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Flood Frequency Estimates for Sub-Himalayan Region By Regional Flood Frequency Approach

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Abstract

In this paper, flood frequency analysis has been carried out for Sub-Himalayan region (Zone-7) using peak flood series data of ten small and medium catchments varying in size from 6 sq.kms. to 2072 sq.kms. The study presented, involves application of Extreme Value Type-I, General Extreme Value and Wakeby distributions using (i) at site data (ii) at site and regional data combined and (iii) regional data alone. Statistical test based on U.S.G.S. method has been performed in order to test the homogeneity of the region. The data of eight sites are utilised for estimating the parameters, keeping the data of remaining two sites for the purpose of testing the methodology based on descriptive ability criteria. The predictive ability of the different methods considered in the study is also tested through Monte Carlo experiments; wherein synthetic flood series have been generated using the regional EV1, GEV and Wakeby parameters derived from the historical data. Generated data sets of specific record lengths (same as the record length of historical data for respective gauging sites) have been considered for the eight sites. For the two independent sites variable record lengths viz.1, 5, 10, 13 ,20, 30 and 40 one at a time, have been considered.

The above methodology has been applied to the generated data of different sample sizes for each population for the two independent gauging sites. Performance of different methods has been evaluated based on predictive ability criteria viz. bias, and root mean square error. It is seen that the methods based on EV1(PWM), GEV(PWM) and Wakeby (PWM) approaches using at site and regional data in combined form provide estimates of flood peaks with computationally less bias and comparable root mean square error for the two test catchments.

1.0 INTRODUCTION

Estimation of flood magnitudes and their frequencies have been engaging attention of the engineers the world over for planning and design of water resources projects, since time immemorial . Flood Frequency analysis procedures provide such information from the available limited historical flood records. The peak flood data used for frequency analysis should be of good quality ,random , homogeneous ,adequate,and the sample size should be such that the population parameters can be estimated from it.In 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 fitting distribution is selected on the basis of some chosen goodness of fit criteria.The floods of different recurrence intervals are computed using the estimated parameters of the best fit distribution ,based on those criteria.

There are various distributions and methods of parameter estimation available in the flood frequency analysis literature.Correct inference about the distributions which fit the peak flood series of a site is crucial in flood frequency analysis, as various distributions fitted to the same data result in different estimated values in the extrapolation range. There is no general agreement among the hydrologists as to which of the various theoretical distributions available should be used for modelling the peak flood series at a site. The reason being that the hydrologists try to infer about the population distribution from the sample data which is subjected to sampling variability. The conclusions arrived regarding the correct distribution based on the given sample data are influenced by the extent, the data satisfy the basic assumptions of flood frequency analysis and the techniques employed like the adjustment of data, presence of outliers, historical information etc., method of parameter estimation, distribution model used and goodness of fit test adopted.

The inference about the best fit distribution for a sample data observed at a site is made based on some goodness of fit criteria. In spite of a number of attempts no uniform goodness of fit criteria has been developed for selecting the best fit distribution,so far. As a result recommendations about different, design flood estimates for the same site depend upon the adopted goodness of fit criteria. In order to avoid such subjectivity, hydrologosts are always in search of a robust frequency distribution for fitting the peak flood series.Whenever ,peak flood data are available over adequate number of years the flood frequency analysis may be carried out by fitting frequency distributions to the at site records. However, the reliability of such analysis is somewhat limited for the catchments with short record lengths. Such a situation can be overcome by adopting regional flood frequency approach, based on at site and regional data For ungauged catchment ,it is not possible to carry out at site flood frequency analysis in absence of flow records.Regional flood frequency analysis based on regional data provides the flood frequency estimates for such catchments.

In India,regional flood frequency studies have been carried out using conventional methods such as USGS method,regression based methods and Chow's methods etc.,for some typical regions.Attempts have been made to study application of the new approaches in the studies conducted at some of the Indian research institutions and academic organizations(Seth,1984-85).Very few studies have been carried out to test comparative performance of the existing rationalization techniques.Lettenmaier and Potter(1985) and Lattenmaier et al.(1987) have conducted some studies ,wherein performance of various flood frequency methods were compared.

In present study, probability weighted moment based EV1, GEV and Wakeby distributions, which are simple and widely used distributions available in recent flood frequency analysis literature, have been considered to fit the annual peak flood series data of hydrometeorologically homogeneous Sub-Himalyan region. The analysis has been carried out with : (i) at site data, (ii) at site and regional data, and (iii) regional data alone without considering at site data. Descriptive ability of various methods is tested based on the three numerical measures of goodness of fit described in section 3.3. The performance of different methods including modified U.S.G.S. method has been compared.

In the second part of the study, Monte Carlo experiments have been conducted, wherein the regional parameters of EV1,GEV and Wakeby distributions are utilised for generating the respective populations at each gauging site including the two independent gauging sites. The computations are made with the generated data for an independent gauging site taking samples of different sizes viz. 1, 5, 10, 13, 20, 30 and 40 respectively. Similar computations are also repeated for the second independent gauging site . The predictive ability of various methods has been testes based on the numerical criteria such as bias and root mean square error computed from the generated samples of different sizes by considering 1000 replications .The results obtained from the two generated populations using the above mentioned procedures have been compared with an objective of selecting a robust method among various methods considered in the present study.

Study Area and Data Used

The study area comprises of small and medium catchments ranging in size from 6 sq. kms. to 2072 sq. kms. in the Sub-Himalyan region:Zone no.7.The Himalyan region upto its foot-hill,lying within the great arc passing through Madhopur near Dara Baba Nanak in the north east between $76^{\circ}$to 96° E longitude and 26° to 32° N lattitude has been grouped under this zone.The data collected by Indian railways for eleven bridge sites were available for the study(Venkatraman and Gupta,1986).The locations of the railwaw bridges considered in the study are shown in Fig.1. The record lengths vary from 13 to 20 years over the period of 1966 to 1985.The sample statistics computed from the available data are given in Table-1,along with respective catchment area and sample sizes.It is observed that coefficient of variation is unusually high for the data of bridge no.213.Hence,annual peak flood records of ten sites,excluding bridge no.213 have been used in the study.Out of ten gauging sites,data of eight gauging sites are used for the calibration of regional parameters, while data for the remaining two gauging sites are kept independent for the purpose of testing.

3.0 METHODOLOGY

Methods used in the study to carry out Flood Frequency Analysis involve the fitting of Extreme Value Type -I (EV1),General Extreme Value (GEV) and Wakeby distributions using (i) at site data ,(ii) at site and regional data and (iii) regional data alone.

(A) 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:

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

where, F(x) is the probability of non exceedence 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 different techniques for parameters estimation available in literature Method of probability weighted moments (PWM) is one of the most popular 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.

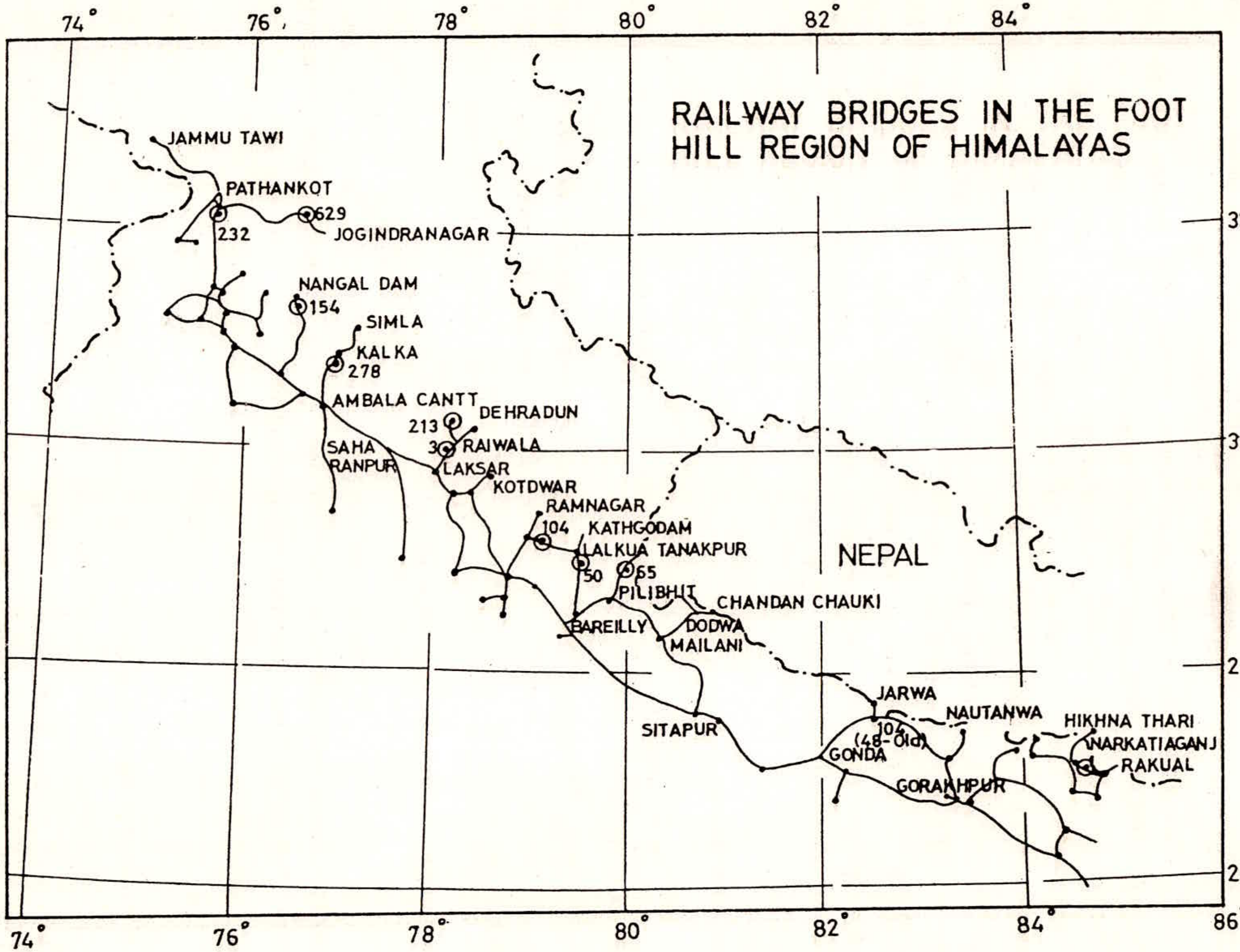

FIG.1 RAILWAY BRIDGES IN THE FOOT HILL REGION OF HIMALAYAS

The method of probability weighted moments is ,therefore used for estimating the EV1 distribution parameters.

(B) 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 Report (NERC,1975). The cummulative density function F(x) for GEV distribution is expressed as:

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

where u,α and κ are location, scale and shape parameters of GEV distribution respectively. For estimating these parameters , a procedure based on method of probability weighted moments (Singh,1989) is used in the study.

(C) Wakeby Distribution

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

$$x = m+a\,[1-(1-F)^{b}] - c\,[1-(1-F)^{-d}] \qquad (3)$$

where F = F(x) = 1-1/T

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.

3.1 Methods Used

Depending upon the amount and type of data available, ten methods have been used for the study. These are classified in three groups: (a) At Site Flood Frequency Methods,(b) At Site and regional Flood Frequency Methods, and (c) Regional Flood Frequency Methods without using at site data.

(a) At Site Flood Frequency Methods

(i) At Site EV1 PWM Method (EV1)

(ii) At Site GEV PWM Method (GEV)

(b) At Site and Regional Flood Frequency Methods

(iii) Flood Frequency analysis (FFA) using Modified U.S.G.S. Method based on at site and regional data (SREV1-I)

(iv) FFA Using EV1 PWM Method based on at site and regional data (SREV1-II)

(v) FFA Using GEV PWM Method based on at site and regional Data (SRGEV)

(vi) FFA using Wakeby PWM method based on at site and regional data (SRWAKE)

(c) Regional Flood Frequency Methods

(vii) FFA Using Modified U.S.G.S. Method bsed on regional data (REV1-I)

(viii)FFA using EV1 PWM Method based on regional data (REV1-II)

(ix) FFA Using GEV PWM Method based on regional Data (RGEV)

(X) FFA using Wakeby PWM method based on regional data (RWAKE)

3.2 Homogeneity Test

In regional frequency analysis, available historical peak flood data of different sites which belong to a hydrometeorologically homogeneous region are required to be grouped for estimating regional parameters. In this study the hydrometeorological homogeneity of the region was tested using the U.S.G.S. Homogeneity test as described by Singh(1989).The homogeneity test graph is shown in Fig.2.

3.3 Evaluation Criteria for Selecting a Suitable Frequency Analysis Method

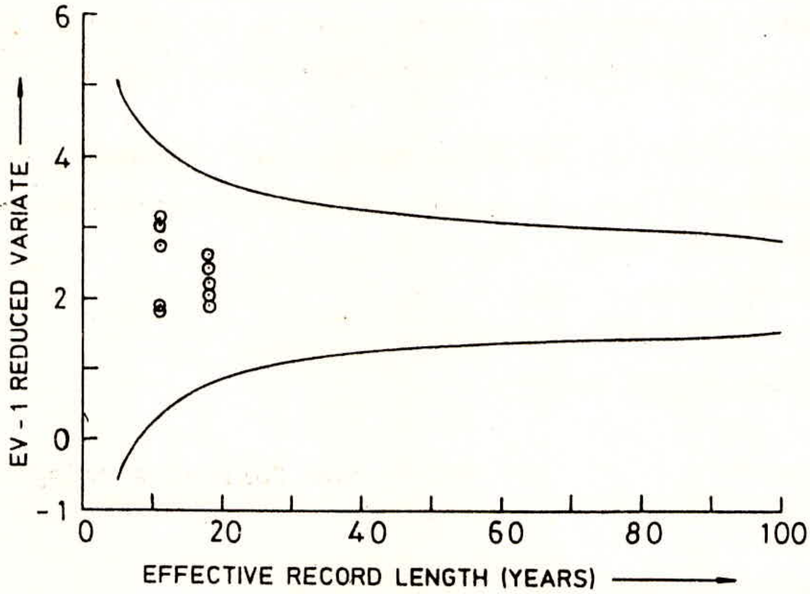

FIG : 2 HOMOGENEITY TEST GRAPH

Evaluation criteria for selecting an appropriate frequency analysis procedure can be divided in to two categories: i) Descriptive ability, and ii) Predictive ability

3.3.1 Descriptive ability

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

a) Average of the relative deviations between computed observed values of annual maximum discharge peak (ADF)

b) Efficiency (EFF)

c) Standard error (SE)

a) Computation of ADF Values:

For computation of ADF values the following relationship is used:

$$ADF = \frac{1}{n} \sum_{i=1}^{n} | QO_i - QC_i | / QO_i \qquad (4)$$

b) Computation of EFF values:

EFF values are computed using the relations :

$$EFF = (IV - MV)/IV \qquad (5)$$

$$\text{where, } IV = \sum_{i=1}^{n} (QO_i - \overline{Q})^2 \qquad (6)$$

$$MV = \sum_{i=1}^{n} (QO_i - QC_i)^2 \qquad (7)$$

$\overline{Q}$ = Mean of the observed peak discharge series, QO_i

QC_i = ith values of the computed peak discharge series

n = sample size

c) **Computation of SE values**

SE values are computed, in non dimensional form using the following relationship:

$$SE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (QRO_i - QRC_i)^2} \qquad (8)$$

here, $QRO_i = QO_i / \bar{Q}$

$QRC_i = QC_i / \bar{Q}$

3.3.2 **Predictive abili ty criteria:**

Predictive ability criteria relate to statistical ability of procedure to achieve its assigned task, with minimum bias and maximum efficiency and robustness. In the study the following two predictive ability criteria are used :

a) Bias(BIAS)
b) Root mean square Error (RMSE)

a) Bias

It is a measure which indicates the tendency to over estimate or under estimate a given event level corresponding to the population estimate. A positive Bias indicates the over estimation and a negative bias indicates the under estimation. Mathematically, it is expressed as :

$$BIAS = \frac{E(\hat{x}_T) - x_T}{x_T} * 100 \qquad (9)$$

where, $E(\hat{x}_T)$ = mean of the estimates of x_T for a given sample size.

x_T = the population estimate of flood corresponding to T-year recurrence interval.

b) Root mean square error (RMSE) :

RMSE is a common statistical measure which combines the effects of suggested methodology in fitting the population estimates. It is measured as:

$$\text{RMSE} = \frac{[\{E\ (\hat{x}_T - x_T)\ ^2\}\ ]^{1/2}}{x_T} * 100 \qquad (10)$$

4.0 ANALYSIS

Analysis has been carried out with historical as well as generated data as follows:

4.1 Analysis Using Historical Data

The flood frequency analysis involving use of historical data has been performed in the following steps :

(i) Calculate the sample statistics such as mean,standard deviation,co-effiecient of variation and skewness from the available historical records of annual maximum peak flow records of annual maximum peak flood series for the ten gauging sites.

(ii) Test for homogeneity of data from various gauging stations using the procedures described in Section 3.2.

(iii) Carryout flood frequency. analysis using the ten different methods discussed in section 3.1. The regional parameters required for some of the methods are estimated using the historical data of flood peaks for nine gauging sites considered for calibration. The relationship between mean annual flood and catchment area (CA) developed for the region using least square method is: $\overline{Q} = 12.049\ (CA)^{0.625}$ for whichcorrelation coefficient is ,r = 0.83.

(iv) Estimate the floods for different return periods at the two independent gauging sites (the gauging sites not considered for calibration) using the ten different methods The at site estimates for these two gauging sites are derived from the available annual maximum flood records of the respective gauging sites.

(v) Compute,ADF,EFF and SE values for each catchment by the ten different flood frequency analysis methods using eq.(4) to (8).

4.2 Analysis Using Generated Data

Simulation study was carried out using the data generated from regional EV1,GEV and WAKE populations through Monte Carlo Experiments.The regional EV1, GEV and WAKE population parameters were derived from historical records of the eight gauging sites using SREV1-II, SRGEV and SRWAKE methods respectively. The steps followed in the analysis are as given below:

i) Generate NS = 8 (no. of gauging sites) random samples of size n(j), where j = 1...NS using regional EV1 population parameters, derived from historical records of nine gauging sites and at site means. Here no. of gauging sites ,NS,is equal to eight for the study and n(j) is the sample size of the available historical records at the j^{th} gauging sites.

ii) Generate random samples for each independent gauging sites of the size m(j), where j = 1.. NI, using the regional EV1 population parameters (Case-1), and at site means of each independent sites respectively. Initially m(j) =1. Here m(j) is the sample size for the j^{th} independent gauging site and NI= no. of independent gauging sites.

iii) Calculate the sample means:

$$\overline{Q}_j = \sum_{i=1}^{n(j)} x_{i,j} \,/\, n\,(j)\,, \qquad j = 1 \ldots\ldots NS \tag{11}$$

$$\overline{QI}_j = \sum_{i=1}^{m(j)} x_{i,j} \,/\, m\,(j). \qquad j = 1 \ldots\ldots NI \tag{12}$$

where, $\overline{Q}_j$ = at site mean for the j^{th} gauging site considered in calibration.

$\overline{QI}_j$ = at site mean for the j^{th} independent gauging site, and

$x_{i,j}$ = i^{th} observation at j^{th} independent gauging site,

iv) Estimate floods corresponding to T =2,10,20,50,100,200,500 and 1000-years recurrence intervals at each independent gauging site by :

a) EV1 method (except for sample size m(j)=1)

b) SREV1-I method

c) REV1-I method wherein the mean annual flood peaks, $\overline{QI}_j$,at the j^{th} independent gauging site are obtained from the regional regression model estimate at the required independent site The regression Model generally used is in the following form:

$$\widehat{\overline{QI}}_j = a\ (CA_j)^b\ \exp(z) \qquad (13)$$

where, z is an $N(0, Se^2)$ variate where Se^2 is the regression model variance. CA_j is the catchment area up to j^{th} gauging site, a and b are the coefficients to be estimated from the linear regression in the log domain. The noise term z is added in every simulation because individual values of Q, rather than mean values, are being simulated.

d) SREV1-II method

e) REV1-II method using the mean annual flood peaks obtained form eq.(13) for the the respective independent gauging sites.

f) GEV Method (except for sample size m(j)=1)

g) SRGEV method

h) RGEV method using the mean annual flood peaks obtained from eq.(13) for respective independent gauging sites.

i) SRWAKE method

j) RWAKE method using the mean annual flood peaks obtained from the eq.(13) for the respective independent gauging sites.

v) Store Quantiles ($\hat{Q}_T$, T = 2,10,20,50,100,200,500 and 1000 years) for each independent sites ,obtained from the applications of the ten methods except for EV1and GEV methods which are not applicable when sample size m(j)=1 , for subsequent calculation of bias, and root mean square error estimates.

vi) Repeat steps (i) to (v), 1000 times.

vii) Calculate bias and root mean square error and coefficient of variation using the equations (9) and (10) respectively.

viii) Compute weighted mean values of BIAS and RMSE using the following equations:

$$R_1 = \frac{\sum_{i=1}^{m} n_i \sum_{j=1}^{NR} F_{i,j} * T_j}{\sum_{i=1}^{m} n_i \sum_{j=1}^{NR} T_j} \quad (14)$$

$$R_2 = \frac{\sum_{i=1}^{m} \frac{1}{n_i} \sum_{j=1}^{NR} F_{i,j} * T_j}{\sum_{i=1}^{m} \frac{1}{n_i} \sum_{j=1}^{NR} T_j} \quad (15)$$

$$R_3 = \frac{\sum_{i=1}^{m} n_i \sum_{j=1}^{NR} F_{i,j} * 1/T_j}{\sum_{i=1}^{m} n_i \sum_{j=1}^{NR} 1/T_j} \quad (16)$$

$$R_4 = \frac{\sum_{i=1}^{m} \frac{1}{n_i} \sum_{j=1}^{NR} F_{i,j} * 1/T_j}{\sum_{i=1}^{m} \frac{1}{n_i} \sum_{j=1}^{NR} 1/T_j} \quad (17)$$

Where, $F_{i,j}$ is either BIAS or RMSE for i^{th} sample and j^{th} return period and m the number of sample size considered.

ix) Repeat step (i) to (viii) using m(j) =5, 10, 13 20, 30, and 40 respectively for the two independent gauging sites.

x) Repeat step (i) to (ix) twice with generated samples using regional GEV population parameters (Case-2) and Wakeby population parameters(Case-3), respectively in place of the generated samples of the regional EV1 population (Case-1), and at site means for each gauging site.

5.0 DISCUSSION OF RESULTS

The sample statistics computed from the historical flood records of eleven gauging sites located in Sum-Himalyan region are given in Table- 1 along with their catchment areas and sample sizes. It is seen from the table that Br.No.213 has coefficient of variation equal to 1.368, which unusually higher as compared to other sites. The records available for Br.No. 213 are, therefore discarded from the analysis. It is observed from the table that the catchment area for the remaining ten gauging sites vary from 6 to 2072 sq.kms. The sample sizes of the historical flood record for the ten gauging sites are between 13 to 20 years. The homogeneity of the region has been tested using U.S.G.S. Homogeneity Test. This test is performed using the procedures described in Sections 3.2.. It is observed (figure-2) that all the ten gauging sites are within the regional confidence band which indicates the data for all ten gauging sites are regionally homogeneous and thus suitable for regional analysis.

The flood estimates for different recurrence intervals obtained by the ten different methods are given in Table 2 for the two test catchments. The table indicates wide range of variatios in flood estimates obtained by different methods specially at higher recurrence intervals. In order to evaluate the descriptive ability of different methods, ADF, EFF and SE values have been computed for each test catchment using eq.(4) to (8) and those values are given in Table 3. The larger values of ADF, and SE, and low values of EFF observed from the table for some of the methods may be attributed to the assumption regarding the distribution, method of parameter estimation, inaccurate assessment of the mean flood and the regional population as the data of those sites might have come from some other populations rather than the

TABLE 1 : SAMPLE STATISTICS IN REAL SPACE

S.NO.	BR.NO.	SAMPLE SIZE	MEAN (Cumec)	STAND.DEV. (Cumec)	COEFF.OF VAR.	SKEWNESS	CATCH.AREA (Sq.Km.)
1	104	20	855.0	633.5	0.741	1.214	2072
2	104(old)	20	677.8	442.9	0.654	2.681	234
3	65	20	296.0	142.4	0.481	0.536	190
4	3	13	145.8	110.7	0.759	1.150	178
5	629	13	530.8	238.2	0.449	-0.075	104
6	154	13	264.5	106.0	0.401	-0.819	43
7	48	20	68.4	47.8	0.699	0.413	27
8	278	13	20.5	15.4	0.752	0.235	6
9	50	20	17.1	11.0	0.645	1.143	25
10	232	13	1606.8	643.6	0.401	-0.170	710
*11	213	13	68.6	93.9	1.368	0.896	45

* Note : The records available at Br.No.213 are discarded from the analysis due to unusually high value of co-efficient of variasion as compared to the other gauging sites.

TABLE 2 : FLOOD IN CUMEC

	TEST CATCHMENT -1 (BRIDGE NO. - 50)							:	TEST CATCHMENT -2 (BRIDGE NO.- 232)							
METHOD	2	10	20	50	100	200	500	1000 :	2	10	20	50	100	200	500	1000
EV1	15.3	31.6	37.9	46.0	52.0	58.1	66.0	72.0	1491.4	2523.3	2917.6	3428.0	3810.5	4191.5	4694.3	5074.3
SREV1-I	15.2	31.6	37.9	46.0	52.1	58.2	66.2	72.2	1425.1	2968.8	3558.7	4322.2	4894.3	5464.4	6216.5	6784.9
REV1-I	79.9	166.5	199.5	242.3	274.4	306.4	348.5	380.4	647.0	1347.8	1615.6	1962.2	2221.9	2480.7	2822.1	3080.2
SREV1-II	15.4	31.2	37.2	45.0	50.9	56.7	64.4	70.2	1445.4	2928.6	3495.4	4228.9	4778.6	5326.4	6049.0	6595.1
REV1-II	81.0	164.2	196.0	237.1	267.9	298.6	339.1	369.8	656.2	1329.5	1586.8	1919.8	2169.4	2418.0	2746.1	2994.0
GEV	14.9	31.6	38.5	48.0	55.5	63.3	74.2	82.8	1603.5	2486.0	2717.2	2954.5	3095.5	3211.0	3332.4	3405.4
SRGEV	15.2	31.0	37.3	45.5	51.7	58.0	66.4	72.9	1424.5	2916.1	3501.0	4270.7	4857.0	5449.3	6243.6	6853.5
RGEV	79.9	163.5	196.3	239.4	272.3	305.5	350.1	384.3	646.7	1323.8	1589.4	1938.8	2205.0	2473.9	2834.4	3111.4
WAKE	15.3	30.8	38.2	49.1	58.3	68.4	83.3	95.9	1692.3	2251.2	2513.3	3030.2	3612.7	4436.5	6071.2	7913.6
SRWAKE	15.3	31.3	37.8	46.3	52.6	58.8	66.8	72.7	1439.5	2936.6	3554.1	4353.0	4944.3	5524.6	6275.2	6830.9
RWAKE	80.7	164.6	199.3	244.1	277.2	309.7	351.8	383.0	653.5	1333.1	1613.5	1976.1	2244.6	2508.0	2848.8	3101.1

TABLE 3 : VALUES FOR DIFFERENT CATCHMENTS

	TEST CATCHMENT -1 (BRIDGE NO. - 50)			TEST CATCHMENT -2 (BRIDGE NO.- 232)		
METHOD	ADF	EFF	RMSE	ADF	EFF	RMSE
EV1	0.131	0.979	1.565	0.150	0.859	232.582
SREV1-I	0.130	0.979	1.560	0.238	0.382	486.220
REV1-I	4.309	-66.209	88.102	0.576	-1.092	894.319
SREV1-II	0.131	0.979	1.540	0.206	0.467	451.568
REV1-II	4.523	-65.279	87.490	0.566	-1.080	891.741
GEV	0.128	0.978	1.589	0.084	0.941	150.339
SRGEV	0.129	0.981	1.484	0.209	0.451	458.207
RGEV	4.496	-64.691	87.101	0.568	-1.107	897.471
WAKE	0.111	0.979	1.545	0.064	0.971	105.161
SRWAKE	0.117	0.982	1.459	0.214	0.416	472.502
RWAKE	4.464	-66.030	87.985	0.569	-1.082	892.280

assumed one. It is observed from table-3 that the regional methods REV1-I ,REV1-II,RGEV and RWAKE result unusually higher values of ADF and RMSE as compared to the other methods for the two test catchments.The values of EFF are extremely low for these regional methods.It is, therefore, difficult to identify the suitable method for the region as whole based on the computed values of ADF, EFF and SE for the two test catchments out of the remaining six methods. Neverthless,this comparative study may be useful for judging the relative performance of various methods. The flood frequency analysis is usually carried out with an objective of estimating the floods in the extrapolation range .Since the superiority of one method over others could not be established based on the descriptive ability tests, therefore one may not be able to decide which method or methods should be used for computing the floods in extrapolation range, out of the ten methods considered in the study. It leads to carryout the simulation study using all of them and test their predictive ability in order to choose the most robust method for the region. In light of this the simulation study has been conducted using the procedure described in section 4.2.

In the simulation study Monte Carlo Experiments have been performed using the generated data for three different populations. The generated data have been utilised to compute the performance criteria such as Bias and RMSE using the eq.(9) and (10) respectively corresponding to different recurrence intervals for the two test catchments for sample sizes of 1,5,10,13,20,24,30 and 40 respectively. Table 4 provides the estimates of Bias obtained from the different methods for a typical sample sizes of 20 Case-1 and Case-2 and Case-3 generated populations. Similar estimates for root mean square errors were also obtained by each method for different sample sizes considered and the same are given in Tables-5 for the sample size 20. The weighted mean values for Bias and RMSE are also computed using the eq.(14) and (17) respectively ,adopting four different procedures of averaging. These values are given in Tables 6 and 7 for BIAS and RMSE respectively.The averaging method R_1 gives more weights to the

TABLE 4 : PERCENTAGE BIAS OF FLOOD ESTIMATES

	TEST CATCHMENT -1 (BRIDGE NO. - 50)								TEST CATCHMENT -2 (BRIDGE NO.- 232)							
METHOD	2	10	20	50	100	200	500	1000	2	10	20	50	100	200	500	1000
								SAMPLE SIZE= 20								
EV1																
CASE-1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
CASE-2	1.0	0.0	-1.0	-1.0	-2.0	-3.0	-4.0	-4.0	1.0	-1.0	-1.0	-2.0	-3.0	-3.0	-4.0	-5.0
CASE-3	1.0	0.0	-2.0	-3.0	-3.0	-3.0	-3.0	-3.0	0.0	-1.0	-2.0	-3.0	-4.0	-4.0	-4.0	-4.0
SREV1-I																
CASE-1	0.0	-1.0	-1.0	-1.0	-2.0	-2.0	-2.0	-2.0	0.0	-1.0	-1.0	-2.0	-2.0	-2.0	-2.0	-2.0
CASE-2	1.0	-1.0	-2.0	-3.0	-3.0	-4.0	-5.0	-6.0	1.0	-1.0	-2.0	-3.0	-3.0	-4.0	-5.0	-6.0
CASE-3	1.0	-1.0	-2.0	-4.0	-4.0	-5.0	-5.0	-5.0	0.0	-1.0	-3.0	-4.0	-4.0	-5.0	-5.0	-5.0
REV1-I																
CASE-1	749.0	737.0	735.0	733.0	732.0	731.0	730.0	730.0	-27.0	-28.0	-28.0	-28.0	-28.0	-29.0	-29.0	-29.0
CASE-2	761.0	742.0	736.0	728.0	722.0	716.0	708.0	702.0	-26.0	-28.0	-28.0	-29.0	-29.0	-30.0	-31.0	-31.0
CASE-3	752.0	737.0	724.0	713.0	708.0	705.0	705.0	706.0	-27.0	-28.0	-29.0	-30.0	-31.0	-31.0	-31.0	-31.0
SREV1-II																
CASE-1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CASE-2	1.0	0.0	-1.0	-2.0	-2.0	-3.0	-4.0	-4.0	1.0	0.0	-1.0	-2.0	-2.0	-3.0	-4.0	-5.0
CASE-3	1.0	0.0	-2.0	-3.0	-3.0	-4.0	-4.0	-4.0	0.0	0.0	-2.0	-3.0	-4.0	-4.0	-4.0	-4.0
REV1-II																
CASE-1	748.0	745.0	744.0	744.0	744.0	743.0	743.0	743.0	-27.0	-27.0	-27.0	-27.0	-28.0	-28.0	-28.0	-28.0
CASE-2	760.0	750.0	744.0	737.0	732.0	726.0	719.0	713.0	-26.0	-27.0	-27.0	-28.0	-29.0	-29.0	-30.0	-30.0
CASE-3	751.0	743.0	731.0	721.0	716.0	714.0	714.0	715.0	-27.0	-28.0	-29.0	-29.0	-30.0	-30.0	-30.0	-30.0
GEV																
CASE-1	-1.0	-1.0	0.0	2.0	4.0	6.0	10.0	14.0	-1.0	-1.0	-1.0	1.0	3.0	5.0	9.0	13.0
CASE-2	-1.0	-1.0	0.0	2.0	3.0	6.0	10.0	13.0	0.0	-1.0	-1.0	1.0	3.0	5.0	9.0	12.0
CASE-3	-1.0	-1.0	-1.0	1.0	3.0	5.0	10.0	15.0	-1.0	-1.0	-2.0	0.0	2.0	4.0	9.0	14.0
SRGEV																
CASE-1	-1.0	0.0	0.0	1.0	2.0	3.0	5.0	6.0	-1.0	0.0	0.0	1.0	2.0	3.0	5.0	6.0
CASE-2	-1.0	0.0	0.0	1.0	2.0	3.0	4.0	5.0	-1.0	0.0	0.0	1.0	2.0	3.0	4.0	5.0
CASE-3	-1.0	0.0	-1.0	0.0	1.0	2.0	5.0	7.0	-1.0	-1.0	-1.0	0.0	1.0	2.0	4.0	7.0
RGEV																
CASE-1	740.0	744.0	749.0	758.0	766.0	774.0	787.0	797.0	-28.0	-28.0	-27.0	-26.0	-25.0	-25.0	-23.0	-22.0
CASE-2	747.0	748.0	753.0	760.0	767.0	775.0	786.0	796.0	-27.0	-27.0	-27.0	-26.0	-25.0	-24.0	-23.0	-22.0
CASE-3	737.0	742.0	740.0	745.0	753.0	765.0	785.0	802.0	-28.0	-28.0	-28.0	-27.0	-26.0	-25.0	-24.0	-22.0
WAKE																
CASE-1	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
CASE-2	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
CASE-3	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
SRWAKE																
CASE-1	0.0	0.0	1.0	2.0	3.0	3.0	5.0	6.0	0.0	0.0	1.0	2.0	3.0	3.0	5.0	6.0
CASE-2	0.0	0.0	0.0	1.0	2.0	2.0	3.0	4.0	0.0	0.0	0.0	1.0	2.0	2.0	3.0	4.0
CASE-3	0.0	-1.0	-1.0	1.0	2.0	4.0	7.0	10.0	0.0	-1.0	-1.0	0.0	2.0	4.0	7.0	10.0
RWAKE																
CASE-1	746.0	743.0	751.0	762.0	769.0	776.0	787.0	796.0	-28.0	-28.0	-27.0	-26.0	-25.0	-25.0	-24.0	-23.0
CASE-2	751.0	748.0	755.0	763.0	768.0	773.0	780.0	787.0	-27.0	-27.0	-26.0	-26.0	-25.0	-25.0	-24.0	-24.0
CASE-3	745.0	737.0	740.0	750.0	763.0	779.0	805.0	830.0	-28.0	-28.0	-28.0	-27.0	-26.0	-24.0	-22.0	-20.0

TABLE 5 : PERCENTAGE RMSE OF FLOOD ESTIMATES

	TEST CATCHMENT -1 (BRIDGE NO. - 50)								TEST CATCHMENT -2 (BRIDGE NO.- 232)							
METHOD	2	10	20	50	100	200	500	1000	2	10	20	50	100	200	500	1000
SAMPLE SIZE= 20																
EV1																
CASE-1	15.0	15.0	16.0	17.0	17.0	17.0	18.0	18.0	14.0	15.0	15.0	16.0	16.0	17.0	17.0	17.0
CASE-2	15.0	16.0	17.0	17.0	17.0	18.0	18.0	18.0	14.0	15.0	16.0	16.0	17.0	17.0	17.0	18.0
CASE-3	15.0	16.0	17.0	17.0	18.0	18.0	18.0	18.0	14.0	15.0	16.0	16.0	17.0	17.0	18.0	18.0
SREV1-I																
CASE-1	15.0	15.0	15.0	15.0	15.0	15.0	16.0	16.0	13.0	14.0	14.0	14.0	14.0	15.0	15.0	15.0
CASE-2	15.0	15.0	15.0	15.0	16.0	16.0	16.0	16.0	14.0	14.0	14.0	14.0	15.0	15.0	15.0	15.0
CASE-3	15.0	15.0	15.0	16.0	16.0	16.0	16.0	16.0	14.0	14.0	14.0	15.0	15.0	15.0	15.0	15.0
REV1-I																
CASE-1	1280.0	1260.0	1257.0	1255.0	1254.0	1253.0	1251.0	1251.0	97.0	96.0	95.0	95.0	95.0	95.0	95.0	95.0
CASE-2	1299.0	1269.0	1259.0	1247.0	1237.0	1228.0	1216.0	1207.0	98.0	96.0	95.0	95.0	94.0	94.0	93.0	93.0
CASE-3	1284.0	1260.0	1240.0	1223.0	1215.0	1211.0	1210.0	1212.0	97.0	96.0	95.0	94.0	93.0	93.0	93.0	93.0
SREV1-II																
CASE-1	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	13.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
CASE-2	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
CASE-3	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
REV1-II																
CASE-1	1277.0	1274.0	1274.0	1273.0	1273.0	1273.0	1273.0	1273.0	97.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0
CASE-2	1296.0	1281.0	1273.0	1263.0	1254.0	1246.0	1234.0	1225.0	98.0	97.0	96.0	96.0	95.0	95.0	94.0	94.0
CASE-3	1283.0	1271.0	1252.0	1236.0	1229.0	1226.0	1226.0	1228.0	97.0	96.0	95.0	94.0	94.0	94.0	94.0	94.0
GEV																
CASE-1	16.0	15.0	18.0	23.0	28.0	34.0	44.0	54.0	14.0	14.0	17.0	22.0	27.0	33.0	43.0	53.0
CASE-2	16.0	16.0	18.0	23.0	29.0	35.0	46.0	56.0	15.0	15.0	17.0	23.0	28.0	34.0	45.0	55.0
CASE-3	16.0	16.0	18.0	23.0	29.0	35.0	46.0	57.0	14.0	15.0	18.0	23.0	28.0	34.0	45.0	56.0
SRGEV																
CASE-1	15.0	15.0	15.0	16.0	17.0	18.0	21.0	23.0	14.0	14.0	14.0	15.0	16.0	18.0	20.0	22.0
CASE-2	15.0	15.0	15.0	16.0	17.0	19.0	21.0	23.0	14.0	14.0	14.0	15.0	16.0	18.0	20.0	22.0
CASE-3	15.0	15.0	15.0	16.0	17.0	18.0	21.0	24 0	14.0	14.0	14.0	15.0	16.0	18.0	20.0	23.0
RGEV																
CASE-1	1264.0	1272.0	1282.0	1299.0	1314.0	1330.0	1355.0	1377.0	96.0	96.0	97.0	98.0	99.0	100.0	102.0	104.0
CASE-2	1275.0	1279.0	1288.0	1302.0	1316.0	1332.0	1356.0	1377.0	97.0	97.0	97.0	98.0	99.0	100.0	102.0	104.0
CASE-3	1259.0	1269.0	1267.0	1278.0	1294.0	1316.0	1354.0	1388.0	96.0	96.0	96.0	97.0	98.0	99.0	102.0	104.0
WAKE																
CASE-1	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
CASE-2	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
CASE-3	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
SRWAKE																
CASE-1	15.0	15.0	15.0	16.0	17.0	19.0	22.0	25.0	14.0	14.0	14.0	15.0	16.0	18.0	21.0	25.0
CASE-2	16.0	15.0	15.0	16.0	17.0	19.0	22.0	25.0	14.0	14.0	14.0	15.0	17.0	18.0	21.0	25.0
CASE-3	16.0	15.0	15.0	16.0	17.0	19.0	23.0	27.0	14.0	14.0	14.0	15.0	16.0	19.0	23.0	27.0
RWAKE																
CASE-1	1272.0	1273.0	1287.0	1304.0	1316.0	1329.0	1350.0	1369.0	96.0	97.0	97.0	98.0	99.0	99.0	100.0	101.0
CASE-2	1281.0	1281.0	1293.0	1306.0	1315.0	1325.0	1341.0	1356.0	97.0	97.0	98.0	99.0	99.0	99.0	100.0	100.0
CASE-3	1271.0	1263.0	1268.0	1286.0	1307.0	1334.0	1382.0	1427.0	96.0	96.0	97.0	98.0	98.0	100.0	102.0	104.0

TABLE 6 : AVERAGE PERCENTAGE BIAS OF FLOOD ESTIMATES COMPUTED BY DIFFERENT AVERAGING PROCEDURES

METHOD	TEST CATCH. NO.: 1	TEST CATCH. NO.: 2	TEST CATCH. NO.: 1	TEST CATCH. NO.: 2	TEST CATCH. NO.: 1	TEST CATCH. NO.: 2	TEST CATCH. NO.: 1	TEST CATCH. NO.: 2
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
EV1								
CASE-1	0.3	-0.4	0.2	0.0	-5.0	-7.5	0.6	-2.5
CASE-2	-3.3	-3.7	0.8	0.6	-8.7	-11.1	0.6	-2.0
CASE-3	-3.0	-3.4	0.5	0.0	-8.4	-11.2	0.4	-2.8
SREV1-I								
CASE-1	-1.1	-1.6	0.4	0.0	-0.6	-3.7	0.4	-2.2
CASE-2	-4.7	-5.0	0.5	0.3	-4.1	-6.8	1.0	-1.7
CASE-3	-4.1	-4.3	0.3	0.0	-3.5	-6.3	0.7	-2.4
REV1-I								
CASE-1	733.3	-28.5	745.8	-27.3	731.9	-28.5	745.5	-27.3
CASE-2	710.6	-30.5	754.8	-26.5	708.8	-30.5	754.7	-26.6
CASE-3	709.8	-30.6	745.9	-27.5	708.5	-30.8	745.8	-27.5
SREV1-II								
CASE-1	0.0	0.0	0.1	0.1	0.5	-2.1	0.8	-2.0
CASE-2	-3.6	-3.9	0.7	0.6	-3.1	-5.7	1.2	-1.4
CASE-3	-3.2	-3.5	0.5	0.2	-3.1	-5.8	0.9	-2.3
REV1-II								
CASE-1	744.2	-27.8	747.2	-27.0	744.8	-27.2	747.1	-27.0
CASE-2	719.0	-29.7	756.0	-26.4	718.8	-29.5	756.0	-26.4
CASE-3	716.2	-29.9	746.8	-27.4	716.1	-29.9	746.8	-27.3
GEV								
CASE-1	9.3	9.5	0.2	-0.2	-37.4	-38.2	17.5	14.1
CASE-2	9.0	9.3	0.3	0.2	-38.4	-39.6	18.5	14.5
CASE-3	10.0	10.1	-0.1	-0.5	-38.2	-39.1	17.7	13.8
SRGEV								
CASE-1	5.4	5.1	-0.4	-0.3	6.1	3.1	0.1	-2.6
CASE-2	4.8	4.4	0.0	-0.3	5.4	2.3	0.1	-2.6
CASE-3	5.5	5.3	-0.6	-0.8	6.0	3.3	-0.1	-2.8
RGEV								
CASE-1	789.5	-23.5	742.9	-27.8	789.6	-23.1	742.6	-27.7
CASE-2	788.9	-23.6	748.4	-26.9	788.7	-23.2	748.5	-26.9
CASE-3	789.6	-23.6	739.1	-27.9	789.0	-23.5	738.9	-27.9
WAKE								
CASE-1	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
CASE-2	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
CASE-3	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
SRWAKE								
CASE-1	5.4	5.2	0.3	0.2	5.8	3.1	0.8	-1.9
CASE-2	3.8	3.7	0.3	0.2	4.6	1.4	0.8	-2.0
CASE-3	8.0	7.6	0.0	-0.1	8.4	5.4	0.4	-2.7
RWAKE								
CASE-1	786.4	-23.7	746.7	-27.3	789.4	-23.7	746.9	-27.0
CASE-2	778.7	-24.4	751.9	-26.9	782.0	-24.3	752.3	-26.9
CASE-3	807.9	-21.9	744.6	-27.6	810.6	-21.7	744.9	-27.7

TABLE 7 : AVERAGE PERCENTAGE RMSE OF FLOOD ESTIMATES COMPUTED BY DIFFERENT AVERAGING PROCEDURES

METHOD	TEST CATCH. NO.: 1	TEST CATCH. NO.: 2	TEST CATCH. NO.: 1	TEST CATCH. NO.: 2	TEST CATCH. NO.: 1	TEST CATCH. NO.: 2	TEST CATCH. NO.: 1	TEST CATCH. NO.: 2
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
EV1								
CASE-1	16.7	16.7	14.6	14.4	46.8	44.8	48.3	46.2
CASE-2	17.1	17.3	14.8	14.8	46.3	44.5	49.5	47.0
CASE-3	17.2	17.5	14.9	14.8	46.3	45.0	49.0	46.5
SREV1-I								
CASE-1	15.3	15.2	14.2	13.9	48.2	46.3	48.6	46.1
CASE-2	15.4	15.6	14.5	14.5	47.7	45.3	49.4	46.6
CASE-3	15.4	15.5	14.5	14.3	47.7	45.6	48.8	46.6
REV1-I								
CASE-1	1256.0	96.1	1274.3	96.8	1251.0	96.2	1273.8	96.8
CASE-2	1219.8	94.5	1288.6	97.6	1215.1	94.4	1288.3	97.6
CASE-3	1218.6	94.6	1274.4	96.7	1213.5	94.2	1273.8	96.6
SREV1-II								
CASE-1	14.7	14.4	14.1	13.8	48.9	46.2	48.6	46.1
CASE-2	14.8	14.8	14.4	14.2	47.6	45.6	49.4	46.6
CASE-3	14.7	14.6	14.4	14.2	47.5	45.5	48.8	46.6
REV1-II								
CASE-1	1273.7	96.6	1276.3	96.9	1272.1	97.6	1276.0	97.0
CASE-2	1234.0	94.8	1290.2	97.7	1232.2	95.3	1290.5	97.8
CASE-3	1229.3	94.6	1276.1	96.7	1227.5	94.8	1276.1	96.8
GEV								
CASE-1	44.7	45.1	16.1	15.6	68.9	70.2	68.1	64.7
CASE-2	46.9	47.1	16.2	16.0	70.3	71.7	69.7	65.4
CASE-3	47.2	47.1	16.2	15.9	70.5	71.8	69.3	65.4
SRGEV								
CASE-1	21.6	21.4	14.2	14.2	54.5	51.8	48.3	46.2
CASE-2	21.7	21.5	14.5	14.6	54.9	51.9	49.0	46.4
CASE-3	22.1	21.9	14.5	14.6	55.3	52.5	49.0	46.3
RGEV								
CASE-1	1349.8	102.6	1270.6	96.5	1347.7	102.2	1270.9	96.6
CASE-2	1349.3	102.7	1280.1	96.9	1346.8	102.2	1279.8	96.8
CASE-3	1351.6	102.5	1264.6	96.0	1348.3	101.9	1264.8	96.3
WAKE								
CASE-1	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
CASE-2	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
CASE-3	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0	-99.0
SRWAKE								
CASE-1	22.8	22.9	14.6	14.6	54.9	52.2	48.8	46.3
CASE-2	22.8	22.9	15.0	14.6	55.0	52.2	49.2	46.4
CASE-3	24.8	25.0	15.0	14.6	57.6	54.7	49.2	46.3
RWAKE								
CASE-1	1345.2	101.6	1277.3	96.5	1346.5	102.7	1278.1	97.1
CASE-2	1333.8	101.1	1285.5	97.0	1335.3	102.4	1286.3	97.3
CASE-3	1381.5	103.4	1273.3	96.6	1380.4	105.1	1274.4	96.9

estimates obtained from larger sample sizes for higher return periods. In the averaging method R_2 ,more weights are given to the estimates which are obtained from smaller sizes of sample for higher return periods. Thus, R_2 represents the realistic solution which is generally encountered for estimation of design flood using the field data. The averaging method R_3 and R_4 give more weights to the lower return period estimates for larger and smaller sample sizes respectively. For the four different procedures of averaging ,first three best methods have been identified for Case-1, Case-2 and Case-3 population based on BIAS and RMSE for the two test catchments. Tables-8 and 9 provide a comparison of average Bias and average RMSe values respectively for the first three best methods.

It is also observed that the methos REV1-I, REV1-II, RGEV and RWAKE have generally larger bias and RMSE as compared to the other methods. Whenever small generated samples are used to estimate higher recurrence interval floods, the computed bias values are quite high using the at site methods. It indicates that at site flood frequency methods are not capable of providing the reliable estimates of floods in the extrapolation range from the samples of the size generally available for the historical flood records in our country. The regional methods without using at site data are rejected as the computed Bias as well as RMSE values are unusually high even for the larger sample sizes. Thus the regional methods together with at site data may be preferred for flood frequency analysis. Out of four regional and at site methods(SREV1-I, SREV1-II, SRGEV ,and SRWAKE), SREV1-II and SREV1-I SRGEV and SRWAKE methods estimate floods with relatively less bias using generated samples for both the populations particularly from samples of smaller sizes at higher recurrence intervals. The computed values of Biasness using SREV1-II ,SREV1-I , SRGEV and SRWAKE methods are much lower than that of the other methods even when the samples of size one have been considered. Similar conlusions are also drawn from analysing other samples of different sizes for the two test catchments, except that the minor decrease in the computed values of Bias are evident with increase

TABLE 8 : COMPARISION OF AVERAGE BIAS VALUES FOR FIRST THREE BEST METHODS

R1		R2		R3		R4	
CATCHMENT-1							
CASE-1							
SREV1-II	0.0	SREV1-II	0.5	SREV1-II	0.1	SRGEV	0.1
EV1	0.3	SREV1-I	-0.6	EV1	0.2	SREV1-I	0.4
SREV1-I	-1.1	EV1	-5.0	GEV	0.2	EV1,SREV1-II	0.6
CASE-2							
EV1	-3.3	SREV1-II	-3.1	SRGEV	0.0	SRGEV	0.1
SREV1-II	-3.6	SREV1-I	-4.1	GEV	0.3	EV1	0.6
SRWAKE	3.8	SRWAKE	4.6	SRWAKE	0.3	SRWAKE	0.8
CASE-3							
EV1	-3.0	SREV1-II	-3.1	SRWAKE	0.0	SRGEV	-0.1
SREV1-II	-3.6	SREV1-I	-3.5	GEV	-0.1	EV1	0.4
SREV1-I	-4.1	SRGEV	6.0	SREV1-I	0.3	SRWAKE	0.4
CATCHMENT -2							
CASE-1							
SREV1-II	0.0	SREV1-II	-2.1	EV1	0.0	SRWAKE	-1.9
EV1	-0.4	SRGEV	3.1	SREV1-I	0.0	SREV1-II	-2.0
SREV1-I	-1.6	SRWAKE	3.1	SREV1-II	0.1	SREV1-I	-2.2
CASE-2							
EV1	-3.7	SRWAKE	1.4	GEV	0.2	SREV1-II	-1.4
SRWAKE	3.7	SRGEV	2.3	SRWAKE	0.2	SREV1-I	-1.7
SREV1-II	-3.9	SREV1-II	-5.7	SREV1-I	0.3	EV1	-2.0
				SRGEV	-0.3	SRWAKE	-2.0
CASE-3							
EV1	-3.4	SRGEV	3.3	EV1	0.0	SREV1-II	-2.3
SREV1-II	-3.5	SRWAKE	5.4	SREV1-I	0.0	SREV1-I	-2.4
SREV1-I	-4.3	SREV1-II	-5.8	SRWAKE	-0.1	SRWAKE	-2.7

TABLE 9 : COMPARISION OF AVERAGE RMSE VALUES FOR FIRST THREE BEST METHODS

R1		R2		R3		R4	
				CATCHMENT-1			
CASE-1							
SREV1-II	14.7	EV1	46.8	SREV1-II	14.1	EV1,SRGEV	48.3
SREV1-I	15.3	SREV1-I	48.2	SREV1-I	14.2	SREV1-I	48.6
EV1	16.7	SREV1-II	48.9	SRGEV	14.2	SREV1-II	48.6
CASE-2							
SREV1-II	14.8	EV1	46.3	SREV1-II	14.4	SRGEV	49.0
SREV1-I	15.4	SREV1-II	47.6	SREV1-I	14.5	SRWAKE	49.2
EV1	17.1	SREV1-I	47.7	SRGEV	14.5	SREV1-I	49.4
						SREV1-II	49.4
CASE-3							
SREV1-II	14.7	EV1	46.3	SREV1-II	14.4	SREV1-I	48.8
SREV1-I	15.4	SREV1-II	47.5	SREV1-I	14.5	SREV1-II	48.8
EV1	17.2	SREV1-I	47.7	SRGEV	14.5	EV1,SRGEV	49.0
				CATCHMENT -2			
CASE-1							
SREV1-II	14.4	EV1	44.8	SREV1-II	13.8	SREV1-I	46.1
SREV1-I	15.2	SREV1-II	46.2	SREV1-I	13.9	SREV1-II	46.1
EV1	16.7	SREV1-I	46.3	SRGEV	14.2	EV1,SRGEV	46.2
CASE-2							
SREV1-II	14.8	EV1	44.5	SREV1-II	14.2	SRGEV	46.4
SREV1-I	15.6	SREV1-I	45.3	SREV1-I	14.5	SRWAKE	46.4
EV1	17.3	SREV1-II	45.6	SRGEV	14.6	SREV1-I	46.6
				SRWAKE	14.6	SREV1-II	46.6
CASE-3							
SREV1-II	14.6	EV1	45.0	SREV1-II	14.2	SRGEV	46.3
SREV1-I	15.5	SREV1-II	45.5	SREV1-I	14.3	SRWAKE	46.3
EV1	17.5	SREV1-I	45.6	SRGEV	14.6	EV1	46.5
				SRWAKE	14.6		

in sample size. Further it is also observed that the computed values of RMSE by different methods have been considerably reduced with increase in sample sizes except for the regional methods without using at site data, wherein such patterns are missing.

6.0 CONCLUSIONS

The regional flood frequency analysis has been carried out for Sub-Himalayan region using the ten
different methods
considering (i) at site data, (ii) at site and regional data together , and (iii) regional data alone without using at site data. From the study the following conclusions are drawn:

(a) The superiority of one method over others could not be established based on the computed values of ADF, EFF and SE .

(b) At-site EV1(PWM), GEV(PWM) and WAKE(PWM) methods are not applicable for analysing the samples of size one. WAKE(PWM) method is not used to analyse the at site data.

(c) All regional methods without considering at site data (REV1-I, REV1-II, RGEV and RWAKE) estimate the floods with larger Biasand RMSE for both the gauging sites. It indicates the unreliability associated with the regional methods without considering the at site data while estimating the floods for different recurrence intervals. Efforts, therefore, should be made to collect the historical flood records even from indirect sources in order to provide some at site data for regional frequency analysis.

(d) At-site methods generally estimate the floods for higher recurrence intervals with larger Bias from the samples of the size of the historical records sample size less than 20 generally available in India. Thus at-site methods may not always be able to provide reliable and consistent flood estimates in the extrapolation range which are usually needed for design of medium and major water resources structures.

(e) PWM based at-site and regional SREV1-II ,SRGEV and SRWAKE methods in general estimate the floods with less bias and comparable root mean square errors for the two test catchments. Thus, out of the studied ten methods, SREV1-II,SRGEV and SRWAKE methods may be considered suitable methods for this region,particularly when dealing with limited data situations

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DISCUSSION

D.S. UPADHYAY (IMD New Delhi) : In Wakeby distribution X_T (T-year values) increase very fast with T, particularly for higher values of T. Hence it provides higher over estimated values g x. It may be slightly useful for analyzing the series with outliers but not suitable for frequency analysis of hydrological variables for any operational purposes.

AUTHOR(S) : As Wakeby distribution is a five parameters distribution, its parameters may not be that reliable, when estimated from the at-site data having a small sample size. In such a situation, the Wakeby parameters derived from the region with at-site mean can be used to provide reliable and consistent flood estimates. Therefore, the Wakeby distribution with sample size of short length should not be used. However, the Wakeby distribution whose parameters are estimated on regional basis should be used with at site mean.