769.	1007.	1368.	1685.	2047.	2605.	3098.
15	600.	317.	859.	1125.	1529.	1883.	2287.	2911.	3462.
16	700.	348.	944.	1236.	1680.	2069.	2513.	3198.	3804.
17	800.	377.	1024.	1341.	1822.	2245.	2726.	3470.	4126.
18	900.	405.	1101.	1441.	1958.	2412.	2929.	3728.	4434.
19	1000.	432.	1174.	1536.	2088.	2572.	3124.	3976.	4728.
20	1100.	458.	1244.	1628.	2213.	2726.	3311.	4214.	5011.
21	1200.	483.	1312.	1717.	2334.	2874.	3491.	4443.	5284.
22	1300.	507.	1377.	1803.	2450.	3018.	3666.	4666.	5549.
23	1400.	531.	1441.	1886.	2564.	3158.	3835.	4881.	5805.
24	1500.	554.	1503.	1968.	2674.	3294.	4000.	5091.	6055.
25	1600.	576.	1563.	2047.	2781.	3426.	4161.	5296.	6298.
26	1700.	598.	1622.	2124.	2886.	3555.	4318.	5495.	6535.
27	1800.	619.	1680.	2199.	2989.	3681.	4471.	5690.	6767.
28	1900.	640.	1736.	2273.	3089.	3804.	4621.	5881.	6994.
29	2000.	660.	1791.	2345.	3187.	3925.	4768.	6068.	7216.

Table 9.6 Variation of flood frequency estimates with catchment area for subzone 3(f)

S.No.	Catchment Area (Sq.Km.)	Return Period							
		2	10	20	50	100	200	500	1000
1	10.	34.	71.	86.	106.	121.	137.	159.	176.
2	20.	57.	118.	143.	176.	202.	228.	264.	292.
3	30.	76.	159.	192.	236.	271.	306.	355.	392.
4	40.	94.	196.	237.	292.	334.	378.	438.	484.
5	50.	111.	230.	279.	343.	393.	445.	515.	570.
6	60.	127.	263.	318.	392.	449.	508.	588.	651.
7	70.	142.	294.	356.	439.	503.	569.	658.	728.
8	80.	156.	325.	393.	484.	554.	627.	726.	803.
9	90.	170.	354.	428.	527.	604.	683.	791.	875.
10	100.	184.	382.	462.	569.	652.	738.	854.	945.
11	200.	305.	634.	766.	944.	1082.	1224.	1417.	1568.
12	300.	410.	852.	1030.	1269.	1455.	1645.	1905.	2108.
13	400.	506.	1051.	1271.	1566.	1795.	2030.	2350.	2600.
14	500.	595.	1237.	1496.	1843.	2112.	2389.	2765.	3060.
15	600.	680.	1413.	1709.	2106.	2413.	2729.	3159.	3496.
16	700.	761.	1581.	1913.	2356.	2701.	3054.	3535.	3912.
17	800.	839.	1743.	2108.	2598.	2977.	3366.	3897.	4313.
18	900.	914.	1900.	2298.	2831.	3244.	3669.	4247.	4700.
19	1000.	987.	2052.	2481.	3057.	3504.	3962.	4587.	5076.
20	1100.	1058.	2200.	2660.	3278.	3756.	4247.	4917.	5441.
21	1200.	1127.	2344.	2835.	3492.	4003.	4526.	5240.	5798.
22	1300.	1195.	2485.	3005.	3703.	4243.	4798.	5555.	6147.
23	1400.	1262.	2623.	3172.	3908.	4479.	5065.	5864.	6489.
24	1500.	1327.	2759.	3336.	4110.	4711.	5326.	6167.	6824.
25	1600.	1391.	2892.	3497.	4309.	4938.	5583.	6464.	7153.
26	1700.	1454.	3023.	3655.	4504.	5161.	5836.	6757.	7477.
27	1800.	1516.	3151.	3811.	4695.	5381.	6085.	7045.	7796.
28	1900.	1577.	3278.	3965.	4885.	5598.	6330.	7329.	8109.
29	2000.	1637.	3403.	4116.	5071.	5811.	6571.	7608.	8419.

Table 9.7 Variation of flood frequency estimates with catchment area for subzone 3(h)

S.No.	Catchment Area (Sq.Km.)	Return Period							
		2	10	20	50	100	200	500	1000
1	10.	14.	35.	45.	59.	72.	85.	105.	122.
2	20.	22.	56.	72.	95.	115.	136.	169.	196.
3	30.	29.	74.	95.	125.	151.	180.	222.	258.
4	40.	35.	90.	115.	152.	184.	218.	270.	314.
5	50.	41.	105.	134.	177.	214.	254.	314.	366.
6	60.	47.	119.	152.	201.	242.	288.	356.	414.
7	70.	52.	132.	169.	223.	269.	320.	395.	460.
8	80.	57.	144.	185.	244.	294.	350.	433.	504.
9	90.	61.	156.	200.	264.	319.	379.	469.	546.
10	100.	66.	168.	215.	284.	343.	407.	504.	586.
11	200.	106.	269.	344.	455.	549.	653.	807.	939.
12	300.	139.	354.	454.	600.	723.	860.	1063.	1237.
13	400.	169.	431.	552.	729.	880.	1046.	1293.	1504.
14	500.	197.	501.	642.	849.	1024.	1217.	1505.	1751.
15	600.	223.	567.	727.	961.	1159.	1378.	1704.	1982.
16	700.	248.	630.	807.	1067.	1287.	1530.	1892.	2201.
17	800.	271.	690.	884.	1168.	1409.	1675.	2072.	2410.
18	900.	294.	748.	958.	1266.	1527.	1815.	2245.	2611.
19	1000.	316.	803.	1029.	1360.	1640.	1950.	2411.	2805.
20	1100.	337.	857.	1098.	1451.	1750.	2080.	2573.	2993.
21	1200.	357.	909.	1165.	1539.	1856.	2207.	2730.	3175.
22	1300.	377.	960.	1230.	1625.	1960.	2331.	2882.	3353.
23	1400.	397.	1010.	1293.	1709.	2062.	2451.	3031.	3526.
24	1500.	416.	1058.	1356.	1792.	2161.	2569.	3177.	3695.
25	1600.	434.	1105.	1416.	1872.	2258.	2684.	3320.	3861.
26	1700.	453.	1152.	1476.	1951.	2353.	2797.	3459.	4024.
27	1800.	471.	1198.	1534.	2028.	2446.	2908.	3596.	4183.
28	1900.	488.	1243.	1592.	2104.	2537.	3017.	3731.	4340.
29	2000.	506.	1287.	1648.	2179.	2627.	3124.	3863.	4494.

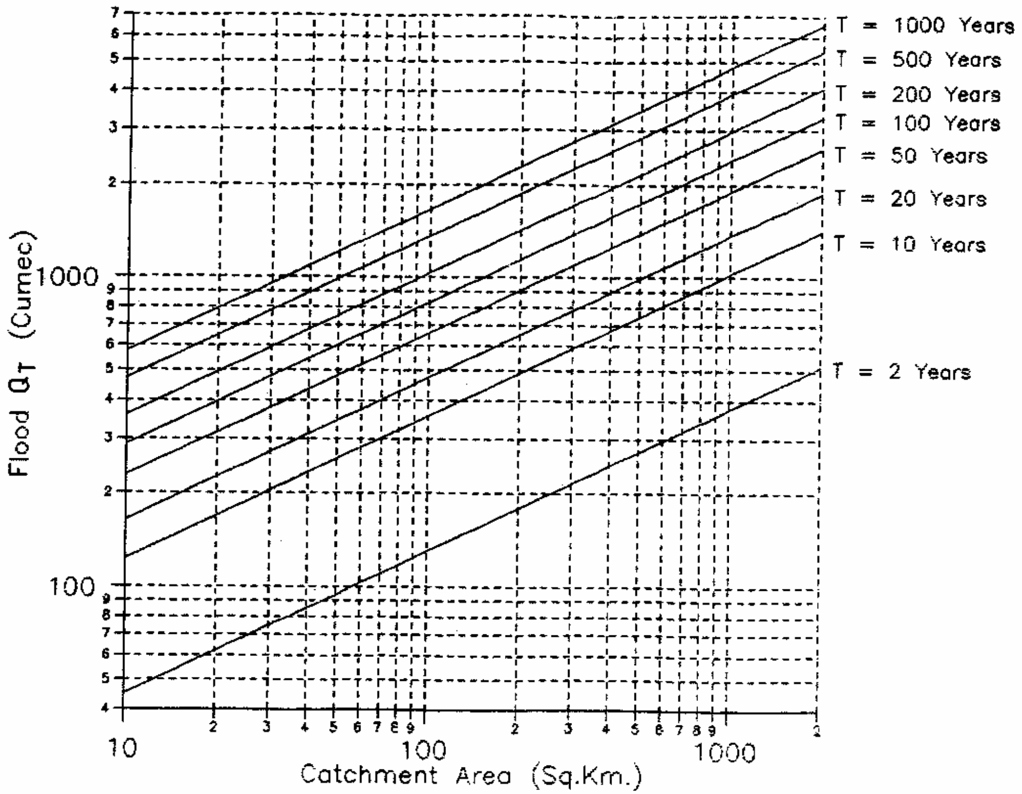

Fig.4.1 Variation of flood frequency estimates with catchment area for subzone 3(a)

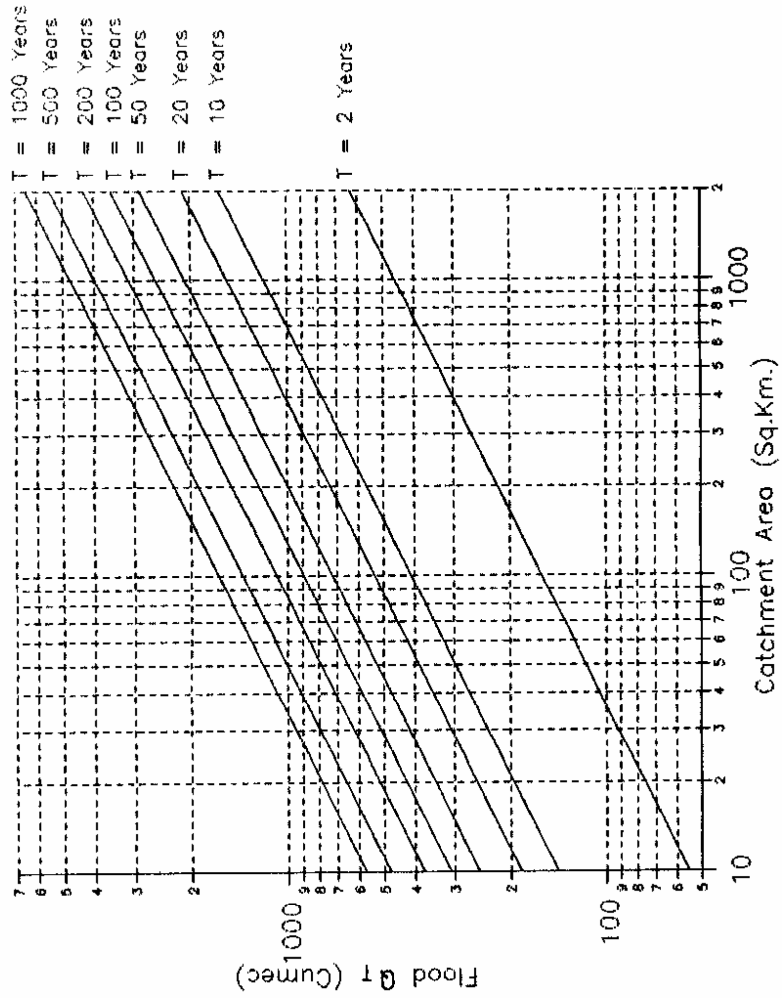

Fig.4.2 Variation of flood frequency estimates with catchment area for subzone 3(b)

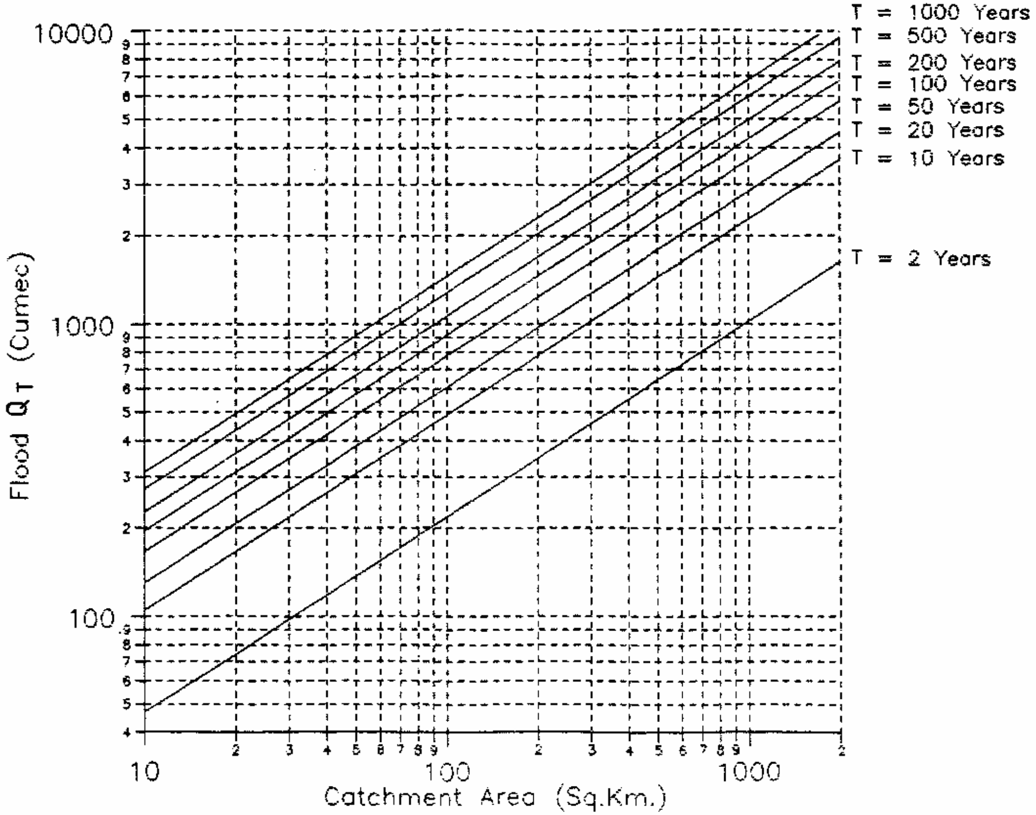

Fig.4.3 Variation of flood frequency estimates with catchment area for subzone 3(c)

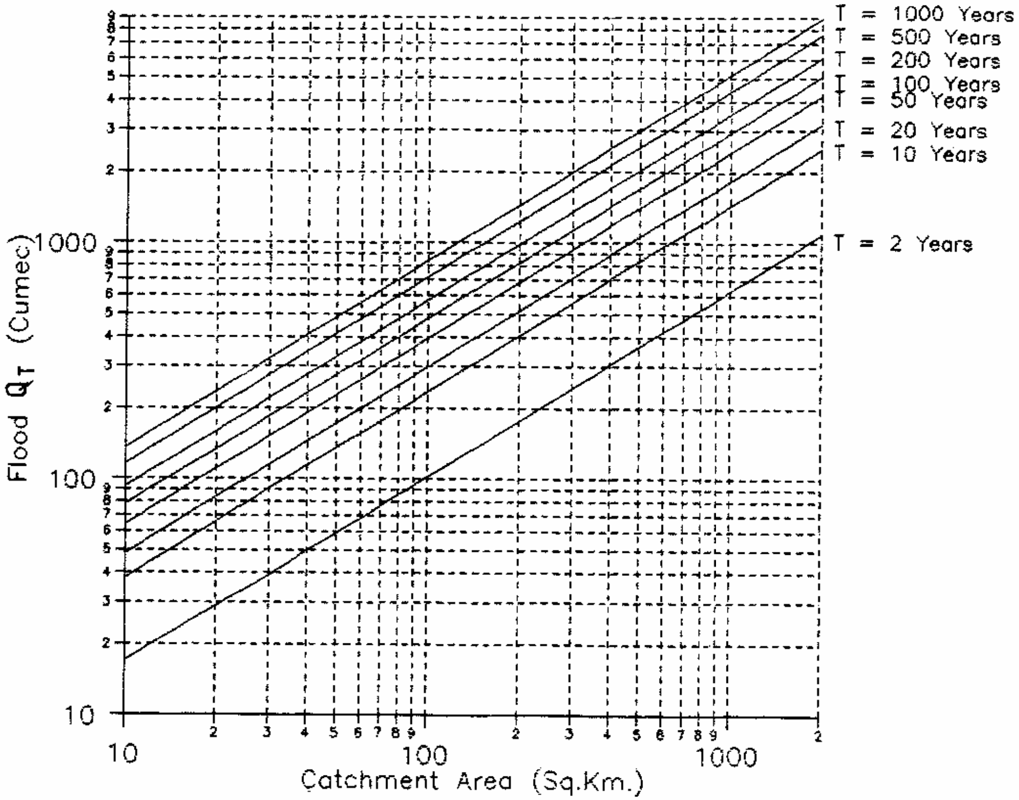

Fig.4.4 Variation of flood frequency estimates with catchment area for subzone 3(d)

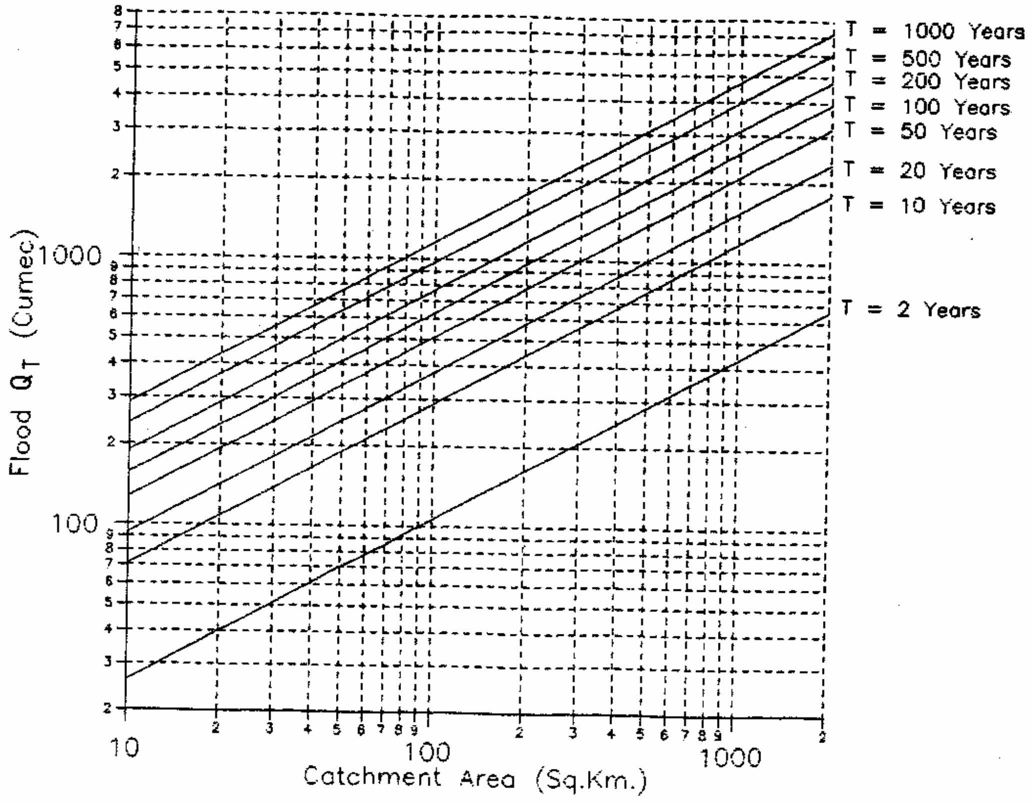

Fig.4.5 Variation of flood frequency estimates with catchment area for subzone 3(e)

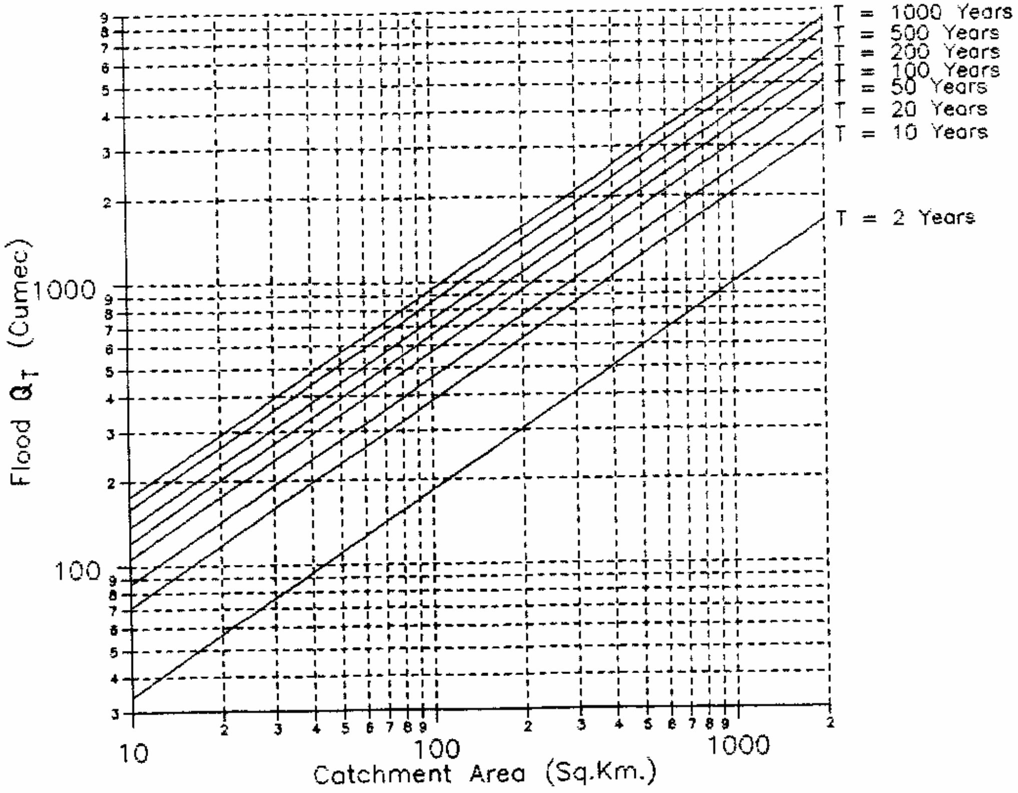

Fig.4.6 Variation of flood frequency estimates with catchment area for subzone 3(f)

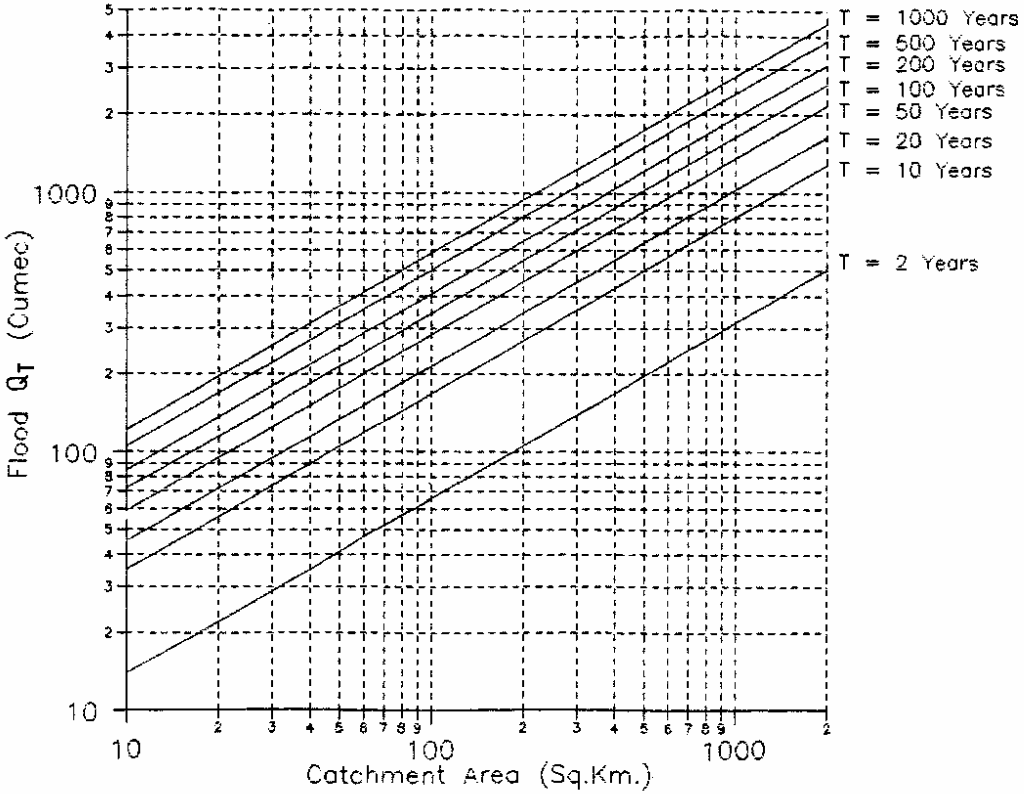

Fig.4.7 Variation of flood frequency estimates with catchment area for subzone 3(h)

8.0 CONCLUSIONS

On the basis of this study following conclusions are drawn:

(i) The flood frequency estimates obtained by the PWM based estimates are not much different from those obtained by the L moment approach, particularly for smaller return periods upto 50 years.

(ii) For estimation of floods of different return periods for gauged catchments the regional flood frequency curves developed for the respective subzones together with the at-site mean annual peak floods may be used.

(iii) The conventional empirical formulae can not provide floods of desirable return periods. However, the flood formulae developed in this study are capable of providing flood estimates for different return periods.

(iv) The study indicates that adopting the regional flood frequency curves using the data of the seven subzones in combined form or one combined regional flood formula for all the seven subzones may lead to erroneous flood estimates. These erroneous flood estimates may be attributed to the effect of sample size and regional heterogeneity in the development of the regional flood frequency curves as well as the relationship between mean annual peak flood and catchment area.

(vi) 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 and these formulae may be used by the field engineers for estimation of floods of desired return periods.

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DIRECTOR : S.M. SETH

DIVISIONAL HEAD : R.D. SINGH

STUDY GROUP

RAKESH KUMAR
R.D. SINGH