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DEVELOPMENT OF REGIONAL FLOOD FREQUENCY RELATIONSHIPS AND FLOOD FORMULAE FOR VARIOUS SUBZONES OF ZONE 3 OF INDIA

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PREFACE

Estimation of magnitudes of likely occurrence of floods is of a great importance for solution of a variety of water resources problems such as design of various hydraulic structures, urban drainage systems, flood plain zoning and economic evalvation of flood protection works etc. Whenever, rainfall or river flow records are not available at or near the site of interest, it is difficult for hydrologists or engineers to derive reliable flood estimates directly. In such a situation, the regional flood frequency relationships or the flood formulae developed for the region are one of the alternative methods which may be adopted for estimation of design flood specially for small catchments. Most of the flood formulae developed for different regions of the country are empirical in nature and do not provide flood estimates for the desired return period.

In this report, based on the comparative flood frequency studies, probability weighted moment (PWM) based at site and regional General Extreme Value (SRGEV) and at site and regional Wakeby (SRWAKE) methods, in general, are found to be the suitable methods for estimation of flood frequency estimates for the seven hydrometeorological homogeneous subzones of our country. The regional flood frequency curves, developed for the GEV distribution have been coupled with the regional relationship established between mean annual peak floods and the physiographic characteristics, in order to develop the regional flood formulae for the various subzones.

The study has been carried out by Shri Rakesh Kumar and Shri R.D. Singh, Scientists of the Institute. It is expected that the developed regional flood frequency curves of the respective subzones, together with at site mean annual peak floods will provide rational flood frequency estimates for gauged catchments of the various subzones, while for computing the floods of different return periods for the ungauged catchments of the various subzones the developed regional flood formulae may serve as an useful alternative.

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ABSTRACT

A comparative regional flood frequency study has been carried out using annual maximum peak flood series data of the small to medium size catchments defined by the bridge sites for the seven hydrometeorological subzones of Zone 3. Extreme Value type-1 (EV1) distribution, following modified U.S.G.S. method as well as probablity weighted moments (PWM) fitting method; General Extreme Value (GEV) and 5 parameter Wakeby (WAKE) distributions fitted by PWM, utilizing: (i) at site data, (ii) at site and regional data combined, and (iii) regional data alone, have been considered. The homogeneity of the various subzones has been tested by the U.S.G.S. homogeneity test. A regional relationship between mean annual peak flood and catchment area has also been developed for each of the subzones for computation of mean annual peak floods for the ungauged catchments.

Descriptive ability of the various methods has been tested based on the goodness of fit criteria viz. (i) average of relative deviations between computed and observed values of annual maximum peak floods (ADF), (ii) efficiency (EFF) and (iii) standard error (SE). Performance of various methods has also been evaluated based on the predictive ability criteria viz. (i) bias (BIAS), (ii) root mean square error (RMSE), and (iii) coefficient of variation (CV) computed from samples of different sizes drawn from generated EV1, GEV and WAKE populations by considering 1000 replications of the computation procedure for each sample size. The data of two catchments in each subzone viz. second smallest and second largest in size have not been used for estimation of parameters of the flood frequency distributions as these catchments have been treated as ungauged for computing the at site mean annual peak flood values and testing the predictive ability of the various methods. The regional flood frequency curves have also been developed for the combined Zone 3 considering the mean annual peak flood data of the 101 bridge sites out of total 115 bridge sites of the 7 subzones in combined form. Effect of regional heterogeneity is studied by comparing the growth factors of various sub-zones and combined zone 3.

The relationship between mean annual peak flood and catchment area for each subzone has been coupled with the respective regional flood frequency curves of the GEV distribution, and regional flood formulae have been derived for the various subzones and combined zone 3. The developed regional flood formulae have also been expressed in the form of Dicken's formula and revised Dicken's coefficients have also been computed. For estimation of floods of different return periods for gauged catchments, the regional flood frequency curves developed for each subzone together with at site mean annual peak flood may be used; while for ungauged catchments, the regional flood formulae developed for the respective subzones may be adopted.

1.0 INTRODUCTION

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. Most of the flood formulae developed for different regions of the country are empirical in nature and do not provide estimates for the desired return period. Inspite of the advancement in the techniques of design flood estimation, these empirical formulae are being used by the field engineers in their design practice, specially for flood estimation of small structures.

A number of studies have been carried out for estimation of design floods for various structures by various Indian organizations. Prominent among these include the studies carried out jointly by Central Water Commission(CWC), Research Designs and Standard Organization(RDSO), Ministry of Railways and India Meteorological Department(IMD) for various hydrometeorological sub-zones of India using the method based on synthetic unit hydrograph and design rainfall considering physiographic and meteorological characteristics to estimate design floods(for example CWC, 1985) and regional flood frequency studies carried out by RDSO for the various hydrometeorological sub-zones using the USGS and pooled curve methods(for example RDSO, 1991)

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 indentify the robust flood frequency method. At site and regional methods viz. SRGEV and SRWAKE have been found to estimate floods of varios 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.

2.0 REVIEW OF LITERATURE

Flood frequency analysis for those gauging sites, where the historical peak discharges are available for sufficiently long period, may be carried out using at-site data. For at-site flood frequency analysis, generally various theoretical frequency distributions are fitted to historical flood records. The parameters of the distributions are estimated using one or more parameter estimation techniques. The best fit distribution is selected on the basis of some goodness of fit criteria. The floods of different return periods are computed using the estimated parameters of the best fit distribution. However, for the ungauged sites or sites with short record lengths, such analysis may not be able to provide consistent and reliable flood estimates. In such a situation, flood frequency analysis may be performed using regional approaches with 'regional and at-site data' or 'regional data' alone. Farquharson et al.(1992) assembled GEV (PWM) based regional flood frequency curves for a number of semi-arid and arid areas of some parts of the world.

Various issues involved in regional flood frequency analysis are testing regional homogeneity, development of frequency curves and derivation of relationship between MAF and the catchment characteristics.Inspite of a large number of existing regionalisation techniques, very few studies have been carried out with 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). In this study the robust flood frequency analysis method has been identified by comparing the various methods based on descriptive and predictive ability criteria. The detailed review of flood frequency studies is presented in N.I.H. (1994-95).

The empirical formulae used for the estimation of the flood peak are the essentially regional formulae based on statistical correlation of the observed peaks and important catchment characteristics. The catchments, considered for developing the regional formulae, must be from a hydrologically homogeneous region. Quality control of the peak discharge data is, therefore, a prerequisite to the analysis, Some of the elements to be considered in the quality analysis are given below:

(i) All peak discharges should represent virgin flow (negligible man made influences);

(ii) Peak-stage data should be complete and reliable;

(iii) Any extraneous or variable back water effects on the peak stage, such as these cause by ice, aquatic vegetation, or reservoir operation downstream, should be noted and taken into consideration when computing the peak discharge;

(iv) Methods used to measure or compute peak discharge should be examined for reliability; and

(v) The runoff distribution between flood plain and stream channels at the time of peak discharge should be determined.

2.1 Commonly Used Empirical Formulae

In order to simplify the form of the regional formulae, only a few of the many parameters affecting the flood peak are used. For example, the catchment area, considered to be an important parameter affecting the flood peak, is used in almost all formulae. However, most of the formulae neglect the flood frequency as a parameter. In view of these, the empirical formula are applicable only in the region from which they were developed and when applied to other areas they can at best give approximate values. The empirical formulae are usually based on data obtained for the larger streams because relatively few small streams are gauged in any region. Consequently, the empirical equations are usually applied in computing peak discharges for rivers having large catchment areas where stream flow data are inadequate. Some of the empirical flood formulae commonly used in India, in metric units along with the values of constants used in the formulae and the limitations of these formulae are mentioned in Appendix-I of the technical report of N.I.H.(1994-95).

2.2 Envelope Curves

In regions having same climatological characteristics, if the available flood data are scanty, the enveloping curve technique can be used to develop a relationship between the maximum flood flow and catchment area. In this method the available flood peak data are collected from a large number of catchments which are similar in hydrometeorological characteristics. The data are then plotted on log-log paper as flood peak V/s catchment area. This would result in a plot in which the data would be scattered. If an enveloping curve that would encompass all the plotted points is drawn, the resulting curve can be used to compute maximum peak discharge for any given area. Envelope curves are very much useful in getting the rough estimate of peak values quickly. An empirical flood formulae of the type $Q = f(A)$ can be derived if equations are fitted to these enveloping curves.

Kanwar Sain and Karpov (quoted in Varshney, 1979) collected the data on Indian rivers and have drawn two envelope curves which suit basins of south India and central India. Since in these curves the peak discharge has been correlated with the catchment area only and other catchment characteristics are ignored, the results obtained may not be precise. However, these can be used for preliminary guidance for determining peak flood discharge. This method is definitely better than the empirical formulae in the sense that it does not require the selection of coefficients on the basis of judgment as required in empirical formulae.

The limitation of these curves lies in the fact that they are based on past records available up to the time such curves are drawn. Such curves, should, therefore, be revised from time to time as more and more data become available.

2.3 Application of Empirical Formulae for Design Flood Estimation

Whenever the hydrological records are inadequate for frequency analysis or unit hydrograph analysis, the empirical formulae developed for the region are only alternative method to provide an estimate of flood at project site. Many empirical formulae have been devised as discussed above. These formulae are essentially the regional formulae based on statistical correlation of the observed peaks and important catchment properties. Most of the empirical formulae involve only one or two physical characteristics for the estimation of the flood peak. Since the flood peaks not only depend on one or two physical characteristics involved in those empirical formulae but also on many other factors , therefore those formulae can not be expected to give generalized precise results. In view of these, the empirical formulae are applicable only in the region from which they were developed. Also its applicability is limited for estimating the flood peaks up to the range of values considered in developing the formula. Care has to be taken while using these formula in extrapolation range of peak values and catchments sizes.

The empirical formulae developed for a specific region based on past available records should be revised from time to time as more and more data becomes available. Those catchments, which have been affected by various land use changes, should be excluded while revising the empirical formulae unless the factors reflecting those changes are already included in the empirical formulae. In general, it can be stated that the empirical formulae must be used with great prudence and must never be used unless their origin has been investigated.

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. In this study, regional flood frequency analysis has been carried out using Extreme Value Type-1(EV1) distribution, General Extreme Value distribuitin and Wakeby distribution based on (i) at site data, (ii) at site and regional data and regional data in order to identify robust method for various Zones. The flood frequency curves developed by the robust method have have been coupled with the relationship between mean annual peak flood and physiographic characteristics for deriving a regional flood formulae for the various subzones of Zone 3 of India.

The objectives of this study are:

(a) Testing the regional homogeneity of the study area.

(b) Development of regional flood frequency curves using the EV1, GEV and Wakeby distributions.

(c) Identification of robust flood frequency analysis methods for various subzones based on descriptive and predictive ability criteria.

(d) 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.

(e) Coupling the relationship between mean annual peak flood and physiographic characteristics with the robost flood frequency analysis method for developing the regional flood formulae for various 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.

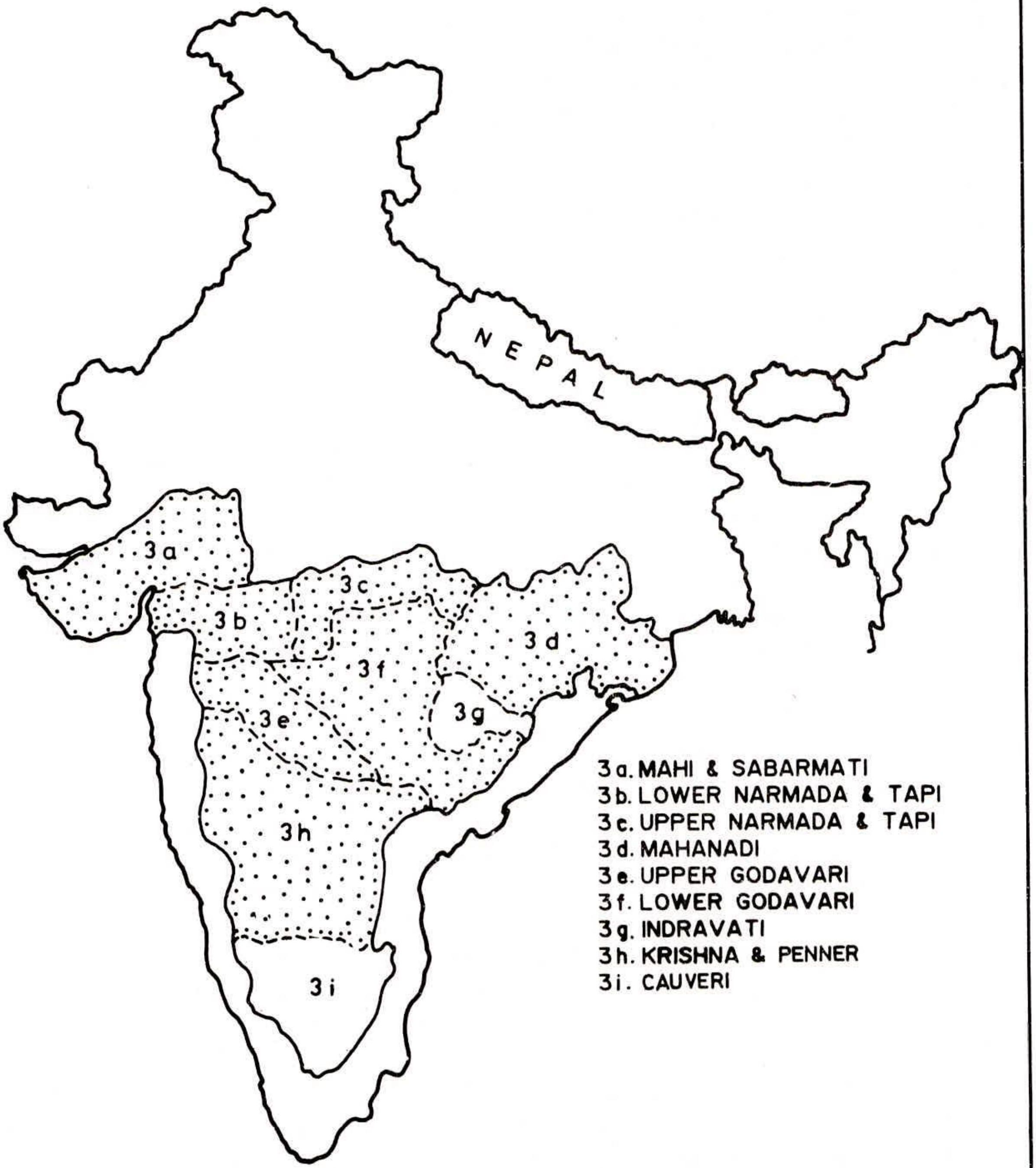

FIG. 1. LOCATION MAP OF HYDROMETEOROLOGICAL ZONE 3 OF INDIA AND ITS SUB-ZONES

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 7 sub-zones

Sub-zone	Area of sub-zone (Sq Km)	No of sites	Range of catchment area (sq km)	Range of mean annual peak flood (cumec)	Range of Record lengths (years)
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 various frequency distributions used in the study along with the methodology adopted are described here under.

6.1 Frequency Distributions Used

Methods used in the study to carry out flood frequency analysis involved fitting of Extreme Value Type I(EV1), General Extreme Value (GEV) and Wakeby (WAKE) distributions, which are briefly discussed here under.

6.1.1 Extreme value type-I distribution (EV1)

This is a two parameter distribution and it is popularly known as Gumbel Distribution. The cummulative density function for EV1 distribution is given by:

$$F(x) = e^{-e^{\frac{-(x-u)}{\alpha}}} \qquad (1)$$

where, F(x) is the probability of nonexceedence and equal to 1-1/T ; T is the recurrence interval in years, u and α are the location and shape parameters respectively. These parameters can be estimated from the sample of annual maximum peak floods using the parameters estimation techiniques available in literature. Method of probability weighted moments (PWM) is one of the parameter estimation techniques which has been successfully applied by Landerwehr et al.(1979) for estimating the parametres of EV1 distribution more efficiently with less bias and the same has been used in this study.

6.1.2 General extreme value distribution(GEV)

GEV distribution is a generalised three parameter extreme value distribution . Its theory and practical applications are reviewed in the Flood Studies (NERC,1975). The cummulative density function F(x) for GEV distribution is expressed as:

$$F(x) = e^{-(1-k\frac{(x-u)}{\alpha})^{1/k}} \qquad (2)$$

where u, α and K are location, scale and shape parameters of GEV distribution respectively. For estimating these parameters, a procedure based on method of probability weighted moments has been used.

The form of regional frequency relationship is expressed as:

$$x_T/\bar{x} = u + \alpha\, Y_T \tag{3}$$

$$Y_T = [1- \{-\ln\ (1 - 1/T)\}^k\ ]/k \tag{4}$$

Where, x_T is T-year return period flood estimate, $\bar{x}$ the mean annual peak flood, and Y_T is the GEV reduced variate correspondind to T-year return flood.

6.1.3 Wakeby distribution

A random variable x is said to be distributed as Wakeby if:

$$x = m+a\ [1-(1-F)^b\ ] - c\ [1-(1-F)^{-d}\ ] \tag{5}$$

where F = F(x) = 1-1/T, and a, b, c, d and m are the parameters of Wakeby distribution which can be estimated using a special algorithm proposed by Landwehr et al.(1979) based on method of probability weighted moments.

The methodology adopted for testing the regional homogeneity and carrying out regional flood frequency analysis is discussed below.

6.2 Regional Homogeneity Test

In this study regional homogeneity has been tested by the U.S.G.S. homogeneity test. This test has widely been used for testing homogeneity of a region. The steps involved in U.S.G.S. homogeneity test are:

(i) Compute the EV1 reduced variate corresponding to 10 year return period flood using the relation:

$$Y_T = -\ln\ (-\ln\ (1-1/T\ )) \tag{6}$$

for example,

$$Y_{10} = -\ln\ (-\ln\ (\ 1\ -1/10)) \tag{7}$$

$$=2.25$$

(ii) Compute the 10 year flood putting Y_{10} = 2.25 in the following equation developed for the different catchments using least square approach :

$$x_{10} = u + \alpha\ Y_{10} \tag{8}$$

$$= u + 2.25\ \alpha \tag{9}$$

(iii) Repeat step (i) and (ii) to compute 2.33 year flood, which is the annual mean flood for EV1 distribution, for the different catchments.

(iv) Compute the ratio of 10 year flood to annual mean flood ($Q_{2.33}$) at each gauging sites. This ratio is known as the 10 year frequency ratio.

(v) Average the 10 year frequency ratios of all the gauging sites to obtain the mean 10 year frequency ratio for the region as a whole.

(vi) Determine the EV1 reduced variate corresponding to the product of annual mean annual flood and the average 10 year frequency ratio from the linear regression equations developed for each catchment . Thus :

$$Y_T = (x_T - u)/\alpha \qquad (10)$$

(vii) Plot the EV1 reduced variates obtained from step (vi) against the effective length of records for that station on a test graph, where upper and lower regional limits of 95 % confidence are already plotted using the following coordinate pairs :

Sample size (n)	Lower Limit (Y)	Upper Limit (Y)
5	-0.59	5.09
10	0.25	4.25
20	0.83	3.67
50	1.35	3.15
100	1.52	2.88
200	1.80	2.70

(viii) If the plotted points for all the gauging sites lie between the 95 % confidence limits, then they are considered to be homogeneous.

6.3 Development of Regional Flood Frequency Curves

In order to develop the regional flood frequency curves a sample comprising the station-year data of standardized values of annual maximum peak floods i.e. $x/\bar{x}$ values for different catchments of the various subzones are considered for the analysis. Then the flood frequency analysis is performed with the sample of $x/\bar{x}$ In case of the at site methods annual maximum peak flood data of the specific site are used for estimation of parameters of the frequency distributions; whereas, in case of the at site and regional methods data of all the sites of the hydrologically homogeneous region are used for estimation of the parameters of the frequency distributions and annual mean peak flood of the specific site are used for scaling the quantile x_T for estimation of flood frequency estimates. In case of regional methods, a relationship between annual mean peak flood and catchment characteristics developed for the region on the basis of annual mean peak flood data of the gauged catchments is used for computing the annual mean peak flood for the ungauged catchment in the region. The annual mean peak flood computed the the regional relationship is used for scaling the quantile x_T for estimation of flood frequency estimates.In case of the at site methods annual maximum peak flood data of the specific site are used for estimation of parameters of the frequency distributions; whereas, in case of the at site and regional methods data of all the sites of the hydrologically homogeneous region are used for estimation of the parameters of the frequency distributions and annual mean peak flood of the specific site are used for scaling the quantile x_T for estimation of flood frequency estimates. In case of regional methods, a relationship between annual mean peak flood and catchment characteristics developed for the region on the basis of annual mean peak flood data of the gauged catchments is used for computing the annual mean peak flood for the ungauged catchment in the region. The annual mean peak flood computed the the regional relationship is used for scaling the quantile x_T for estimation of flood frequency estimates.In case of the at site methods annual maximum peak flood data of the specific site are used for estimation of parameters of the frequency distributions; whereas, in case of the at site and regional methods data of all the sites of the hydrologically homogeneous region are used for estimation of the parameters of the frequency distributions and annual mean peak flood of the specific site are used for scaling the quantile x_T for estimation of flood frequency estimates. In case of regional methods, a relationship between annual mean peak flood and catchment characteristics developed for the region on the basis of annual mean peak flood data of the gauged catchments is used for computing the annual mean peak flood for the ungauged catchment in the region. The annual mean peak flood computed the the regional relationship is used for scaling the quantile x_T for estimation of flood frequency estimates.$\bar{x}$ values. The following methods based on (i) at site data, (ii) at site and regional data and (iii) regional data alone have been used in the study.

(a) At site flood frequency methods

(i) At site EV1 (PWM) method (EV1)
(ii) At site GEV (PWM) method (GEV)
(iii) At site Wakeby (PWM) method (WAKE)

(b) At site and regional flood frequency methods

(i) Modified U.S.G.S. method based on at site and regional data (SREV1-I)
(ii) EV1 (PWM) method method based on at site and regional data (SREV1-II)
(iii) GEV (PWM) based on at site and regional data (SRGEV)
(iv) Wakeby (PWM) method based on at site and regional data (SRWAKE)

(c) Regional flood frequency methods

(i) Modified U.S.G.S. method based on regional data (REV1-I)
(ii) EV1 (PWM) method method based on regional data (REV1-II)
(iii) GEV (PWM) based on regional data (RGEV)
(iv) Wakeby (PWM) method based on regional data (RWAKE)

In case of the at site methods annual maximum peak flood data of the specific site are used for estimation of parameters of the frequency distributions; whereas, in case of the at site and regional methods data of all the sites of the hydrologically homogeneous region are used for estimation of the parameters of the frequency distributions and annual mean peak flood of the specific site are used for scaling the quantile x_T for estimation of flood frequency estimates. In case of regional methods, a relationship between annual mean peak flood and catchment characteristics developed for the region on the basis of annual mean peak flood data of the gauged catchments is used for computing the annual mean peak flood for the ungauged catchment in the region. The annual mean peak flood computed the the regional relationship is used for scaling the quantile X_T for estimation of flood frequency estimates. Description of these methods is given in N.I.H.(1994-95). However, the at site and regional methods Viz. SREV1, SRGEV, SRWAKE as well as the regional method RGEV are described here under.

6.3.1 PWM based EV1 method applied to single sample of normalized data (SREV1)

The steps involved in the regional flood frequency analysis using this method are given below:

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

(ii) Test for homogeneity of data obtained from various gauging stations.

(iii) Discard those catchments from the anlaysis which are not homogeneous.

(iv) Scale the data by dividing the 'at site' data by 'at site' mean so that the regional flood curve will have a mean equal to unity.

(v) Pool the data from each selected site.

vi) Combine the scaled data obtained from step (v) for each site together to form a sample of scaled data having mean equal to unity. Hence, $\bar{m}_o = 1.0$

(vii) Compute $\bar{m}_1$ for the region by using the sample data obtained from step

(vi). Thus,

$$\bar{m}_1 = \frac{1}{L} \sum_{i=1}^{L} z_i \ (1-F_i) \qquad (11)$$

where,

$$L = \sum_{j=1}^{ns} n(j) \quad (12)$$

ns = number of gauging sites
$Z_i = x_i/\bar{x}$ are normalised data obtained from step (vi);
F_i = Plotting positions to be computed using the eq. given below:

$$F_i = \frac{i-0.35}{n} \quad (13)$$

viii) Compute the regional EV1 parameters u and α using the PWM relations given by the following eqs:

$$\alpha = \frac{\bar{m}_0 - 2\,\bar{m}_1}{\ln 2} \quad (14)$$

$$u = \bar{m}_0 - 0.5772\,\alpha \quad (15)$$

(ix) Estimate the quantiles x_T using the relation:

$$x_T/\bar{x} = u + \alpha\,(-\ln(-\ln(1 - 1/T))) \quad (16)$$

(x) Scale the quanitles x_T by at site mean (same as $m_{100,\,j}$) in order to estimate T year flood for any particular site:

$$x_{T,j} = m_{100,\,j}\; x_T/\bar{x} \quad (17)$$

where, $x_{T,j}$ is T-year flood at jth gauging site.

6.3.2 PWM based GEV method applied to single sample of normalized data (SRGEV)

The regional flood frequency analysis may be carried out by this method in the following steps.

(i) Repeat step (i) to (vi) described in Section 6.3.1

(ii) Compute $\bar{m}_1$ *and* $\bar{m}_2$ for the region from the sample:

$$\bar{m}_1 = \frac{1}{L}\sum_{i=1}^{L} Z_i\,(1-F_i) \qquad (18)$$

$$\bar{m}_2 = \frac{1}{L}\sum_{i=1}^{L} Z_i\,(1-F_i)^2 \qquad (17)$$

(iii) Estimate the regional parameters, k, u and α by following the procedure described in Singh(1989)

(iv) Estimate the quantiles of T-year recurrence interval for any site using the relation:

$$X_T = u + \alpha\,(1-(-\ln(1-1/T))^k)/k \qquad (20)$$

(v) Follow step (x) of Section 6.3.1 for estimation of T year flood for any site.

6.3.3 PWM based Wakeby method applied to single sample of normalized data (SRWAKE)

The steps followed for carrying out the regional flood frequency analysis by this method are:

(i) Repeat step (i) to (vi) described in Section 6.3.1

(ii) Compute regional probability weighted moments from the sample using the equation:

$$\bar{m}_r = \frac{1}{L}\sum_{i=1}^{L} Z_i\,(1-F_i)^r \qquad (21)$$

where r = 0, 1, 2, 3, 4.

(iii) Estimate the regional Wakeby parameters based on the regional probability weighted moments obtained from step (ii) using the special algorithm suggested by Landwehr et al.(1979 c).

(iv) Estimate the regional quantiles x_T using the relation:

$$\frac{x_T}{\bar{x}} = m + a[1-(1/T)^{b}] - c[1-(1/T)^{-d}] \qquad (22)$$

(v) Compute the T year flood for any gauging site by scaling the quantiles x_T obtained in step (v) by the as site mean following the Step (x) of 6.3.1

6.3.4 PWM based GEV method using regional data (RGEV)

The procedure mentioned in Section 6.3.2 is followed, except that the regional mean computed from the regional relationship between mean annual peak flood ($\bar{x}$) and catchment area (A), developed as discussed below is used for scaling the quantiles X_T , in place of the at site mean annual peak flood of the respective site.

For the ungauged catchments at site mean cannot be computed in absence of the flow data. In such a situation, a relationship between mean annual peak floods of the gauged catchments and their pertinent physiographic and climatological characteristics is needed for estimation of mean annual peal flood for the ungauged of the region. The procedure for development of such a relationship is mentioned below.

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

For the ungauged catchments at site mean cannot be computed in absence of the flow data. In such a situation, a relationship between mean annual peak floods of the gauged catchments and their pertinent physiographic and climatological characteristics is needed for estimation of mean annual peal flood for the ungauged of the region. The form of such a relationship is mentioned below.

$$\bar{X} = a\ A^b\ S^c\ L^d\ D^e \qquad (23)$$

Here, $\bar{x}$ is the mean annual peak flood, A is the catchment area, S is the slope of the catchment, L is the length of main channel and D is the drainage density (or any ther relevant physiographic anf climatological characteristics may be adopted), a, b, c, d and e are the coefficients to be estimated using the least square approach.

6.5 Evaluation Criteria for Identifying Robust Frequency Analysis Method

The evaluation criteria based on descriptive ability and predictive ability criteria has been adopted for identifying the robust flood frequency analysis method.

6.5.1 Descriptive ability criteria

The descriptive ability criteria relate to ability of a chosen model to describe/reproduce chosen aspects of observed flood peaks. The descriptive ability criteris used in the study are:

(a) Average of relative deviations between computed and observed valuse of annual maximum peak peak discharege (ADF)

(b) Efficiency (EFF)

(c) Standard Error (SE)

6.5.2 Predictive ability criteria

Predictive ability criteria relate to statistical ability of procedure to acieve its assigned task with minimumbias, and maximumefficiency and robustness. In this study following predictive ability criteria have been used.

(a) Bias (BIAS)

(b) Root mean square error (RMSE)

(c) Coefficient of variation (CV)

The details of these criteria are discussed in N.I.H.(1994-95).

6.6 Development of Regional Flood Formula

The form of regional flood formula developed by coupling the relationship, between catchment area and mean annual peak flood, together with regional flood frequency curves, developed based on the methodology discussed above is:

$$x_T = [\beta+\gamma(-\ln(1-\frac{1}{T}))^K] A^b \qquad (24)$$

where,

$$\beta = a(\alpha/K+u) \qquad (25)$$

$$\gamma = -\alpha\, a/K \qquad (26)$$

and x_T is flood estimate for T year return period in cubic meter per second (Cumec), A is the catchment area in square kilometers, a and b are the regional coefficients obtained for the relationship expressed in eq. (23).

6.7 Representation of Revised Flood Formula in the Form of Dicken's formula

The regional flood formula may be represented in the form of the Dicken's formula using the procedure described earlier. The conventional Dicken's formula is:

$$Q\,,\ \text{or}\ x = C\,A^{0.75} \tag{27}$$

Where, Q is the peak flood, which has been denoted by x. There is no return period associated with the conventional Dicken's formula. If the conventional Dicken's formula is revised as:

$$x_T = C_T\ A^{0.75} \tag{28}$$

If only catchment area is considered as a physiographic characteristic for development of regional relationship between mean annual peak flood and physiographic characteristics then Equation (23), is expressed as:

$$\bar{x} = a\,A^b \tag{29}$$

Dividing Equation (28) by Equation (29) the equation obtained is:

$$\frac{x_T}{\bar{x}} = \frac{C_T\ a\ A^b}{a}\ A^b = \frac{C_T A^{0.75-b}}{a} \tag{30}$$

or C_T is obtained as:

$$C_T = \frac{x_T\ a\ A^{b-0.75}}{\bar{x}} \tag{31}$$

Substituting the value of $x_T/\bar{x}$, form Equation (3) and (4), in the above equation; the expression is obtained as:

$$C_T = (\dot{u}+\alpha Y_T)\ a\ A^{b-0.75} \tag{34}$$

Here, C_T is a function of catchment area, regional coefficients of the GEV distribution and relationship between catchment area and mean annual peak flood. Thus, the coefficient C_T in the Dicken's formula can also be associated with the return period and it can be evaluated using the various physiographic characteristics such as A, S, L and D etc. and regional coefficients appearing in Equation (23) as given below.

7.0 ANALYSIS AND DISCUSSION OF RESULTS

The analysis carried out and the results of the study are discussed below.

7.1 Development of Regional Flood Frequency Curves

Regional homogeneity of the each subzone has been tested using the U.S.G.S. homogeneity test. The data of bridge sites which pass the regional homogeneity test have been used in the study. The details of catchment area, sample statistics and sample size are given in Table 2.1 through 2.6 for the various subzones except subzone 3(d) for which these are given in N.I.H.(1994-95).

In order to develop the regional flood frequency curves a sample comprising the station-year data of standardized values of annual maximum peak floods i.e. $x/\bar{x}$ values for different catchments of each subzone are considered for the analysis. Then the flood frequency analysis is performed with the sample of $x/\bar{x}$ values using the EV1, GEV and Wakeby distributions. The annual maximum peak flood data of the 2 catchments viz. the second smallest and second largest in catchment area have not been used in development of flood frequency curves as well as the relationship between mean annual peak flood and catchment area, as these catchments have been treated as ungauged for testing the predictictive ability of the various methods and estimation of flood frequency estimates treating these catchments as ungauged. The values of regional parameters of the EV1, GEV and Wakeby distributions obtained for the various subzones are given in Table 3 to Table 5 respectively.

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

As catchments areas of the various catchments were available; therefore, the regional relationship of following form has been developed between mean annual peak floods($\bar{x}$) and catchment areas(A) using linear regression approach.

$$\bar{x} = aA^b \qquad (36)$$

The null hypothesis i.e. the catchment area is not significant as independent variable in the regression equation, is rejected based on T-test. The values of regression coefficients, standard errors and corelation coefficients are given in Table 6.

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(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-2.5 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-2.6 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 papameters for EV1 distribution

S. No.	Subzone	u	α
1.	3(a)	0.637	0.629
2.	3(b)	0.636	0.630
3.	3(c)	0.689	0.539
4.	3(d)	0.701	0.517
5.	3(e)	0.613	0.671
6.	3(f)	0.716	0.491
7.	3(h)	0.630	0.642

Table 4 Regional papameters for GEV distribution

S. No.	Subzone	k	u	α
1.	3(a)	-0.198	0.587	0.505
2.	3(b)	-0.191	0.588	0.511
3.	3(c)	-0.087	0.668	0.494
4.	3(d)	-0.141	0.671	0.446
5.	3(e)	-0.181	0.563	0.550
6.	3(f)	-0.040	0.708	0.473
7.	3(h)	-0.133	0.594	0.559

Table 5 Regional papameters for Wakeby distribution

S. No.	Subzone	a	b	c	d	m
1.	3(a)	0.191	2.086	47.403	0.017	0.069
2.	3(b)	2.405	0.479	0.114	0.602	0.050
3.	3(c)	0.320	3.880	-13.850	-0.0.51	0.067
4.	3(d)	0.295	4.813	22.646	0.027	0.119
5.	3(e)	2.674	0.440	0.174	0.524	-0.009
6.	3(f)	0.323	6.462	-5.743	-0.129	0.066
7.	3(h)	0.307	1.868	-18.680	-0.045	-0.004

Table 6 Regression coefficients of mean annual peak flood and catchment area relationship

S. No.	Subzone	a	b	Standard Error (S_E)	Corelation Coefficient (r)
1.	3(a)	24.779	0.43	0.285	0.893
2.	3(b)	16.440	0.55	0.472	0.809
3.	3(c)	6.619	0.78	0.372	0.913
4.	3(d)	3.819	0.76	0.571	0.794
5.	3(e)	10.176	0.57	0.345	0.904
6.	3(f)	4.953	0.79	0.356	0.918
7.	3(h)	2.248	0.77	0.566	0.782

7.3 Evaluation of Robust Frequency Analysis Method

Based on the evaluation criteria described in mentioned 6.5 the descriptive ability as well as predictive ability of the various methods has been tested. The detailed results for subzones 3(c) and 3(f) are given in the technical reports N.I.H.(1990-91) and N.I.H.(1994-95) respectively. The results for one of the suzones viz. 3(b) are given in Appendix-I. The superiority of one method could not be established based on the descriptive ability criteria. Based on the predictive ability criteria it has been observed that SRGEV and SRWAKE methods, in general, estimate the floods of various return periods with relatively less bias and comparable root mean square error and coefficient. As GEV distribution involves only three parameters as compared to the 5 parameters of the Wakeby distribution; therefore regional flood formulae for the various subzones have been developed based on the regional parameters of the GEV distribution and the relationship between mean annual peak flood and catchment area for each of the subzones. Fig. 2 shows variation of $x_T/\bar{x}$ with return period for the various subzones. Table 7 gives the statistics of the GEV reduced variate. Table 8.1 to 8.6 gives the flood estimates for various subzones using the regional flood frequency curves and at site mean, except subzone 3(d) for which these are given in N.I.H.(1994-95).

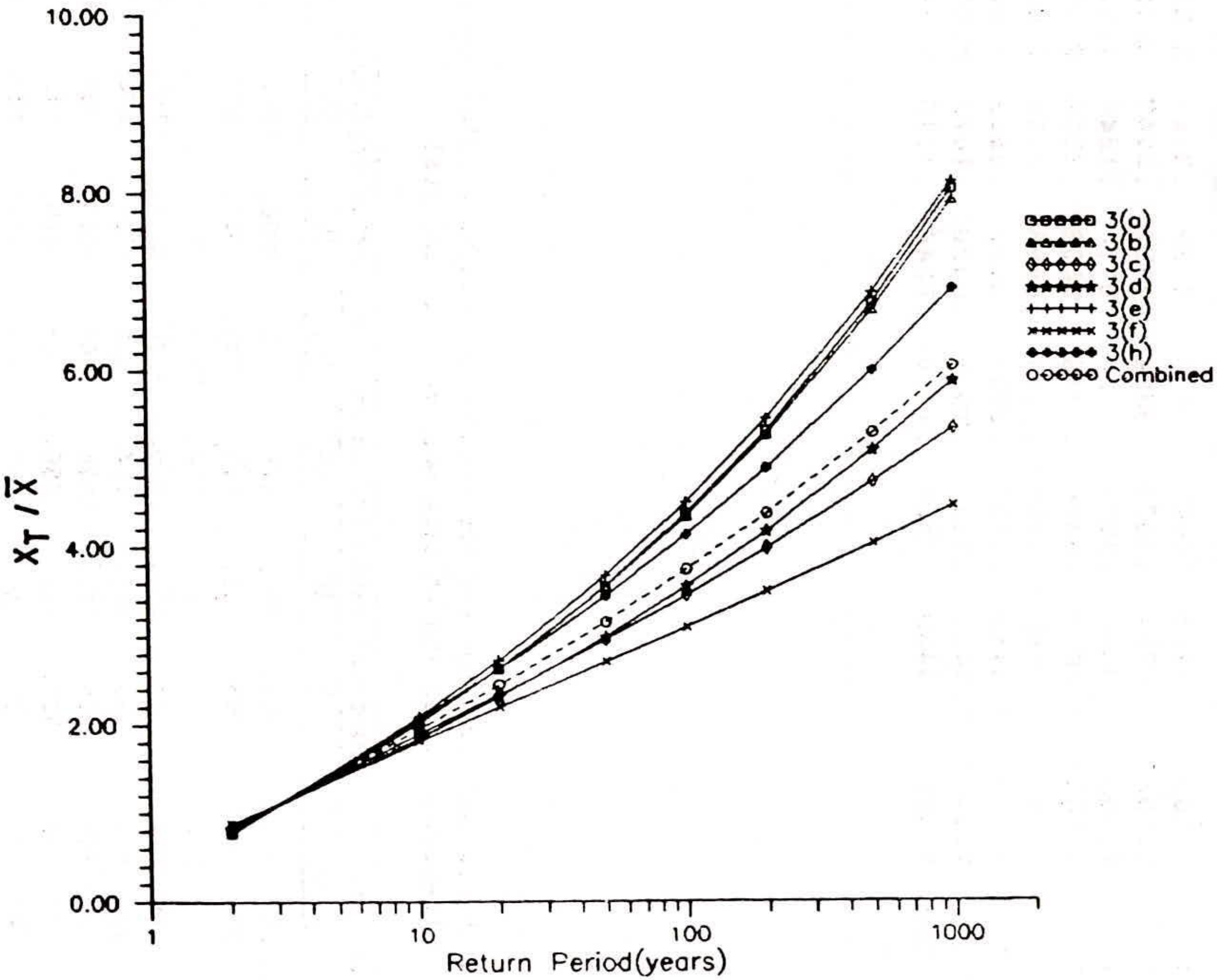

FIG: **2** Variation of $X_T / \overline{X}$ with return period

Table 7 - Statistics of GEV reduced variate

Sub-zone	$\bar{y}$	y_{med}	y_{mod}	σ_y	σ_y^2	CV_y	g_y
3(a)	1.1642	1.0761	.9642	.3657	.1338	.3141	3.5350
3(b)	1.1532	1.0721	.9675	.3394	.1152	.2943	3.2842
3(c)	1.0607	1.0335	.9923	.1320	.0174	.1244	1.8125
3(d)	1.1031	1.0527	.9818	.2249	.0506	.2039	2.3849
3(e)	1.1425	1.0682	.9706	.3144	.0988	.2752	3.0631
3(f)	1.0247	1.0148	.9984	.0542	.0029	.0529	1.3999
3(h)	1.0941	1.0488	.9842	.2049	.0420	.1872	2.2519
Combined zone 3	1.0853	1.0450	.9865	.1856	.0344	.1710	2.1292

Table- 8·1 Flood estimates for various recurrence intervals using regional frequency curves and at site mean for Sub-Zone 3(a)

S.No.	Br. No.	Flood estimates for various recurrence intervals							
		2	10	20	50	100	200	500	1000
1	192/253	148.	383.	498.	675.	830.	1008.	1282.	1526.
2	281/334	59.	153.	199.	269.	331.	401.	511.	608.
3	5	275.	712.	927.	1255.	1543.	1874.	2385.	2838.
4	99	201.	521.	678.	918.	1130.	1371.	1745.	2077.
5	945	165.	428.	557.	754.	928.	1126.	1434.	1706.
6	26	349.	905.	1179.	1596.	1963.	2383.	3033.	3610.
7	11	128.	332.	433.	586.	721.	875.	1113.	1325.
8	141	85.	220.	286.	388.	477.	579.	737.	876.
9	8	58.	149.	194.	263.	324.	393.	500.	595.
10	46	275.	712.	927.	1256.	1544.	1875.	2386.	2840.

Table-8.2: Flood estimates for various recurrence intervals using regional frquency curves and at site mean for Subzone 3(b)

S.No.	Br. No.	Flood estimates for various recurrence intervals							
		2	10	20	50	100	200	500	1000
1.	105	174.9	452.9	588.4	793.8	973.5	1178.0	1492.8	1770.0
2.	502/3	183.0	473.8	615.6	830.5	1018.4	1232.4	1561.7	1851.7
3.	200	27.3	70.7	91.9	124.0	152.0	184.0	233.1	276.4
4.	162	54.1	140.2	182.1	245.7	301.3	364.6	462.0	547.8
5.	21(DEV)	384.9	996.6	1294.8	1746.8	2142.2	2592.2	3284.9	3895.0
6.	701	186.8	483.6	628.3	847.6	1039.5	1257.9	1594.0	1890.0
7.	374/1	247.1	639.6	830.9	1121.1	1374.8	1663.6	2108.2	2499.7
8.	497/1	60.7	157.1	204.1	275.4	337.7	408.7	517.9	614.1
9.	21(KIM)	470.0	1216.9	1581.0	2133.0	2615.8	3165.2	4011.1	4756.0
10.	50	275.2	712.4	925.5	1248.6	1531.2	1852.9	2348.8	2784.1
11.	666	285.4	738.9	960.0	1295.1	1588.3	1921.8	2435.4	2887.7
12.	411/1	436.3	1129.7	1467.7	1980.0	2428.2	2938.3	3723.4	4415.0
13.	485/4	194.1	502.5	652.8	880.7	1080.1	1307.0	1656.2	1963.9
14.	53	214.9	556.3	722.7	975.0	1195.7	1446.9	1833.5	2174.1
15.	561	326.3	844.9	1097.7	1480.8	1816.1	2197.5	2784.7	3302.0
16.	293/1	326.0	844.1	1096.6	1479.5	1814.4	2195.5	2782.2	3298.9
17.	476/1	215.0	556.6	723.1	975.6	1196.4	1447.7	1834.5	2175.3
18.	110	91.2	236.0	306.7	413.7	507.4	614.0	778.0	922.5
19.	361/2	190.7	493.8	641.6	865.6	1061.5	1284.5	1627.7	1930.0

Table-8·3 Flood estimates for various recurrence intervals using regional frquency curves and at site mean for subzone 3(c)

S.No.	Br. No.	Flood estimates for various recurrence intervals							
		2	10	20	50	100	200	500	1000
1	731/6	216.	480.	593.	750.	876.	1010.	1200.	1353.
2	294	784.	1745.	2156.	2727.	3187.	3674.	4363.	4921.
3	897/1	730.	1625.	2008.	2540.	2968.	3421.	4063.	4583.
4	634/2	324.	721.	891.	1127.	1317.	1518.	1803.	2034.
5	813/1	181.	402.	496.	628.	734.	846.	1005.	1133.
6	863/1	1438.	3201.	3955.	5004.	5847.	6740.	8004.	9029.
7	253	185.	412.	508.	643.	752.	866.	1029.	1161.
8	584/1	212.	472.	583.	738.	862.	994.	1180.	1331.
9	512/3	187.	417.	516.	652.	762.	879.	1043.	1177.
10	710/1	95.	212.	262.	332.	388.	447.	531.	599.
11	776/1	488.	1087.	1343.	1699.	1985.	2288.	2717.	3065.
12	625/1	1475.	3283.	4057.	5132.	5997.	6913.	8210.	9260.
13	787/2	692.	1540.	1903.	2407.	2813.	3243.	3851.	4344.
14	831/1	178.	397.	490.	620.	725.	836.	992.	1119.
15	644/1	466.	1036.	1281.	1620.	1893.	2182.	2591.	2923.

Table- 8·4 Flood estimates for various recurrence intervals using regional frequency curves and at site mean for Sub-Zone 3(e)

S.No.	Br. No.	Flood estimates for various recurrence intervals							
		2	10	20	50	100	200	500	1000
1	139	126.	342.	446.	602.	738.	891.	1126.	1331.
2	51	52.	141.	184.	248.	304.	367.	464.	548.
3	234	671.	1818.	2371.	3203.	3925.	4742.	5990.	7082.
4	346	157.	426.	556.	751.	920.	1112.	1404.	1660.
5	295	70.	190.	248.	335.	410.	496.	626.	741.
6	55	51.	139.	181.	244.	299.	362.	457.	540.
7	368	159.	432.	563.	760.	932.	1126.	1422.	1681.
8	66	104.	282.	367.	496.	608.	734.	928.	1097.
9	44	166.	449.	586.	791.	970.	1171.	1480.	1749.
10	289	204.	552.	720.	972.	1192.	1440.	1819.	2150.
11	79	46.	126.	164.	222.	272.	328.	415.	490.
12	76	537.	1455.	1897.	2563.	3141.	3795.	4794.	5667.

Table-8·5 Flood estimates for various recurrence intervals using regional frequency curves and at site mean for Sub-Zone 3(f)

S.No.	Br. No.	Flood estimates for various recurrence intervals							
		2	10	20	50	100	200	500	1000
1	184	304.	627.	757.	931.	1066.	1204.	1392.	1538.
2	57	167.	345.	416.	512.	586.	662.	765.	846.
3	59TT	80.	165.	200.	246.	281.	317.	367.	406.
4	973/1	446.	920.	1110.	1365.	1563.	1765.	2040.	2255.
5	912/1	357.	737.	890.	1094.	1253.	1415.	1635.	1808.
6	20	181.	373.	450.	553.	633.	715.	827.	914.
7	214	69.	142.	171.	210.	241.	272.	314.	347.
8	51	182.	376.	454.	559.	639.	722.	835.	923.
9	807/1	1070.	2208.	2666.	3279.	3753.	4238.	4899.	5415.
10	228	949.	1958.	2364.	2907.	3327.	3757.	4343.	4801.
11	15	754.	1557.	1879.	2311.	2645.	2987.	3453.	3817.
12	969/1	459.	947.	1143.	1406.	1609.	1817.	2100.	2321.
13	881/1	272.	560.	677.	832.	952.	1075.	1243.	1374.
14	161	83.	171.	206.	254.	290.	328.	379.	419.
15	36	151.	311.	375.	462.	528.	597.	690.	763.
16	224	607.	1252.	1511.	1858.	2127.	2402.	2777.	3069.
17	65	640.	1320.	1594.	1960.	2244.	2534.	2929.	3238.
18	4	210.	433.	523.	643.	736.	832.	961.	1062.
19	875/1	687.	1417.	1711.	2103.	2407.	2719.	3143.	3474.

Table-8.6 Flood estimates for various recurrence intervals using regional frequency curves and at site mean for Sub-Zone 3(h)

S.No.	Br. No.	Flood estimates for various recurrence intervals							
		2	10	20	50	100	200	500	1000
1	642	328.	584.	745.	978.	1172.	1385.	1697.	1959.
2	16	53.	135.	173.	227.	272.	321.	393.	454.
3	53(i)	63.	162.	206.	271.	325.	384.	470.	543.
4	378/3	72.	185.	236.	310.	371.	439.	537.	620.
5	53(ii)	639.	1637.	2089.	2742.	3287.	3883.	4758.	5493
6	215	36.	91.	116.	153.	183.	216.	265.	306.
7	215(GTL)	71.	181.	231.	304.	364.	430.	527.	608.
8	18	95.	242.	309.	406.	487.	575.	705.	814.
9	322	41.	105.	134.	176.	211.	249.	305.	352.
10	480/3	74.	190.	242.	318.	381.	451.	552.	637.
11	179	127.	325.	415.	545.	653.	771.	945.	1091.
12	449/3	143.	366.	467.	613.	734.	867.	1063.	1227.
13	601	225.	577.	736.	967.	1159.	1369.	1677.	1937.
14	313	356.	913.	1165.	1529.	1833.	2165.	2652.	3062.
15	66	23.	58.	74.	98.	117.	138.	169.	196.
16	98	101.	258.	329.	432.	518.	612.	750.	866.
17	123	90.	230.	293.	385.	461.	545.	667.	770.
18	63	324.	831.	1060.	1391.	1668.	1970.	2414.	2787.

7.4 Development of Regional Flood Formula

The form of regional flood formula developed by coupling the relationship, between catchment area and mean annual peak flood, together with regional flood frequency curves, developed based on the methodology discussed above is:

$$x_T = R_T\ A^b \tag{37}$$

$$R_T = [\beta+\gamma(-\ln(1-\frac{1}{T}))^K] \tag{38}$$

$$x_T = [\beta+\gamma(-\ln(1-\frac{1}{T}))^K]A^b \tag{39}$$

where, $\beta = a(\alpha/K+u)$, $\gamma = -\alpha\ a/K$, R_T is the regional coefficient for the developed flood formulae, and x_T is flood estimate for T year return period in cubic meter per second (Cumec), A is the catchment area in square kilometers, a and b are the regional coefficients for various subzones as given below.

Table 9 Regional coefficients of the flood formulae

Subzone	ß	γ	K	a	b
3(a)	-48.654	-63.199	-0.20	24.78	0.43
3(b)	-34.713	-43.984	-0.19	16.44	0.55
3(c)	-33.162	37.584	-0.09	6.62	0.78
3(d)	-9.512	12.080	-0.14	3.82	0.76
3(e)	-25.193	30.922	-0.18	10.18	0.57
3(f)	-55.063	58.569	-0.04	4.95	0.79
3(h)	-8.113	9.448	-0.13	2.25	0.77
Combined Zone 3	-24.928	29.158	-0.12	6.62	0.69

Substituting values of the regional coefficients mentioned in Table 9, the regional flood formulae for the various subzones are expressed as:

Subzone 3(a),	$x_T = [63.2(-\ln(1-\frac{1}{T}))^{-0.2} - 48.65]A^{0.43}$	(40)

Subzone 3(b),	$x_T = [44.0(-\ln(1-\frac{1}{T}))^{-0.19} - 34.3]A^{0.55}$	(41)

Subzone 3(c),	$x_T = [37.6(-\ln(1-\frac{1}{T}))^{-0.087} - 33.2]A^{0.78}$	(42)

Subzone 3(d),	$x_T = [12.08(-\ln(1-\frac{1}{T}))^{-0.14} - 9.51]A^{0.76}$	(43)

Subzone 3(e),	$x_T = [30.92(-\ln(1-\frac{1}{T}))^{-0.18} - 25.2]A^{0.57}$	(44)

Subzone 3(f),	$x_T = [58.57(-\ln(1-\frac{1}{T}))^{-0.04} - 55.1]A^{0.79}$	(45)

Subzone 3(h),	$x_T = [9.45(-\ln(1-\frac{1}{T}))^{-0.13} - 8.1]A^{0.77}$	(46)

(Here, x_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 Table 10.1 to 10.6 and the same are shown in Fig. 3.1 to 3.6.

Table 10·1 Variation of flood frequency estimates with catchment area for sub-zone 3(a)

S.No.	Catchment Area (Sq Km)	Return Period (Years)							
		2	10	20	50	100	200	500	1000
1	18.44	68.	175.	228.	309.	380.	461.	587.	698.
2	30.14	83.	216.	282.	381.	469.	570.	725.	863.
3	48.43	102.	265.	345.	468.	575.	698.	889.	1058.
4	73.19	122.	317.	413.	559.	687.	834.	1062.	1264.
5	98.16	139.	360.	468.	634.	780.	946.	1205.	1434.
6	144.50	164.	425.	553.	748.	921.	1118.	1423.	1693.
7	230.00	200.	518.	675.	914.	1124.	1365.	1737.	2067.
8	231.11	200.	520.	677.	916.	1127.	1368.	1741.	2072.
9	580.00	298.	772.	1005.	1361.	1674.	2032.	2586.	3077.
10	1094.00	391.	1014.	1320.	1787.	2199.	2669.	3397.	4043.

Table 10·2 Variation of flood frequency estimates with catchment area for sub-zone 3(b)

S.No.	Catchment Area (Sq Km)	Return Period (Years) 2	10	20	50	100	200	500	1000
1	17.22	62.	159.	207.	279.	342.	414.	525.	623.
2	18.90	65.	168.	218.	294.	360.	436.	553.	656.
3	27.18	79.	205.	266.	359.	440.	533.	675.	801.
4	28.23	81.	209.	272.	366.	449.	544.	689.	818.
5	53.09	114.	296.	384.	519.	636.	770.	976.	1157.
6	59.59	122.	315.	410.	553.	678.	820.	1040.	1233.
7	101.10	163.	422.	548.	739.	907.	1097.	1391.	1649.
8	103.26	165.	426.	554.	748.	917.	1110.	1407.	1668.
9	105.07	166.	431.	559.	755.	926.	1121.	1420.	1685.
10	193.73	233.	603.	783.	1057.	1296.	1569.	1989.	2358.
11	202.28	238.	617.	802.	1082.	1328.	1607.	2036.	2415.
12	225.84	253.	656.	852.	1150.	1410.	1707.	2164.	2566.
13	261.59	275.	711.	924.	1247.	1529.	1851.	2346.	2782.
14	284.90	288.	745.	968.	1307.	1603.	1940.	2459.	2916.
15	371.15	333.	862.	1120.	1511.	1854.	2243.	2843.	3372.
16	378.04	336.	871.	1131.	1527.	1873.	2266.	2872.	3406.
17	542.39	410.	1062.	1380.	1862.	2284.	2764.	3503.	4155.
18	828.00	518.	1340.	1741.	2350.	2882.	3488.	4421.	5243.
19	1017.94	580.	1501.	1951.	2632.	3229.	3907.	4953.	5874.

Table 10.3 Variation of flood frequency estimates with catchment area for sub-zone 3(c)

S.No.	Catchment Area (Sq Km)	Return Period (Years)							
		2	10	20	50	100	200	500	1000
1	41.80	104.	231.	285.	361.	421.	486.	577.	651.
2	53.68	126.	280.	346.	438.	512.	590.	701.	791.
3	70.18	155.	346.	427.	540.	631.	728.	864.	975.
4	114.22	227.	505.	624.	790.	923.	1064.	1263.	1425.
5	115.90	230.	511.	632.	799.	934.	1076.	1278.	1441.
6	139.08	265.	589.	728.	921.	1076.	1241.	1473.	1662.
7	142.97	271.	602.	744.	941.	1100.	1268.	1505.	1698.
8	179.90	324.	720.	890.	1126.	1316.	1516.	1801.	2031.
9	321.16	509.	1132.	1399.	1769.	2067.	2383.	2830.	3192.
10	341.88	534.	1189.	1468.	1858.	2171.	2502.	2971.	3351.
11	348.92	543.	1208.	1492.	1887.	2205.	2542.	3019.	3405.
12	518.67	739.	1645.	2033.	2571.	3005.	3463.	4113.	4639.
13	535.40	758.	1687.	2084.	2636.	3080.	3550.	4216.	4755.
14	989.89	1224.	2724.	3365.	4257.	4974.	5734.	6809.	7680.
15	2110.85	2210.	4917.	6075.	7685.	8980.	10350.	12291.	13864.

Table10·4 Variation of flood frequency estimates with catchment area for sub-zone 3(e)

S.No.	Catchment Area (Sq Km)	Return Period (Years)							
		2	10	20	50	100	200	500	1000
1	31.31	56.	152.	198.	267.	327.	395.	499.	589.
2	35.22	60.	162.	211.	285.	350.	422.	533.	630.
3	61.90	82.	223.	291.	393.	482.	582.	735.	869.
4	64.88	85.	230.	299.	404.	495.	598.	755.	893.
5	77.70	94.	254.	332.	448.	549.	663.	837.	989.
6	93.60	104.	283.	369.	498.	610.	737.	931.	1100.
7	136.75	130.	351.	458.	618.	757.	915.	1155.	1365.
8	152.33	138.	373.	487.	657.	806.	973.	1229.	1452.
9	157.55	140.	381.	496.	670.	821.	992.	1252.	1480.
10	458.00	258.	699.	912.	1231.	1509.	1822.	2301.	2720.
11	1197.76	446.	1209.	1577.	2130.	2609.	3152.	3980.	4704.
12	2227.39	635.	1722.	2246.	3033.	3716.	4489.	5669.	6700.

Table10·5 Variation of flood frequency estimates with catchment area for sub-zone 3(f)

S.No.	Catchment Area (Sq Km)	Return Period (Years)							
		2	10	20	50	100	200	500	1000
1	35.00	73.	150.	181.	222.	254.	287.	332.	367.
2	50.00	96.	198.	240.	295.	337.	381.	440.	487.
3	53.00	101.	208.	251.	309.	353.	399.	461.	510.
4	60.00	111.	229.	277.	340.	390.	440.	509.	562.
5	65.00	118.	244.	295.	363.	415.	469.	542.	599.
6	87.00	149.	307.	371.	456.	522.	590.	682.	754.
7	137.00	213.	440.	531.	653.	748.	845.	977.	1080.
8	139.00	216.	445.	537.	661.	756.	854.	988.	1092.
9	158.00	239.	492.	595.	731.	837.	945.	1093.	1208.
10	163.00	245.	505.	609.	749.	858.	969.	1120.	1239.
11	208.00	296.	612.	739.	909.	1040.	1175.	1358.	1502.
12	362.00	459.	948.	1145.	1408.	1611.	1820.	2104.	2326.
13	364.00	461.	952.	1150.	1414.	1618.	1828.	2114.	2336.
14	459.00	554.	1143.	1381.	1698.	1944.	2195.	2538.	2806.
15	483.00	577.	1190.	1437.	1768.	2024.	2286.	2643.	2921.
16	731.00	800.	1651.	1994.	2452.	2807.	3171.	3666.	4053.
17	750.00	816.	1685.	2035.	2503.	2865.	3236.	3741.	4136.
18	751.00	817.	1687.	2037.	2505.	2868.	3239.	3745.	4140.
19	824.00	879.	1815.	2192.	2696.	3086.	3486.	4030.	4455.

Table10.6 Variation of flood frequency estimates with catchment area for sub-zone 3(h)

S.No.	Catchment Area (Sq Km)	Return Period (Years)							
		2	10	20	50	100	200	500	1000
1	31.72	26.	66.	85.	111.	133.	157.	193.	223.
2	64.75	45.	115.	147.	193.	231.	273.	334.	386.
3	70.84	48.	123.	157.	206.	247.	292.	358.	414.
4	79.00	52.	134.	171.	224.	269.	318.	390.	450.
5	102.45	64.	164.	209.	274.	329.	388.	476.	550.
6	118.23	71.	183.	233.	306.	367.	434.	532.	614.
7	131.52	77.	198.	253.	332.	399.	471.	577.	666.
8	139.08	81.	207.	264.	347.	416.	492.	602.	696.
9	167.32	93.	239.	305.	400.	480.	567.	695.	802.
10	220.45	115.	295.	377.	495.	593.	701.	859.	992.
11	230.87	119.	306.	390.	513.	615.	726.	890.	1028.
12	251.17	127.	326.	417.	547.	656.	775.	950.	1097.
13	270.60	135.	346.	441.	579.	695.	821.	1006.	1161.
14	326.00	156.	399.	509.	669.	802.	947.	1161.	1341.
15	348.40	164.	420.	536.	704.	844.	997.	1222.	1411.
16	398.60	182.	466.	595.	781.	936.	1106.	1355.	1565.
17	1357.15	467.	1196.	1527.	2005.	2404.	2840.	3481.	4020.
18	1689.92	553.	1417.	1808.	2374.	2846.	3363.	4122.	4760.

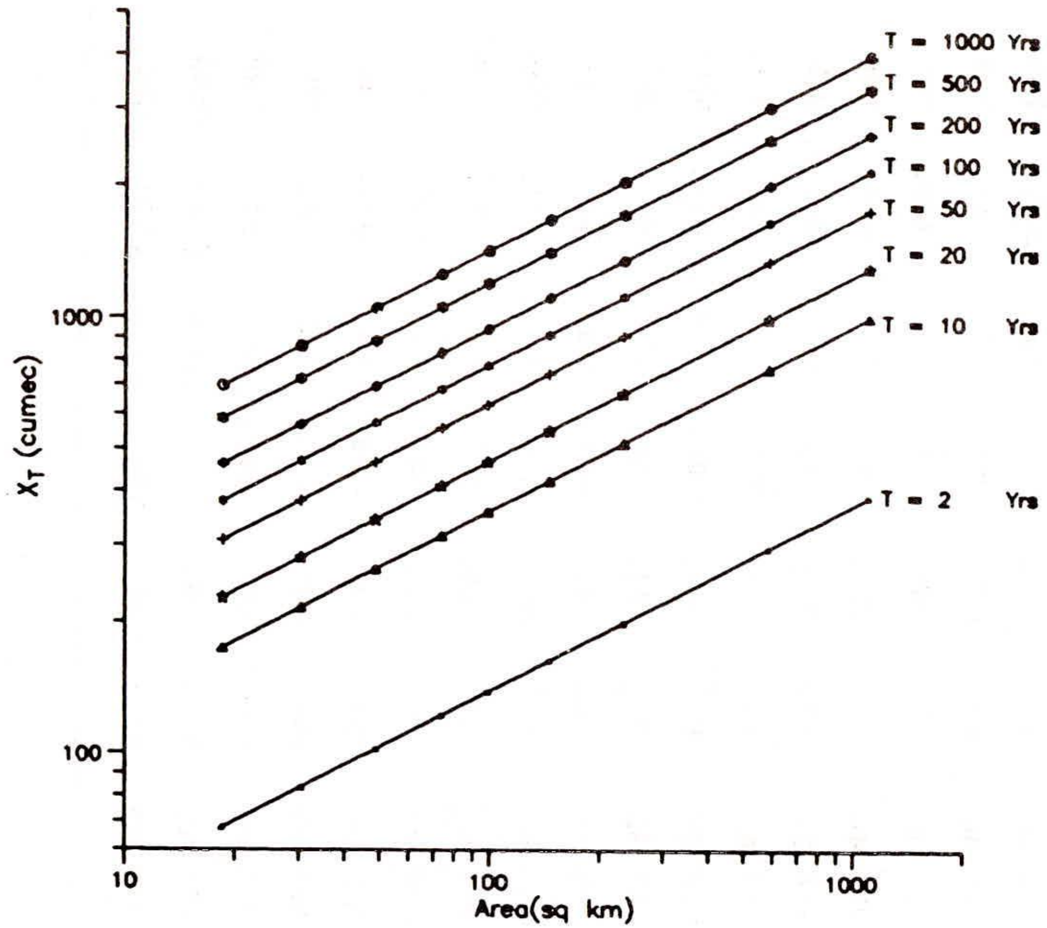

Fig.3·1 Variation of flood frequency estimates with catchment area for sub-zone 3(a)

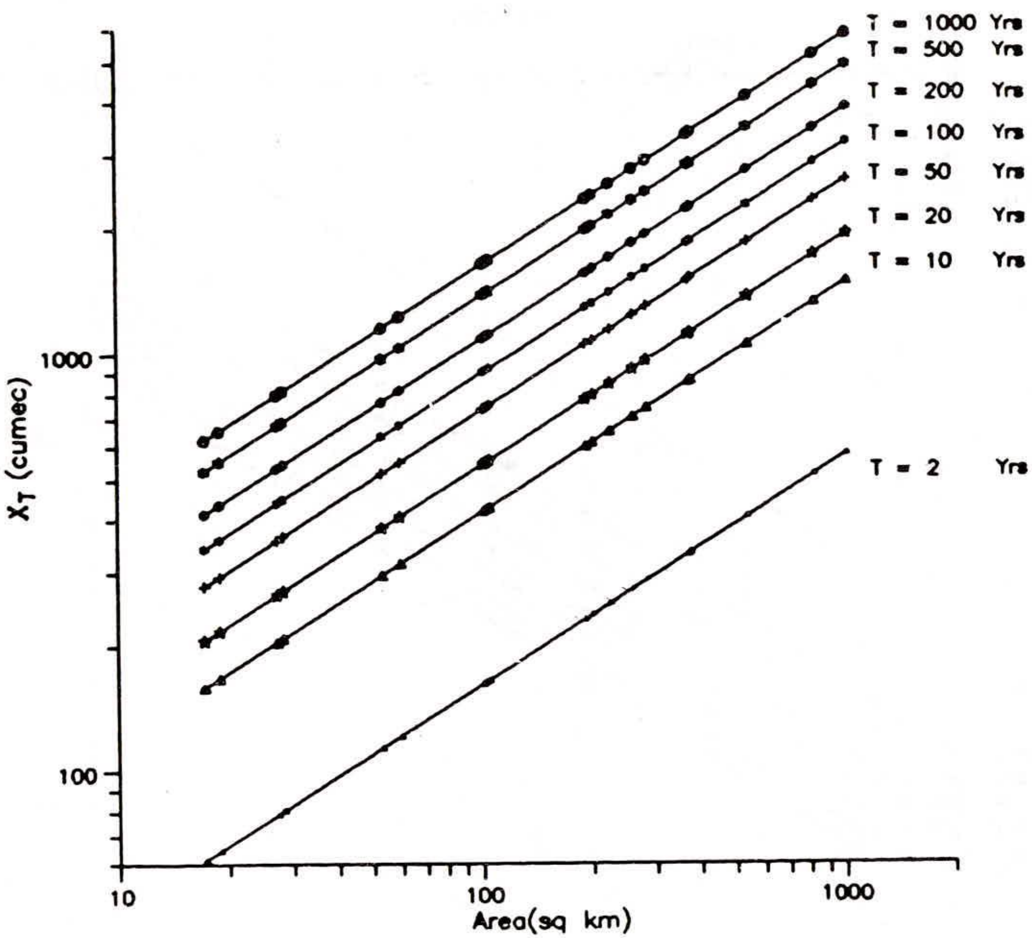

Fig.3·2 Variation of flood frequency estimates with catchment area for sub-zone 3(b)

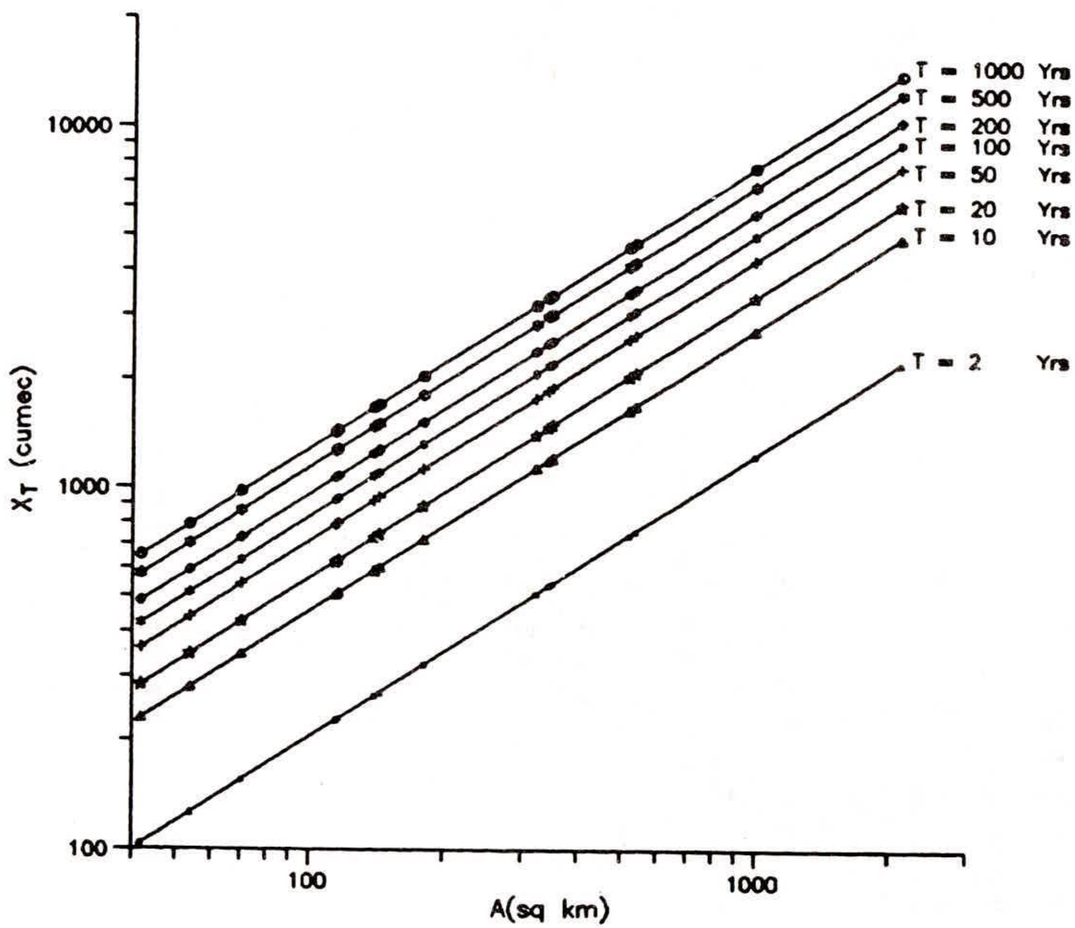

Fig.3·3 Variation of flood frequency estimates with catchment area for sub-zone 3(c)

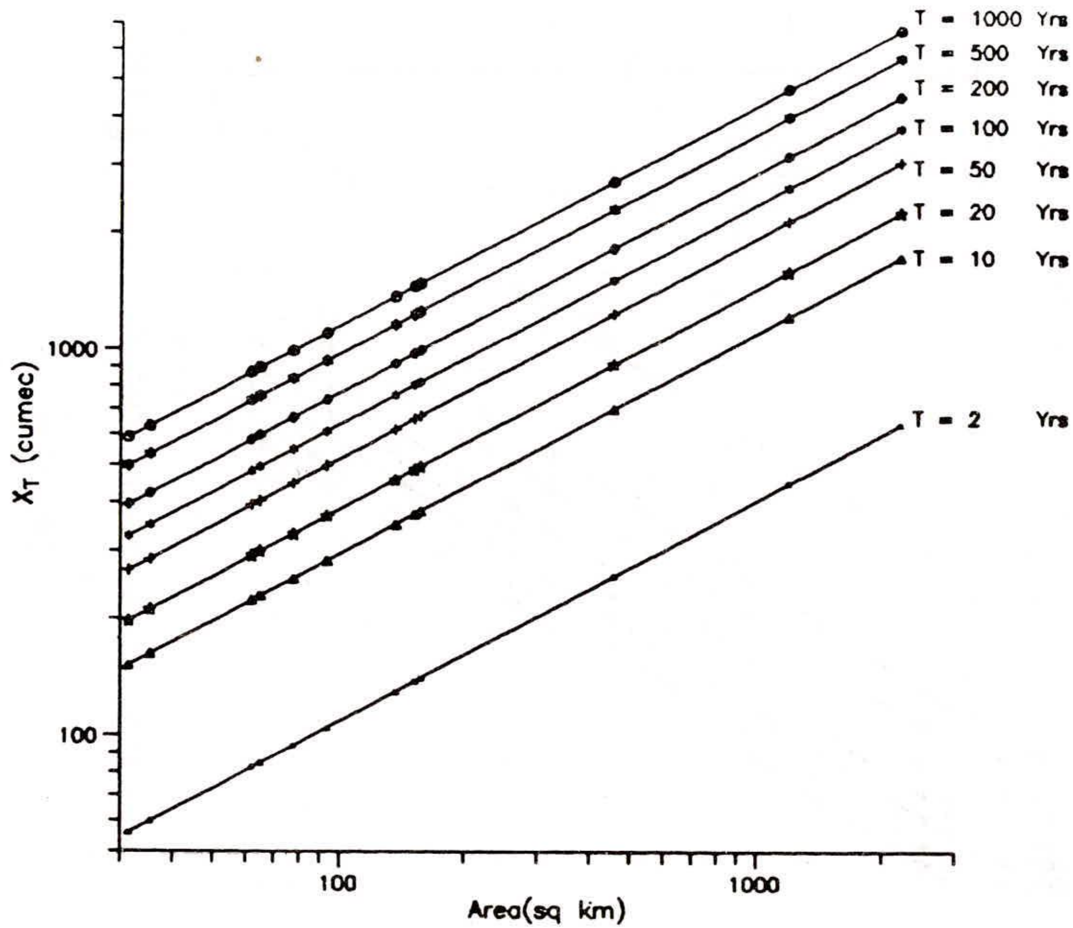

Fig.3·4 Variation of flood frequency estimates with catchment area for sub-zone 3(e)

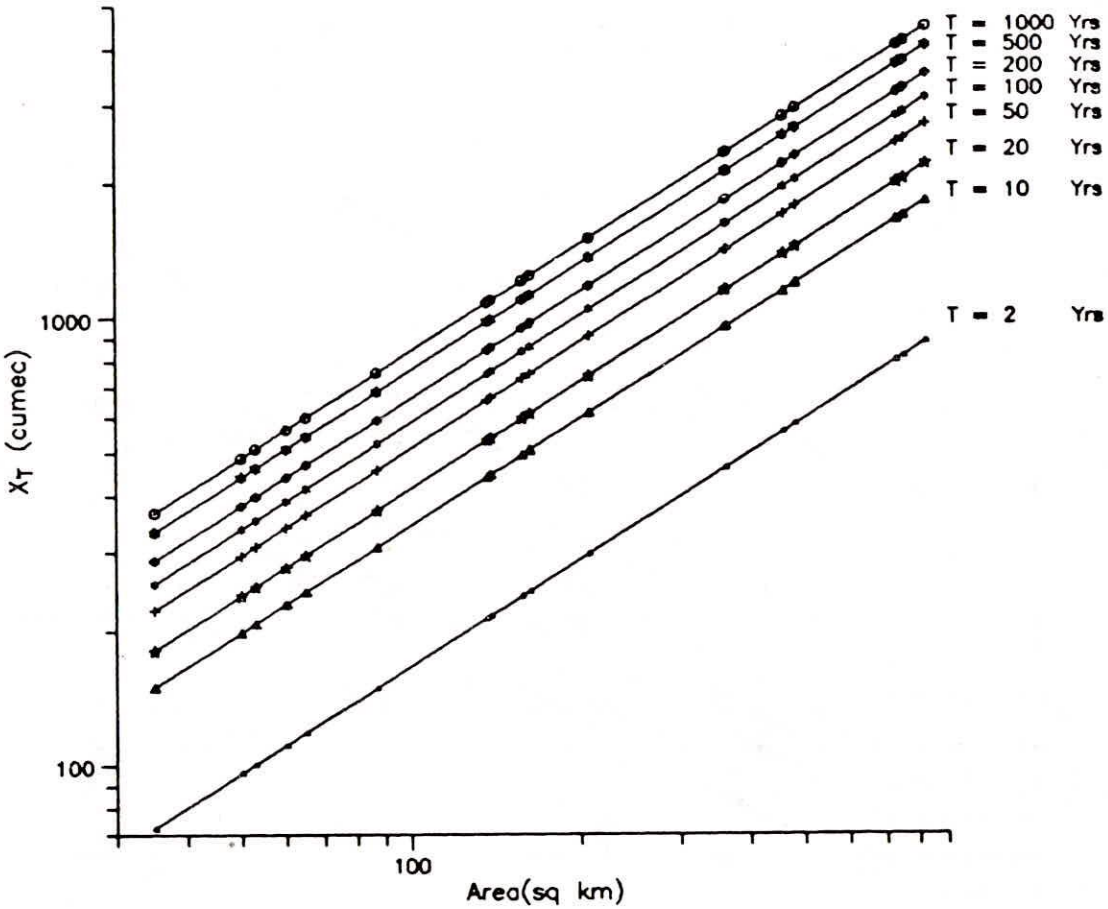

Fig.3·5 Variation of flood frequency estimates with catchment area for sub-zone 3(f)

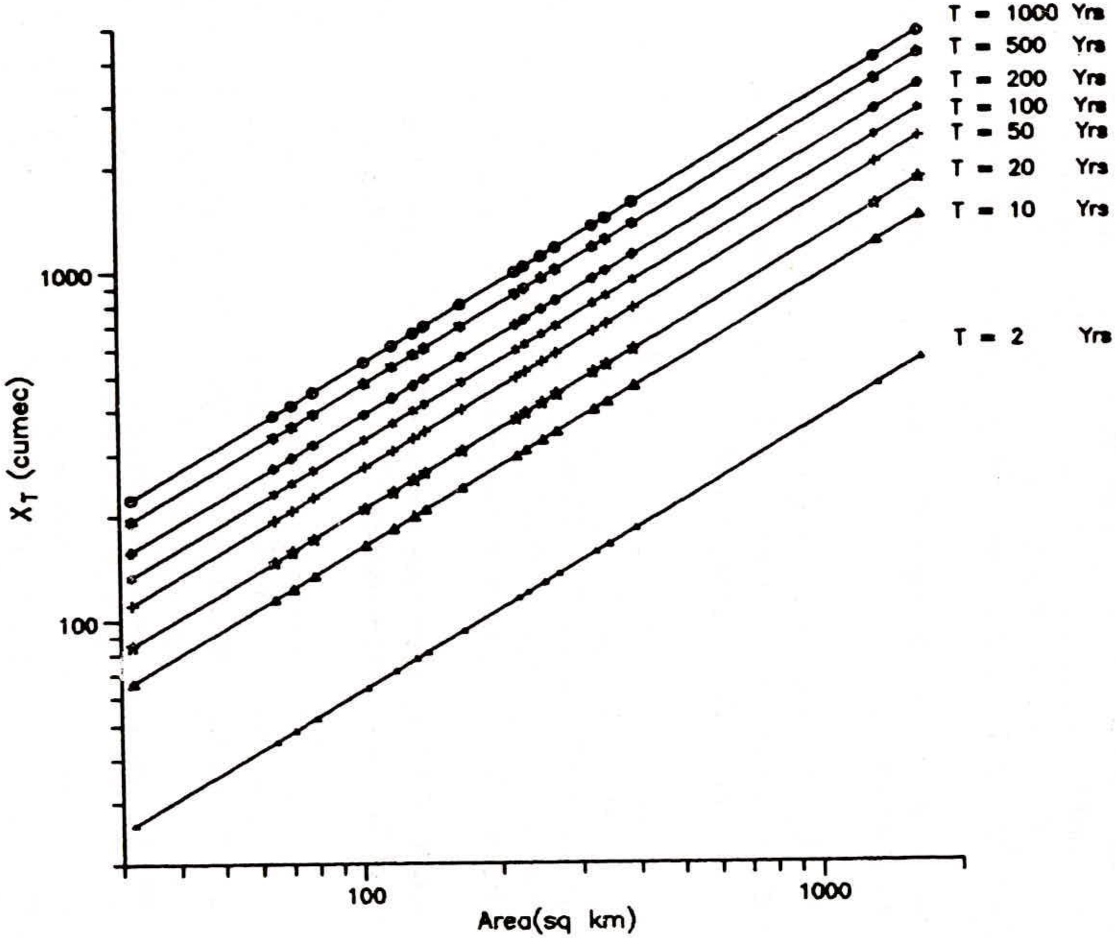

Fig.3·6 Variation of flood frequency estimates with catchment area for sub-zone 3(h)

For any catchment the ratios of flood frequency estimates (based on regional mean and at site mean) would be same as ratio between the respective regional mean and the at-site mean. It is seen from the Table 11 that the ratio of regional mean to at site mean is 0.91 for the test catchment of group 1 (bridge number 325; Area = 26 sq. km.) and 0.58 for the test catchment of group 2 (bridge number 489; Area = 823 sq. km.) for the subzone 3(d). It indicates that there is not much variability in the flood frequency estimates obtained by at-site mean and regional mean for the smaller catchment; whereas for the larger catchment there is a considerable variation in flood estimates obtained by using the at-site mean and the regional mean. The larger deviations in the flood estimates may be mainly attributed to the higher standard errors associated with the relationship between mean annual peak floods and catchment areas.

7.5 Representation of the Developed Regional Flood Formula in the Form of Dicken's formula

The developed regional flood formula may be represented in the form of the Dicken's formula using the procedure described in Section 6.7, and its revised coefficient C_T is expressed in Equation (34).

The revised Dicken's coefficients for the different catchments of the various subzones for different return periods are given in Table-12.1 to 12.6. It may be observed that the coefficient(C_T) of revised Dicken's formula is dependent on catchment area as well as return period, while the coefficient (R_T) used in the developed regional flood formula is dependent on return period only.

7.6 Comparison of Flood Estimates Computed by Regional Formulae of the Respective Subzones and Combined Formula for the Zone-3

In order to explore the possibility of using the combined regional flood formula developed by adopting the data of all the 7 subzones of the Zone-3; the floods of different return periods have been computed by the combined regional flood formula and compared with the flood frequency estimates obtained by the regional flood formulae of the respective subzones. Percentage deviations between the combined and regional values of $x_T/\bar{x}$ (growth factors) for the various subzones are given in Table-13. Fig. 4 also shows variation of percentage of deviations between $x_T/\bar{x}$ for combined Zone-3 and the respective subzones. It is observed that percent deviation between the flood estimates are quite significant for the various subzones except for the subzones 3(c) and 3(d). Hence, for estimation of floods of various return periods for the ungauged catchments for the various subzones of Zone-3, the regional flood formulae developed for the respective subzones should be used.

Table 11 - Catchment area(A), at site mean ($\bar{x}_{asm}$), regional mean($\bar{x}_{rm}$) and ratio of regional mean to at site mean ($\bar{x}_{asm}$)/($\bar{x}_{rm}$) for the various test catchments

Sub-zone	A (sq. km.)	$\bar{x}_{asm}$ (Cumec)	$\bar{x}_{rm}$ (Cumec)	$\bar{x}_{asm}/\bar{x}_{rm}$
Test catchments of group 1				
3(a)	30.14	74.00	107.18	1.45
3(b)	18.90	116.65	82.79	0.71
3(c)	53.68	209.17	147.95	0.71
3(d)	26.00	50.00	45.44	0.91
3(e)	35.22	60.13	77.52	1.29
3(f)	50.00	237.97	108.84	0.46
3(h)	64.75	111.48	55.83	0.50
Test catchments of group 2				
3(a)	580.00	352.95	382.27	1.08
3(b)	828.00	244.05	661.94	2.71
3(c)	989.89	546.25	1436.86	2.63
3(d)	823.00	1071.95	627.72	0.59
3(e)	1197.76	695.33	578.65	0.83
3(f)	751.00	778.10	925.47	1.19
3(h)	1357.15	403.37	581.17	1.44

Table-12.1 Revised Dicken's coefficients for Sub-Zone 3(a) for various return periods

S.No.	Catchment Area (Sq.Km.)	Revised Dicken's coefficients for various return periods							
		2 (Yrs)	10 (Yrs)	20 (Yrs)	50 (Yrs)	100 (Yrs)	200 (Yrs)	500 (Yrs)	1000 (Yrs)
1	42.	6.3	14.0	17.3	21.9	25.6	29.5	35.1	39.6
2	54.	6.4	14.1	17.5	22.1	25.8	29.8	35.4	39.9
1	18.	7.6	19.7	25.6	34.7	42.7	51.8	66.0	78.5
2	30.	6.5	16.8	21.9	29.7	36.5	44.3	56.4	67.1
3	48.	5.6	14.5	18.8	25.5	31.3	38.0	48.4	57.6
4	73.	4.9	12.7	16.5	22.3	27.5	33.3	42.4	50.5
5	98.	4.4	11.5	15.0	20.3	25.0	30.3	38.6	46.0
6	145.	3.9	10.2	13.3	18.0	22.1	26.8	34.1	40.6
7	230.	3.4	8.8	11.4	15.5	19.0	23.1	29.4	35.0
8	231.	3.4	8.8	11.4	15.5	19.0	23.1	29.4	35.0
9	580.	2.5	6.5	8.5	11.5	14.2	17.2	21.9	26.0
10	1094.	2.1	5.3	6.9	9.4	11.6	14.0	17.9	21.3

Table12·2: Revised Dicken's coefficients for Subzone 3(b) for various return periods

S.No.	Catchment Area (Sq.Km.)	Revised Dicken's coefficients for various return periods							
		2 (Yrs)	10 (Yrs)	20 (Yrs)	50 (Yrs)	100 (Yrs)	200 (Yrs)	500 (Yrs)	1000 (Yrs)
1.	17	7.3	18.9	24.5	33.1	40.6	49.2	62.3	73.9
2.	19	7.1	18.5	24.0	32.4	39.7	48.1	61.0	72.3
3.	27	6.7	17.2	22.4	30.2	37.0	44.8	56.8	67.4
4.	28	6.6	17.1	22.2	30.0	36.8	44.5	56.4	66.9
5.	53	5.8	15.0	19.6	26.4	32.4	39.2	49.6	58.9
6.	60	5.7	14.7	19.1	25.7	31.6	38.2	48.4	57.4
7.	101	5.1	13.2	17.2	23.2	28.4	34.4	43.6	51.8
8.	103	5.1	13.2	17.1	23.1	28.3	34.3	43.5	51.5
9.	105	5.1	13.1	17.1	23.0	28.2	34.2	43.3	51.4
10.	194	4.5	11.6	15.1	20.4	25.0	30.2	38.3	45.4
11.	202	4.4	11.5	15.0	20.2	24.8	30.0	38.0	45.1
12.	226	4.3	11.3	14.6	19.7	24.2	29.3	37.1	44.1
13.	262	4.2	10.9	14.2	19.2	23.5	28.5	36.1	42.8
14.	285	4.2	10.8	14.0	18.8	23.1	28.0	35.5	42.1
15.	371	3.9	10.2	13.3	17.9	21.9	26.5	33.6	39.9
16.	378	3.9	10.2	13.2	17.8	21.8	26.4	33.5	39.7
17.	542	3.7	9.5	12.3	16.6	20.3	24.6	31.2	37.0
18.	828	3.4	8.7	11.3	15.2	18.7	22.6	28.6	34.0
19.	1018	3.2	8.3	10.8	14.6	17.9	21.7	27.5	32.6

Table-12·3 Revised Dicken's coefficients for Sub Zone 3(c) for various return periods

S.Nc.	Catchment Area (Sq.Km.)	Revised Dicken's coefficients for various return periods							
		2 (Yrs)	10 (Yrs)	20 (Yrs)	50 (Yrs)	100 (Yrs)	200 (Yrs)	500 (Yrs)	1000 (Yrs)
1	42.	6.3	14.0	17.3	21.9	25.6	29.5	35.1	39.6
2	54.	6.4	14.1	17.5	22.1	25.8	29.8	35.4	39.9
3	70.	6.4	14.3	17.6	22.3	26.0	30.0	35.6	40.2
4	114.	6.5	14.5	17.9	22.6	26.4	30.5	36.2	40.8
5	116.	6.5	14.5	17.9	22.6	26.4	30.5	36.2	40.8
6	139.	6.5	14.6	18.0	22.7	26.6	30.6	36.4	41.0
7	143.	6.5	14.6	18.0	22.8	26.6	30.7	36.4	41.1
8	180.	6.6	14.7	18.1	22.9	26.8	30.9	36.7	41.3
9	321.	6.7	14.9	18.4	23.3	27.3	31.4	37.3	42.1
10	342.	6.7	14.9	18.5	23.4	27.3	31.5	37.4	42.2
11	349.	6.7	15.0	18.5	23.4	27.3	31.5	37.4	42.2
12	519.	6.8	15.1	18.7	23.7	27.6	31.9	37.8	42.7
13	535.	6.8	15.2	18.7	23.7	27.7	31.9	37.9	42.7
14	990.	6.9	15.4	19.1	24.1	28.2	32.5	38.6	43.5
15	2111.	7.1	15.8	19.5	24.7	28.8	33.2	39.5	44.5

Table-12·4 Revised Dicken's coefficients for Sub-Zone 3(e) for various return periods

S.No.	Catchment Area (Sq.Km.)	Revised Dicken's coefficients for various return periods							
		2 (Yrs)	10 (Yrs)	20 (Yrs)	50 (Yrs)	100 (Yrs)	200 (Yrs)	500 (Yrs)	1000 (Yrs)
1	31.	4.2	11.4	14.9	20.2	24.7	29.8	37.7	44.5
2	35.	4.1	11.2	14.6	19.7	24.2	29.2	36.9	43.6
3	62.	3.7	10.1	13.2	17.8	21.8	26.4	33.3	39.4
4	65.	3.7	10.0	13.1	17.7	21.7	26.2	33.0	39.1
5	78.	3.6	9.7	12.7	17.1	21.0	25.3	32.0	37.8
6	94.	3.5	9.4	12.3	16.6	20.3	24.5	30.9	36.6
7	137.	3.2	8.8	11.4	15.5	18.9	22.9	28.9	34.1
8	152.	3.2	8.6	11.2	15.2	18.6	22.4	28.3	33.5
9	158.	3.2	8.6	11.2	15.1	18.5	22.3	28.2	33.3
10	458.	2.6	7.1	9.2	12.4	15.2	18.4	23.2	27.5
11	1198.	2.2	5.9	7.7	10.5	12.8	15.5	19.5	23.1
12	2227.	2.0	5.3	6.9	9.4	11.5	13.8	17.5	20.7

Table 12.5 Revised Dicken's coefficients for Sub-Zone 3(f) for various return periods

S.No.	Catchment Area (Sq.Km.)	Revised Dicken's coefficients for various return periods							
		2 (Yrs)	10 (Yrs)	20 (Yrs)	50 (Yrs)	100 (Yrs)	200 (Yrs)	500 (Yrs)	1000 (Yrs)
1	35.	5.0	10.4	12.6	15.4	17.7	20.0	23.1	25.5
2	50.	5.1	10.6	12.7	15.7	17.9	20.3	23.4	25.9
3	53.	5.1	10.6	12.8	15.7	18.0	20.3	23.5	26.0
4	60.	5.1	10.6	12.8	15.8	18.1	20.4	23.6	26.1
5	65.	5.2	10.7	12.9	15.8	18.1	20.5	23.7	26.2
6	87.	5.2	10.8	13.0	16.0	18.3	20.7	24.0	26.5
7	137.	5.3	11.0	13.3	16.3	18.7	21.1	24.4	27.0
8	139.	5.3	11.0	13.3	16.3	18.7	21.1	24.4	27.0
9	158.	5.4	11.0	13.3	16.4	18.8	21.2	24.5	27.1
10	163.	5.4	11.1	13.4	16.4	18.8	21.2	24.6	27.1
11	208.	5.4	11.2	13.5	16.6	19.0	21.4	24.8	27.4
12	362.	5.5	11.4	13.8	17.0	19.4	21.9	25.4	28.0
13	364.	5.5	11.4	13.8	17.0	19.4	21.9	25.4	28.0
14	459.	5.6	11.5	13.9	17.1	19.6	22.1	25.6	28.3
15	483.	5.6	11.6	14.0	17.2	19.6	22.2	25.7	28.4
16	731.	5.7	11.7	14.2	17.4	20.0	22.6	26.1	28.8
17	750.	5.7	11.8	14.2	17.5	20.0	22.6	26.1	28.9
18	751.	5.7	11.8	14.2	17.5	20.0	22.6	26.1	28.9
19	824.	5.7	11.8	14.3	17.5	20.1	22.7	26.2	29.0

Table·12·6 Revised Dicken's coefficients for Sub-Zone 3(h) for various return periods

S.No.	Catchment Area (Sq.Km.)	Revised Dicken's coefficients for various return periods							
		2 (Yrs)	10 (Yrs)	20 (Yrs)	50 (Yrs)	100 (Yrs)	200 (Yrs)	500 (Yrs)	1000 (Yrs)
1	32.	1.9	5.0	6.3	8.3	10.0	11.8	14.4	16.7
2	65.	2.0	5.0	6.4	8.4	10.1	12.0	14.6	16.9
3	71.	2.0	5.0	6.4	8.5	10.1	12.0	14.7	16.9
4	79.	2.0	5.1	6.5	8.5	10.2	12.0	14.7	17.0
5	102.	2.0	5.1	6.5	8.5	10.2	12.1	14.8	17.1
6	118.	2.0	5.1	6.5	8.5	10.2	12.1	14.8	17.1
7	132.	2.0	5.1	6.5	8.6	10.3	12.1	14.9	17.2
8	139.	2.0	5.1	6.5	8.6	10.3	12.1	14.9	17.2
9	167.	2.0	5.1	6.5	8.6	10.3	12.2	14.9	17.2
10	220.	2.0	5.2	6.6	8.6	10.4	12.2	15.0	17.3
11	231.	2.0	5.2	6.6	8.7	10.4	12.3	15.0	17.4
12	251.	2.0	5.2	6.6	8.7	10.4	12.3	15.1	17.4
13	271.	2.0	5.2	6.6	8.7	10.4	12.3	15.1	17.4
14	326.	2.0	5.2	6.6	8.7	10.4	12.3	15.1	17.5
15	348.	2.0	5.2	6.6	8.7	10.5	12.4	15.2	17.5
16	399.	2.0	5.2	6.7	8.8	10.5	12.4	15.2	17.5
17	1357.	2.1	5.4	6.8	9.0	10.8	12.7	15.6	18.0
18	1690.	2.1	5.4	6.9	9.0	10.8	12.8	15.6	18.1

Table 13 Percent deviation between $X_T/\overline{X}$ values for various sub- zones with respect to combined zone 3.

S.NO.	Return Period (Years)	Zone - 3 Combined $X_T/\overline{X}$	Sub - Zone 3(a) $X_T/\overline{X}$	3(a) % Dev.	3(b) $X_T/\overline{X}$	3(b) % Dev.	3(c) $X_T/\overline{X}$	3(c) % Dev.	3(d) $X_T/\overline{X}$	3(d) % Dev.	3(e) $X_T/\overline{X}$	3(e) % Dev.	3(f) $X_T/\overline{X}$	3(f) % Dev.	3(h) $X_T/\overline{X}$	3(h) % Dev.
1.	2	0.8303	0.7790	-6.59	0.7820	-6.17	0.8520	2.55	0.8388	-1.01	0.7714	-7.64	0.8826	5.93	0.8040	-3.27
2.	10	1.9530	2.0188	3.26	2.0246	3.54	1.8960	-3.00	1.8522	-5.44	2.0908	6.59	1.8218	-7.20	2.0605	5.22
3.	20	2.4510	2.6288	6.76	2.6307	6.83	2.3423	-4.64	2.3162	-5.82	2.7262	10.09	2.1998	-11.42	2.6301	6.81
4.	50	3.1607	3.5592	11.12	3.5497	10.96	2.9631	-6.67	2.9913	-5.66	3.6818	14.15	2.7054	-16.83	3.4532	8.47
5.	100	3.7450	4.3780	14.46	4.3539	13.98	3.4625	-8.16	3.5586	-5.24	4.5113	16.98	3.0969	-20.93	4.1404	9.55
6.	200	4.3763	5.3145	17.65	5.2692	16.95	3.9911	-9.65	4.1822	-4.64	5.4489	19.68	3.4980	-25.11	4.8916	10.53
7.	500	5.2910	6.7649	21.78	6.6787	20.78	4.7393	-11.64	5.1043	-3.66	6.8809	23.11	4.0445	-30.82	5.9953	11.75
8.	1000	6.0499	8.0499	24.85	7.9206	23.62	5.3458	-13.17	5.8848	-2.81	8.1326	25.61	4.4711	-35.31	6.9235	12.62

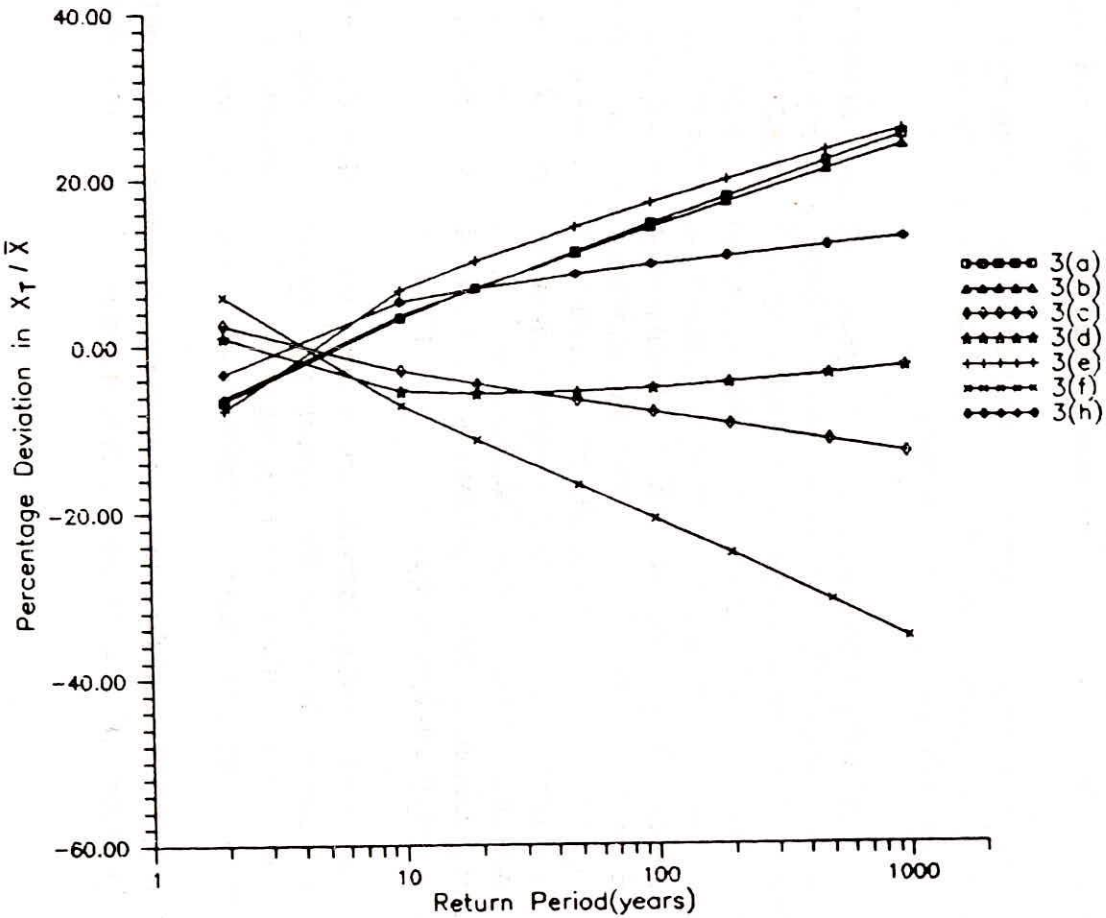

Fig 4 Variation of percent deviation between combined and regional values of $X_T / \overline{X}$ with return period

8.0 CONCLUSIONS

On basis of this study the following conclusions are drawn:

(i) Regional flood frequency curves are developed by fitting PWM based EV1, GEV and Wakeby distributions to the station year data of $x/\bar{x}$ values for the various subzones. At site and regional methods SRGEV and SRWAKE have been identified as suitable methods for estimation of floods of various return periods.

(ii) Whenever, at site mean annual peak flood estimates are available for catchments of various subzones, the developed regional flood frequency curves together with at-site mean may be used for estimation of floods for different return periods.

(ii) In case of ungauged catchments, more rational flood estimates of various return periods may be obtained using the developed regional formulae than those obtained from the conventional empirical formulae.

(iii) The relationship between mean annual peak flood and catchment area as only physiographic characteristic has been developed, because other phisiographic as well as climatic characteristics were not available. Since the standard error for such a relationship is very high; therefore, the values of regional mean annual peak flood are subject to these errors and the developed formulae have limited scope because of higher standard error associated with the estimation of regional mean annual peak flood. However, if the physiographic characteristics other than area as well as climatological characteristics of all the catchments could have been considered, it would have further improved the developed regional flood formulae. Also the data of the catchments of various sizes could have been categorized in different groups viz. large and small catchment area groups based on some objective criteria, if the data for large number of catchments would have been available.

(iv) Similar regional flood formulae are required to be developed for other regions of India to discourage the use of the conventional empirical formulae such as Dicken's, Ryve's and Inglis formulae by the field engineers as these formulae are not capable of providing the rational estimates of floods for desired return periods.

(v) The regional flood frequency relationships as well as flood formulae may be further improved when additional annual maximum peak flood data become available.

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APPENDIX-I

A-1: ADF, EFF, and SE values for subzone 3(a)

Method	Bridge No. 99			Bridge No. 11		
	ADF	EFF	SE	ADF	EFF	SE
EV1	16	93	46	30	86	55
GEV	12	89	57	9	10	15
WAKE	6	94	42	8	10	17
SREV1-I	23	92	49	32	87	54
SREV1-II	22	89	59	32	87	54
SRGEV	15	76	85	20	95	33
SRWAKE	13	81	75	21	93	38

A-2: ADF, EFF, and SE values for subzone 3(b)

	Bridge No. 50			Bridge No. 502/3		
Method	ADF	EFF	SE	ADF	EFF	SE
EV1	38	88	122	14	94	36
GEV	15	97	62	12	90	47
WAKE	11	83	144	13	94	37
SREV1-I	36	83	142	36	86	56
SREV1-II	31	86	128	29	85	57
SRGEV	20	94	88	19	72	78
SRWAKE	13	81	114	19	83	61

A-3: ADF, EFF, and SE values for subzone 3(d)

	Bridge No. 59BSP			Bridge No. 66K		
Method	ADF	EFF	SE	ADF	EFF	SE
EV1	34	97	28	27	89	66
GEV	28	97	27	10	82	85
WAKE	27	98	21	11	87	72
SREV1-I	21	91	44	24	86	74
SREV1-II	18	95	34	24	88	68
SRGEV	33	97	24	18	90	63
SRWAKE	37	98	23	18	91	60

A-4: ADF, EFF, and SE values for subzone 3(e)

	Bridge No. 368			Bridge No. 139		
Method	ADF	EFF	SE	ADF	EFF	SE
EV1	27	94	33	16	99	13
GEV	36	97	23	11	98	17
WAKE	11	98	19	7	98	15
SREV1-I	30	96	26	19	99	13
SREV1-II	51	86	51	37	94	28
SRGEV	29	70	75	23	86	43
SRWAKE	16	81	60	19	92	32

A-5: ADF, EFF, and SE values for subzone 3(h)

	Bridge No. 313			Bridge No. 215		
Method	ADF	EFF	SE	ADF	EFF	SE
EV1	21	93	84	85	97	7
GEV	13	90	101	33	96	8
WAKE	9	94	82	15	98	6
SREV1-I	26	91	95	61	93	8
SREV1-II	26	91	96	63	94	8
SRGEV	20	90	104	37	98	6
SRWAKE	19	92	94	19	98	5

A-6: Percentage BIAS for Bridge No. 110 subzone 3(b)

	Return period in years							
Method	2	10	20	50	100	200	500	1000
EV1	11	1	-5	-13	-19	-25	-32	-37
SREV1-I	11	2	-5	-13	-19	-24	-32	-37
REV1-I	-3	-11	-16	-23	-29	-34	-40	-45
SREV1-II	11	0	-6	-14	-20	-26	-33	-38
REV1-II	-2	-12	-18	-25	-30	-35	-41	-46
GEV	0	-2	-2	-1	1	4	9	15
SRGEV	3	-1	-2	-5	-6	-8	-10	-11
RGEV	-10	-13	-15	-16	-18	-19	-21	-22
SRWAKE	2	1	-1	-5	-8	-11	-16	-20
RWAKE	-10	-12	-13	-16	-19	-22	-26	-29

A-7: Percentage CV for Bridge No. 110 of subzone 3(b)

	Return period in years							
Method	2	10	20	50	100	200	500	1000
EV1	23	25	24	23	22	20	19	17
SREV1-I	20	21	26	35	44	55	75	95
REV1-I	70	65	61	56	52	48	44	36
SREV1-II	23	21	20	18	17	16	14	13
REV1-II	71	64	60	54	51	47	43	39
GEV	0	-2	-2	-1	1	4	9	15
SRGEV	22	21	21	21	21	21	22	23
RGEV	66	63	62	61	60	59	58	58
SRWAKE	22	21	21	21	21	21	22	23
RWAKE	65	64	63	61	59	57	55	54

A-8: Percentage RMSE for Bridge No. 110 subzone 3(b)

	Return period in years							
Method	2	10	20	50	100	200	500	1000
EV1	25	25	25	26	29	32	37	41
SREV1-I	26	21	21	22	25	29	35	39
REV1-I	71	66	63	61	59	59	59	60
SREV1-II	26	21	21	23	26	30	36	40
REV1-II	71	65	62	60	59	59	59	61
GEV	20	21	26	34	44	55	76	96
SRGEV	22	21	21	21	22	23	24	25
RGEV	66	65	64	63	63	62	62	62
SRWAKE	22	21	21	21	22	24	27	30
RWAKE	66	65	65	63	62	62	61	61

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