CS/AR-1/2002-03

REGIONAL FLOOD FREQUENCY MODELLING FOR RIVER PARVATI (M.P.)

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2002 - 2003

PREFACE

The probabilistic approach for estimation of design flood is one of the most active areas of research in the field of hydrology. This approach is based on the frequency analysis of past flood records and requires lesser data as compared to deterministic approach. Two types of approaches adopted in flood frequency modelling are annual flood series models and partial duration series model. The method of flood frequency analysis consists of selection of the probability distribution coupled with the choice of parameter estimation procedure. For modelling the annual flood series at-site, at-site regional and regional only approaches can be applied depending on the availability of data.

In the study, at-site flood frequency analysis has been performed at Pilukhedi site of river Parvati in Madhya Pradesh. The annual flood series method of flood frequency analysis has been applied in case of at-site analysis. The regional parameters have also been determined to estimate the flood quantiles at any ungauged sites in the basin.

Various methods of parameter estimation including method of moments, probability weighted moments and L-moments have been applied and evaluated for flood frequency modelling. Simulation techniques have been used for determination of robust technique and development of confidence envelope.

The study entitled "Regional flood frequency modelling for river Parvati (M.P.)" is the part of the work programme of the Regional Centre, Sagar for the year 2002-2003.

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ABSTRACT

Determination of magnitude and the probability of likely occurring floods is of great importance for the solution of variety of water resources problems such as design of various hydraulic structures, urban drainage system, flood plain zoning, economic evaluation of flood protection works, flood insurance computation etc. Flood frequency analysis is a tool used to estimate the frequencies of likely occurrence of future floods. In this approach the sample data are used to fit frequency or probability distributions, which in turn are used to extrapolate from recorded events to design events.

In the present study, flood frequency analysis has been applied for river Parvati in Madhya Pradesh. The river Parvati is an important tributary of Yamuna river system, which rises in the Vindhyan Mountains near Ashta village in Sehore district of Madhya Pradesh. The annual flood series analysis has been carried out to estimate the flood quantiles at different return period at Pilukhedi site of river Parvati. The regional parameters for basin have also been evaluated using limited data of two other sites in the basin. The regional approach provides a significant advantage of estimation of floods at any sites in the homogeneous region with very less or no data.

In the at-site analysis of annual flood series the Normal, Log normal, Pearson type III, Log Pearson type III, EV- I and Log EV distributions were applied using method of moments. The Wakeby IV, Wakeby V, EV- I, GEV distributions have been applied using probability weighted moments. The L-moments have been used for estimation of parameters of EV-I, GEV, Logistic, Generalised logistic, Generalised Pareto, Normal and Log normal distribution. The standardized PWMs and L-moments approach have been used to estimate regional parameters in the basin. The L-moment ratio diagram and other tests based on simulation technique were used to evaluate the best-fit distribution. The regional parameters may be used to compute the flood frequency estimates at any ungauged sites in the region

From the analysis of different goodness of fit tests, it has been found that the GEV distribution with L-moments as parameter estimation found the best-fit distribution for Pilukhedi and other sites in the region. . It is recommended that the regional parameters for Parvati basin may be used only for primary estimation of flood and should be reviewed when more regional data available.

CHAPTER - 1

INTRODUCTION

1.0 GENERAL

A flood is a relatively high flow that may or may not overtop the banks of a stream. The general public often refers to a flood is a high flow that may cause damage, and engineers, manager and scientists of water resources engineers frequently relate flood to a flow with magnitude close to its annual peak value. Recurrence intervals of floods often play a key role cost benefit analysis and design of eater resources projects. The flood peaks occur in no set physical pattern, either in time or in magnitude. There is no means of forecasting the exact sequence of flood peaks in time and magnitude, which will occur over the next specified period at any site. However, if it is assumed that the sequence, which will occur, will have the same statistical characteristics as sequences that occurred in the past then it is possible to estimate the probability of any magnitude being exceeded during the desired period. Estimation of flood peaks at various points are required frequently to design variety of hydraulic structures such as weirs, barrages, dams, spillways, bridges etc.

The design flood at any point of river can be determined by (a) Physical indication of past flood, (b) Empirical formulae, (c) Envelope curves, (d) Rational methods, (e) Deterministic approach based on unit hydrograph theory, (f) Watershed models, and, (g) Probabilistic approaches etc.

In the physical indication method, flood marks at an existing bridge opening or obstruction is considered for determining the peak flood. The empirical formulae and envelope curves used for the estimation of the flood peaks are essentially regional formulae and curves based on statistical correlation of the observed peak and important catchment characteristics. The empirical formulae and envelope curves are applicable to the region for which they were developed within the range of flood peaks only. For the north Indian Plains and hilly regions, Dicken's formula ($C*A^{0.75}$) has been recommended with value of C varying from 11 to 14 for hilly regions. This formula does not provide flood estimates for desired return periods and can be used only for preliminary and a quick estimate of peak flood. The rational method uses coefficient of runoff as a representative of catchment characteristics. This method gives satisfactory results in case of small catchments only. Unit hydrograph approach and watershed models are more efficient methods than the other discussed above and provide floods and its distribution over a period of time. However, these methods require lot of hydrological data. The probabilistic approach is based on the frequency analysis of past flood records and requires lesser data as compared to deterministic approach.

1.1 FLOOD FREQUENCY ANALYSIS

The objective of flood frequency analysis is to estimate a flood peak magnitude corresponding to any required return period. The return period is defined as the expected value of average time elapsing between successive occurrences of some hydrological event. This average is understood in the long-term sense, being the average of all the values occurring over a long period of time.

The following methods are used for flood frequency analysis.

a) Annual Maximum Series Method

b) Partial Duration Series or Peak Over a Threshold method

The values of the annual maximum flood from a given catchment area for large number of successive years constitute a hydrologic data series called the annual maximum series. If Q_1, Q_2, Q_3 ....Q_N is a collection of maximum data of each year where N is the number of years of observed time series. The probability distribution of AM values may be defined by its distribution function as:

$$F(q) = PR(Q\langle q)$$

then the variate value having return period T, namely QT is defined implicitly by the equation

$$1 - F(Q_T) = \frac{1}{T}$$

The flood frequency modelling based on annual maximum series are carried out in three ways: i.e., At-site, At-site regional and regional only analysis. In the at-site analysis, the annual flow series of the site is considered and is suitable when the discharge data of nearby sites in the region are not available or of very short duration. The at-site regional and regional modelling is applied when the data of other sites in the region are also available. The annual maximum series considers only one maximum value of flood per year. There may be more than one independent flood may occur in a year and many of these may be of appreciably high magnitude. To enable the entire large flood peaks to be considered for analysis, a flood magnitude larger than an arbitrary selected base value are included in the analysis. Such a data series is called partial duration series.

1.2 APPLICATION OF L-MOMENTS IN FLOOD FREQUENCY ANALYSIS

The oldest and most widely used technique for fitting frequency distribution to the observed data is the method of moment (MOM). In this method, estimates of distribution's parameters are obtained by equating the sample moments with theoretical moments, resulting in system of algebraic equation. The main advantages of the MOM method are (a) ease in computation (b) simplicity (c) reasonable reproduction of theoretical moments. However, the estimated parameters of distribution fitted by this method, are often found to be less accurate as compared to method of maximum likelihood. On the other hand, the maximum likelihood estimates are more efficient, suffers from the limitations concerning convergence due to complex non-linear formulations. Of late, new parameter estimation techniques such as probability weighted moments (PWM) and linear combinations of order statistics (L-moments) have emerged, which are able to yield relatively unbiased estimates of the basic moments, parameters and quantiles compared to the conventional estimation methods. L-moments are more robust than conventional moments to outliers in the data and sometimes yield more efficient parameter estimates than maximum likelihood estimates particularly with small size samples. L-moments can also be used for testing regional homogeneity and goodness of fit in the flood frequency modelling. Hosking and Wallis (1993) suggested a graphical instrument based on L-moments called L-moment ration diagram. A significant advantage of L-moment ratio diagram is that the several distributions can be compared at a time.

1.3 STATEMENT OF THE PROBLEM

The present study was taken with the aim of determining the flood of river Parvati quantiles at Pilukhedi (M.P.) using regional flood frequency approach. As the available discharge data of other sites in the basin are of only 5 to 6 years, it was decided to conduct at-site flood frequency analysis at Pilukhedi using annual maximum and partial duration series modelling. The regional parameters for the basin have also been determined using approach of standardized probability weighted moments and L-moments. These parameters can be used for estimation of flood flow at any ungauged site in the basin. The various objectives of the study are as follows:

- Collection and processing of discharge data for flood frequency modelling.
- Analysis of annual flood series for randomness, trend and outliers.
- Application of various parameter estimation techniques for quantile estimation.
- Application of L-moments for parameter estimation and selection of best-fit distribution.
- Evaluation of simulation and behaviour analysis for determination of robust flood frequency model.
- Estimation of flood quantiles at Pilukhedi using annual flood series.
- Determination of regional parameters for flood frequency formula.

CHAPTER - 2
REVIEW OF LITERATURE

2.0 GENERAL

Statistical flood frequency analysis is one of the most active areas of research. The developments in the areas of includes analysis of annual flood series, partial duration series, homogeneity tests, regional flood frequency analysis, L-moments, simulation and behaviour analysis and flood frequency studies in India are reviewed in this chapter.

2.1 ANNUAL MAXIMUM SERIES

An AM series is a sequence of annual floods, with annual flood defined as the largest peak discharge of each year of record. Many candidate distributions have been suggested for AM series includes Normal, Log Normal, Pearson Type III, Extreme Type I, Extreme Type II, Extreme Type III, Gamma, Pearson Type III, Log Pearson Type III, Weibull, Wakeby, Two Component EV, Generalised Logistic, Generalised Pareto and many more.

In the annual maximum series (AM) based flood frequency modelling, at-site, at-site regional or regional only analysis may be performed. In the regional flood frequency modelling various sites of a region are grouped together for estimation of regional parameters. These sites should be hydrometeorologically homogeneous. For testing the homogeneity of the region, several tests have been suggested from time to time. Dalrymple (1949, 1960) has provided homogeneity test to check homogeneity of a region. Wiltshire (1986) suggested some drawbacks of Dalrymple tests. Lettermaier et al. (1987) pointed out the importance of identifying homogeneous region for regional flood frequency analysis by means of Monte-Carlo experiments. Hosking and Wallis (1993) recommended a homogeneity test based on L-moment ratio. Lu and Stedinger (1992) suggested yet another homogeneity test based on variability of normalized at site GEV flood quantiles. Fill and Stedinger (1995) analyzed the Dalrymple's homogeneity test and proposed a revised version of Dalrymple test. Another test using L-moment and statistical simulation has been proposed by Hosking and Wallis (1997). Burn and Goel (2000) developed a new technique for identifying groups for regional flood frequency analysis. This technique uses a clustering algorithm as a starting point for partitioning the collection of catchments. The groups formed using the clustering algorithm are subsequently revised to improve the regional characteristics based on three requirements that are defined for effective groups.

2.1.1 Regional Flood Frequency Analysis

Dalrymple (1960) described an index flood technique (USGS method) to carry out regional flood frequency analysis. The index flood procedure is a simple regionalization technique with a long history in hydrology and flood frequency analysis. Benson (1962) pointed out the deficiencies in the index-flood method, proposed by Darlymple (1960), and suggested many modifications in the method. The National Environment Research Council (1975) gave a method for regional flood frequency analysis based on order statistics in 1975 (NERC method).

Greenwood et al. (1979) developed a probability weighted moment method for quantile estimation. Wallis (1980) recommended the method based on standardized probability weighted moments for regional flood frequency analysis. The Generalised extreme value distribution was recommended for U.K. conditions (Wallis, 1980). Gries and Wood (1981) investigated the use of probability weighted moment (PWM) for improving estimates of flood quantile. Landwehr et al. (1978, 1979, and 1984), Wallis (1981, 1982), Gries and Wood (1983), Kuczera (1983), Hosking et al. (1985, 1986) have investigated various issues involved in the regionalization.

2.1.2 Use of L-moments in Flood Frequency Analysis

Hosking (1986) introduced L-moments, which are analogous to conventional moments, but are estimated as a linear combination of order statistics and hence are subjected to less bias. Hosking (1986, 1990) defined L-moments as a linear combination of probability weighted moments. Hosking et al. (1987) have given parameter and quantile estimation for generalised Pareto distribution using L-moments. Hosking (1988) introduced 4 parameter Kappa distribution of which specific cases are Generalised Pareto, Generalised Logistic and GEV distribution. Sample L-moments are found less bias than traditional product moment estimator, and thus are better suited for use in constructing moment diagrams. Plotting sample statistics on such diagram allows a choice between alternative families of distributions (WMO, 1989). Chowdhary et al. (1991) derived the sampling variance of regional τ_2, τ_3 and τ_4 as a function of k for the GEV distribution to provide a powerful test of whether a particular data set is consistent with a GEV distribution with a regionally estimated value of k and $C_{v.}$

2.1.3 Simulation and Behaviour Analysis

Statistical simulation has been used for long time for solving various problems. The statistical simulation method is based on the simulation (imitation) of studied phenomena on computers using theoretical relations with the direct simulation of the simplest (primary) random factors and the subsequent statistical treatment of resulting data. The statistical simulation often called "*MONTE-CARLO SIMULATION*". In case of flood frequency analysis, the behavior of a distribution and the robustness of a distribution/parameter estimation technique can be evaluated by generating large number of samples and subsequently comparing bias and root mean square error.

Houghton (1978) described that the traditional distributions such as log normal distribution, inadequately model flood flows for certain records. The five parameters

Wakeby distribution can be used to overcome this deficiency and its analytical forms proved easy to use in many applications. It is possible to fit a single distribution, the Wakeby as a grand parent distribution, rather than several distribution functions.

Landwehr et al. (1979) compared the estimates of the parameters and quantiles of EV-I distribution by the method of probability weighted moment, conventional moments and maximum likelihood. Results were derived from Monte-Carlo experiments by using both independent and serially correlated Gumbel distributed random numbers. The method of probability weighted moment compared favourably with other two techniques.

Landwehr et al. (1980) used 5-parameters Wakeby distribution as a parent distribution having skewness varying from 0.0 to 4.14 as the basis of robustness test on three quantile estimating technique. These were EV-1 (MOM, ML, PWM), LN3 (MOM) and WAK (PWM). He found that flexible WAK (PWM) estimate is less bias than EV-1 and LN3.

Kuczera (1982) used the wakeby distributions estimated regionally by Houghton (1977) from long records in four regions in U.S.A. as parent distribution and considered a selection of competing model distribution (Normal, LN2, LP-3, EV-1 and EV-2 and Wakeby) fitted by variety of methods. He found that LN2 was the most resistant at site estimator, followed closely by EV-1 for return period up to 200 years and sample size 15 and 30.

Lettenmaier and Potter (1985) have shown that site procedures based on the two parameter EV-1 distribution are likely to suffer from quantile bias, if the parent distribution is not EV-1 while these based on 3 parameter GEV distribution are likely to suffer from unacceptably large standard error of quantile estimates.

Hosking et al. (1985) indicated from the study that for testing suitable method, simulation of random samples from a parent distribution in which Q-T relationship is known exactly could be used. To be authentic, in the context the parent distribution must produce random samples which are flood like in behaviour. Such parent distribution would be a Wakeby, TCEV, GLOG, or possibly GEV distribution with suitable parameter values.

Singh et al. (1990-91) carried out simulation study using the data generated from regional EV-1 population and GEV population through Monte Carlo experiments. Result of study indicated that PWM based at site and regional GEV method (SRGEV) in general estimated the flood with less bias and comparable coefficient variation and root mean square error for two test catchments. Singh et al. (1993-94) and Kumar & Singh (1995-96) carried out similar study for other regions of India.

2.2 PARTIAL DURATION SERIES

Water Resources Council, USA (1976) defined the Peak over Threshold (POT) series as a sequence of separate flood events above a specified magnitude. Zalenhasic (1970) defined the partial flood series as all flood peaks, which are called exceedances above a given truncation level. In case of a multiple peak flood hydrograph, only the largest discharge was considered to be the flood peak. This treatment of peak is a hope rather than a proof that the independence of flood peaks would be preserved. It is feasible to separate a complex hydrograph in such a way as to obtain independent flood peaks.

Todorovic and Zalenhasic (1970) recommended the exponential distribution for POT series and is the most widely used. Other distributions have also been suggested including Log Normal, Pearson Type III, Log Pearson Type III, Pearson IV, Gamma, Geometric, Goodrich and EV I distributions. Taesombut and Yevjevich (1978) recommended both the mixed exponential and the simple exponential distributions for modelling the frequency distributions of the magnitude of exceedances. They used the data of 17 catchments of USA for tests of goodness of fit parameters. Goel (1989) used exponential distribution for generated daily flow data with the help of time series modelling. Langrien (1949) and Chow (1950) investigated the relationship between the return period T_{AM} assigned to a particular flow value Q by AM model, and the return period T_{PD}, assigned to same flow value by POT model. The commonly used Langbein formula relates the two return periods is as follows:

$$T_{AM}(Q) = \frac{1}{1 - e^{\left\{\frac{-1}{T_{PD}(Q)}\right\}}} \qquad \ldots 2.1$$

Chow pointed out that the differenre between T_{AM} and T_{PD} evaluated by the relative difference is less than 5% when $T_{PD} \geq 10$ years, and greater than 10% when TPD ≤ 5 years. Rosbjerg (1977) and Takeuchi (1984) reviewed the Langbein formula and confirmed its validity when events take place accoriding to a Poisson process.Rosbjerg (1985) studied the exponentially distirbuted peak exceedance values of partial duration series for both the case of independent and dependent peaks

2.3 FLOOD FREQUENCY STUDIES IN INDIA

Thiruvengadachari et al. (1973), Seth and Goswami (1979), Jhakade et al. (1984), Singh and Seth (1985), Seth et al. (1985), NIH (1985-86), Mehta and Sharma (1986), Huq et al. (1986), Gupta (1987), Seth and Singh (1987), Goel (1988), Singh (1989), Singh et al (1990-91), Singh et al. (1993-94), Singh, B. (1995), Goel and Seth (1988), Kumar and Singh (1995-96), Vankatesh and Singh (96-97), Shafi (1997), Parida et al. (1998), Upadhyaya (1999), Kumar et al. (1999), Kumar et al. (1999-00), Jaiswal et al. (2003) and many others conducted flood frequency studies for different hydrological regions in India.

CHAPTER - 3

STUDY AREA

The river Parvati is an important tributary of Yamuna river system which rises in the Vindhyan mountains near Ashta village in Sehore district of Madhya Pradesh at 22° 50' N and 76° 35' E at about R.L. 582.55 m above M.S.L. It flows for nearly 224 kms in the Madhya Pradesh before entering in the Rajasthan. The river Parvati forms the boundary between M.P. and Rajasthan for about 80 km. Again after running for a distance of about 96 km. in Rajasthan, it again forms the boundary between Rajasthan and M.P for about 64 km. Finally, the river Parvati joins the Chambal river about 32 km. south-east of Sawai Madhopur town in Rajasthan. The total catchment area of the river up to its confluence with the Chambal river is about 15, 670 sq. km. out of which nearly 10, 736 sq. km. lies in M.P. The river Tem, Ahili, Parna, Ajnar and the Papras are the important tributaries of river Parvati. A map showing Parvati river system up to Maksudangarh has been given in Fig 3.1. The river Parvati is fordable in many places during non-monsoon period except in the rains where it is crossed by country boats. The river flows generally through high banks in the rainy seasons, while its discharge falls very low in winter month of January to March and becomes negligible during the summer months of April to June leaving some pools of water in the riverbed.

The annual rainfall of the catchment varies from 181 cm to 51.5 cm. Nearly 90% of the total rainfall occurs in the monsoon season. The summer temperature rises to a maximum of 45°C while the minimum temperature recorded as 2.8° C at Bairagarh observatory near Bhopal. The relative humidity in the area varies from 7% in the summer season and reaches up to 93% in the monsoon season.

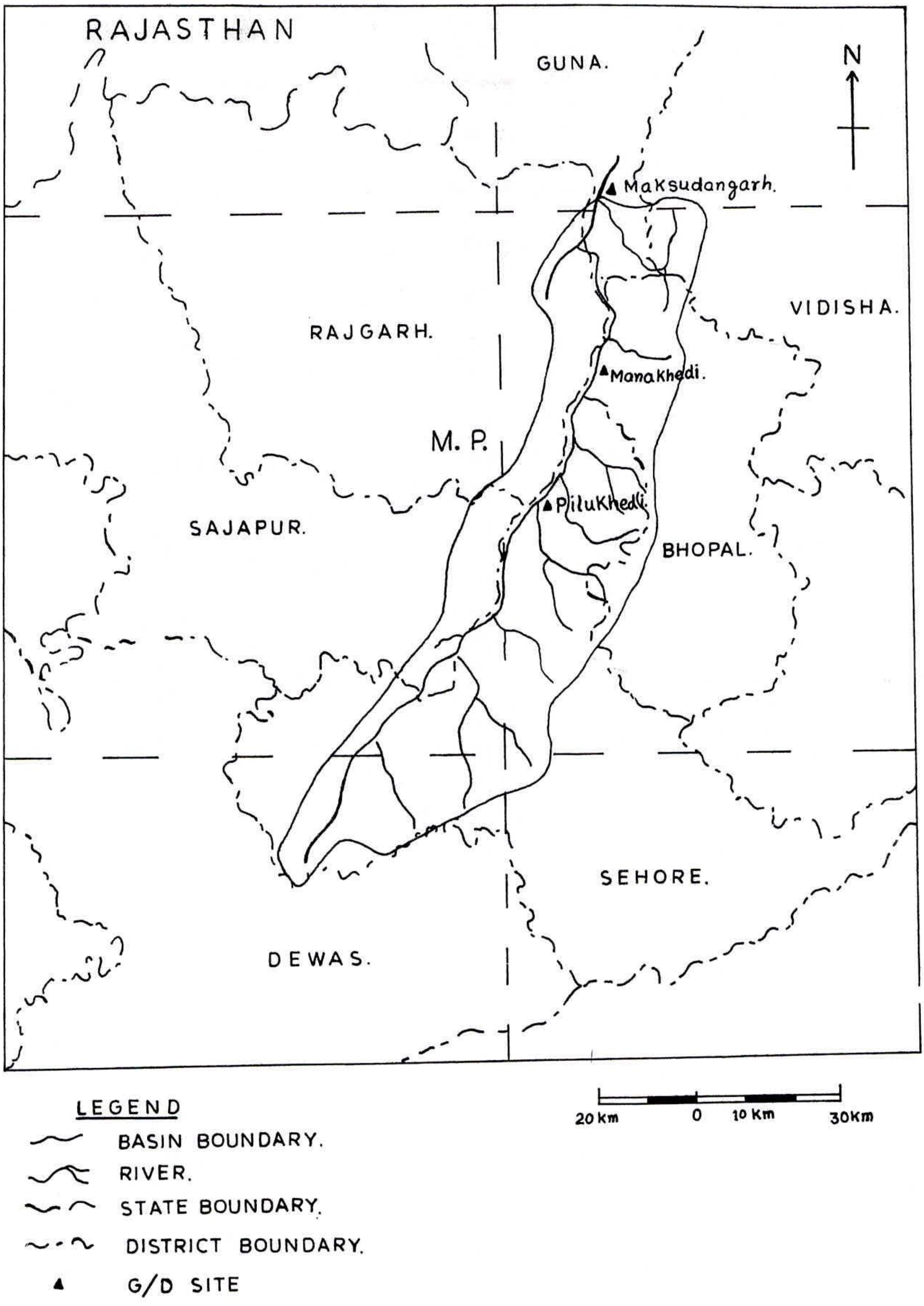

FIG. 3·1: DRAINAGE MAP OF PARVATI RIVER BASIN.

The daily discharge data of river Parvati for 14 years have been used in the analysis. From the daily data, annual flood peaks and series for partial duration analysis have been obtained. Also, the 6 year discharge data of river Parvati at Manakhedi and 5 years for Maksudangarh have been used for regional flood frequency modelling. The catchment area of river Parvati up to Pilukhedi, Manakhedi and Maksudangarh are 2624 sq. km, 3484 sq. km and 4876 sq. km respectively. The statistical analysis of annual flood series at Pilukhedi has been presented in Table 3.1.

TABLE 3.1: STATISTICAL INFORMATION OF ANNUAL FLOOD SERIES.

S. N.	Statistical Parameters	Annual Flood series	
		Original	Log
1.	Mean	1421.82	7.091
2.	Standard deviation	873.187	0.609
3.	Maximum	3550.28	8.18
4.	Minimum	495.79	6.21
5.	Coefficient of Skewness	1.252	0.0009
6.	Coefficient of Kurtosis	1.641	-0.715
7.	Lag 1 Coefficient of correlation	-0.444	-0.541
8.	Lag 2 Coefficient of correlation	0.184	0.339
9	Lag 3 Coefficient of correlation	-0.177	-0.273

CHAPTER - 4

METHODOLOGY FOR FLOOD FREQUENCY MODELLING

Flood frequency analysis is essentially a problem of information scarcity. Records are usually too short to ensure reliable estimates of probability quantiles needed in many practical problems. One way is to provide more information is to use many records from a region with similar flood behaviour, rather than only at-site data. This is particularly useful in case of arid and semiarid region, where in general, flow records are scare and for ungauged sites with no data.

In the present study, the at-site flood frequency analysis using annual flood series has been done for estimation of probable floods at Pilukhedi on river Parvati. At-site approach of flood frequency analysis for river Parvati at Pilukhedi has been preferred because very few data of other sites were available. In the at site flood frequency analysis, annual flood series of the site of interest is used and various distributions and parameter estimation techniques are used to estimate flood quantiles of desired return periods. In the analysis of annual maximum series (AMS), the method of moments, probability weighted moments and L-moments have been used for parameter estimation. The most efficient and less bias distribution is selected on the basis of various goodness of fit criterions.

The regional flood frequency modelling have been performed using the annual flood series of river Parvati at Pilukhedi, Manakhedi and Maksudangarh. In the regional approach of flood frequency analysis, standardized PWM's and L-moments have been used to obtain the regional parameters of different distributions. These regional parameters may be useful to estimate the probable floods at any ungauged site in the basin.

4.1 TESTS FOR RANDOMNESS, TRENDS, OUTLIERS AND DEPRNDENCY

The flood frequency modelling of annual flood series assumes that the observations used for analysis are independently distributed in time and space. In other words, the occurrence of an event is assumed to be independent of all previous events. Hence, before carrying out the analysis it is necessary to check the series for randomness, trends and outliers. In the analysis Turning point test have been used for determining the randomness, Kendall's rank correlation test and linear regression test for trends and a test for outliers have also been applied.

4.2 PARAMETER ESTIMATION TECHNIQUES

The various distributions and parameter estimation techniques employed for flood frequency analysis is presented in Table 4.1.

TABLE 4.1: PARAMETER ESTIMATION TECHNIQUES AND DISTRIBUTIONS USED IN FLOOD FREQUENCY ANALYSIS.

S.N.	Parameter estimation technique	Distributions applied
1.	Method of moments	Normal, Log normal, Pearson type III, Log Pearson type III, EV I, Log EV I, Generalised Extreme Value (GEV) distribution
2.	Probability weighted moments	Wakeby-4, Wakeby-5, EV I, GEV distribution
3.	L-moments	EV I, GEV, Logistic, Generalised logistic, Generalised Pareto, Normal, Log normal distribution

Details of these methods may be seen in any standard book of statistics and in the references of Seth et. al. (1985), Singh (1995), Singh (1989), Jaiswal et al. (2003), Goel and Seth (1988), Seth and Singh (1987), Reddy (1987), WMO (1989), Singh et al (90-91), Singh et al (93-94) and many more. The parameter estimation for EV-1, GEV, WAKEBY-4 and WAKEBY-5 using method of probability weighted moments is presented in Appendix I.

In the recent past, the L-moments technique has emerged as a simple, less biased and efficient technique for parameter estimation and selection of the best-fit distribution in flood frequency. Therefore, the details of L-moments technique have been presented here.

4.2.1 L-Moments

The L-moments, which are analogous to the conventional moments and can be defined as the linear combination of order statistics. Hosking introduced the L-moments in 1986. The simplest approach to describe L-moments is through probability weighted moments L-moments are linear functions of PWMs (Hosking, 1986, 1990) as follows:

$$\lambda_1 = M_{100} \qquad \text{....4.1}$$

$$\lambda_2 = 2M_{110} - M_{100} \qquad \text{....4.2}$$

$$\lambda_3 = 6M_{120} - 6M_{110} + M_{100} \qquad \text{....4.3}$$

$$\lambda_4 = 20M_{130} - 30M_{120} + 12M_{110} - M_{100} \qquad \text{....4.4}$$

Where, $$M_{i,j,k} = \int_0^1 x^i(F)\, F^j\, (1-F)^k\, dF \qquad \text{....4.5}$$

The L-moments can be used as a measure of scale and shape of probability distribution, clearly, λ_2 is a measure of scale or dispersion of distribution. It is often convenient to standardize the higher moments such as λ_r, $r \geq 3$, so that they are independent of unit of measurement of x. The L-moment ratios of x are defined to be

$$\tau_r = \frac{\lambda_r}{\lambda_2}, \qquad r = 3,4\cdots \qquad \text{....4.6}$$

Analogous to conventional moment ratios, such as the coefficient of skewness τ_3 and reflects degree of symmetry of a sample. Similarity τ_4 is a measure of peakedness and is referred to as L-kurtosis. In addition, L-coefficient of variation L-C_v are also a useful parameter, L-skew, L-kurt and L-C_v can be expressed as,

$$\text{L-skew} = \tau_3 = \frac{\lambda_3}{\lambda_2} \quad \ldots.4.7$$

$$\text{L-kurt} = \tau_4 = \frac{\lambda_4}{\lambda_2} \quad \ldots.4.8$$

$$\text{L-}C_v = \tau_2 = \frac{\lambda_2}{\lambda_1} \quad \ldots.4.9$$

L-moments can be used to estimate parameter when fitting a distribution to a sample by equating the first p-sample L-moments to corresponding population L-moments. Parameter estimation with L-moments are more accurate than even the maximum likelihood estimate, in case of small sample (Hosking, 1990). Parameter estimation for EV-1, GEV, Logistic, Generalised Logistic, Generalised Pareto, Normal and Log Normal distributions using L-moments are given in Appendix II.

4.3 SELECTION OF THE BEST FIT DISTRIBUTION / APPROACH

The measures for Goodness are used to evaluate the suitability of a flood frequency technique. These tests measure whether the data of a particular site are consistent with the fitted probability distribution function to that site or not. A number of analytical tests are available for testing the goodness of fit of the proposed models. Recently, L-moment based criterions have also been developed which are very efficient and simple for selection of robust technique. The following tests have been used in the study

- Average of relative deviations between computed and observed discharge (ADA)
- Average of square of relative deviations between computed and observed discharge (ADR)
- Efficiency
- D-index
- Bias

- RMSE
- L-Moment Ratio Diagram
- L-kurtosis
- Z-statistics

4.4 DEVELOPMENT OF CONFIDENCE ENVELOPE

Hydrologic variables such as annual peak floods or rainfall do not occur in a set pattern and are mostly random in nature. The estimates, usually, arrived from a single set of sample data are variable because of randomness associated with these events and the size of the sample used for arriving at the estimates. Moreover, the sample under consideration is assumed to have resulted from a specific parent population and is random. This results in the fact that there are many equally likely possible samples that can be originated from this assumed population. If estimates of the variables for all such samples for the desired return period are plotted, they seem to follow a normal or t-distribution with its mean as the expected value of the variables at that return period. This therefore indicates that due to sampling variation there can be many estimates and therefore, should be defined through a confidence interval and can be written as:

$$\text{Prob}\ (Q_{TL} \leq Q_T \geq Q_{TU}) = 1\text{-}\alpha \qquad \text{....4.10}$$

Where Q_{TL} and Q_{TU} are lower and upper confidence limits of the estimates Q_T so that the interval Q_{TL} to Q_{TU} is the confidence interval and (1-α) is the confidence level (α = significant level). A criterion of standard error of estimates is used for determination of confidence band. At 90% confidence interval Q_{TU} and Q_{TL} is usually evaluated as

$$Q_{TU}/Q_{TL} = Q_T \pm 1.645\ \text{Se}\ (\hat{Q}_T) \qquad \text{....4.11}$$

Where Se($\hat{Q}_T$) is the standard error of T year return period flood.

Standard error of simple two parameters normal, log normal, EV-1 can be determined with the help of standard formulae. These standard formulae indicate the standard error in the estimation may vary due to size of sample, return period and parameter of the distribution. But in case of 3 and 4-parameter complex distribution, formulae for calculation of standard error are not available. So, if statistical simulation is conducted with the help of Monte-Carlo simulation technique, a large number of samples can be generated. Such random samples have the characteristic that different samples, when treated in the same way, generally yield numerically different values of quantile estimates. The proposed method is based on assumption that sub-samples of long annual flood series also yield different values of quantiles estimates and their variation is similar to what would be expected to occur among estimates obtained from truly random samples (NERC, 1975).

4.5 REGIONAL FLOOD FREQUENCY MODELLING

In the regional flood frequency analysis, available peak flood data of different sites of a homogeneous region are required to be grouped for the estimation of regional parameters. The best-fit regional distribution is decided on the basis of goodness of fit tests, L-moment ratio disgram and simulation experiments. The regional flood frequency analyses are generally preferred over at-site analysis because grouping of data of many sites may eliminate sampling error and the estimated parameters can be used for determination of probable flood at any sites in the region. The regional flood frequency modelling may be divided in two groups; i.e. at-site regional and regional flood frequency modelling. The main difference in these two methods is that in the at site regional flood frequency analysis, mean annual flow is calculated form the observed data, while the same is computed with the help of relationship between the mean annual flow and catchment characteristics in regional only analysis.

4.5.1 Relationship between Mean Annual Flood and Catchment Characteristics

For ungauged basins of a hydrologically homogeneous basin, the mean annual flood is required. For a homogeneous region, the relationship can be developed between mean annual flood and any one or more of the following basin characteristics:

- Size and shape (Area)
- Catchment storage (Lake index)
- Density and distribution of streams (Stream frequency)
- Soil index / geology
- Overland and channel slope
- Rainfall / climate (Mean annual rainfall)

In the present study only catchment area has been considered because of non-availability of other data related to catchment characteristics. The relationship between mean annual flood and catchment area is of the following form:

$$\overline{Q} = mA^d \qquad \text{....4.12}$$

4.5.2 Methods Based on Standardized PWM's and L-moments

In the study, method based on standardized PWM's has been used for computation of regional parameters of various distributions. Following sequential steps have been carried out for at site regional and regional flood frequency analysis:

- Determine at site values of probability weighted moments for each site.
- Standardize the at-site values of PWM's by dividing them by at site mean.
- Compute standardized L-moments for each site using standardised PWMs.
- Compute the regional values of standardized PWMs and L-moments averaged across all sites in the region in the ratio of record length.
- Estimate regional parameter of different distributions.
- Flood quantile for any site (Q_{Ti}) can be determined using following equation.

$$Q_{T_i} = Q_r * \overline{Q} \quad \text{....4.13}$$

Where Q_{T_i} = flood of T year return period for any site i,

Q_r = flood quantile calculated from regional parameters,

$\overline{Q}$ = Mean annual flood of that site.

4.6 SELECTION OF BEST-FIT DISTRIBUTION FOR REGIONAL APPROACH

The various goodness of fit tests such as ADA, ADR, D-index, efficiency, bias, RMSE and L-moment ratio diagram, etc applicable in the at-site analysis can be applied in regional approach of flood frequency modelling also. But in case of regional flood frequency analysis, some tests, which are based on L-moment ratios and simulation experiments have been identified as very strong indicator for the selection of the best-fit distribution. For selecting the best-fit distribution in regional flood frequency modelling, the L-moment ratio diagram, Measures based on L-kurtosis and Z-statistics have been used.

4.6.1 L-Moment Ratio Diagram

Hosking (1990) has introduced L-moment diagram for the purpose of selecting a suitable probability density function for modelling hydrologic variable at many sites. The L-moment ratio diagram can be constructed by plotting the theoretical L-skewness and L-kurtosis for different distribution. A significant advantage of L-moment ratio diagram is that the several distributions can be compared using a simple graphical instrument. The goodness of fit can be judged by how well the L-skewness and L-kurtosis of the fitted distribution match the L-skewness and L-kurtosis of the observed data.

4.6.2 Measure Based on L-Kurtosis

The goodness of fit based on L-moment ratio diagram is subjective to some extent. Hosking and Wallis (1993) proposed a convenient method for goodness of fit based on L-kurtosis. The quality of fit is judged by the difference between the L-kurtosis of fitted distribution and the average L-kurtosis of the region. To assess the significance of this difference we compare it with the sampling variability of τ_4.

Let σ_4 denote the standard deviation of τ_4, the good of fit measure is

$$Z^{GEV} = (\tau_4 - \tau_4^{GEV})/\sigma_4 \qquad \text{....4.14}$$

σ_4 can be obtained by repeated simulation of a homogeneous region with GEV distribution. For other distributions simulation can be done with the parameter of that distribution and τ_4^{GEV} will be replaced by the τ_4 of that distribution. The theoretical values of different distributions as proposed by Hosking and Wallis (1993) are:

$$\tau_4^{GEV} = (1.0 - 6*2^k + 10*3^{-k} - 5*4^{-k})/(1-2^{-k}) \qquad \text{....4.15}$$

$$\tau_4^{EV\text{-}I} = 0.1504 \qquad \text{....4.16}$$

$$\tau_4^{LOG} = 1/6 \qquad \text{....4.17}$$

$$\tau_4^{GLOG} = (1+5k^2)/6.0 \qquad \text{....4.18}$$

$$\tau_4^{GPD} = (1-k)(2-k)/((3+k)(4+k)) \qquad \text{....4.19}$$

$$\tau_4^{NOR} = 0.1226 \qquad \text{....4.20}$$

4.6.3 Z-Statistics

Hosking (1997) proposed a technique of Z-statistics for various distributions. This goodness of fit statistics judged, how well the L-skew, L-kurt and L-Cv of the fitted distribution match with the regionally averaged L-skew, L-kurt and L-Cv.

The goodness of fit measure for a distribution is given by statistics Z_i^{dist} (Z-LCV, Z-LCK, Z-LCS) and the distribution gives the minimum $\left|Z^{dist}\right|$ is considered the best fit.

$$Z_i^{dist} = \frac{\bar{\tau}_i^{R} - \tau_i^{dist}}{\sigma_i^{dist}} \qquad \text{....4.21}$$

Where, $\bar{\tau}_i^{R}$ = weighted regional average of L-moment ratios

τ_i^{dist} , σ_i^{dist} = simulated regional average and standard deviation of L-moment statistic i respectively.

CHAPTER – 5

ANALYSIS AND RESULTS

Initially at the time of taking up of this study it was proposed to conduct the regional flood for Parvati basin. But it has been found during data collection that runoff data for other sites except Pilukhedi are of only 5 to 6 years. Considering the data availability, at-site flood frequency modelling using AFS has been conducted at Pilukhedi gauge site of river Parvati. Method of moments (MOM), Probability weighted moment (PWM) and L-moments have been applied for parameter estimation. The Monte-Carlo simulation technique was used for evaluation of efficient distribution and determination of confidence envelop. Also, the regional flood frequency approach has been applied with available data of other sites in the basin to estimate the regional parameters for the basin.

5.1 TESTS FOR RANDOMNESS, TRENDS, OUTLIERS AND DEPENDENCY

Annual maximum series of river Parvati at Pilukhedi have been obtained from the data and series has been checked for randomness and trends using turning point, Kendal's rank correlation test, and linear regression test. A test for detection of outliers has also been applied.

In the turning point test, the total 10 turning points were found. The value of $|z|$ has been computed as 0.8708, which is less than 1.64, and hence series can be considered as random at 90% confidence level.

According to Kendal's rank correlation test the value of p has been worked out as 53, while test statistics (τ) has been computed as 0.04949, which shows that there is no trend in the series at 90% confidence level.

The results of linear regression test show the value of S_b and T_b are 60.241 and –0.07 respectively. As the absolute t_b is less than 1.73 and hence the slope of the series is not significant at 90% confidence level.

The result of outlier test indicates that X_H and X_L are 9412.35 and –6624.78 cumecs respectively. There is no value in the series outside this range and hence there is no outliers in the series.

Test for dependency has been applied to determine the presence of persistence in the series. The value of r_l has been computed as –0.40. The 95% upper and lower confidence limits or r_l have been worked out as -0.08 and 0.26 respectively. As the value of r_l lies within the limits, it may be concluded that the observed series is random at 95% confidence level.

5.2 AT-SITE FLOOD FREQUENCY ANALYSIS

At-site flood frequency model has been applied in the study. Using methods of moment Normal, Log Normal, PT III, log PT III, EV I, log EV I and GEV distributions have been fitted. The probability-weighted moments have been used to estimate the parameters of Wakeby-4, Wakeby-5, EV-1 and GEV distributions. A more efficient and less bias method of parameter estimation L-moments were applied to estimate the parameters of EV-1, GEV, Logistic, Generalised Logistic, Generalized Pareto, normal and Log normal distributions. The PWM's, L-moments, L-moment ratios and parameters of different distributions and approaches have been presented in Table 5.1.

5.3 SELECTION OF THE BEST-FIT DISTRIBUTION / APPROACH

ADA, ADR, efficiency, D-index, bias, RMSE with experiment-I and II, Goodness of fit measure based on L-moment ratio diagram have been used. The ADA, ADR, efficiency,

TABLE 5.1: PARAMETERS OF VARIOUS DISTRIBUTIONS USED IN THE ANALYSIS.

S.N.	Parameter Estimation Technique	Name of Distribution	Parameters of Distribution
1.	Method of Moments	Normal	μ = 1421.82, σ = 873.19
		Log Normal (LND)	μ = 7.09, σ = 0.61
		PT III	μ = 1421.82, σ = 873.19, Cs = 1.252
		Log PT III (LPT)	μ = 7.09, σ = 0.61
		EV I	u = 1028.45, α = 681.17
		Log EV (LEV)	u = 6.815, α = 0.476
2.	Probability Weighted Moments	Moments	M100 = 1421.82, M101 = 473.45, M102 = 257.01, M103 = 167.95, M104 = 121.493
		Wakeby 5	α = 1691.17, β = 0.932, γ = 97.67, δ = 0.603, Xi =300.155
		Wakeby 4	α = 8356.19, β = 14.48, γ = 877.35, δ = 0.005
		EV-I	u = 1026.33, α = 685.17
		GEV	u = 987.42, α = 594.87, k = -0.135
3.	L – Moments	Moments	λ_1 = 1421.82, λ_2 = 474.92, λ_3 = 123.17, λ_4 = 91.57, L-skewness = 0.26, L-kurtosis = 0.19
		EV-I	u = 1026.33, α = 685.17
		GEV	u = 987.42, α = 594.87, k = -0.135
		Logistic	u = 1421.82, α = 474.92
		Generalised Logistic (GLD)	u = 1225.83, α = 424.09, k = -0.259
		Generalised Pareto (GPD)	u = 388.26, α = 1215.74, k = 0.176
		Normal	μ = 1421.82, σ = 841.56
		Log Normal	μ = 7.23, σ = 0.53

D-index have been presented in Table 5.2. In the study, 2000 random samples have been generated using Monte-Carlo simulation. The two types of experiments have been conducted for estimation of bias and root mean square error for different return periods. In Experiment I, the parameters of same distribution has been used for generation of random samples, while the Wakby-5 distribution has been considered as the flood like distribution in case of experiment II. The results obtained from analysis of bias and RMSE are given in Table 5.3. The L-skewness and L-kurtosis of the AFS obtained from data of river Parvati at Pilukhedi have been plotted on L-moment ratio diagram and presented in Fig 5.1. From the careful review of literature and analysis of results, it has been observed that the L-moment ratio diagram is more efficient for flood frequency flood frequency modelling where a simple diagram can be used to compare several distributions simultaneously. From the analysis of Fig. 5.1, it may be observed that the GEV distribution may be the best-fit distribution for river Parvati at Pilukhedi. The results obtained from ADA test indicated that the Generalised Pareto distribution gives the minimum value but other tests such as ADR, Efficiency, D-index, bias and RMSE indicate the GEV may be the best-fit distribution. From the analysis of all goodness of fit tests and L-moment ratio diagram, the *Generalised Extreme Value* distribution has been selected the best-fit distribution with $u = 987.42$, $\alpha = 594.87$, $k = -0.135$.

Flood quantiles (Q_T) for different return periods (T) can be computed using the following relationship.

$$Q_T = 4406.44 * \left(-\ln\left(1 - \frac{1}{T}\right)\right)^{-0.135} - 3419.02 \qquad \ldots 5.1$$

The flood quantiles for different return periods have been given in Table 5.4.

TABLE 5.2: THE RESULTS OF GOODNESS OF FIT TESTS

S.N	Estimation Technique	Name of Distribution	ADA	ADR	Efficiency	D-Index
1.	Method of Moments	Normal	29.14	35.08	61.04	1.502
		Log Normal	23.65	22.88	78.05	0.960
		PT III	24.29	30.81	71.24	1.022
		Log PT III	23.65	22.88	78.05	0.961
		EV I	18.93	12.08	78.44	1.086
		Log EV I	22.14	11.79	84.79	1.027
2.	Probability Weighted Moments	Wakeby 5	12.22	1.36	94.35	0.829
		Wakeby 4	13.66	2.94	95.29	0.746
		EV-I	11.75	3.07	95.94	0.648
		GEV	11.34	0.98	96.88	0.622
3.	L – Moments	EV-I	11.75	3.07	95.94	0.648
		GEV	11.34	0.98	96.08	0.622
		Logistic	21.56	10.66	90.22	1.185
		Generalised Logistic	12.12	2.36	95.88	0.923
		Generalised Pareto	9.41	1.48	95.54	0.672
		Normal	21.12	9.72	89.30	1.336
		Log Normal	10.81	1.81	94.07	0.709

TABLE 5.3: THE RESULTS OF BIAS AND RMSE

S.N	Estimation Technique	Name of Distribution	Experiment - I		Experiment - II	
			Weighted bias	Weighted RMSE	Weighted bias	Weighted RMSE
1.	Probability Weighted Moments	Wakeby 5	-41.29	2.712	-41.29	2.712
		Wakeby 4	37.38	1.197	46.42	1.224
		EV-I	-12.34	0.409	-16.85	0.663
		GEV	-11.49	0.328	-10.82	0.541
2.	L - Moments	EV-I	-12.34	0.409	-16.85	0.663
		GEV	-11.49	0.328	-10.82	0.541
		Logistic	-20.46	0.738	-21.46	0.780
		Generalised Logistic	-22.75	0.688	-30.84	0.775
		Generalised Pareto	-18.55	0.630	-30.07	0.761
		Normal	-22.59	0.814	-25.15	1.256
		Log Normal	-21.42	0.953	-23.98	1.172

TABLE 5.4: FLOOD QUANTILES FOR RIVER PARVATI AT PILUKHEDI.

S.N.	Return Period (Yrs)	Flood quantiles (cumecs)	
		At-site Analysis	Regional Analysis
1.	2	1210.93	1238.93
2.	5	1976.56	1880.19
3.	10	2551.97	2368.44
4.	20	3161.54	2891.02
5.	50	4043.97	3656.31
6.	100	4782.00	4303.66
7.	200	5589.96	5019.26

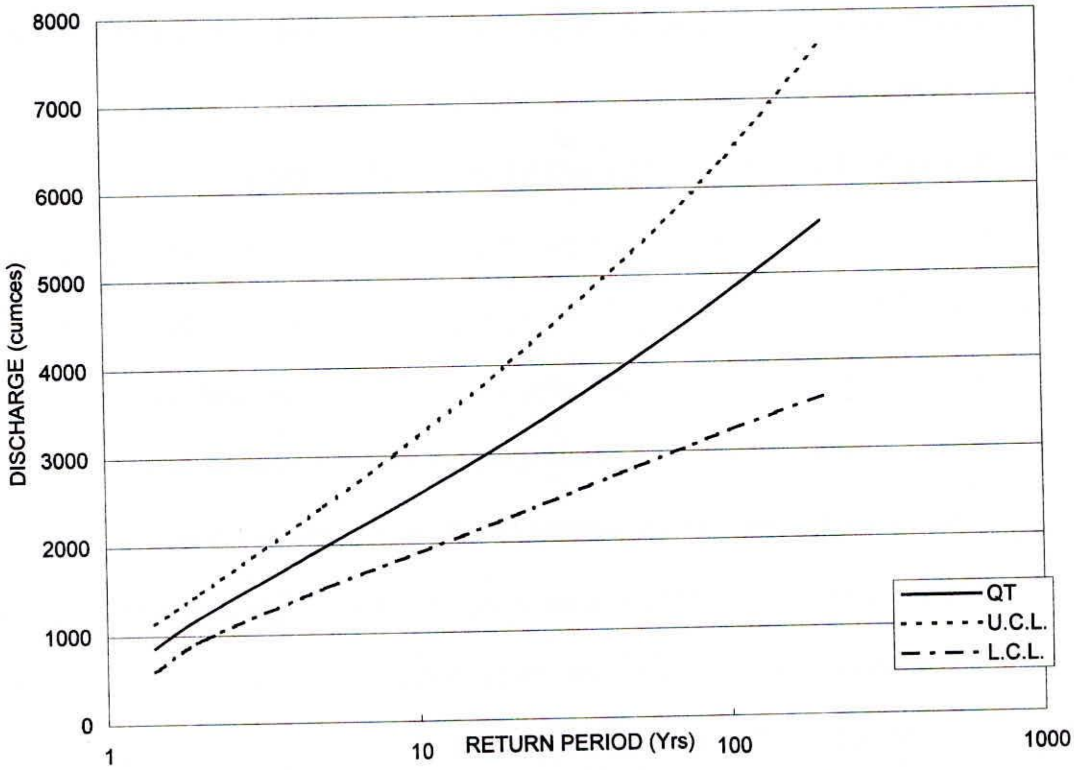

FIG. 5.2: FLOOD FREQUENY CURVE AND CONFIDENCE ENVELOP FOR RIVER PARVATI AT PILUKHEDI

5.4 DETERMINATION OF CONFIDENCE LIMITS

For development of upper and lower confidence limits, five thousands random samples using regional GEV parameters have been generated with the help of Monte-Carlo simulation experiments. The upper and lower confidence limits for different recurrence intervals at 90% confidence level have been determine and plotted. The flood frequency curve and the envelope curve have been given in the Fig. 5.2.

5.5 REGIONAL APPROACH FOR THE PARVATI BASIN

For the determination of regional parameters for the Parvati basin, approach of standardized PWM's and L-moments have been applied. The regional parameters have been estimated using data of three sites only. Therefore, these regional parameters may be used only for primary estimation of flood quantiles at any sites in the basin.

5.5.1 Relationship between Mean Annual Flood and Catchment Area

For estimation of mean annual flood at any ungauged site in the Parvati basin, a relation has been developed between the mean annual flood and catchment area of Pilukhedi, Manakhedi and Maksudangarh G/D sites.

The following equation may be used to compute the mean annual flow $(\overline{Q})$ in cumecs and catchment area (A) in km^2.

$$\overline{Q} = 3.097 A^{0.785} \qquad \ldots.5.2$$

5.5.2 L-moment ratio Diagram

The regional L-skewness (0.268) and L-kurtosis (0.193) have been plotted on L-moment ratio diagram (Fig. 5.1). From the analysis of L-moment ratio diagram, it is found that the GEV distribution may be the best fit for the region.

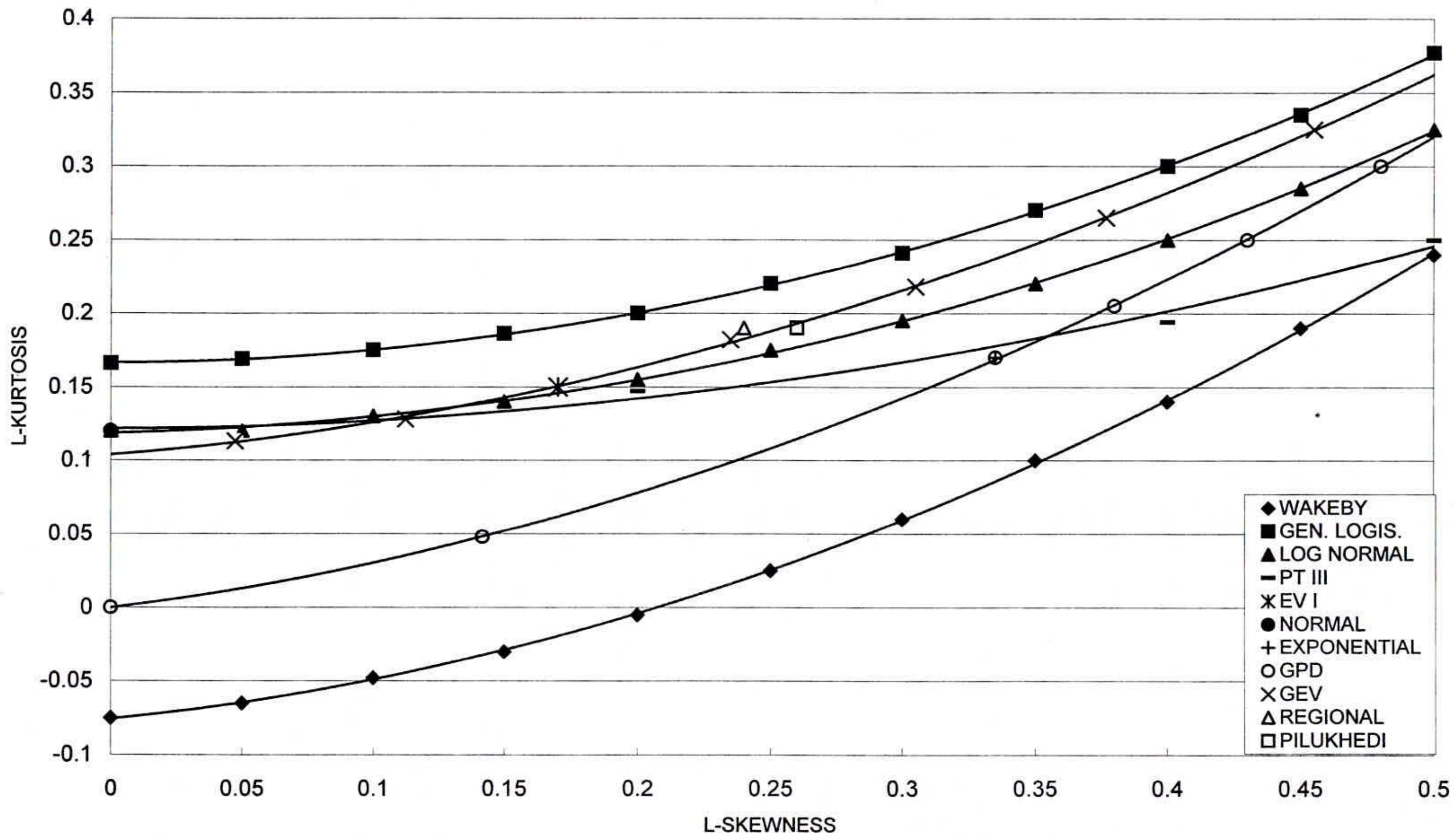

FIG. 5.1: L-MOMENT RATIO DIAGRAM

5.5.3 Goodness of fit measure based on L-kurtosis

In the case of goodness of fit measure based on L-kurtosis, Z-values for different distributions used in the regional flood frequency modelling have been computed using repeated simulation. The values of Z for different distributions are given in Table 5.5. Out of all the distributions used in simulation, the GEV has given the minimum value of Z and hence can be considered the best-fit distribution for the region.

TABLE 5.5: RESULTS OF GOODNESS OF FIT TEST BASED ON L-KURTOSIS

S.N.	DISTRIBUTIONS	Z
1.	EV-I	4.66
2.	**GEV**	**0.47**
3.	LOGISTIC	2.89
4.	GENERALISED LOGISTIC	3.69
5.	GENERALISED PARETO	2.29
6.	NORMAL	7.69
7.	LOG NORMAL	6.59

5.5.4 Z-Statistics

Z-statistics for various distributions have been computed and the values of Z_{LCV}, Z_{LCK} and Z_{LCS} for each distribution have been calculated. The GEV distribution with the minimum overall Z-statistics can be considered the best-fit distribution for the region.

All the results for selection of bast-fit distribution based on L-moments and other tests shows that the GEV distribution may be the distribution, which can be used for computation of probable flow at any site in the basin. The regional parameters of GEV distribution may be the $u = 0.741$, $\alpha = 0.346$ and k = -0.149. The following regional equation may be used for the region.

$$Q_T = \left[2.322 \left\{ -\ln\left(1 - \frac{1}{T}\right) \right\}^{-0.149} - 1.581 \right] \overline{Q} \qquad \ldots.5.3$$

CHAPTER - 6

CONCLUSIONS

Flood frequency modelling is one of the simplest and widely used applications of statistics in the field of hydrology. In the present study, an attempt has been made to apply annual flood and partial duration series at Pilukhedi of river Parvati. The method of moment, PWM and L-moments have been applied for estimation of parameters. The regional parameters for the region have also been computed to estimate the flood quantiles for any ungauged catchment in the basin. From the analysis of results, following conclusions can be drawn:

- The annual flood series of Pilukhedi at Parvati is random and does not indicate any trend. Hence, this series can be used for probabilistic analysis.
- It may be concluded based on all goodness of fit tests that the Generalised Extreme Value distribution may be the best-fit distribution for Pilukhedi. The flood quantile at any return period can be computed using following equation.

$$Q_T = 4406.44 * \left(-\ln\left(1-\frac{1}{T}\right)\right)^{-0.135} - 3419.02 \qquad \ldots 6.1$$

- Different parameter estimation techniques of parameter estimation have been critically evaluated and it may be concluded that the L-moment method may be the most efficient, simple and less biased.
- The L-moment ratio diagram can be used as a simple tool to compare many distributions at a time. For the goodness of fit tests, the other methods of L- moments supported with simulation techniques are found very useful especially in case of regional flood frequency analysis.

- The GEV distribution may be considered as the best fit regional distribution for primary estimation of likely occurrence of flood at any ungauged site in the basin. The flood quantiles can be computed using following equation.

$$\overline{Q} = 3.097 * A^{0.785} \qquad \ldots.6.2$$

$$Q_T = \left[2.322 \left\{ -\ln\left(1 - \frac{1}{T}\right) \right\}^{-0.149} - 1.581 \right] \overline{Q} \qquad \ldots.6.3$$

- As only 5 to 6 years data were available for other two sites in the region for computation of regional parameters, it is recommended that these parameters should be revised with more runoff data of other sites of river Parvati, its tributaries and other nearby river systems of homogeneous region.

APPENDIX – I

FLOOD QUANTILE ESTIMATION USING PWM

Estimation of parameters and flood quantiles for different distributions used in the analysis are given below:

1. EV-I DISTRIBUTION

Inverse from of EV-1 distribution is given as,

$$X = u + \alpha\ (-\ln\ (-\ln F)) \quad \text{....(1)}$$

Parameter estimates u and α is given by:

$$\alpha = (2M_{110} - M_{100})/\ln 2 \quad \text{....(2)}$$

$$u = M_{100} - 0.57722 * \alpha \quad \text{....(3)}$$

T year return flood is given by:

$$X_T = u - \alpha \ln\ (-\ln\ (1 - \frac{1}{T})) \quad \text{....(4)}$$

2. GENERAL EXTREME VALUE DISTRIBUTION (GEV)

Jenkinsom (1955) developed the GEV distribution as a generalization of three extreme value distribution EV-1, EV-2, and EV-3. The cumulative density function F(x) is given by

$$F(x) = \exp\left\{-\left[1 - k(\frac{x-u}{\alpha})\right]^{1/k}\right\} \quad \text{....(5)}$$

Inverse form of distribution is given by:

$$x = u + \frac{\alpha}{k}\left[1 - (-\ln F)^k\right] \quad \text{....(6)}$$

Here u, α and k are location, scale and shape parameters respectively. The Parameter u, α and k are obtained using PWMs in following ways

$$k = 7.8590C + 2.9554C^2 \quad \text{....(7)}$$

$$\text{Where, } C = \frac{2M_{110} - M_{100}}{3M_{120} - M_{100}} - \frac{\ln 2}{\ln 3} \quad \text{....(8)}$$

$$\alpha = \frac{(2M_{110} - M_{100})k}{\Gamma(1+k) * (1 - 2^{-k})} \quad \text{....(9)}$$

$$u = M_{100} + \alpha\ [\Gamma(1+k) - 1]\ /\ k \qquad ....(10)$$

The T year return flood is given by:

$$X_T = u + \alpha \left[1 - (-\ln(1 - \frac{1}{T}))^k\right] / k \qquad ....(11)$$

3. WAKEBY DISTRIBUTION

Houghton (1978) first introduces the Wakeby distribution. A random variable X is said to be distributed as Wakeby if,

$$X = m + a\ [1 - (1 - F)^b] - c\ [1 - (1 - F)^{-d}] \qquad ....(12)$$

a, b, c, d and m are five parameters of Wakeby distribution. In Wakeby-4 parameter distribution m is assumed to be zero. Wakeby distribution in reparameterised form (Hosking 1986) can be expressed as:

$$x = \xi + \frac{\alpha}{\beta}[1 - (1 - F)^\beta] - \frac{\gamma}{\delta}[1 - (1 - F)^{-\delta}] \qquad ....(13)$$

There are two distinct advantages of this distribution.

(i) The right and left-hand side of the distribution can be modeled separately. The parameter a and b govern the left hand trail (low flows) while parameters c, d and m govern the right hand trail (high flows).

(ii) This distribution can explain some of the separation effects (Metals et al. 1975) which other distribution cannot.

Landwehr et al. (1979) have given an efficient algorithm based on PWMs for the estimation of the parameters of Wakeby-4 parameters and Wakeby-5 parameters distributions. Hosking (1986) modified this algorithm. The revised procedure is as follows.

1. Obtain $M_{(k)} = M_{10k}$ for k = 0, 1,2,3,4

   Case (i) $\xi \neq 0$ (5 parameter Wakeby)

2. Determine parameter estimates from appropriate equations in Table 2. Test for error conditions as given in Table 1. If any held go to step 3.

   Case (ii) $\xi \neq 0$ (4 parameter Wakeby)

3. Taking $\xi = 0$, find parameter from the appropriate equations and apply cheek as per Table 1, if successful, done otherwise Wakeby distribution fails.

TABLE – 1: CONDITIONS TO BE SATISFIED BY WAKEBY DISTRIBUTION PARAMETERS (IN HOSKING'S NOTATION)

No.	Condition	Explanation
1.	$\beta > -1$ and $\delta < 1$	Necessary for mean to To exit
2.	$\beta + \delta$ or $\beta = \gamma = \delta = 0$	Necessary to ensure the uniqueness of x and F
3.	$\mu\ \alpha = 0$ than $\beta = 0$	
4.	If $\gamma = 0$ than $\delta = 0$	
5.	$\gamma \geq 0$	These two in conjunction with 2,3 & 4, ensure That x(f) does define proper probability distribution.
6.	$\alpha + \gamma \geq 0$	

TABLE – 2: SPECIFIC SOLUTION OF WAKEBY PARAMETERS

Parameters		Expression
z_1, z_2	=	$\dfrac{(N_3C_1 - N_1C_3) \pm \left[(N_1C_3 - N_3C_1)^2 - (N_1C_2 - N_2C_1)(N_2C_3 - N_3C_2)\right]^{1/2}}{2(N_2C_3 - N_3C_2)}$
β	=	Max (z_1, z_2)
δ	=	Min (z_1, z_2)
ξ	=	$[\{3\} - \{2\} - \{1\} + \{0\}]/4$
α	=	$\dfrac{(\beta+1)(\beta+2)}{(\beta+\delta)}\left(\dfrac{\{1\}}{2+\beta} - \dfrac{\{0\}}{1+\beta} - \xi\right)$
γ	=	$\dfrac{(1-\delta)(2-\delta)}{(\beta+\delta)}\left(\dfrac{\{1\}}{2+\delta} - \dfrac{\{0\}}{1+\delta} - \xi\right)$
if ξ	=	0
N_{4-j}	=	$-(3)^j M_{(2)} + (2)^{1+j} M_{(1)} - M_{(0)}$
C_{4-j}	=	$-(4)^j M_{(3)} + 2(3)^j M_{(2)} - (2)^j M_{(1)}$
For ξ	$\neq$	0
N_{4-j}	=	$(4)^j M_{(3)} + (3)^{1+j} M_{(2)} + 3(2)^j M_{(1)} - M_{(0)}$
C_{4-j}	=	$(5)^j M_{(4)} - 3(4)^j M_{(3)} + (3)^{1+j} M_{(2)} - (2)^j M_{(1)}$
$\{k\}$	=	$(k+1)(k+1+\beta)(k+1-\delta) M_{(k)}$
		$k = 0, 1, 2, 3, 4$

APPENDIX - II

FLOOD QUANTILE ESTIMATION USING L-MOMENTS

The details of parameter estimation for different distributions are given below:

1. EV-I DISTRIBUTION

L- moments of EVI distribution are given by

$$\lambda_1 = u + r\alpha \quad \text{....(1)}$$

$$\lambda_2 = \alpha \ln 2 \quad \text{....(2)}$$

$$\tau_3 = 0.1699 \quad \text{....(3)}$$

$$\tau_4 = 0.1504 \quad \text{....(4)}$$

Where r is Euler's constant = 0.57721

Equating sample L-moments estimates l_1, l_2, t_3 and t_4 with population L-moments we obtain parameters of distribution, as given below:

$$\alpha = l_2/\ln(2) \quad \text{....(5)}$$

$$u = l_1 - r\alpha \quad \text{....(6)}$$

2. GEV DISTRIBUTION

L-moments of GEV distribution are

$$\lambda_1 = u + \alpha\,[1 - \Gamma(1-K)]/k \quad \text{....(7)}$$

$$\lambda_2 = \alpha\,(1-2^{-k})\,\Gamma(1+k)/k \quad \text{....(8)}$$

$$\tau_3 = 2(1-3^{-k})/(1-2^{-k}) \quad \text{....(9)}$$

$$\tau_4 = ((1-6*2^{-k} + 10*3^{-k} - 5*4^{-k})/(1-2^{-k}) \quad \text{....(10)}$$

Parameter estimation via L-moments for GEV distribution is given as:

$$k = 7.8590\,z + 2.9554z^2 \quad \text{....(11)}$$

$$\text{Where, } z = 2/(3+t_3) - \frac{\ln 2}{\ln 3} \quad \text{....(12)}$$

$$\alpha = l_2k/((1-2^{-k})\,\Gamma(1+k) \quad \text{....(13)}$$

$$u = l_1 + \alpha\,(\Gamma(1+k) - 1)/k \quad \text{....(14)}$$

3. LOGISTIC DISTRIBUTION

This is special case of Generalised Logistic distribution with k being zero. The cumulative distribution function of Logistic distribution is given by

$F(x) = 1/(1 + \exp(-(x - u)/\alpha))$ ....(15)

Where u and α are location a scale parameters respectively.

Inverse from of the distribution is given by,

$$X = u + \alpha \ln \left\{ \frac{F}{1-F} \right\} \quad ....(16)$$

L-moments of Logistic distributions are

$\lambda_1 = u \quad \lambda_2 = \alpha \quad \tau_3 = 0 \quad \tau_4 = 1/6$ ....(17)

Parameter estimates via L-moments are found as

$\alpha = l_2$ ....(18)

$u = l_1$ ....(19)

4. GENERALISED LOGISTIC DISTRIBUTION

The cumulative distribution function of Generalised Logistic Distribution (GLOG) can be written as

$$F(x) = 1/(1 + (1 - k(x-u)/\alpha)^{1/k}) \qquad k \neq 0 \quad ....(20)$$

$$= \frac{1}{1+\exp(-(x-u)/\alpha)} \qquad k = 0 \quad ....(21)$$

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

Inverse from the distribution is given as:

$$X = u + \alpha \left[1 - \{(1-F)/F\}^k\right]/k \quad ....(22)$$

L-moments of Generalised Logistic distribution are given below

$\lambda_1 = u + \alpha \{1 - \Gamma(1+k)\Gamma(1-k)\} / k$ ....(23)

$\lambda_2 = \alpha \{\Gamma(1+k)\Gamma(1-k)\}$ ....(24)

$\tau_3 = -k$ ....(25)

$\tau_4 = (1 + 5k^2)/6$ ....(26)

Using L-moments Parameters have been found as

$k = -t_3$ ....(27)

$\alpha = l_2 / \Gamma(1+k)\Gamma(1-k)$ ....(28)

$u = l_1 + (l_2 - \alpha)/k$ ....(29)

5. GENERALISED PARETO DISTRIBUTION

The cumulative distribution function of Generalised Pareto (GPD) distribution (Hosking and Wallis, 1987) can be written as

$$F(x) = 1- [1-k(x-u)/\alpha]^{1/k} \qquad ....(30)$$

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

Inverse form of Generalised Pareto distribution is given as:

$$X = u + \alpha \{1-(1-F)^{k}\}/k \qquad ....(31)$$

L-moments of Generalised Pareto distribution are given as:

$$\lambda_1 = u + \alpha / (1+k) \qquad ....(32)$$

$$\lambda_2 = \alpha / (1+k)(2+k) \qquad ....(33)$$

$$\tau_3 = (1-k) / (3+k) \qquad ....(34)$$

$$\tau_4 = (1-k)(2-k) / (3+k)(4+k) \qquad ....(35)$$

Parameters are found as:

$$k = \left\{\frac{1-3t_3}{1+t_3}\right\} \qquad ....(36)$$

$$\alpha = l_2 (1+k)(2+k) \qquad ....(37)$$

$$u = l_1 \left\{\frac{\alpha}{1+k}\right\} \qquad ....(38)$$

With lower bound u set to zero distribution reduces two-parameter distribution. In that case parameters are found as,

$$k = l_1 / l_2 - 2 \qquad ....(39)$$

$$\alpha = (1+k)\, l_1 \qquad ....(40)$$

6. NORMAL AND LOG NORMAL DISTRIBUTION

a. Normal distribution

$$F = \phi\left(\frac{x-\mu}{\sigma}\right) \qquad ....(41)$$

Its L-moment (Hosking, 1990) are given as

$$\lambda_1 = \mu,\ \lambda_2 = \frac{\sigma}{\sqrt{\pi}},\ \tau_3 = 0 \text{ and } \tau_4 = 0.1226 \qquad ....(42)$$

Parameters can be estimated as

$\sigma = \sqrt{\pi}\, l_2$ ....(43)

$\mu = l_1$ ....(44)

b. Log Normal distribution:

$$F = \phi\left(\frac{\ln(x-u)-\mu}{\sigma}\right) \qquad ....(45)$$

Population L-moments of Log Normal distribution (Hosking, 1990) are

$$\lambda_1 = u + \exp\left(\mu + \frac{\sigma^2}{2}\right) \qquad ....(46)$$

$$\lambda_2 = \exp\left(\mu + \frac{\sigma^2}{2}\right) \text{erf}\left(\frac{\sigma}{2}\right) \qquad ....(47)$$

$$\tau_3 = 6\pi^{-1/2} \int_0^{\sigma/2} \text{erf}\left(\frac{x}{\sqrt{3}}\right) \exp(-x^2)\, dx / \text{erf}\left(\frac{\sigma}{2}\right) \qquad ....(48)$$

Parameters of Log Normal distribution through L-moments are found as

$$\sigma = 0.999281z - 0.0016118z^3 + 0.000127z^5 \qquad ....(49)$$

$$\text{Where } z = \ln\sqrt{\frac{8}{3}}\, \phi^{-1}\left(\frac{1+t_3}{2}\right) \qquad ....(50)$$

$$\mu = \ln\left\{l_2 / erf(\sigma/2)\right\} - \frac{\sigma^2}{2} \qquad ....(51)$$

$$u = l_1 - \exp\left(\mu + \frac{\sigma^2}{2}\right) \qquad ....(52)$$

Where erf is error function and is given as:

$$\text{erf}\, X = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt \qquad ....(53)$$

Error function can be rationally approximated as given by Abramowitz and Stegun (1970). Eq.7.1.25, page 299 as:

$$\text{erf}X = 1 - (a_1 t + a_2 t^2 + a_3 t^3)\, e^{-x^2} + \varepsilon(x) \qquad ....(54)$$

$$|\varepsilon(x)| \leq 2.5 \times 10^{-5}$$

Where, $t = \frac{1}{1+px}$

with $p = 0.47047$, $a_1 = 0.3480242$

$a_2 = -0.0958798$, $a_3 = 0.7478556$

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