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FLOOD FREQUENCY ANALYSIS OF LOWER TAPI SUB BASIN IN INDIA

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ABSTRACT

The flood frequency analysis was carried out on River Tapi at Ghala Hydrological observation site in Lower Tapi Sub basin using Gumbel's distribution for planning and infrastructure design. This method consists of modeling the annual maximum discharge of the river for a period of 28 years (1978 to 2006) for design return periods of 5, 10, 20, 50, 100, 150 and 200 years. High flood levels are marked on the river cross sections which helpfor design of hydraulic structures and storm management as Surat city as it is located in the downstream. Rainfall analysis is also done with river cross section. The results of the investigation are analyzed and discussed and useful conclusions are drawn.The method of plotting annual flood peaks and fitting a Gumble distribution is valid for any year period chosen. Application of Gumble's distribution indicates a very good fit of observed data series with theoretical variation. The 1 in 100 year return period recommended for design of river control works is 26884.743 cumec.

Keywords: *Gumbel's distribution, flood frequency analysis, return period, design flood.*

INTRODUCTION

Floods are recurrent phenomena in India from time immemorial. Floods of varying magnitude, affect some or the other parts of the country, almost every year due to heavy rainfall and climate changes. With the increase in population and developmental activities in the country, there has been a tendency to occupy the floodplains, often resulting in not only loss of precious human lives, cattle and damage to public and private property but also create a sense of insecurity and fear in the minds of people living in the flood plains. The after-effects of floods like the agony of survivors, spread of epidemic, non-availability of essential commodities and medicines, loss of the dwellings etc. make floods most feared among the natural disasters being faced by human kind (Central Water Commission, 2012). Flood estimates are also required for the safe operation of flood control structures, taking emergency measures such as maintenance of flood levees, evacuating the people to safe localities etc. The analysis of flood frequency of river catchment has therefore become imperative in order to curtail hazards of this nature. Flood frequency analysis involves analysis of time series of observed annual peak flow discharge data to determine statistical information, which are graphs and tables that tell the likelihood of various discharges as a function of recurrence interval or exceedance probability (Bayliss A.C.1999b). Flood frequency distribution can take many forms depending on the equations used to carry out the statistical analysis (Sathe et al. 2012). According to Subramanya (2019) for estimation of the magnitude of a flood peak the available methods are rational method, empirical method, unit-hydrograph technique, or flood-frequency studies. According to Satheet al. (2012), the rational method is applicable only to small-size (<50 km^2) catchments and the unit-hydrograph method is normally restricted to moderate-size catchments with areas less than 5000 km^2. They also found that the method of plotting annual flood peaks and fitting a Gumbel's distribution is valid for any period.Solomon and Prince (2013) found that the Gumbel's distribution is suitable for predicting expected flow in a river. Sonowal and Thakuriah (2019) found that predictions of flood using Gumbel's distribution were nearly accurate. Patel (2020) estimated discharge for different return periods using Gumbel's distribution method at Garudeshwar weir, Narmada basin. Rao et al. (2022) found that Gumbel's extreme value distribution approach was approximate for predicting projected Araniar reservoir flow. The main aim of the present paper is to carry out flood frequency analysis of hydrological data to model the annual peak discharge of the Tapi river at Ghala,upstream of SuratCity using Gumbel'sdistributionto ensure safety and economic hydrologic design in the catchment area from 1978 to 2006 and predict flood design for return periods of 5, 10, 20, 50, 100, 150 and 200 years.

STUDY AREA

Tapi basin can be divided into three sub basins: Upper Tapi basin up to Hathnur (confluence of Purna river) with main Tapi river (drainage area 29,430 sqkm), Middle Tapi basin from Hathnur to Sarangkheda gauging site (drainage area 28,970 sqkm), and LowerTapi basin from Sarangkheda up to sea (drainage area 6,745sqkm). Tapi basin lies between east longitudes of $72^{\circ}38'$ to $78^{\circ}17$and north longitudes of $20^{\circ}05'$ and $22^{\circ}03'$ (Central Water Commission, 2019). Tapi River is one of the major rivers of peninsular India with a length of around 724 km. Tapiriver originates from Multai, a place located in the Betul district. The flood frequency study was carried out of River Tapi at Ghalawhich is in the upstream of Surat City (Fig. 1). Latitude andLongitudeof River Tapi at Ghala are $21^{\circ}17'50''$ and and$73^{\circ}01'31''$, respectively (Central Water Commission, 2019).

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Fig.1 Gauge & Discharge Site Ghala Station in Lower Tapi Basin

PROBABILITY OF OCCURRENCE OF EVENT

The return Period (also known as recurrence interval or frequency) T is the average interval between the occurrence of an event of magnitude equal to or in excess of a specified magnitude X. The probability P of the event being equal to or exceeded (plotting position or order number or rank m of data size N) is given by the plotting-position formula (Weibull formula)

$$P(X \geq X_T) = \frac{m}{N+1} \quad (1)$$

The return period is calculated as

$$T = \frac{1}{P} \quad (2)$$

The probability that the T-year event will not occur in a given year is q = 1-P. The probability of occurrence of the T-year event r times in N successive years is given by

$$P_{r,N} = C_r^N P^r q^{N-r} \quad (3)$$

The probability of occurrence of the T-year event zero times i.e. not occurring at all in N successive years is given by

$$P_{0,N} = P(X < X_T \text{ each year for N years}) = C_0^N P^0 q^{N-0} = q^N = (1-P)^N \quad (4)$$

The complement of this situation [i.e. eq. (4)] is given by

$$P(X \geq X_T \text{atleastonceinNyears}) = 1-(1-P)^N \quad (5)$$

Chow(1951) has shown that the most frequency distribution functions applicable in hydrologic studies can be expressed by the following equation known as the general equation of hydrologic frequency analysis:

$$X_T = \overline{X} + K\sigma_{n-1} \quad (6)$$

Where, X_T is value of variate X of a random hydrologic series with a return Period T, $\bar{X}$ is a mean value of the variants X, K is a frequency factor, and σ_{n-1} is standard mean deviation of sample size N.

GUMBEL'S BASIC EQUATIONS

Gumbel defined a flood as the largest of 365 dailyflows and the annual series of flood flows constitute a series of largest values of flows. According to his theory of extreme events, the probability of occurrence of an event equal to or larger than a value X_O is given by

$$P(X \geq X_O) = 1 - e^{-e^{-Y}} \quad (7)$$

Where, Y is the dimensionless variable given by

$$Y = \alpha(X - a) \quad (8)$$

$$a = \overline{X} - 0.45005\sigma_X \quad (9)$$

$$\alpha = \frac{1.2825}{\sigma_X} \quad (10)$$

Using eqs. (8), (9), and (10), we get

$$Y = \frac{1.285\,(X - \overline{X})}{\sigma_X} - 0.577 \quad (11)$$

Where, $\bar{X}$ = mean, and σ_X = standard mean deviation of the variate X. In practice it is the value of X for a given P and eq. (7) is transposed as

$$Y_P = -\ln[-ln(1-P)] \quad (12)$$

Using eqs. (2) and (12) one can write

$$Y_T = -\left[\ln.\ln\left(\frac{T}{T-1}\right)\right] \quad (13)$$

Where, Y_T is reduced variate for a given T.

Eq.(13) may be also written as

$$Y_T = -[0.834 + 2.303 \log.\log.(T/(T-1))] \quad (14)$$

Rearranging eq.(11), one can write

$$X_T = \overline{X} + K\sigma_X \quad (15)$$

Where, $K = \frac{(Y_T - 0.577)}{1.2825}$ (16)

Eqs.(6) and (15) are of the same form. Eqs. (15) and (16) constitute the basic Gumbel's equations and are applicable to an infinite sample size (i.e. $N \rightarrow \infty$). In real life, annual data series of extreme events such as floods, maximum rainfall depths, etc., all have finite lengths of record [(Eq.(16)] is modified to account for finite N for practical use.

GUMBEL'S EQUATION FOR PRACTICAL USE

The Gumbel's Distributiontime (T) dependent probability frequency analysis is given as Eq. (15).

$$X_T = \overline{X} + K\sigma_{n-1} \quad (17)$$

Where, X_T is Gumbel's distribution in reference to return period (also called recurrence interval) T; $\overline{X}$ is the mean value of the variants X; and σ_{n-1} is standard mean deviation of sample size N. K is the factor of frequency expressed as eq. (18).

$$K = \frac{Y_T - \overline{Y_n}}{S_n} \quad (18)$$

Where, $\overline{Y_n}$is reduced mean, a function of sample size N, for $N \rightarrow \infty, \overline{Y_n} \rightarrow 0.577$; S_n is reduced standard deviation, a function of sample size N, for $N \rightarrow \infty, S_n \rightarrow 1.2825$.

$Y_T$is given by eqs. (19.1 and19.2)

$$Y_T = -\left[\ln.\ln\left(\frac{T}{T-1}\right)\right] \quad (19.1)$$

Or

$$Y_T = -[0.834 + 2.303 \log.\log.(T/(T-1))] \quad (19.2)$$

Where, T is the predicted time period.

3. FLOOD ESTIMATION AND ANALYSIS

The mean value of the variants X is given by eq. (20)

$$\overline{X} = \frac{\sum X}{N} \quad (20)$$

The standard mean deviation is given by eq. (21)

$$\sigma_{n-1} = \sqrt{\frac{\sum(X-\overline{X})^2}{N-1}} \quad (21)$$

The values of $\overline{X}$ and σ_{n-1} for the 28 years annual maximum peak discharge available data has been evaluated and presented in Table 1.

Using eqs. (17) and (18), one may write

$$X_T = \overline{X} + \frac{Y_T - \overline{Y_n}}{S_n}\sigma_{n-1} \quad (22)$$

$\overline{X}$ andσ_{n-1} functionally depend on magnitude (s) and size (N) of data set i.e. these statistic terms are function of a given data set. Therefore, one can write

$$(\overline{X}, \sigma_{n-1}) = f(s, N) \quad (23)$$

$\overline{Y_n}$andS_n depend only on size (N) of data set i.e. function of size (N) of data set. Therefore, one can write eq. (24)

$$(\overline{Y_n}, S_n) = f(N) \quad (24)$$

The flood discharge values are arranged in descending order and the plotting position recurrence interval Tp for each discharge is obtained using eq. (2) as Tp = (N + 1) / m = 29 / m.

Where, m = order number. The discharge magnitude Q is plotted against the corresponding Tp on a Gumbel extreme probability paper (Fig. 2).Thestatistics $\overline{X}$ and $\sigma_{n-1}$for the series are calculated, and presented in Table 1. For N = 28 years, $\overline{X}$ = 5249.65cumec, σ_{n-1} = 7126.19 cumec (Table 1); and $\overline{Y_n}$ = 0.5343, and S_n = 1.1047 (Table 2).

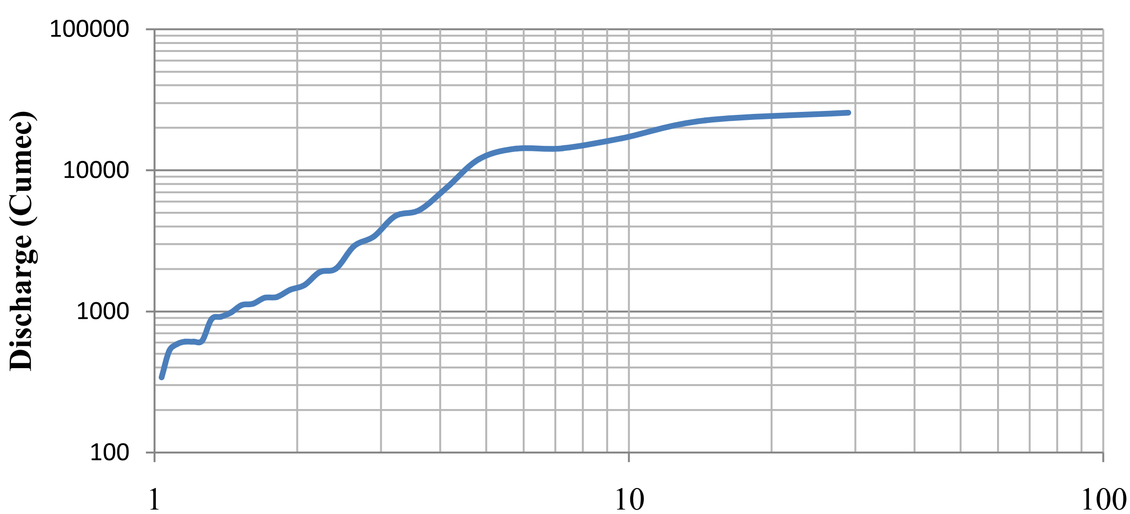

Fig. 2 Flood Probability Analysis by Gumbel's Distribution

Table 1: Tp For Observed Data For Gauge & Discharge Site Ghala Station

Order No. (m)	Observed Maximum Flood Discharge (Cumec)	Tp = (N+1)/N	Order No. (m)	Observed Maximum Flood Discharge (Cumec)	Tp = (N+1)/N
1	25500.00	29.00	15	1419.00	1.93
2	22500.00	14.50	16	1265.00	1.81
3	16887.00	9.67	17	1247.00	1.71
4	14307.90	7.25	18	1131.70	1.61
5	14225.00	5.80	19	1108.00	1.53
6	12022.50	4.83	20	981.60	1.45
7	7592.00	4.14	21	916.26	1.38
8	5223.76	3.63	22	881.20	1.32
9	4735.33	3.22	23	619.90	1.26
10	3400.00	2.90	24	610.00	1.21
11	2905.00	2.64	25	609.20	1.16
12	2015.60	2.42	26	584.56	1.12
13	1900.00	2.23	27	526.00	1.07
14	1536.00	2.07	28	340.80	1.04
N = 28 years, $\bar{x}$ = 5249.65Cumec, σ_{n-1} = 7126.19 Cumec					

Table 2: Reduced mean and reduced standard deviation

Sample Size (N)	10	20	25	28	30	40
Yn	0.4952	0.5236	0.5309	0.5343	0.5362	0.5436
Sn	0.9496	1.0628	1.0915	1.1047	1.1124	1.1413

Using eq. (22), one may write

$$X_T = 5249.65 + \frac{Y_T - 0.5343}{1.1047} 7126.19 \quad (25)$$

Eq. (25) reduces to eq. (26)

$$X_T = 1802.99 + 6450.79\, Y_T \quad (26)$$

Eq. (26) is a linear equation with intercept 1802.99, slope gradient 6450.79; when Y_T is along x-axis and X_T is along y-axis.

Using eqs. (19.1) and (26), eq. (27) may be expressed in terms of X_T and T.

$$X_T = 1802.99 + 6450.79 \left[-\left\{ln.\,ln\left(\frac{T}{T-1}\right)\right\}\right] \quad (27)$$

Using single eq. (27), different values of X_T in Cumec can be predicted for different values of T in years for a given particular set of given data. A graphical plot T vsX_T has been presented in Fig. 3 and a modelled equation is given as

$$X_T = 6612.6\ln(T) + 1016.1,\ R^2 = 0.9999 \quad (28)$$

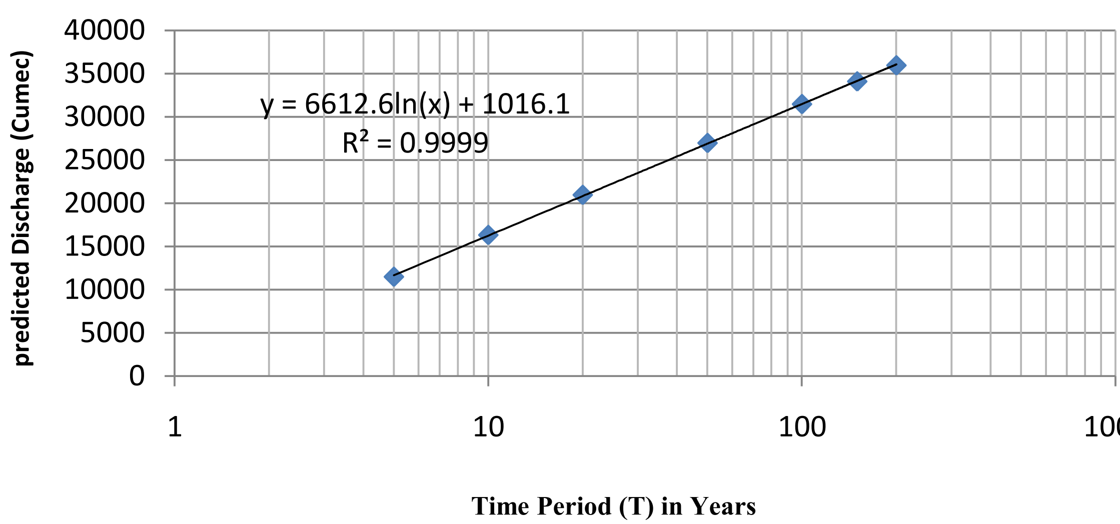

Fig. 3 Graphical plot of Time period (T) vs Predicted Discharge

As R^2 value of modeled eq. (28) is almost equal to unity. Thus, for a given set of data one can get the predicted discharge using eq. (28).

A Table 3 has been presented showing the predicted discharge using eq. (28).

Table 3: Design Discharge Return Period Tp For Gauge & Discharge Site Ghala Station

Tp (Years)	Discharge (Cumec) Evaluated using eq.(28)
5	11658.669
10	16242.174
20	20825.679
50	23506.858
100	26884.743
150	31468.248
200	34149.427

The FRL and minimum WL have been presented with river cross section in Fig. 4. Fig. 4 reveals that there was occurrence of flood as both the banks of river were below the HFL. It was a historical flood occurred due to spillover of banks of river and Surat city witnessed it 2006.

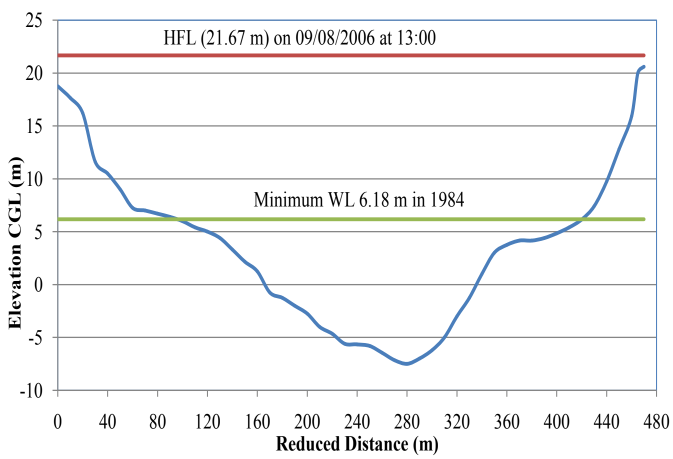

Fig. 4 River cross section with high flood level for river Gauging station at Ghala

CONCLUSIONS

In the present study of flood frequency analysis, annual maximum series data pertaining to period 1978 to 2006 for the Tapi river at Ghala G&D site upstream of Surat city. Tapi river at Ghala wasanalyzed using Gumble's distribution method for design return periods (T) of 5, 10, 20, 50, 100, 150 and 200 years. The design storm rainfall of various return periods have been computed from statistical analysis of point and areal time series annual maximum discharge.It has been observed that the design floodfor a return period of 5 years was almost same as the observed data and verified with historical data. The method of plotting annual flood peaks and fitting a Gumble distribution is valid for any year period chosen. Application of Gumble's distribution indicates a very good fit of observed data series with theoretical variation. The main finding of this study are the 1 in 100 year return period recommended for design of river control works is 26884.743 cumec. High flood levels are mark on the river cross sections which helps for design of hydraulic structures and storm management as Surat city, in the downstream of it.

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