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REGIONAL FLOOD FREQUENCY ANALYSIS

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ABSTRACT

Whenever annual peak flow data are available or the historic recorded annual peak flow data are very short at a site, there are several methodologies available for the estimation of flood at that site using flood frequency analysis approach. A number of studies have appeared to-date which apply some sort of regionalisation in flood frequency analysis for such situations. Some methods of importance are the USGS Index Flood Method, parameter regionalisation method, methods based on regression equations and the region curve method recommended in U.K. flood studies report.

This report describes the study of regional flood frequency analysis carried out for the region of subzone 3-d of Mahanadi basin with annual peak flood series data available at 18 stations for varying number of years. The following three methods were used for the analysis: (i) the Index Flood method,(ii) the method based on normalisation of peak flood data of different sites with reference to then respective site mean values and combine these normalized values to form a single series for regional analysis,and(iii) the method based on regional parameters of Wakeby distribution and James-Stein corrected means. Except the first method, the other two are relatively unknown in the area of regional flood frequency analysis. Out of 18 bridge sites where data are available, the data of 15 sites were analysed and the data of remaining 3 sites were kept as independent data for verifying the results obtained from the analysis. The study

indicates comparable performance of the later two methods with that of Index-Flood method in estimating the peak floods of ungauged catchments. However, further studies are warranted on these two methods .

1.0 INTRODUCTION

Reliable estimates of the magnitude and frequency of occurrence of floods are essential to the proper design of hydraulic structures across rivers as well as to the delination of flood risk areas. One of the common method of estimating the design flood for the design of bridges and culverts especially in small catchments, is by the use of frequency analysis of annual peak flood data recorded at site under consideration. "Flood frequency analysis for a river basin site with a long record can be based almost exclusively on that record alone. Unfortunately many of the streams in small catchments have not been gauged or very scanty data are available at the site. When only a short record or no record is available at a site, the need for procedures for augmenting site specific hydrologic information with regional information arises in order to improve upon or stabilise site specific estimates or to make inference at ungauged river basin sites. The need for such procedures is particularly great in the estimation of extreme hydrologic events where a combination of limited site data and need for inference in the tails of probability distributions unite to destabilise such estimates.

In regional frequency analysis, attempts are made to define a region that is hydrologically homogeneous in terms of the characteristics being studied. Then hydrologic data from several locations within this region are combined for regional frequency analysis. There are many ways that regional studies can be made. Some methods of importance are the USGS Index-Flood method (Dalrymple,1960), parameter regionalisation method (USWRC,1977), methods based on regression equation(Benson, 1962), and the region curve method recommended in U.K.flood studies report (NERC,1975).

This report describes a case study of regional flood frequeny analysis carried out for the region of Mahanadi basin(subzone 3-d) with annual peak flood series data available at 18 bridge sites for varying numbers of years. The following three methods were used for the analysis:

(i) The Index-Flood method

(ii) The method based on normalization of peak flood data of different sites with reference to the respective site specific mean values and combine these normalized values to form a single series for regional analysis.

(iii) The method based on regional parameters of Wakeby distribution and James-Stein corrected means. Except the first method, the other two are relatively unknown methods in the area of flood frequency analysis. It may be inferred from the study that the later two methods are comparable with that of Index-Flood method in estimating the peak floods of various return periods at ungauged catchments indicating that further studies are warranted on these two methods.

Review of relevant literature in the area of regional flood frequency analysis, description of the methodologies adopted, data used, analysis procedure and discussion of results are presented in the following sections.

2.0 REVIEW

During the first two decades of the twentieth century, the data acquired with the expansion of stream gauging activities were used to advantage by the early practioners of statistical methods(Jarvis,1936). This made it possible to relate the peak discharge with the corresponding return period of T-years. Given the Q_T value, the flood corresponding to T-year return period, the prediction of flood flows for flows for ungauged river basins within the same region may be approached in several different ways. For example, separate equations may be derived relating Q_T to catchment characteristics for each return period:

$$Q_T = cA^mB^n \ldots P^r \qquad \ldots.(1)$$

where A, B, ...P are characteristics of the catchment, rainfall etc., which affect the peak flow and c,m,n,..... r are constants. The work of Benson(1962) on the floods corresponding to nine return periods in the north-eastern states of America, and of Rodda (1969) on those associated with 4 return periods in England, Wales and Scottland provide ready examples of this approach. Alternatively, one of the most widely used methods of regionalizing flood estimates is that deviced by the U.S.Geological Survey(USGS) and reported by Dalrymple(1960). The USGS method involves the preparation of two graphs:

(i) A curve based on Gumbel EV-I distribution showing the variation with return periopd of the ratio between the T-year flood and the mean annual flood obtained from graphical fitting of Gumbel EV-I distribution.

(ii) A plot relating the mean annual peak flood of all the sites to the size of the drainage area of the corresponding sites.

The USGS method has been applied in many parts of the world in which the catchment area is adopted as the sole independent variable, relating to the mean annual flood as:

$$\overline{Q} = c A^{m} \qquad \ldots(2)$$

Where $\overline{Q}$ is the mean annual flood by the graphical fitting of Gumbel EV-I distribution to the given annual peak flood series; A, the catchment area, and c and m are constants. The form of the first curve, which is often referred to as the regional growth curve, may be expressed graphically following USGS practice (Cole,1966) or by means of equations similar in form to equation(1) relating the coefficient of variation of observed floods (Nash and Shaw,1966) or the quotient of the T-year flood and the mean annual flood(Gunter,1974) to catchment characteristics.

The regional flood frequency analysis for the British Isles reported in the Flood Studies Report (NERC,1975), employed a similar approach to that described by Darymple (1960). However, the procedure for estimation of region curve and the relationship between mean annual flood and catchment characteristics is different in the case of method recommended in U.K. flood Studies Report from that of USGS methods.

An application of the Probability Weighted Moment(PWM) technique of parameter estimation to regional flood frequency analysis was proposed by Wallis (1982). The method proposes to combine regional and site specific information by simple averaging and scaling. Moments of the regional distribution are obtained by simple averaging of the respective probability weighted moments at each site. The regional quantile estimate is then obtained by scaling at site estimate by a regional estimate of the mean. This methodology appears to work well for situations where records are extremely short;and streamflow observations are highly skewed and highly kurtotic.

Perumal and Seth (1985) have suggested a regional analysis approach in which the annual peak flood data of each gauging site is normalized with reference to the mean annual flood and based on the assumption that normalized series of different gauging sites are the realizations from a single population. These normalized samples of different length are combined to form a single series. Analysis is performed on this series to estimate the normalized floods of required return periods. The mean annual flood is related to the catchment area as adopted in the Index-Flood method.

Singh and Seth(1985) have suggested the use of Wakeby distribution for regional frequency analysis. In this method, the regional parameters of Wakeby distributions are estimated using the probability weighted moments technique and the catchment area is related with the James-Stein corrected mean (as quoted by Wallis,1982). The regional parameters of Wakeby distribution and James-Stein corrected means are used to estimate floods of different return periods. The results obtained in this study indicate good performance of the procedure adopted for regional frequency analysis.

3.0 STATEMENT OF THE PROBLEM

The main objective of the study is to develop regional relationship based on frequency analysis of annual peak flood series recorded at various gauging sites of a hydrologically homogeneous region, for use in estimating floods of desired return period at river sites of the same region where no annual peak flood series data is available.

4.0 DESCRIPTION OF THE STUDY AREA

The subzone 3-d, Mahanadi basin for which sufficient annual peak flood values are available for small catchments was selected as the study area. The subzone 3-d covers an area of 1,95,000 sq.km. and is located between longitudes of 80^{o} -25' E and 87^{o} E and latitudes of 19^{o} - 15' N and 23^{o}-35'N. It comprises part of Madhya Pradesh Orissa and Bihar States and it is traversed by South-eastern railway system. Figure 1 shows the extent of the subzone, railway lines and location of bridge site concerned with this study. The drainage areas of these sites vary between 17 sq.km. to 1150 sq.km.

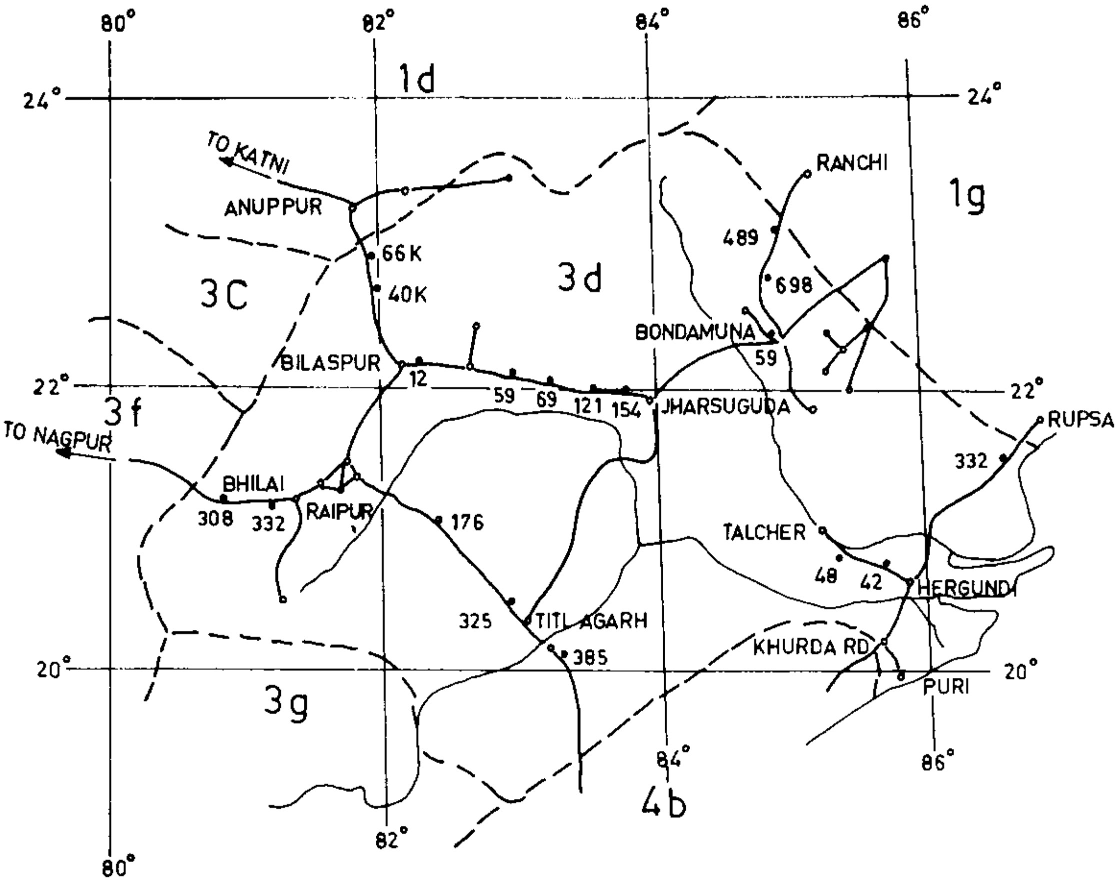

FIG. 1- BRIDGE SITES LOCATED IN SUB ZONE-3d, MAHANADI BASIN

5.0 DATA AVAILABILITY FOR THE STUDY

The annual peak flood series data are available at 18 bridge sites of this zone. These values were computed based on observed peak stage values and the respective stage-discharge curves. Data in respect of years, for which observed peak stage values were missing, have been obtained(Gupta,1983) using the correlation between peak stage values of the concerned site and that of the nearest site for which annual peak records for long period are available. The available and estimated data of 23 annual peak flood series of each of the 18 sites have been presented by Gupta (1983).

6.0 METHODOLOGY

The following three procedures/methodologies were used in this study for regional frequency analysis of flood data:

i) The Index-Flood method

ii) The method based on normalization of peak flood data of different gauging sites with reference to the respective site specific mean values and combine these normalized values to form a single series for regional analysis using power transformation.

iii) The method based on regional parameters of Wakeby distribution and James-Stein corrected means .The description of each procedure is given below:

6.1 Index-Flood Method

Basically, the Index-Flood method(Dalrymple,1960) extrapolates statistical information of runoff events for flood frequency analysis from gauged catchments to ungauged catchments in the vicinity having similar catchment and hydrologic characteristics. The Index-Flood method for estimating design flood of ungauged watersheds consists of eight sequential steps:

1. Select gauged catchments within the region having similar characteristics to the ungauged catchments.
2. Determine time base period to be used for study.
3. Establish flood frequency curves for data at each gauging site using Gumbel EV-I distribution probability paper.
4. Estimate the mean annual flood, $Q_{2.33}$ at each station.
5. Test homogeneity of data
6. Establish the relationship of mean annual flood and catchment characteristics, usually drainage area at each station.

7. Rank ratios of selected return period floods to the mean annual flood at each station, and

8. Compute median flood ratio for each of the selected return period of step(7), multiply by the estimated mean annual flood of the ungauged catchment and plot versus recurrence interval on Gumbel probability paper.

The end result of these eight sequential steps is a flood frequency curve for an ungauged catchment.

6.1.1 Selection of gauged catchments

The first step is to select gauged catchments in the vicinity of the ungauged catchments having similar characteristics. Although the similarity would include characteristics such as average elevation,geology,climate, soil structure etc., the measure of the similarity will be determined by the runoff data in the homogeneity tests (see section 6.1.5)described by Dalrymple(1960), as the runoff from a catchment is the integrated result of all the characteristics of the catchment. Since the effect of one or a combinatioin of several characteristics of a catchment on runoff is not well defined nor quantified, it is reasonable to look only at the statistics of the runoff event to determine homogeneity.

6.1.2 Base period determination

Before the homogeneity of the data can be tested, a time base period of the analysis must be established. The 'time base period', is the longest period of record during which data from each gauging site is utilised. However, missing data poses problem in determining the base period and this problem can be solved using correlation techniques.

6.1.3 Flood Frequency curves

Having established the base period, Flood frequency curve using the ranked annual maximum series and the corresponding plotting position is developed by plotting these points on the Gumbel EV-I probability paper. Care should be taken not to incorporate the estimated missing flood data for developing the frequency curve. These missing flood data have been used only for assigning the plotting position to the observed peak floods according to their rank and not directly used in developing the frequency curve. The data are plotted on Gumbel probability paper with the abscissa being the probability of non-exceedence or exceedence or the reduced variate of EV-I distribution and the ordinate being the magnitude of observed peak floods. Gringorten plotting-position as recommended in the Flood Studies Report(NERC,1975) has been used for plotting the observed peak floods on the Gumbel EV-I probability paper. The Gringortan plotting position for a given probability of non-exceedence is given as:

$$P = \frac{i - 0.44}{N + 0.12} \qquad \ldots(3)$$

where, i is the rank of the flood and N is the sample size.

A straight line is drawn through the plotted points. The suitability of the straight line, fitted for the observations plotted on Gumbel probability paper by eye judgement as envisaged by Dalrymple, is checked by constructing 95% confidence interval for each of the individual predicted value by the fitted relationship. The lower and upper confidence interval respectively are given by the expressions(Haan, 1977).

$$\hat{Q}_{k_1} = \hat{Q}_k - S_{\hat{Q}_k}\, t_{(1-\alpha/2),\,(n-2)} \qquad \ldots(4)$$

$$\hat{Q}_{k_u} = \hat{Q}_k + S_{\hat{Q}_k}\, t_{(1-\alpha/2),(n-2)} \qquad \ldots(5)$$

Where $t_{(1-\alpha/2),(n-2)}$ is the value obtained from t-distribution corresponding to the confidence limit of $(1-\alpha)$ and $(n-2)$ degrees of freedom, and $\hat{Q}_k$ is the predicted value of flood, Q for the given reduced variate of Gumbel EV-I distribution. $\hat{Q}_{k_l}$ and $\hat{Q}_{k_u}$ respectively are the lower and upper level of confidence limits. $S_{\hat{Q}_k}$ is the standard error of $\hat{Q}_k$ which is expressed as (Haan,1977):

$$S_{\hat{Q}_k} = S\,[\,1 + 1/n + (y_k - \bar{y}_k)^2 / \; (y_k - \bar{y}_k)^2\,]^{1/2} \qquad \ldots(6)$$

in which S is the residual standard deviation, y_k is the reduced variate of Gumbel EV-I distribution corresponding to the k^{th} observation and $\bar{y}_k$ is the mean of the reduced variates of all observations at a gauging site.

6.1.4 Determination of mean annual flood

The mean annual flood, which is the Index-Flood, is estimated from the flood frequency curves, determined in step(3) as the flow having an average return period of 2.33 years.

6.1.5 Homogeneity test

The ratio of the 10 year flood to the mean annual flood is the statistic to be used to measure homogeneity of the runoff data from the gauged catchment. The 10 year flood, which is equivalent to the flood magnitude having a probability of non-exceedence of 90 percent, is estimated from the flood frequency curves. Each 10 year flood should be divided by the mean flood to get the 10 year ratio and an average of these ratios should be obtained. For each station of the region the return period corresponding to a discharge equal to the average flood ratio times the mean flood and the length of record in years is computed. If this recurrence interval falls within the envelope curve developed by USGS (Dalrymple,1960) for homogeneity test, the data is regionally homogeneous, and applicable for the analysis. If the return period is not within the domain of the envelope curves, the data is not regionally homogeneous and is eliminated from the analysis.

6.1.6 Relationship of mean annual flood to catchment area

The mean annual flood of an ungauged catchment can be determined from a plot of the log of the drainage area versus the log of the mean annual flood estimated from the developed frequency curve on Gumbel probability paper using observed floods at gauged catchments of the region.

6.1.7. Regional flood frequency relationship

Following the test for homogeneity and determining the relationship between mean annual flood and catchment area, the estimates of peak discharge for selected return periods for each gauging site are computed and they are divided by the respective site specific mean annual flood. The estimated flood ratios corresponding to each selected return period for all stations are to be ranked in ascending or descending order and the median flood for that recurrence interval is noted. Similarly, the median flood ratios for all stations can be computed. These median flood ratios are plotted on the Gumbel EV-I distribution probability paper and this plot forms the regional flood frequency relationship.

6.2 Method Based on Power Transformation

In this method, the annual peak flood series of all the gauging sites of homogeneous region are normalized with reference to the site specific mean annual flood, and flood frequency analysis was carried out on the series obtained after combining the normalized series of each site. Power transformation is used for transforming the combined flood ratio series to near normality (Box and Cox,1964). The flood estimation procedure for ungauged catchments using this methodology involves the following steps:

1) Select gauged catchments within the region having the similar characteristics to the ungauged catchments,

2) Estimate mean annual flood from the observed floods at each station ,

3) Compute the normalized flood series at each gauging site by dividing the observed floods by the corresponding site specific mean value,

4) Test homogeneity of data, based on the USGS method using the mean annual floods of all gauging sites computed from observations instead of $Q_{2.33}$,

5) Establish the relationship between mean annual flood and the catchment area,

6) Combine the normalized flood series of all the gauging sites to form a single series and transform them to near normal distribution using Box-Cox transformation.

7) Perform flood frequency analysis on this transformed series and estimate the normalized flood ratio of desired return period. Multiplication of these ratios by the mean annual flood estimated from step(5) for any ungauged site gives the flood of desired return period.

6.2.1 Determination of mean annual flood

It is computed as the simple arithmatic mean of the observed floods at a gauging site.

6.2.2 Homogeneity test

This method also uses the same technique as the USGS procedure except the observed mean annual flood is used, instead of mean annual flood($Q_{2.33}$) computed based on Gumbel EV-I distribution.

6.2.3 Relationship of mean annual flood to catchment area

The mean annual flood of an ungauged catchment can be determined from a plot of the logarithm of the drainage area versus the logarithm of the mean annual flood estimated from the observation of each gauging site which belong to a hydrologically homogeneous region.

6.2.4 Regional Flood frequency relationship

The variates of annual peak flood series of each site are divided by the site specific annual flood to arrive at the normalized series. This series is assumed independent of catchment characteristics and therefore the normalized series of all the gauged sites are combined together to form a series assumed to be derived from a single population. This combined normalized series is power transformed to near normalization using Box-Cox transformation method (Box and Cox,1964).

The power transformation is achieved using the transformation formula which is given as:

$$Z_i = \frac{Q_i^{\lambda} - 1}{\lambda} \quad \text{when } \lambda \neq 0 \qquad \ldots 7a$$

$$Z_i = \ln (Q_i) \quad \text{when } \lambda \to 0 \qquad \ldots 7b$$

Where Q_i is the observed flood corresponding to ith observation and λ is an exponent.

The Z_i series is considered to be a near normalized series for that λ which reduces the coefficient of skewness (C_s) to nearly zero. The estimate of required return period flood is made in the transformed domain first and then the corresponding estimate in the original domain is arrived by inverse transformation as:

$$Q_T = (Z_T\lambda + 1)^{1/\lambda} \quad (8)$$

where,

Z_T = Estimated variate in the transformed domain with T-year return period,

Q_T = Estimated variate in the original domain with T-year return period

Using this procedure the flood ratios for any desired return period may be estimated and the flood of same return period at any ungauged site can be arrived at by multiplying the flood ratio by the estimated mean annual flood for the given catchment area.

6.3 Method Based on Wakeby Distribution and James-Stein Corrected Means

In this method the Wakeby distribution is used for regional flood frequency analysis. The average values of normalized probability weighted moments are estimated from the normalized probability weighted moments computed from the annual peak flood series of different gauging sites. The regional parameters are estimated using the algorithm suggested by Landwehr et al (1979) based on these averaged normalized values of probability weighted moments. A regression relationship is developed between the computed James-Stein corrected means and the respective catchment areas. This relationship is then used to estimate the James-Stein corrected means for the ungauged catchment. Using this James-Stein corrected means and the regional parameters of Wakeby distribution the floods of desired return periods for an ungauged catchment are estimated. The regional frequency analysis is carried out using this method in the following steps:

1) Select gauged catchments within the region having similar char-

characteristics to the ungauged catchments,

2) Compute James-Stein corrected means for each of the gauged catchment after arranging the flood series at each site in ascending order,

3) Test homogeneity of the sites,

4) Estimate the regional parameters of the Wakeby distribution,

5) Obtain the relationship between James-Stein corrected means and catchment area,

6) Using the regional parameters of Wakeby distribution obtained in step(4) and the James-Stein corrected means, obtained using the relationship of step(5), estimate the flood of desired return period for the ungauged catchment.

6.3.1 Estimation of regional parameters of Wakeby distribution

A random variable, say flood Q_p, is said to be Wakeby distributed, if;

$$Q_p = m + a(1-(1-F)^b) - c\,[1-(1-F)^{-d}] \qquad \ldots(9)$$

where $F = F(Q) = P(Q \leqslant Q_p)$,

and a,b,c,d and m are the parameters for Wakeby distribution.

The regional parameters of Wakeby distribution are estimated based on the concept of probability weighted moment which is defined as:

$$M_{j,k} = \frac{1}{N(J)} \sum_{i=1}^{N(j)} Q_{P_{i,j}} \,(F)\, (1-F_{i,j})^k \qquad \ldots(10)$$

where,

$j = 1,2,\ldots,NS$

$k = 0,1,2,3,4$

$M_{j,k}$ = kth order probability weighted moment for the jth gauging site

NS= Number of gauging sites

N(j) = Number of annual maximum peak floods at jth gauging site

$Q_{p_{i,j}}$ = ith item in the sample of annual maximum peak flows at jth gauging sites, and

$F_{i,j}$ = The probability of non-exceedence for the ith item in the sample of annual maximum peak flows at the jth gauging site and it is evaluated using the plotting position formula (Landwehr, 1979).

$$F_{i,j} = \frac{(i-0.35)}{N(J)} \qquad \ldots(11)$$

The probability weighted moments as expressed by equation(10) are normalized after dividing them by zero order probability weighted moment, which is the sample mean. Therefore, the normalized probability weighted moments may be expressed as:

$$M'_{j,k} = \frac{\sum_{i=1}^{N(j)} Q_{p_{i,j}}(F)\,(1-F_{i,j})^k}{\sum_{i=1}^{N(j)} Q_{p_{i,j}}(F)} \qquad \ldots(12)$$

The average values of normalized probability weighted moments may be estimated using the equation:

$$AM_k = \frac{1}{NS} \sum_{j=1}^{NS} M'_{j,k} \qquad \ldots(13)$$

where AM_k = the average value of normalized probability weighted moments of the order k

A special algorithm suggested by Landwehr et al (1979) is followed for estimating the regional parameters of the Wakeby distribution using the average values of normalized probability weighted moments obtained from equation (13).

6.3.2 Estimation of James-Stein corrected means

The James-Stein corrected means are estimated using the following expressions:

$$JSM_j = SUM1 + ((1-A_j*B_j)*(XB_j-SUM1)) \qquad \ldots(14)$$

$$SUM1 = \sum_{j=1}^{NS} \sum_{i=1}^{N(j)} \frac{Q_{p_{i,j}}}{N(j)*NS} \qquad ...(15)$$

$$A_j = \frac{(NS - 3.0)}{NS*(N(j)-1.0} \qquad ...(16)$$

$$B_j = \frac{SUM2}{N(J)*SUM3} \qquad ...(17)$$

$$SUM2 = \sum_{j=1}^{NS} \sum_{i=1}^{N(j)} (Q_{p_{i,j}} - XB_j) \qquad ...(18)$$

$$XB_J = \frac{1}{N(j)} \sum_{i=1}^{N(j)} Q_{p_{i,j}} \qquad ...(19)$$

$$SUM3 = \sum_{j=1}^{NS} (XB_j - SUM1)^2 \qquad ...(20)$$

where, JSM_j= James-Stein corrected means for jth gauging site, and j=1,2,3,.....NS

Estimates from equation(15) to (20) are required to compute James-Stein corrected means for each gauging site using equation(14).

6.3.3 Homogeneity test

The homogeneity test for this method is made by testing the closeness of normalized probability weighted moments of the first order, computed for each of the site using the observed data. If all site specific normalized first order probability weighted moments are not very much different from the mean of the same, then it may be considered that all the sites are located in a hydrologically homogeneous region.

6.3.4 Relationship between James-Stein corrected means and catchment area

Simple linear regression can be carried out between the log of the James-Stein corrected means of different gauging sites with the log of the catchment areas of corresponding gauging sites, in order to develop a regional relationship of the form given below:

$$JSM_j = a(CA_j)^b \qquad \ldots(21)$$

where

JSM_j = James-Stein corrected means, computed using the procedure described in section 6.3.2, for jth gauging site

CA_j = Catchment area for the catchment of jth gauging site

a and b = Coefficients to be obtained from regression analysis

6.3.5 Estimation of floods for ungauged catchments

The floods of required return period for an ungauged catchment can be estimated using the regional parameters of the Wakeby distribution and the relationship developed in section 6.3.4. First, an estimate for the variate, Q'_T for T-year return period is made using the regional parameters of Wakeby distribution in the following equation:

$$Q'_T = m + a \quad [1-(1-F_T)^b] - c[1-(1-F_T)^{-d}] \qquad \ldots(22)$$

where $F_T = 1-\frac{1}{T} = P(Q'_T \leqslant Q'_P)$ and Q'_T and Q'_P are the normalized floods for T-year return period.

Then the value of Q'_T can be multiplied by the James-Stein corrected means of the ungauged catchment, obtained from the relationship developed in section 6.3.4 to arrive at the estimate of T-year return period flood.

7.0 ANALYSIS

In order to verify the applicability of the regional frequency analysis using the methods discussed herein, only 15 bridge sites data were used for analysis and the preliminary statistics of the data considered for analysis are given in Table 1.

The data of remaining 3 bridge sites were used for verifying the applicability of regional frequency results. The details of these three sites are given below:

Sl.No.	Stream	Br.No.	Drainage Area(Sq.km.)
1.	Lahardonga	59(KGP)	47
2.	Kelo	121	1150
3.	Barai	69	173

Although the data at each site observed were for different durations, Gupta(1982) has adjusted the data base at each site for the base period of 23 years after filling the missing years data by correlating with nearby sites.

7.1 Index-Flood Method

The homogeneity of all the 18 bridge sites located in subzone-3d, Mahanadi basin were tested as discussed in section 6.1.5. The homogeneity test plot using the data of all 18 sites is shown in Figure(2). The computational details to arrive at this plot are given in Tables 2 and 3. The data of each of the 15 sites considered for analysis were plotted on the Gumbel EV-I probability paper after ranking the data in order and assigning the probability of non-exceedence to each of the ranked data

Table 1 : PRELIMINARY STATISTICS OF ANNUAL MAXIMUM FLOOD SERIES DATA CONSIDERED FOR ANALYSIS

Sl. No.	Stream	Bridge No.	Drainage area (sq.km.)	Mean (m^3/sec)	Standard deviation (m^3/sec)	Coefficient of variation	Coefficient of Skewness
1.	Nilagarh	12	665	469	210	0.447	0.851
2.	Barjhora	48	109	157	178	1.136	2.951
3.	Malania	66K	154	314	221	0.721	0.977
4.	Sildha	176	66	59	52	0.878	2.209
5.	Kolera	308	17	44	23	0.516	0.224
6.	Kujanjhor	325	27	37	29	0.778	1.113
7.	Parri	332(NGP)	225	165	134	0.815	0.973
8.	Bisra	698	113	220	131	0.593	0.827
9.	Sagar	40K	115	272	204	0.753	1.781
10.	Sandyl	385	194	124	71	0.574	0.426
11.	Pithakalia	332(KGP)	175	72	59	0.819	1.967
12.	Jetha	59(BSP)	136	221	172	0.777	1.167
13.	Karo	489	823	964	624	0.647	1.544
14.	Ahera	154	58	105	71	0.677	3.446
15.	Barjhora	42	49	69	86	1.252	3.665

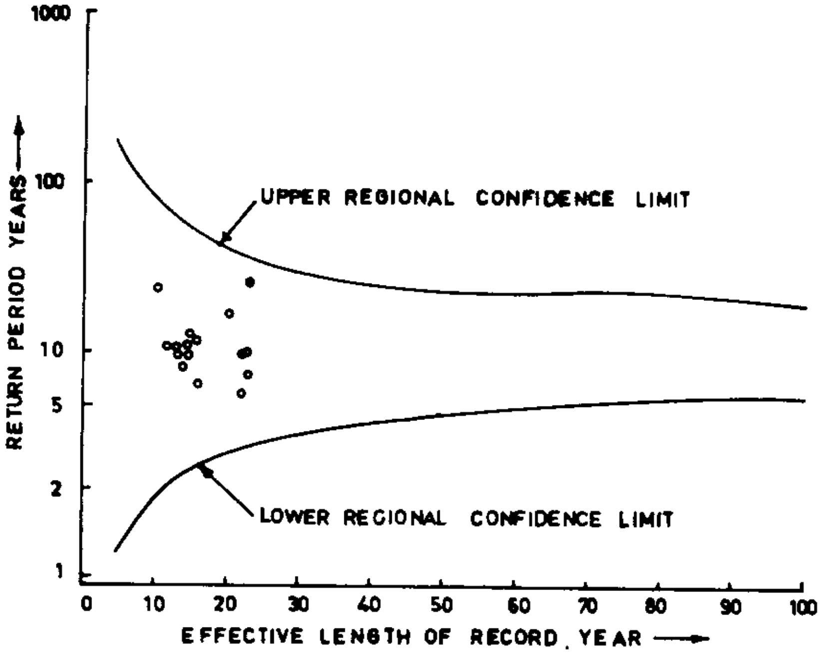

FIG. 2 - HOMOGENEITY TEST GRAPH.

Table 2 : COMPUTATION OF 10 YEAR RETURN PERIOD FLOOD RATIOS FOR THE FIFTEEN BRIDGE SITES OF SUBZONE-3d, MAHANADI BASIN

Sl No.	Br. No.	Stream	Mean annual flood $Q_{2.33}$ (m^3/sec)	10 year flood Q_{10} (m^3/sec.)	$\frac{Q_{10}}{Q_{2.33}} = \alpha$
1	2	3	4	5	6
1	12	Nilagarh	472	748	1.58
2	48	Barjhora	160	378	2.36
3.	66K	Malania	318	616	1.94
4	176	Sildha	60	126	2.11
5	308	Kolera	44	74	1.68
6.	325	Kujanjhor	37	76	2.05
7	332(NGP)	Parri	162	353	2.18
8	698	Bisra	227	409	1.80
9	40K	Sagar	287	560	1.95
10	385	Sandyl	128	229	1.79
11	332(KGP)	Pithakalia	66	126	1.91
12	59(BSP)	Jetha	227	464	2.05
13	489	Karo	997	1921	1.93
14	154	Ahera	131	244	1.86
15	42	Barjhora	59	109	1.86
16	59(KGP)	Lohardonga	66	127	1.92
17	121	Kelo	782	1488	1.90
18	69	Barai	218	350	1.60

MEAN $\bar{\alpha} = 1.92$

TABLE 3 : COMPUTATION OF RETURN PERIODS OF PEAK FLOWS FOR THE FIFTEEN BRIDGE SITES OF MAHANADI BASIN (SUBZONE 3-d) USING MEAN FREQUENCY RATIO ($\bar{\alpha}$) OF 10 YEAR FLOODS

Sl. No.	BR No.	$Q_T = Q_{2.33} \times \bar{\alpha}$ (m^3/sec.)	y_T	T (years)	Period of record available (years)
1	2	3	4	5	6
1	12	906.24	3.205	25.16	23
2	48	307.20	1.704	6.01	22
3	66K	610.56	2.218	9.70	23
4	176	115.20	1.967	7.66	23
5	308	84.48	2.833	17.50	20
6	325	71.04	2.0398	8.20	14
7	332(NGP)	311.04	1.884	7.09	16
8	698	435.84	2.496	12.64	16
9	40K	551.04	2.196	9.50	15
10	385	245.76	2.522	12.96	15
11	332(KGP)	126.72	2.271	10.19	15
12	59(BSP)	435.84	2.049	8.27	14
13	489	1914.24	2.237	9.87	14
14	154	251.52	2.357	11.07	13
15	42	113.28	2.377	11.28	12
16	59(KGP)	126.72	2.236	9.86	22
17	121	1501.44	2.283	10.31	15
18	69	418.56	3.126	23.29	11

using Gringorton plotting position. It is to be noted that the missing data observed by correlation with neighbouring site are used only for the the purpose of plotting position assignment and not for the development of frequency curve. The Gumbel probability plots for all 15 sites considered are shown in Figs.3 to 17 alongwith the 95% confidence bands developed as per the procedure discussed in section 6 . The mean annual floods $Q_{2.33}$ were estimated for all the sites from t probability plots and they were used in the development of the relationship between catchment area and mean annual flood by plotting the log of catchment area with the log of mean annual flood as shown in figure 18. The following relationship has been obtained with the correlation coefficient of r = 0.842

$$Q_{2.33} = 4.11\ (CA)^{0.753} \qquad \ldots(23)$$

From the Gumbel probability plots of each site, the floods of 5,10,20 50,100 and 200 years return period were estimated and the ratios of these floods to the respective site specific mean annual flood, $Q_{2.33}$, were computed. The ratios for 15 sites were arranged in order as given in table 4 and the medium flood ratios for 5,10,20,50,100 and 200 years return period were computed. These ratios were plotted in a Gumbel probability paperand a straight line was drawn through the plotted points. This plot shown in Figure 19 forms the regional frequency curve for the subzone-3d, Mahanadi basin.

The validity of the regional frequency curve was tested by estimating floods of 2,5,10,20,50,100 and 200 years return period for the three test data sites and comparing these estimates with the corresponding estimates arrived by analysing each of the three test bridge sites data in a similar way as was done for each of 15 sites considered for regional analysis.

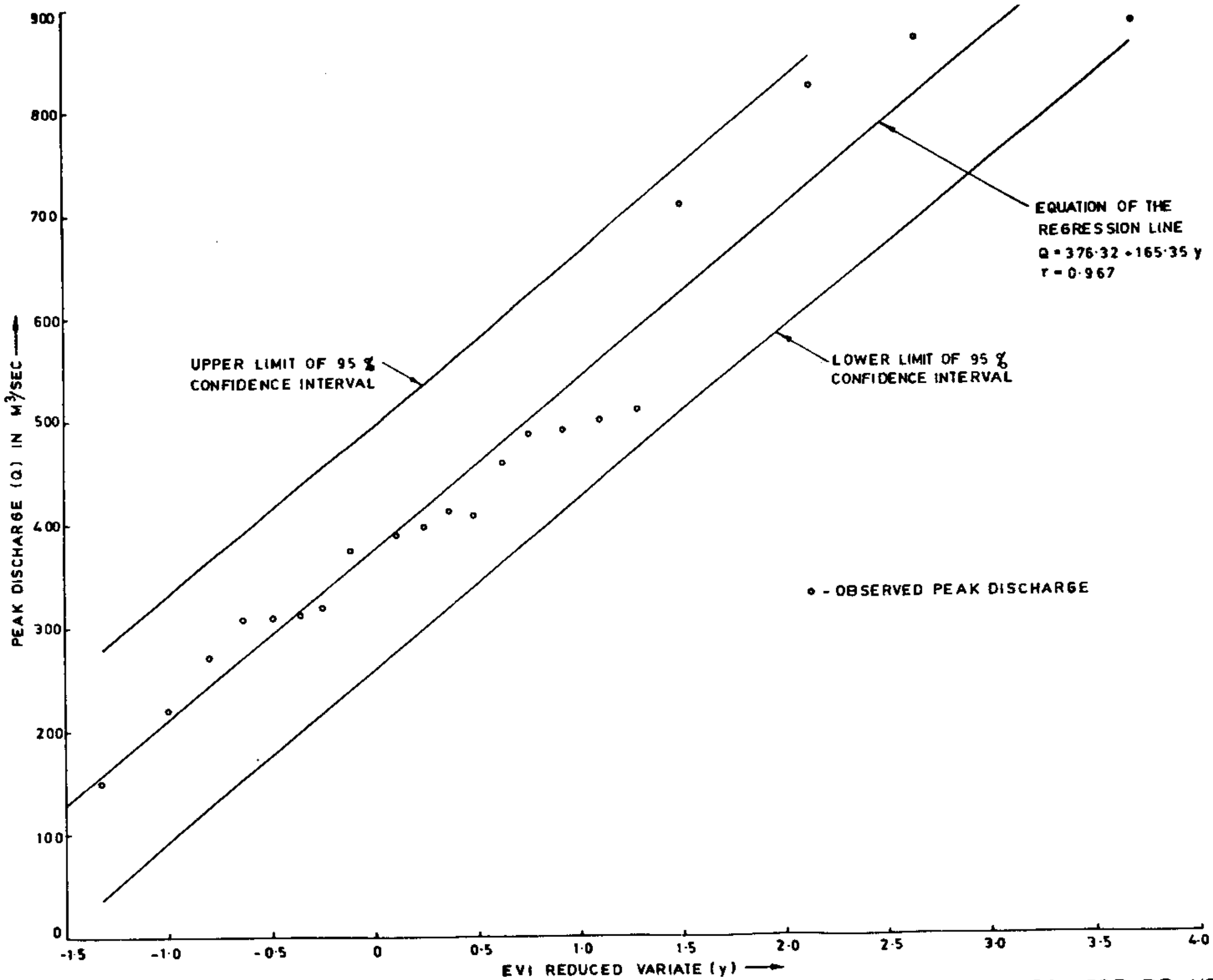

FIG.3-RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO.12

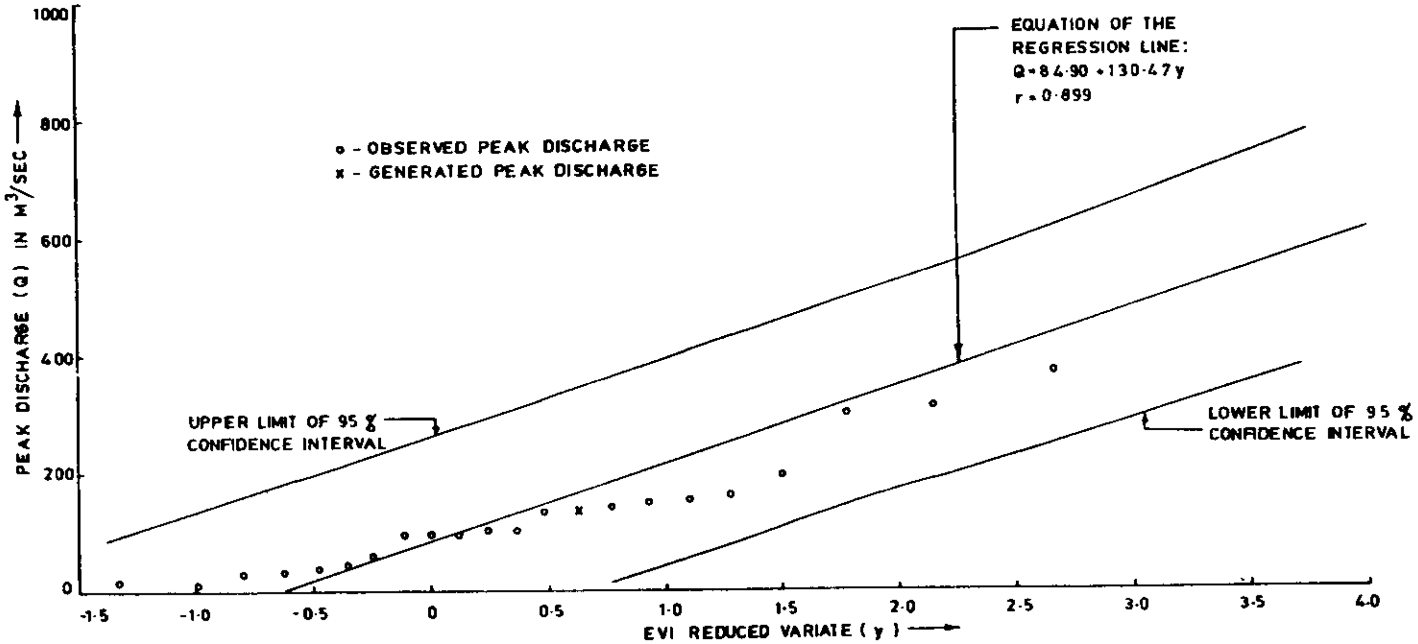

FIG.4 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 48

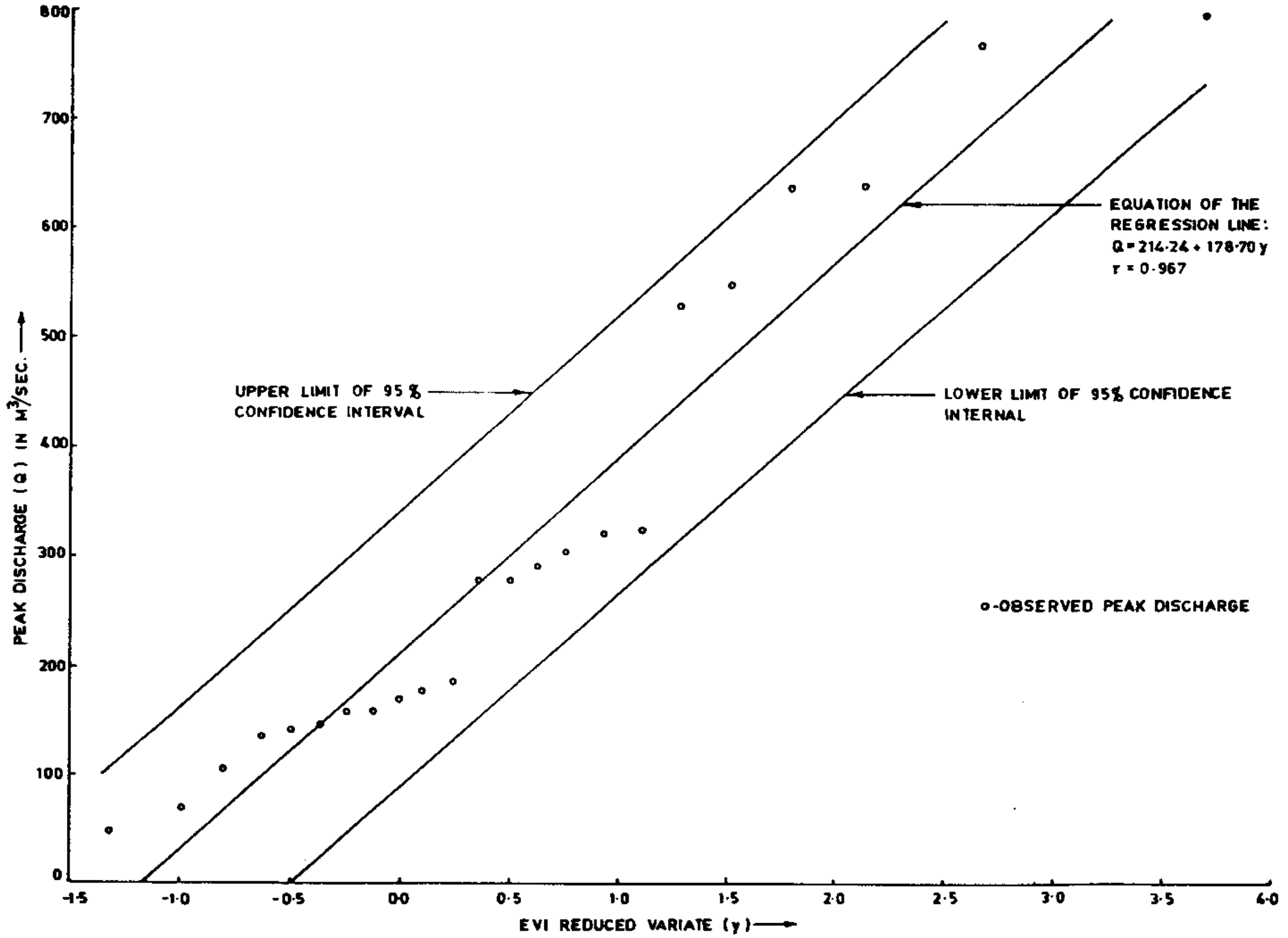

FIG. 5 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 66 K

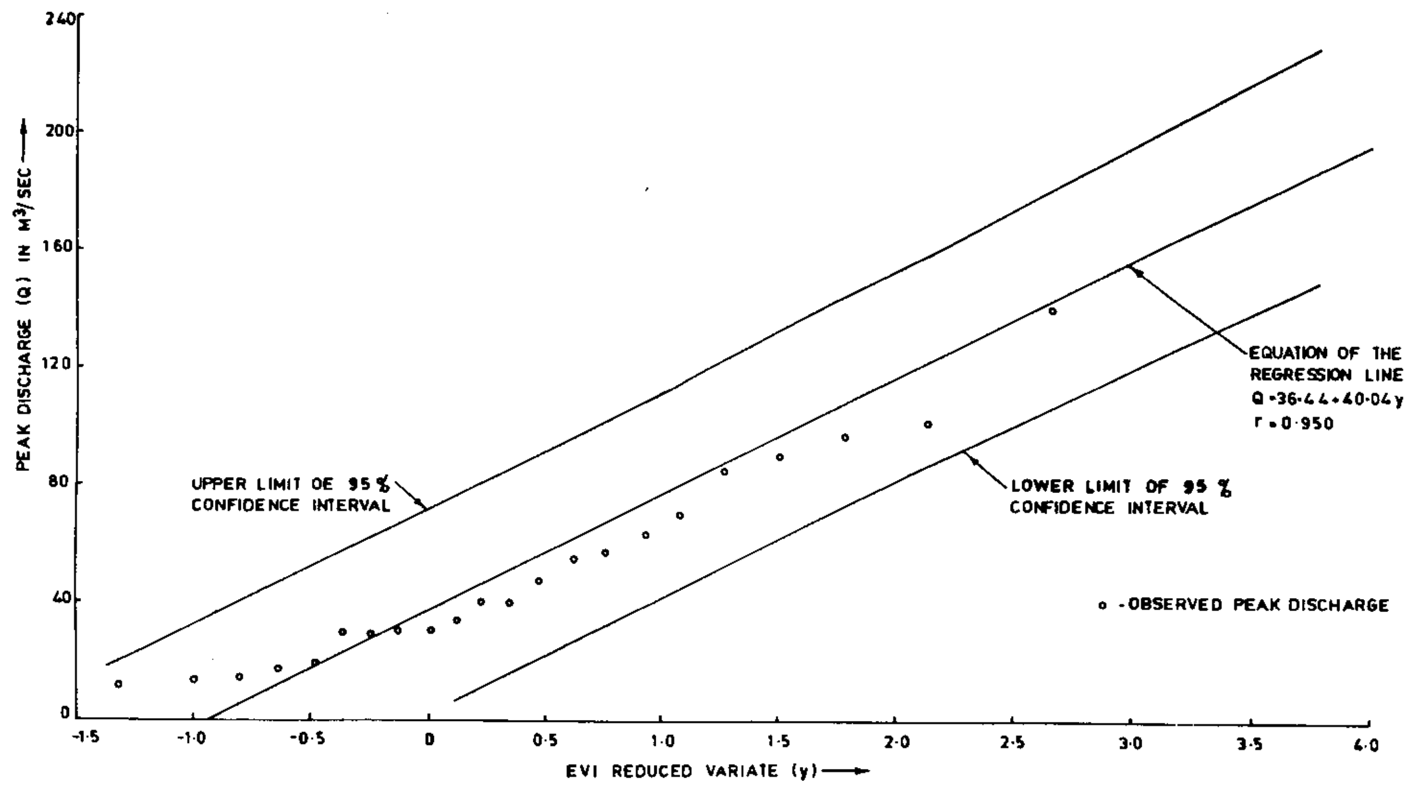

FIG. 6 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 176

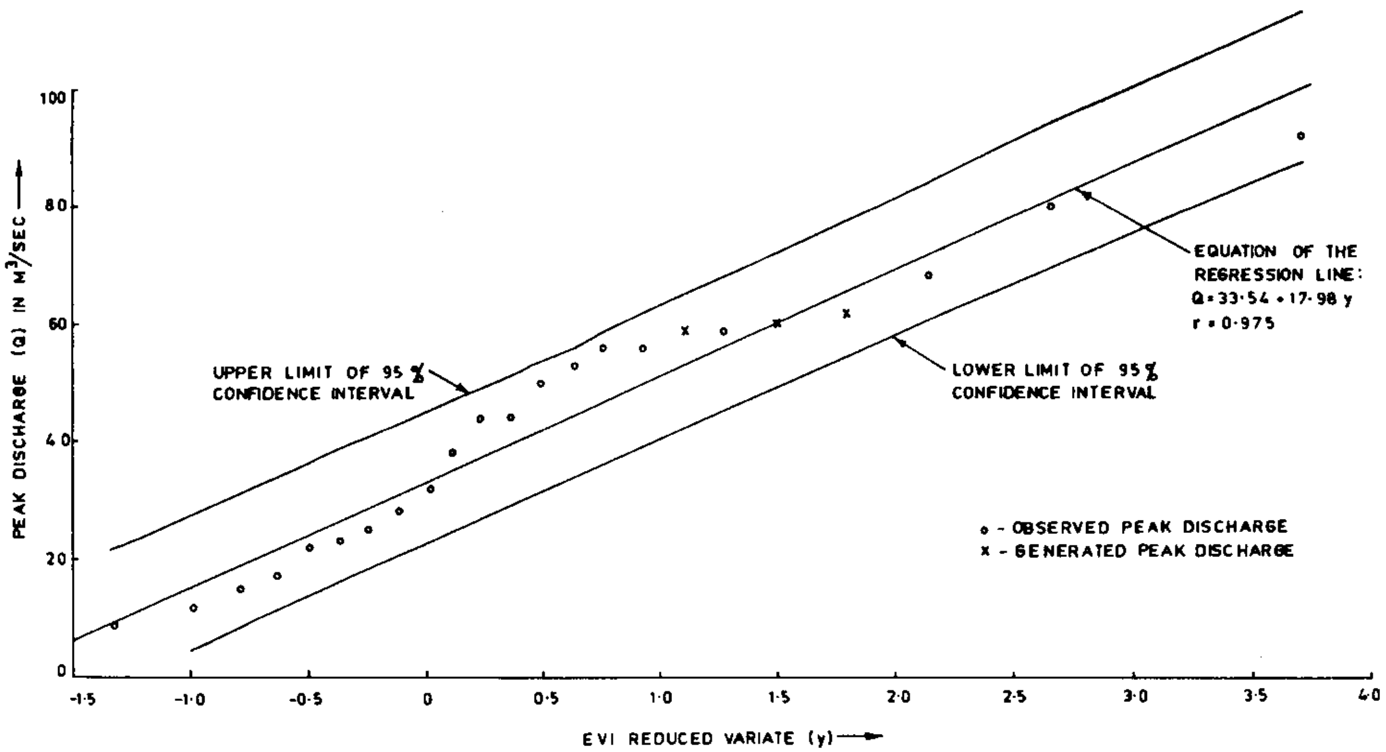

FIG.7 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 308

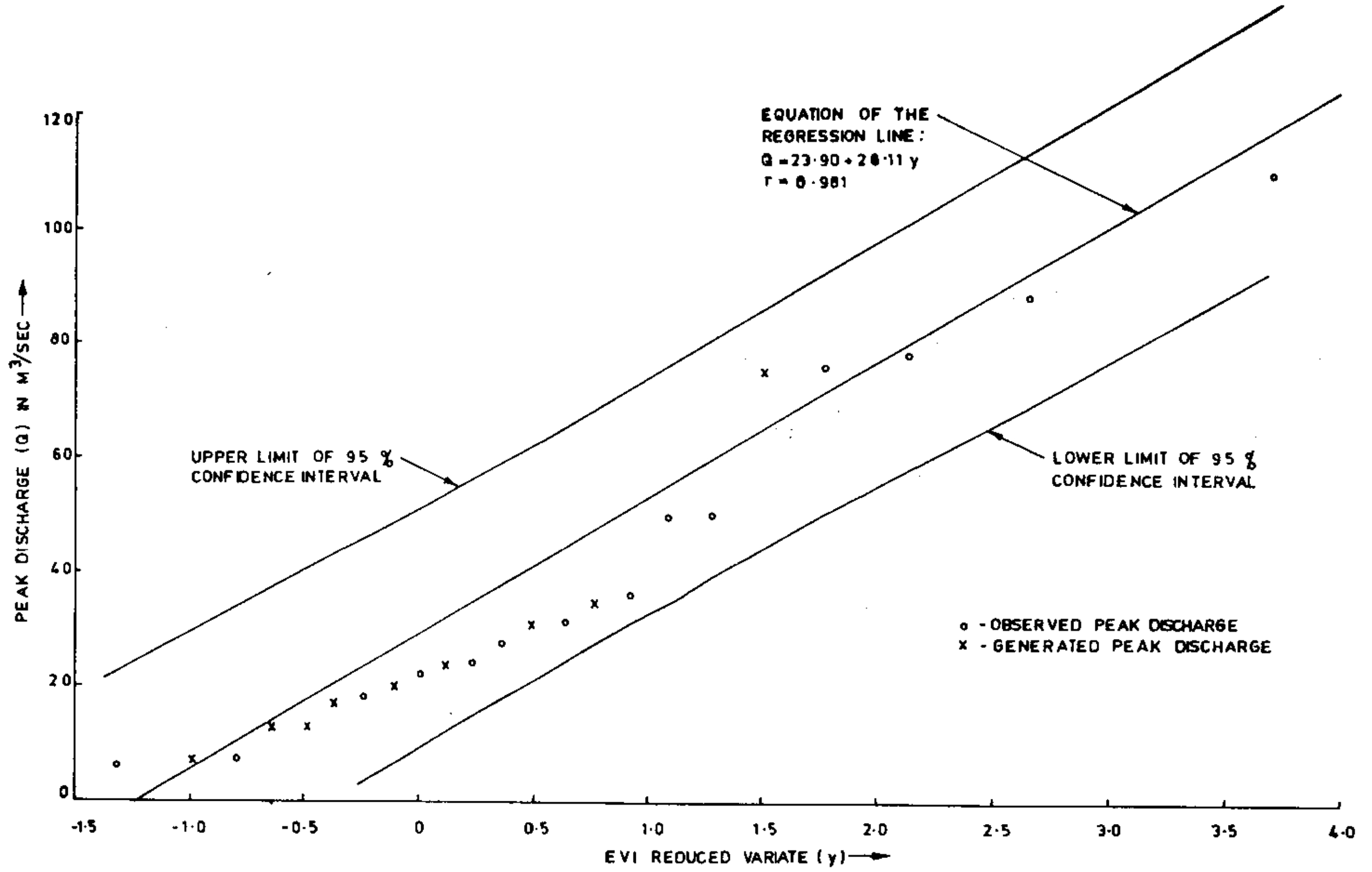

FIG. 8 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 325

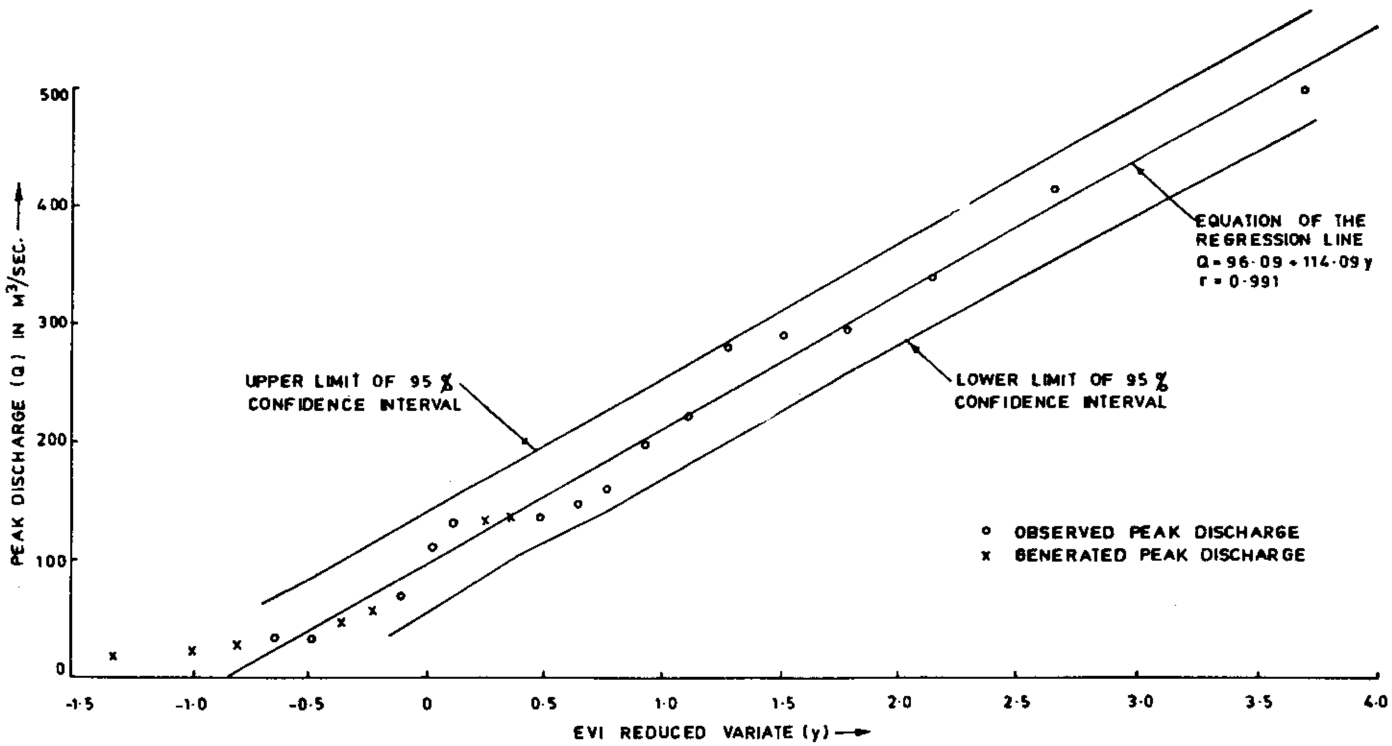

FIG. 9 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 332 (NGP)

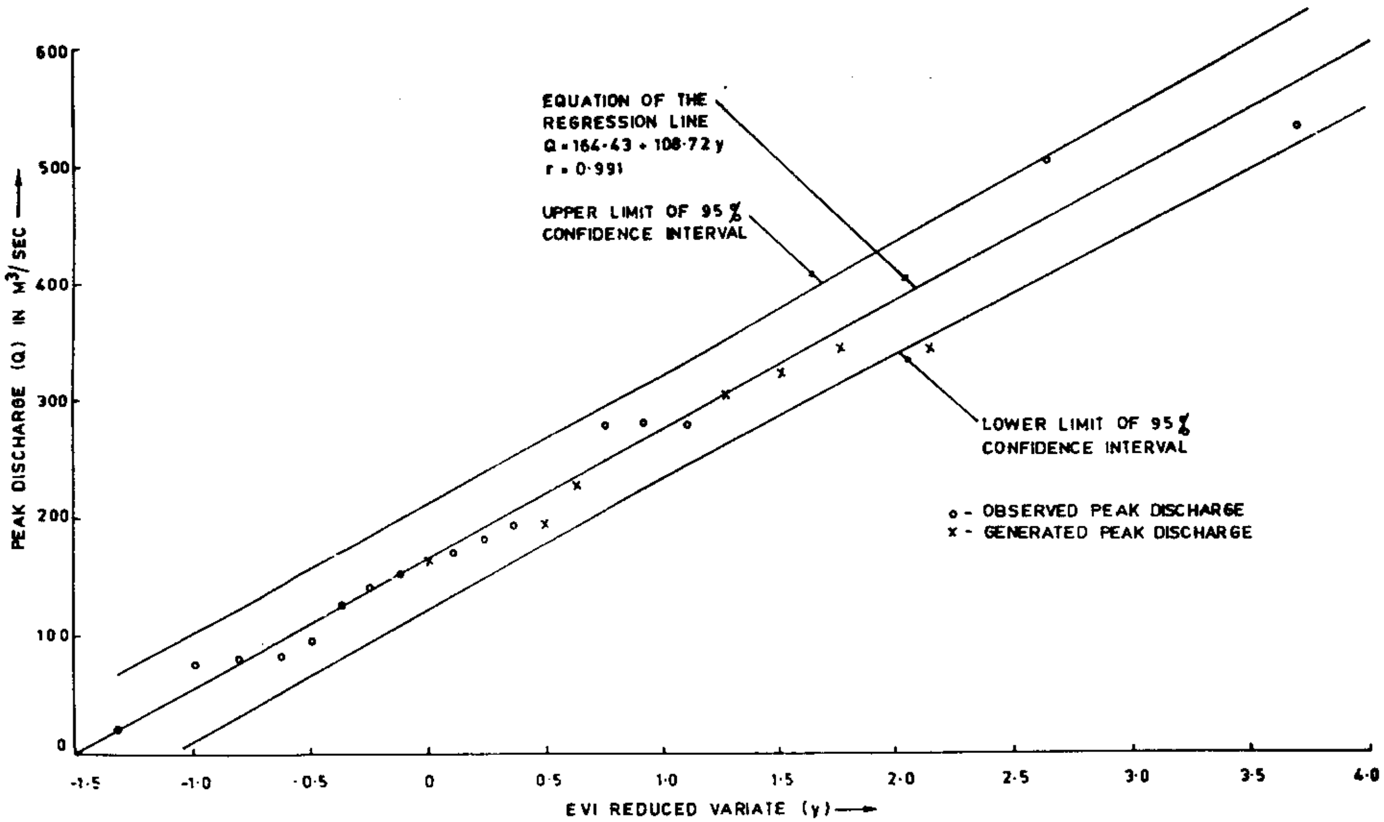

FIG.10- RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 698

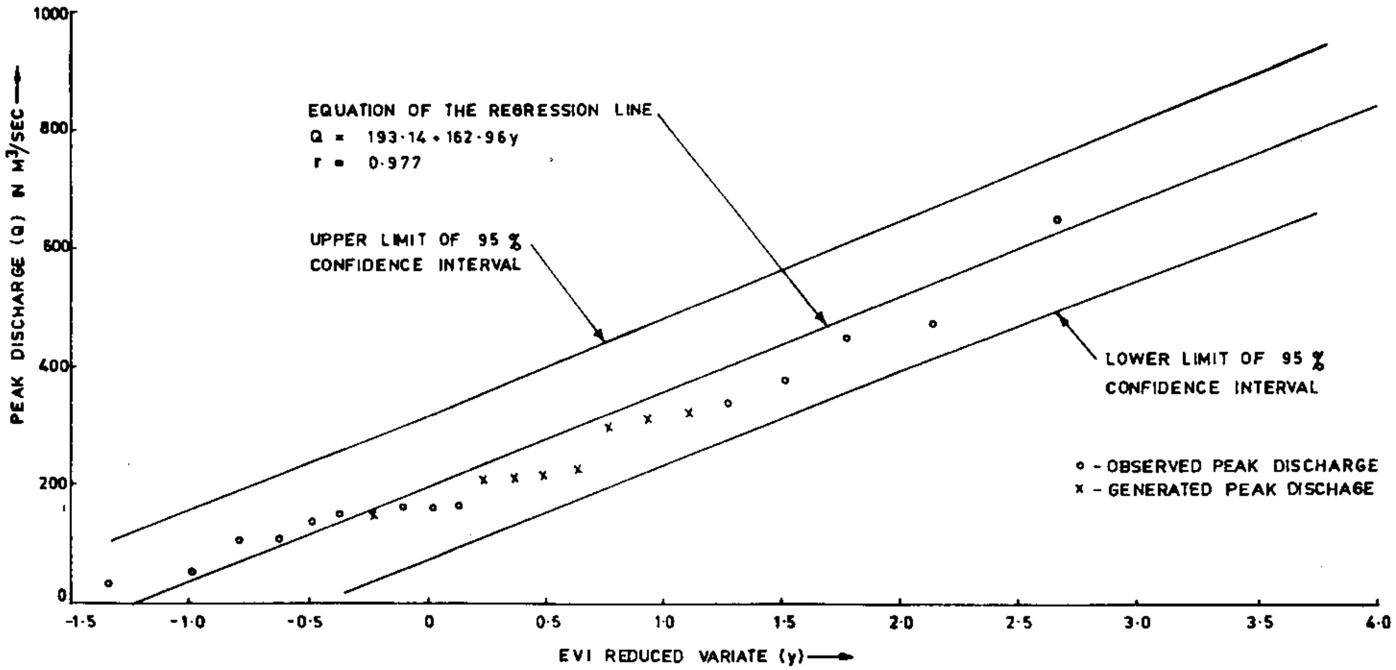

FIG.11 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 40 K

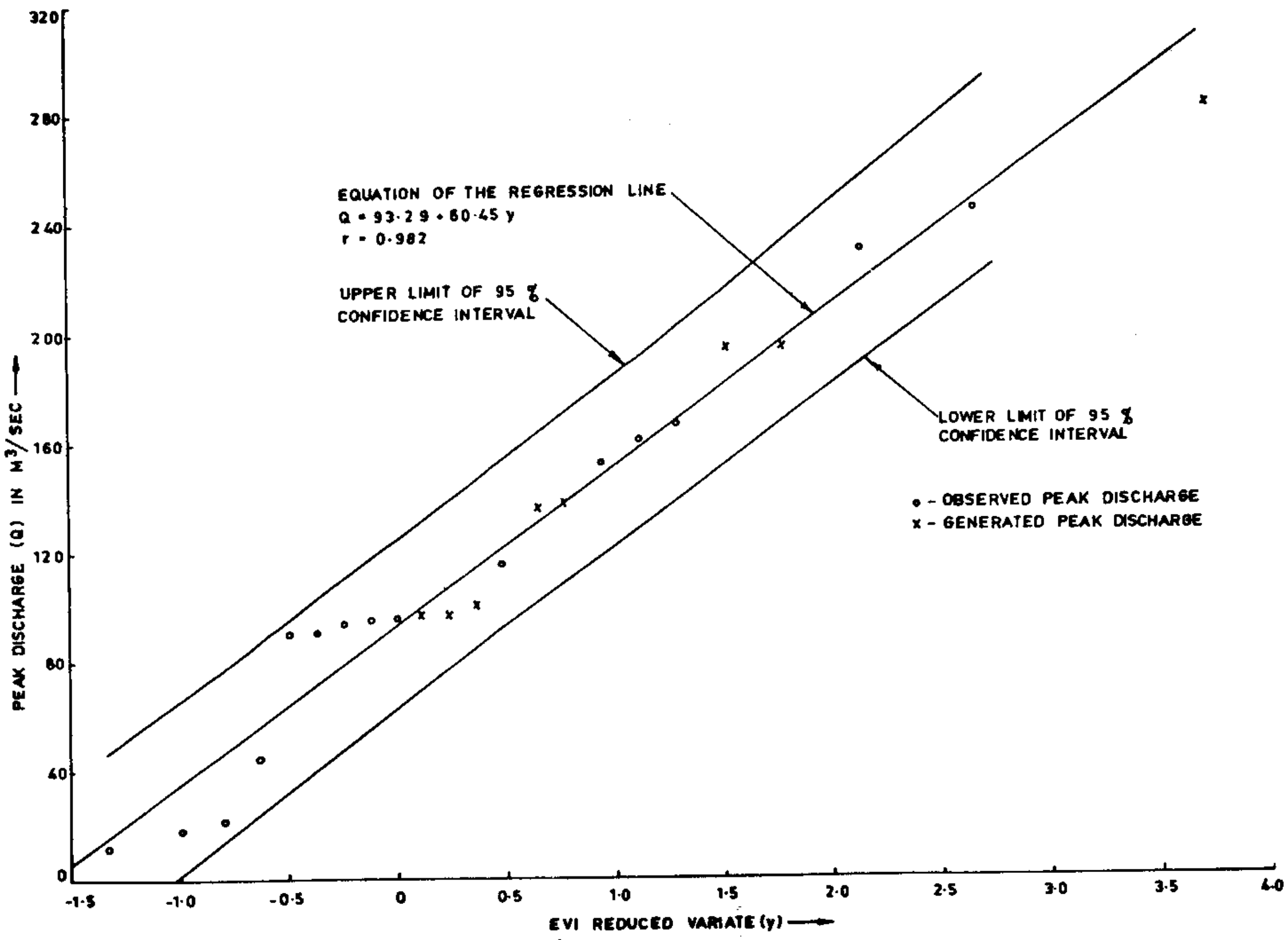

FIG. 12-RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 385

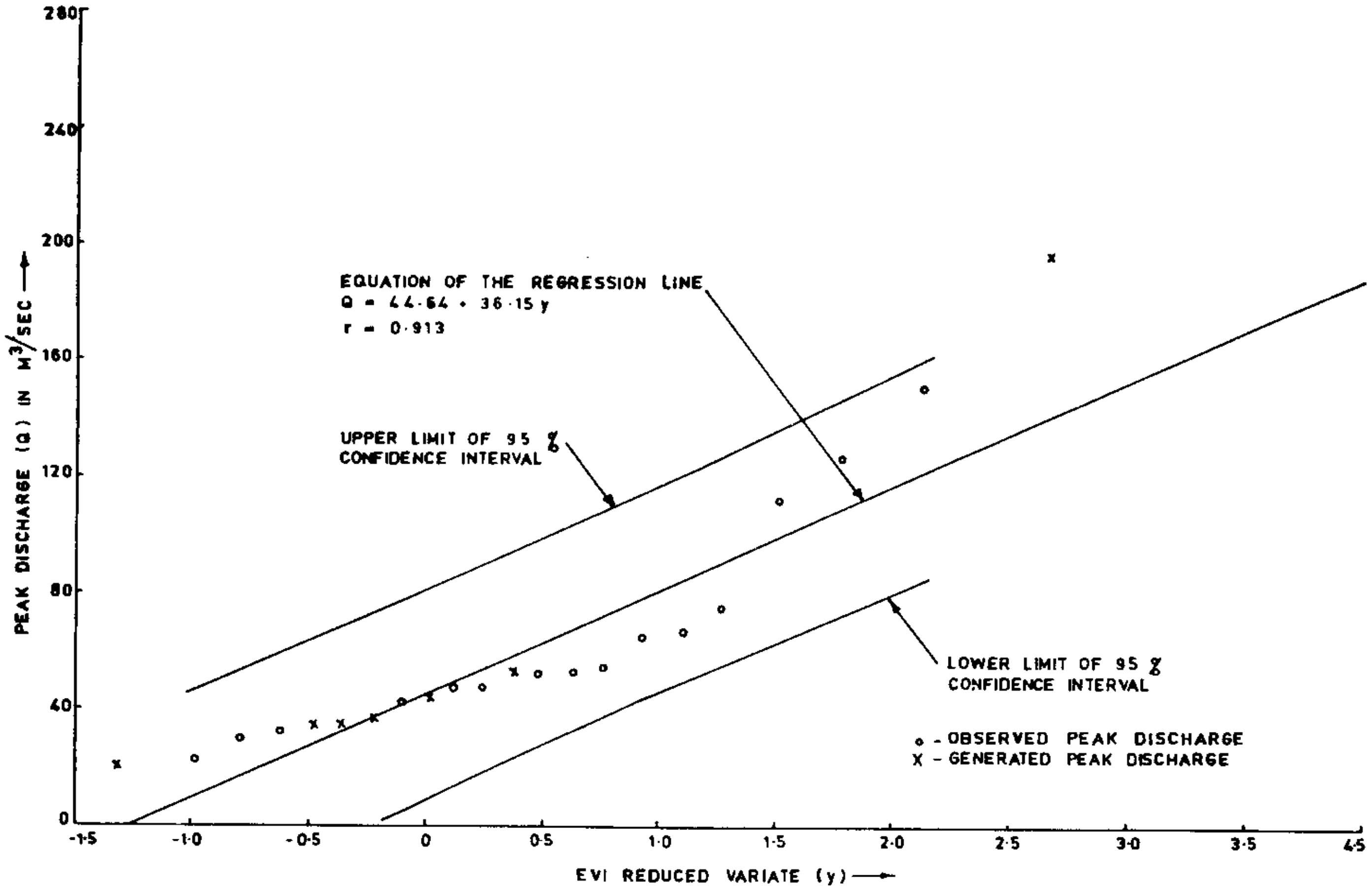

FIG. 13- RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 332(KGP)

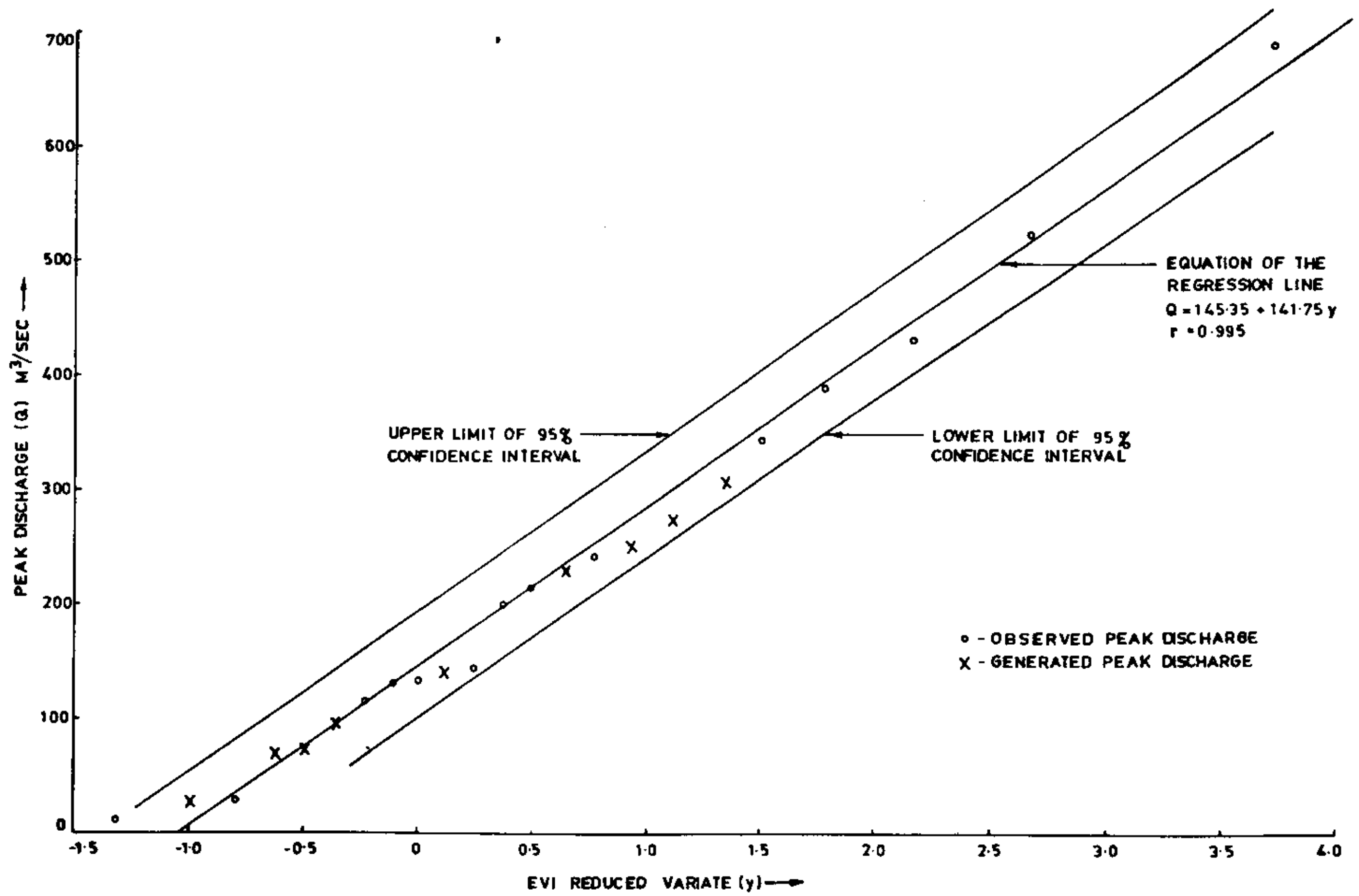

FIG. 14 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BR. NO. 59 (BSP)

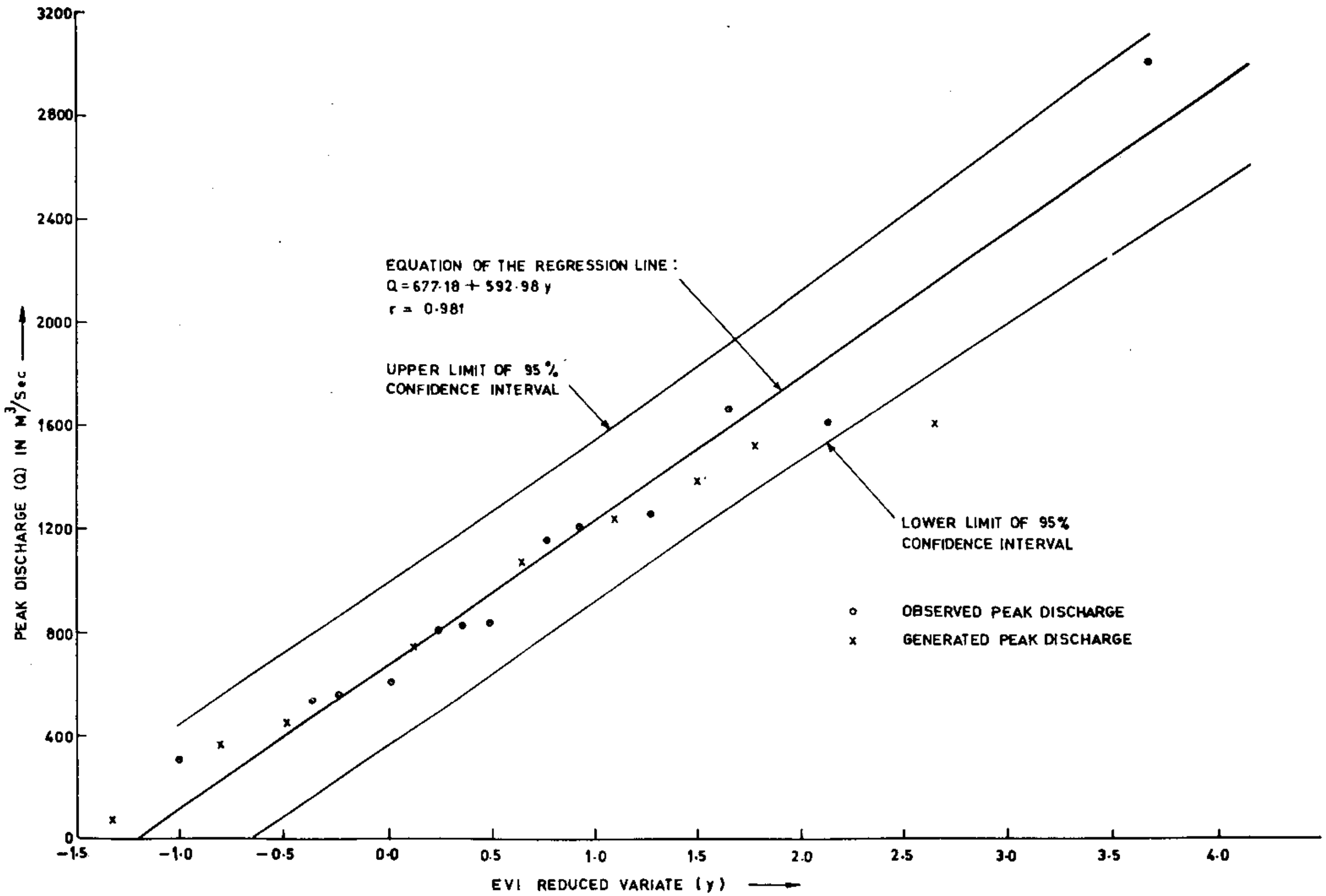

FIG. 15 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BRIDGE NO. 489

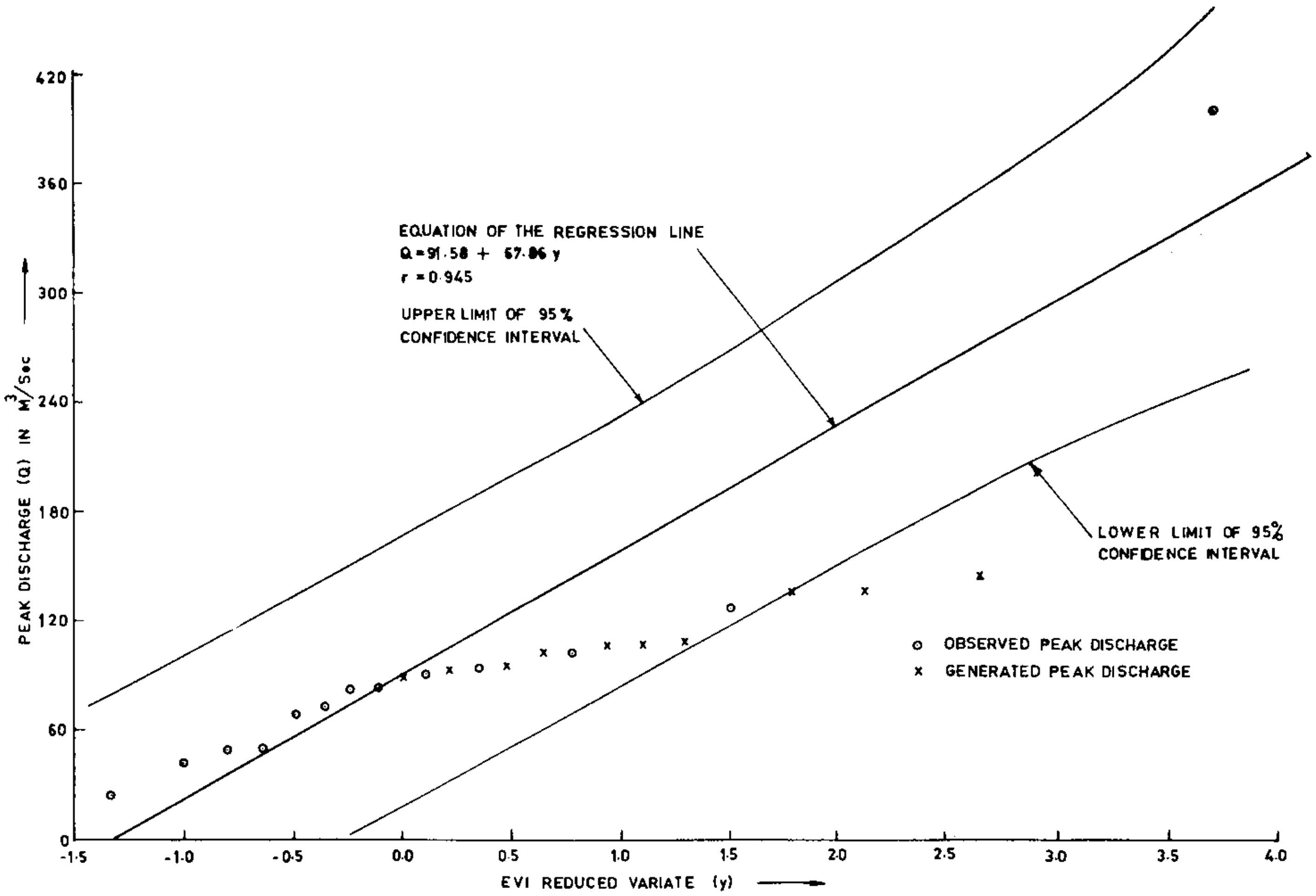

FIG.16-RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BRIDGE NO. 154

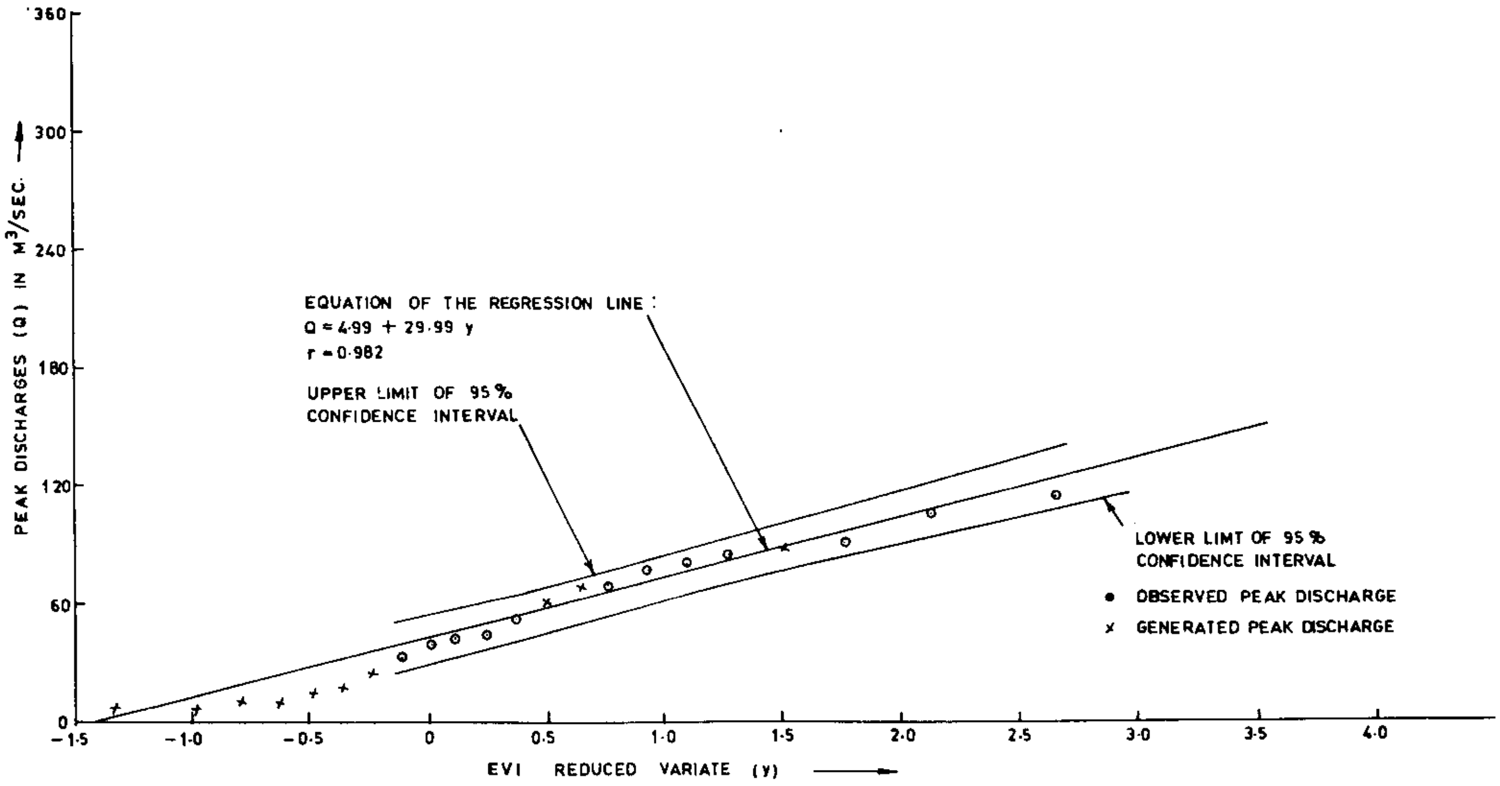

FIG. 17- RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BRIDGE NO. 42

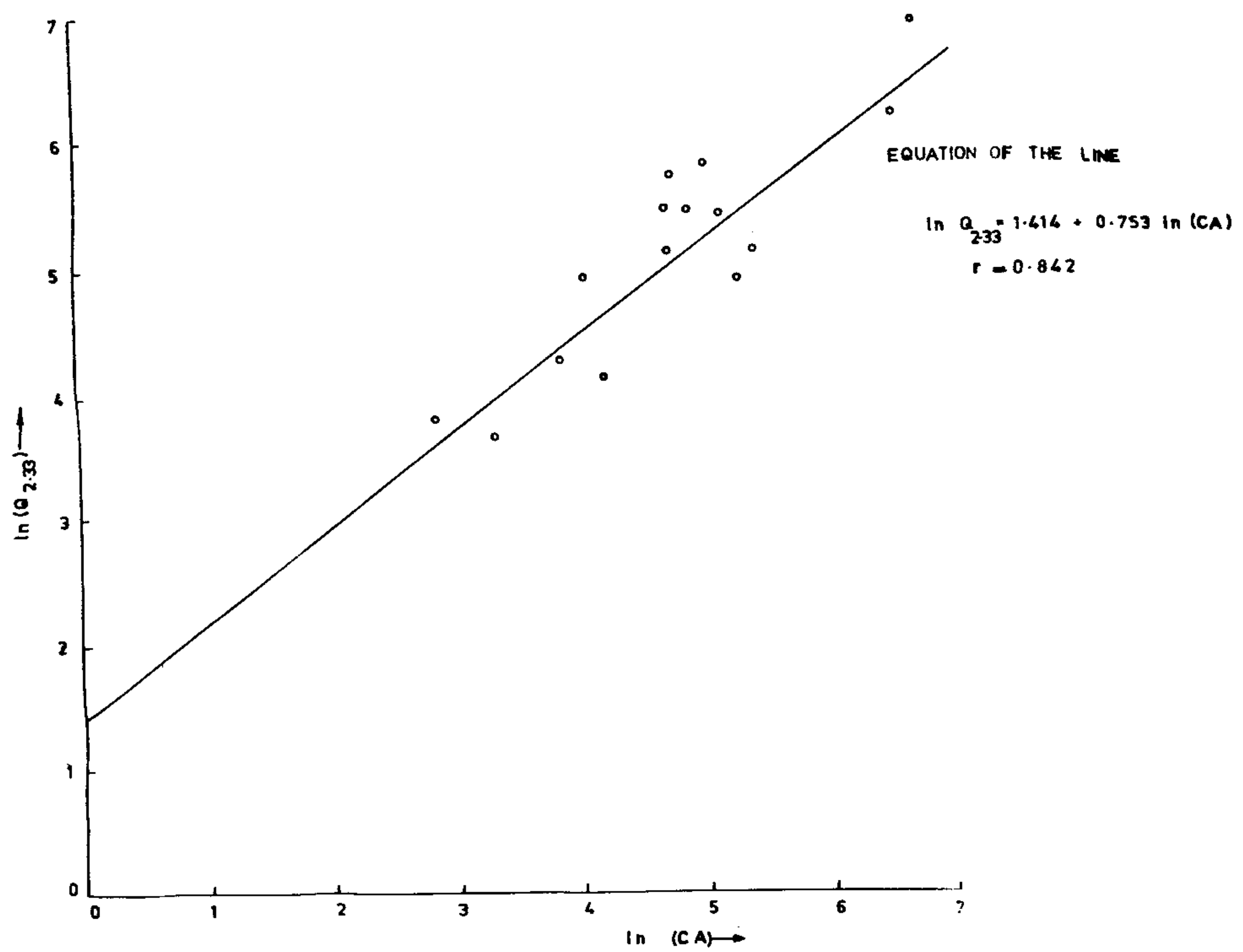

FIG. 18-RELATION BETWEEN ANNUAL MEAN PEAK FLOODS ($Q_{2.33}$) IN CUMEC AND CATCHMENT AREA (CA) IN SQ KM FOR SUBZONE-3d OF MAHANADI BASIN

TABLE 4 : FLOOD RATIOS FOR VARIOUS RETURN PERIODS

Sl No	Br. No.	$Q_{2.33}$ (m^3/sec.)	Q_{50} (m^3/sec.)	$Q_{50}/Q_{2.33}$	Q_{20} (m^3/sec.)	$Q_{20}/Q_{2.33}$	Q_{10} (m^3/sec.)	$Q_{10}/Q_{2.33}$	Q_5 (m^3/sec.)	$Q_5/Q_{2.33}$
1	2	3	4	5	6	7	8	9	10	11
1	12	472	1022	2.17	867	1.84	748	1.58	624	1.32
2	308	44	104	2.36	87	1.98	74	1.68	61	1.39
3	385	128	329	2.57	273	2.13	229	1.79	184	1.44
4	698	227	589	2.59	487	2.15	409	1.80	328	1.44
5	42	59	159	2.69	131	2.22	109	1.85	87	1.47
6	154	131	356	2.72	293	2.24	244	1.86	193	1.47
7	332(KGP)	66	186	2.82	152	2.30	126	1.91	99	1.50
8	489	997	2835	2.84*	2320	2.33 *	1921	1.93*	1507	1.51 *
9	66K	318	912	2.87	745	2.34	616	1.94	482	1.52
10	40K	287	829	2.89	677	2.36	560	1.95	438	1.53
11	59(BSP)	227	698	3.07	566	2.49	464	2.04	358	1.58
12	325	37	114	3.08	93	2.51	76	2.05	59	1.59
13	176	60	193	3.22	155	2.58	126	2.10	97	1.62
14	332(NGP)	162	541	3.34	435	2.69	353	2.18	267	1.65
15	48	160	594	3.71	472	2.95	378	2.36	281	1.76

*Median values

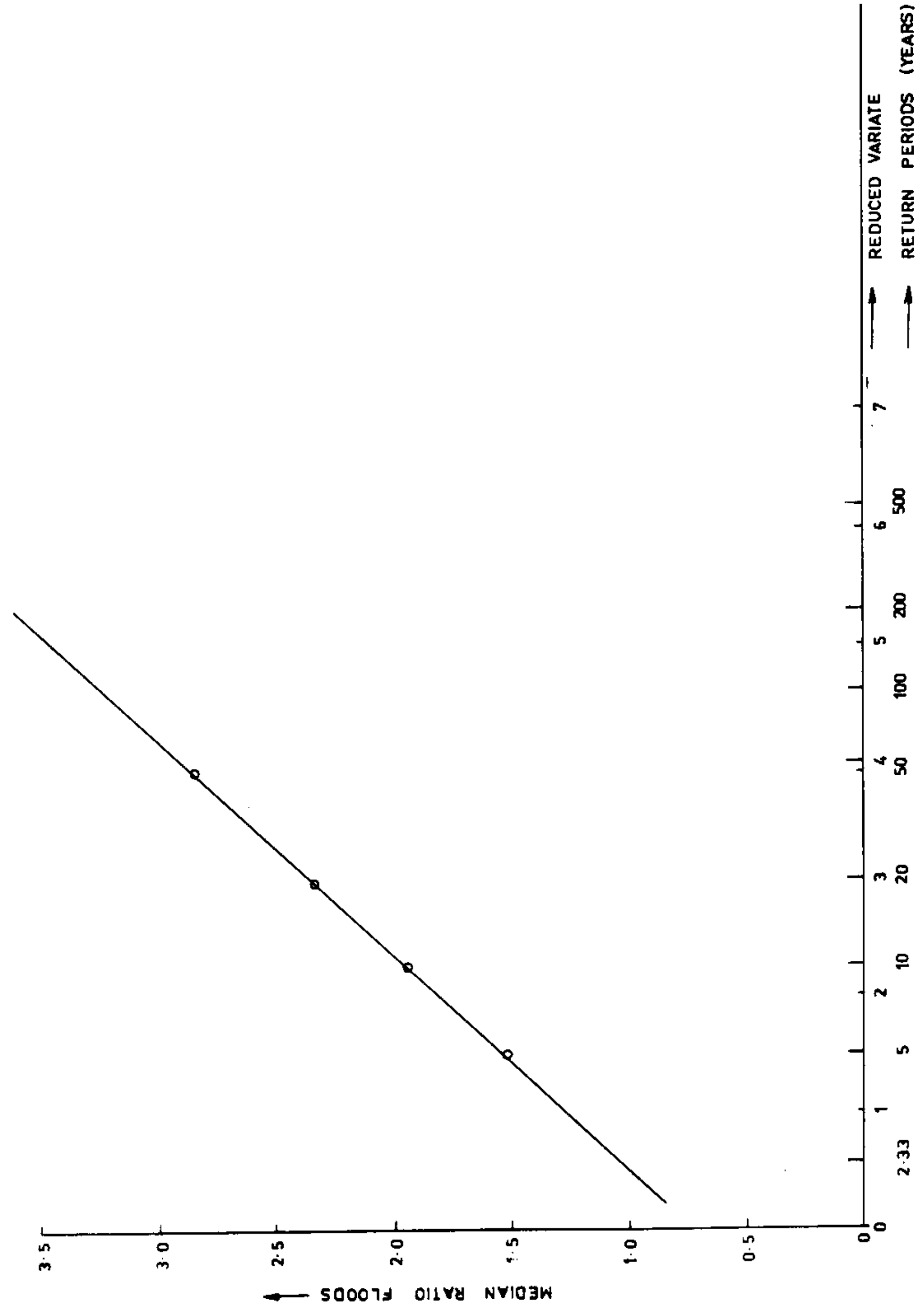

FIG. 19 - REGIONAL FREQUENCY CURVE

Figures 20 to 22 show the Gumbel probability plots developed for these test sites based on the observed data. The mean annual floods for the three test bridge sites were estimated from the relationship between the catchment area and $Q_{2.33}$ given by equation(23). The ratios of 2,5, 10,20,50,100 and 200 years return period floods estimated from the regional curve shown in figure 19 were multiplied by the mean annual floods for arriving at the respective return period floods. The comparison between these estimates and the corresponding estimates arrived by individual site analysis was carried out using the following measure:

$$ER = \frac{|(Q_{obs} - Q_{est})|}{Q_{obs}} \times 100 \qquad \ldots(24)$$

where, ER is the percentage difference between estimated and observed flood magnitude, Q_{obs} is the given return period flood arrived from the direct analysis of the test data and Q_{est} is the same return period flood arrived using the regional relationship. The results of this analysis carried out for three test sites are presented in tables 7 to 9.

7.2. Method Based on Power trnasformtion

The annual peak flood series of each of the 15 sites considered for analysis were divided by the site specific mean annual flood to arrive at the normalized series. This series was assumed independent of catchment characteristics and therefore the normalized series of all 15 bridge sites were grouped together to form a series assumed to be derived from a single population. This normalized series was subjected to power transformation analysis as described in section 6.2. The estimated statistics of the transformed normalized floods are given below:

$\lambda = 0.24$

$\bar{Z} = -0.1967$

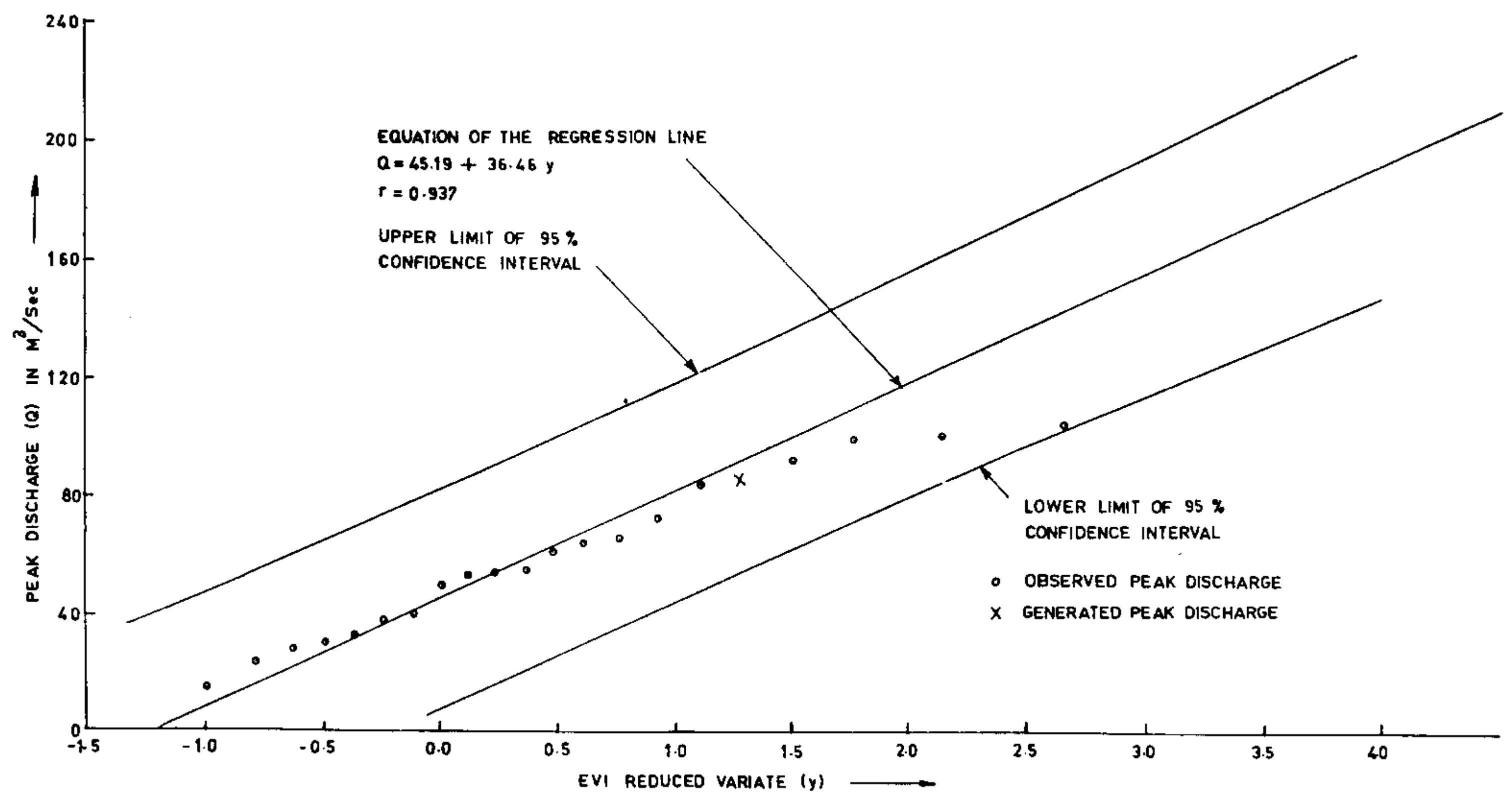

FIG.20 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BRIDGE NO. 59 (KGP)

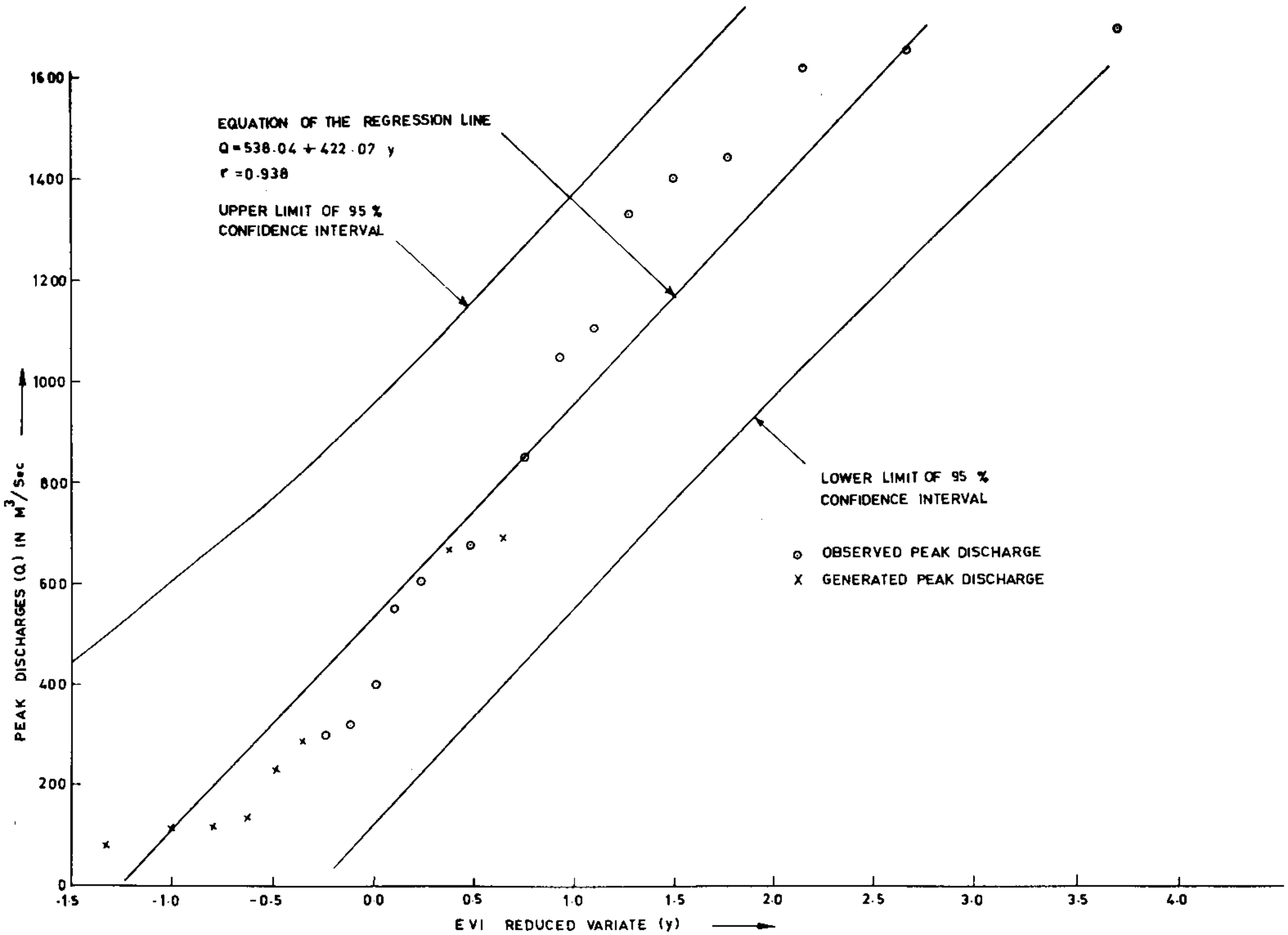

FIG. 21 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BRIDGE NO. 121

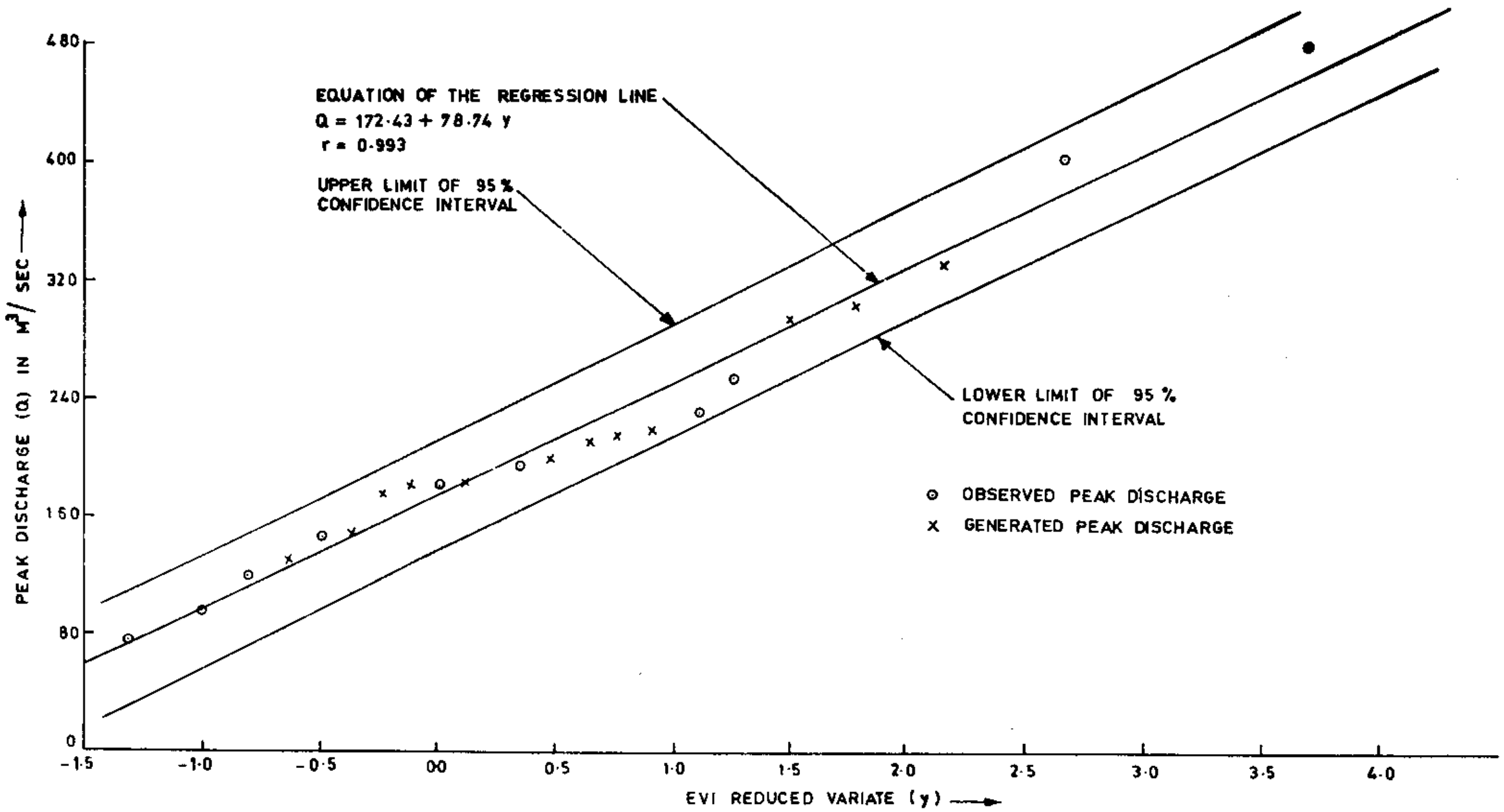

FIG. 22 - RELATIONSHIP BETWEEN ANNUAL PEAK DISCHARGES AND EVI REDUCED VARIATES FOR BRIDGE NO. 69

$S_Z = 0.7217$

$CS = 0.025$

$CK = 3.414$

where, $\bar{Z}$, S_Z, CS and Ck are the sample mean, standard deviation, coefficients of skewness and coefficient of Kurtosis respectively of transformed series. The following regional relationship between mean annual flood and catchment area has been arrived.

$$\bar{Q} = 4.142\ (CA)^{0.7484} \qquad \ldots(25)$$

This relationship as shown in figure 23 has a correlation coefficient of 0.86. As the estimate for mean annual flood is very close to the mean annual flood estimated using the Index-Flood method, it may be considered that the homogeneity test adopted in the case of Index flood method is also valid for this method. Accordingly, all the 18 gauging sites were considered as located in hydrologically homogeneous region. The estimated normalized floods for 2,5,10,20,50,100 and 200 years return period floods are given in Table 5.

Table 5. Estimated Normalized Floods for Various Recurrence Intervals

Sl.No.	Recurrence Interval (Years)	Estimated standardized flood
1	2	0.817
2	5	1.479
3	10	1.956
4	20	2.432
5	50	3.066
6	100	3.5539
7	200	4.0504

The validity of the regional frequency analysis using the method under consideration was tested by estimating floods of 2,5,

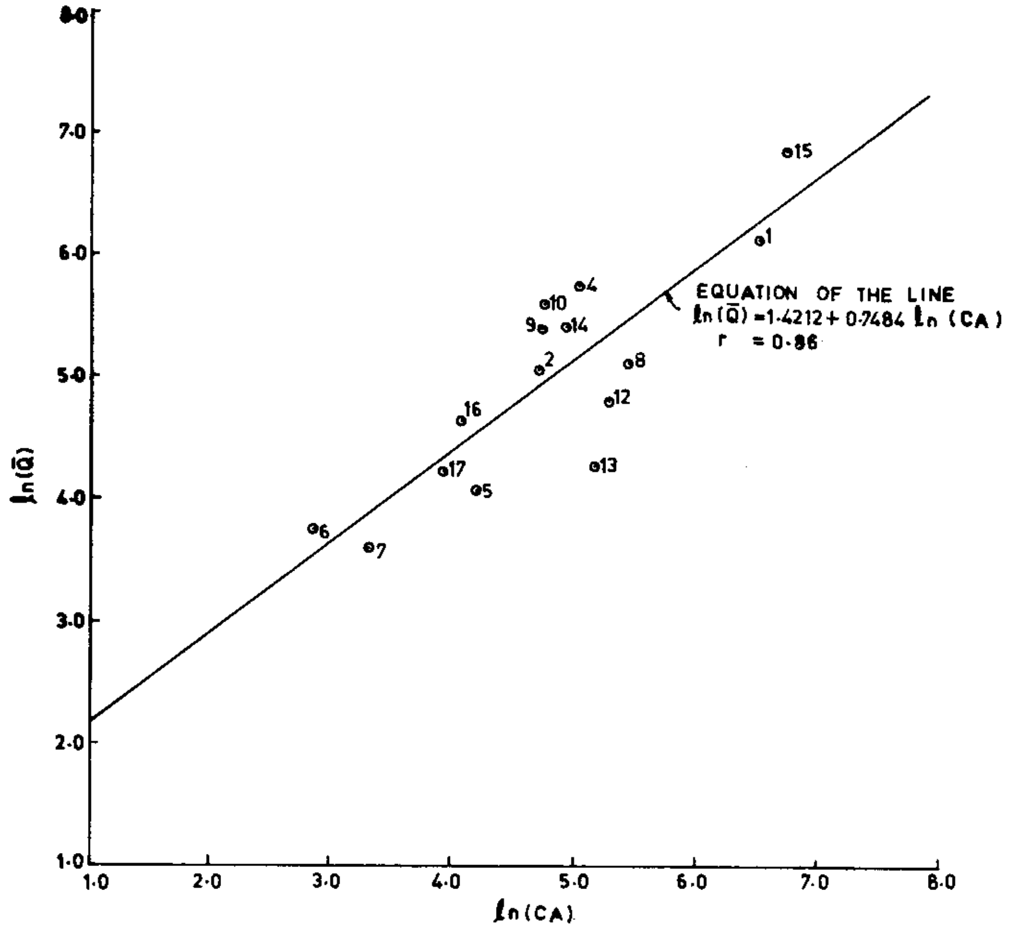

FIG. 23- RELATION BETWEEN ANNUAL MEAN PEAK FLOOD IN CUMEC AND CATCHMENT AREA IN SQ.KM FOR SUBZONE 3d OF MAHANADI BASIN

10,20,50,100 and 200 years return periods for the three test sites, considering them as ungauged catchments, and comparing these estimates with the estimates arrived by analysing each of the three sites test data. This comparison was carried out as follows:

Using the regional relationship given by equation (25), the mean annual flood for the three test data sites were estimated as 74 m^3/sec., 809 m^3/sec. and 196 m^3/sec. while the same mean annual floods were estimated from observed data as 65 m^3/sec., 753 m^3/sec., and 214 m^3/sec. respectively. The flood peaks of return periods 2,5,10,50,100 and 200 years were computed for three test data sites by multiplying the respective flood ratios by the estimated mean annual floods obtained from regional relationship and were compared with the corresponding estimates arrived at using power transformation analysis directly on the test data of the three bridge sites. The comparison is made based on the absolute percentage difference between regional relationship based estimates and direct analysis based estimates as expressed by equation(24). The result of this analysis carried out for data of three independent test sites have been presented in tables 7 to 9.

7.3 Method Based on Wakeby Distribution and James-Stein Corrected Means

The normalized probability weighted moments of the zeroth, first second, third and fourth order were computed using equation(12) for the fifteen bridge sites which were considered for regional analysis. They are given in table 6 along with the arithmatic average of the respective moments.

TABLE 6 : NORMALIZED PROBABILITY WEIGHTED MOMENTS FOR THE BRIDGE SITES OF SUBZONE-3d, MAHANADI BASIN

Sl No	Stream	Br. No.	Normalized probability weighted moments				
			Zero Order	First order	Second order	Third order	Fourth order
1	Nilgarh	12	1.0	0.375	0.218	0.150	0.112
2	Barjhora	48	1.0	0.251	0.121	0.072	0.048
3	Malania	66K	1.0	0.304	0.157	0.100	0.071
4	Sildha	176	1.0	0.286	0.146	0.093	0.066
5	Kolera	308	1.0	0.350	0.187	0.119	0.084
6	Kujanjhar	325	1.0	0.290	0.145	0.090	0.063
7	Parri	332(NGP)	1.0	0.276	0.128	0.075	0.049
8	Bisra	698	1.0	0.334	0.177	0.113	0.08
9	Sagar	40K	1.0	0.308	0.162	0.104	0.074
10	Sandyl	385	1.0	0.337	0.178	0.112	0.077
11	Pithakalia	332(KGP)	1.0	0.303	0.167	0.112	0.084
12	Jetha	59(BSP)	1.0	0.289	0.140	0.083	0.055
13	Karo	489	1.0	0.329	0.175	0.112	0.079
14	Ahera	154	1.0	0.359	0.208	0.141	0.104
15	Barjhora	42	1.0	0.251	0.119	0.069	0.045
AVERAGE NORMALIZED PROBABILITY WEIGHEED MOMENTS			1.0	0.309	0.162	0.103	0.073

The individual probability weighted moments of the same order are not very much different from the respective average probability weighted moments, and from this it may be inferred that all the sites are located within a hydrologically homogenecus region. The James-Stein corrected means were estimated as described in section 6.3.2 and their logarithmic values were related with the respective catchment areas in log domain and a linear regression line is fitted as shown in Figure 24. The relationship thus arrived has a correlation coefficient of 0.86 and it is expressed as:

$$\overline{Q}_{jsm} = 5.00\ (CA)^{0.71} \qquad \ldots(26)$$

The validity of this regional frequency analysis was tested by estimating floods of 2,5,10,20,50,100, and 200 years return periods for three test sites using the regional frequency relationship and comparing these estimated floods with the corresponding return period floods obtained by analysing data of each individual test site directly using Wakeby distribution. The results so obtained have been compared and the absolute percentage difference between respective values have been computed using the equation (24). These results are presented in tables 7 to 9.

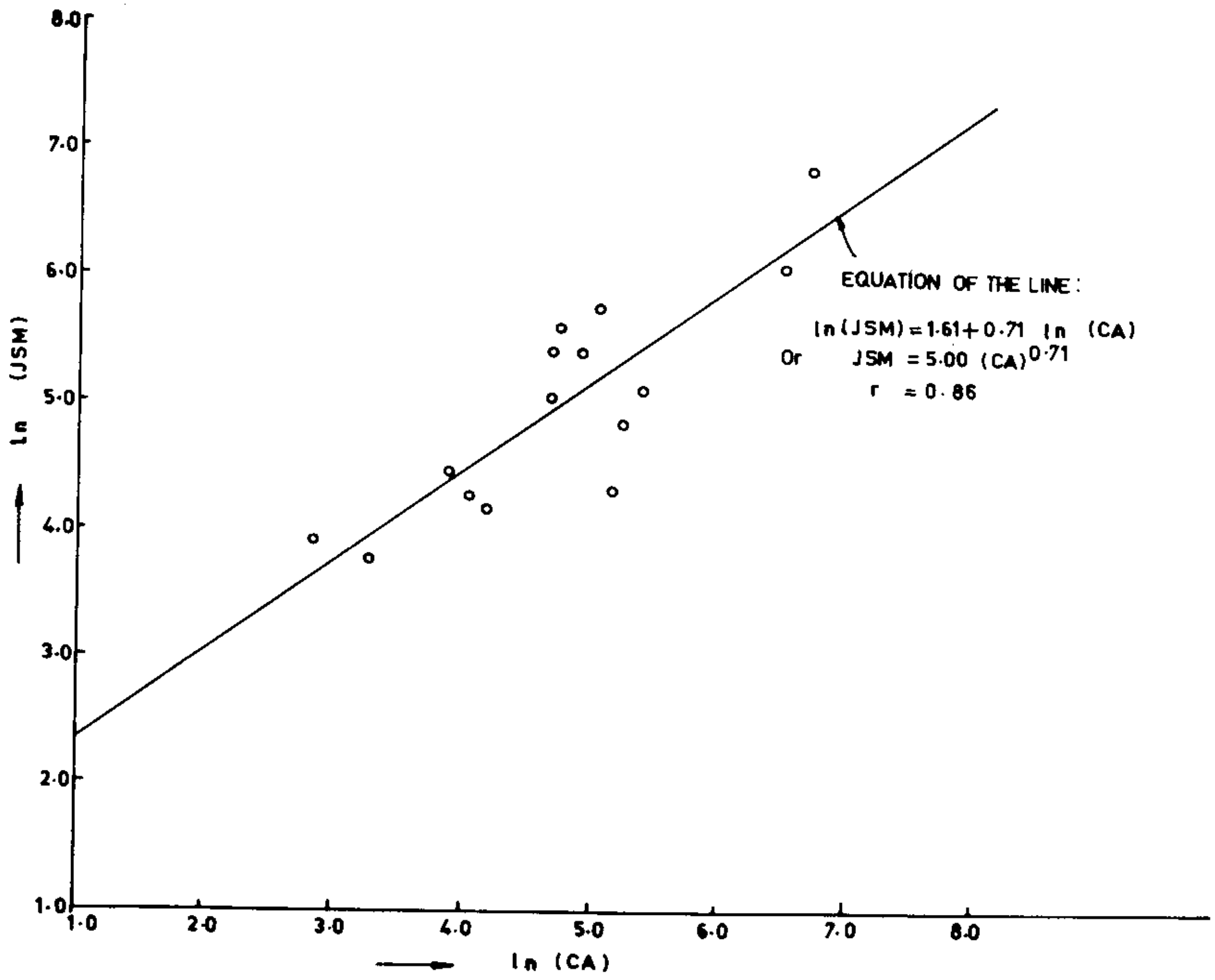

FIG. 24- RELATION BETWEEN JAMES-STEIN CORRECTED MEANS IN CUMEC AND CATCHMENT AREA IN SQ.KM FOR SUBZONE - 3d OF MAHANADI BASIN

Table 7 : COMPARISON OF VARIOUS RETURN PERIOD FLOODS FOR TEST SITE BR. NO.59(KGP) USING ACTUAL AND REGIONAL PARAMETERS

Return Period (Years)	Estimates of flood peak based on						$ER = \frac{[(Q_{obs} - Q_{est})]}{Q_{obs}} \times 100$		
	Actual parameters (m^3/sec.)			Regional parameters (m^3/sec.)					
	Flood Index method	Power Transformation	Wakeby Distribution	Flood index method	Power transformation	Wakeby distribution	Flood index method	Power transformation	Wakeby distribution
1	2	3	4	5	6	7	8	9	10
2	59	55	56	68	60	57	15	9	2
5	100	96	88	114	109	101	14	13	15
10	127	125	116	145	145	136	14	16	17
20	153	154	149	174	180	173	14	17	16
50	187	192	202	212	227	224	13	18	11
100	213	222	249	241	263	294	13	18%	18%
200	238	252	305	268	299	343	13	19%	12%

TABLE 8 : COMPARISON OF VARIOUS RETURN PERIOD FLOODS FOR BR. No.121 USING ACTUAL AND REGIONAL PARAMETERS

Return period (years)	Estimates of flood peak based on: Actual parameters (m^3/sec.)			Regional parameters (m^3/sec.)			$ER = \frac{\lvert(Q_{obs} - Q_{est})\rvert}{Q_{obs}} \times 100$		
	Flood index method	Power transformation	Wakeby distribution	Flood index method	Power transformation	Wakeby distribution	Flood index method	Power transformation	Wakeby distribution
1	2	3	4	5	6	7	8	9	10
2	693	641	624	750	661	559	8	3	10
5	1171	1178	1315	1265	1196	981	8	2	25
10	1488	1526	1626	1605	1582	1319	8	4	19
20	1792	1850	1802	1932	1967	1674	8	6	7
50	2185	2253	1915	2354	2480	2173	8	10	13
100	2480	2544	1954	2674	2875	2845	8	13	46
200	2773	2827	1974	2985	3277	3322	8	16	68

TABLE 9 : COMPARISON OF VARIOUS RETURN PERIOD FLOODS FOR TEST SITE BR. NO. 69 USING ACTUAL AND REGIONAL PARAMETERS

Return period (years)	Estimates of Flood Peak based on: Actual parameters (m^3/sec.)			Regional parameters (m^3/sec.)			$ER = \frac{\lvert (Q_{obs} - Q_{est}) \rvert}{Q_{obs}} \times 100$		
	Flood index method	Power transformation	Wakeby distribution	Flood index method	Power transformation	Wakeby distribution	Flood index method	Power transformation	Wakeby distribution
1	2	3	4	5	6	7	8	9	10
2	201	197	190	180	160	145	10	19	24
5	291	282	271	304	290	255	4	3	6
10	350	339	336	385	383	343	10	13	2
20	406	394	406	464	476	436	14	21	7
50	480	466	507	565	600	566	18	29	12
100	535	520	589	642	696	741	20	34	26
200	589	575	677	716	794	865	22	38	28

8.0 DISCUSSION OF RESULTS

The floods estimated at three test sites for desired return periods using the regional relationships of the three methods studied herein were compared with the flood estimates of respective methods applied independently on the test data set for the same return periods. Tables 7 to 9 show the comparison of estimated and observed flood peaks for the three test catchments using the parameters arrived from regional analysis and direct analysis respectively based on three methods studied herein. The comparison is made based on the ratio of absolute difference between observed and estimated floods of the desired return period to that of observed flood expressed in percentage. If it is considered that bridge

sites Nos.59(KGP),121 and 69 were ungauged, then the estimates arrived using regional parameters at these sites could be very well compared with the estimates arrived from direct application of these three methods studied on the available data at these sites, barring some exceptions. The exception may be due to the reason that the observed annual flood series at these sites are only a single realization, i.e. a sample of limited size. Therefore, based on the analysis of a single realization observed at each of these three test sites, we may not be able to conclude which method out of the three methods studied herein would be more suitable for other regions, since their performance has compared well with each other. However, it may be mentioned that the Index-flood method yields less absolute percentage errors and also yields consistent absolute percentage differences for all the three sites. These results emphasize need for further study of the methods based on power transformation and Wakeby distribution using field data representing different conditions of flow, catchment sizes etc.

9.0 CONCLUSIONS

This regional frequency analysis study based on the data of annual peak flood series at 15 gauged sites, which consist of both observed and estimated flood peaks, of subzone 3d,Mahanadi basin brings out the following:

i) The Index-flood method of USGS yield consistently better regional estimates than the other two methods.

ii) However, the regional estimates of other two methods are comparable with that of Index-flood method and so they may be accepted as possible candidate methods for regional flood frequency analysis.

iii) Further studies with better data base are necessary to arrive at definite conclusions regarding the capability of the other two methods for regional frequency analysis.

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