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Rainfall analysis and design flood estimation for Upper Krishna River Basin Catchment in India

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Abstracts

Design flood estimates have been carried out for Upper Krishna basin catchment employing flood frequency analysis methods for planning and or infrastructure design. This method consists of fitting a theoretical extreme-value probability distribution to the maximum annual flow rate data collected at a stream flow gauging station, thus enabling the hydrologist to estimate, via extrapolation, the flow rate or peak discharge corresponding to a given design return period. Seven gauging sites were analyzed with a view to predicting the floods of different return periods. Flood frequency analysis is carried out by Gumble's distribution. Detail rainfall analysis also done with river cross sections. High flood levels are mark on the river cross sections which helps for design of hydraulic structures like bridges, culverts etc. The results of the investigation are analyzed and discussed and useful conclusions are drawn.

Keywords : Gumbel distribution; Flood frequency ;Design flood;

INTRODUCTION

The estimation of peak flow of a design return period is a necessary task in many civil engineering projects such as those involving design of bridge openings and culverts, drainage networks, flood relief/protection schemes, the assessment of flood risk and the determination of the 'finish-floor level' for both commercial and large-scale residential developments.(Bedient P.B.(1987))

Flood estimates are also required for the safe operation of flood control structures, for taking emergency measures such as maintenance of flood levees, evacuating the people to safe localities etc. Floods not only damage properties and endanger the lives of humans and animals, but also have negative effects on the environment and aquatic life. These include soil erosion, sediment deposition downstream and destruction of spawning grounds for fish and other wildlife habitat. The analysis of flood frequency of river catchment has therefore become imperative in order to curtail hazards of this nature. Flood frequency analysis involves using observed annual peak flow discharge data to compute statistical information such as mean values, standard deviation, skewness and recurrence interval of flood.These statistical data are then used to construct frequency distributions, which are graphs and tables that tell the likelihood of various discharges as a function of recurrence interval or exceedance probability. (BaylissA.C.1999b) Flood frequency distribution can take many forms depending on the equations used to carry out the statistical analysis.

In the design of practically all hydrologic structures the peak flow that can be expected with an assigned frequency (say 1 in 100 years) is of primary importance to adequately design the structure to accommodate its effect. The design of bridges, culvert waterways and spillways for dams and estimation of scour at a hydraulic structure are some examples wherein flood-peak values are required. To estimate the magnitude of a flood peak the following methods are available:

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1. Rational method,
2. Empirical method,
3. Unit-hydrograph technique, and
4. Flood-frequency studies.

The use of a particular method depends upon (i) the desired objective, (ii) the available data and (iii) the importance of the project. Further, the rational method is applicable only to small-size (<50 km2) catchments and the unit-hydrograph method is normally restricted to moderate-size catchments with areas less than 5000 km2.(Bhattari K.P.,2004)The main focus of this paper is on flood frequency analysis of hydrological data is to determine relationship of peak discharge - return period at any site on a river so as to obtain a useful estimate of design flood of extreme event for a selected return period.

Floods are exceedingly complex natural events consisting of a number of component parameters of the hydrologic system and very difficult to model analytically. There are two broad categories of research in flood frequency analysis, namely, 'regionalization' and 'at-site'. Regionalization research investigates the relationship between flood frequency curves of catchments at different locations whereas at-site research investigates the relationship between peak flood discharge and its frequency of occurrence for a single catchment.(Dalrymple T.(1960)) Before carrying out flood frequency analysis of a given flood data series, the hydrologist has to decide on the following three options:

Selection of a suitable flood frequency model (e.g. annual maxim series model, partial duration series or peak over threshold model, or time series model)

Selection of a suitable statistical distribution (e.g. Generalized Extreme Value Distribution, Exponential Distribution, General Logistic Distribution)

Selection of a parameter estimation method to fit the selected distribution to the given flood data, (e.g. the method of ordinary moments, probability weighted moments, L-moments etc.)

Another approach to the prediction of flood flows, and also applicable to other hydrologic process such as rainfall etc. is the statistical method of frequency analysis.(Chow V.T.(1964))

THE STUDY AREA

The study area comprises of an upland watershed and a major tributary of Krishna River in the upper Krishna basin. The river has its source in the Western Ghats on the leeward side of the mountains Maharashtra, India. The river is 310 kms long and the catchment covers an area of 14,539 sq. km falling in Survey of India (SOI) toposheet No: 47 /K,47 /L,47 / P on 1:250,000 scale. The investigated area is enclosed between latitudes 17°18'N and 16°15'N and longitudes 73°50'E and 75°54'E. (Figure 1)

DATA USED

The annual peak flood series data for 10 years varying over period 1965 to 2010 for 7 important stations such as Karad ,Warna, Arjunwad, Kurundwad, Warungi of Upper Krishna basin. The data were collected from the Maharashtra state irrigation department.(Table 1) (Table 5)

TABLE-1

GAUGING STATIONS IN STUDY AREA

Sr.no.	Gauging station	Stream	Catchment Area km2	Period of Data available	Number of year
1	Warungi	Koyna	1690	1967 to2009	42
2	Karad	Krishna	5462	1965 t0 2009	44
3	Samdoli	Warna	1948	1967 to2009	42
4	Arjunwad	Krishna	12660	1969 to 2009	40
5	Terwad	Panchganga	2425	1980 to2009	29
6	Kurundwad	Krishna	15190	1972 to 2009	37
7	Sadalgi	Dudhganga	2322	1969 to2009	40

METHODOLOGY

Before the analysis, the hydrological data were selected to fairly satisfy the assumptions of independence and identical distribution. This is achieved by selecting the annual maximum of the variable being analyzed, which may be the largest instantaneous peak flow occurring at any time during the year (Figure 3).For instantaneous peak flow for all seven gauging stations, mean highest dishcharge,minimum discharge for the year 1965 to 2010 are analyzed statistically and graphs are plot as rainfall analysis, hydraulic data of river cross section and observed high flood levels (HFL) for pre monsoon and post monsoon are analyzed to estimate peak flow and high flood levels marks which required to design of bridge opening,culverts,drainage networks.(Figure 4) .The discharge analyzed was assumed to be independent and identically distributed, and the hydrological system producing them considered being stochastic, space and time independent. (Stediner J.R. and Tasker G.D. (1986)).

3.1 Probability of Flood Occurrence

The return period is said to be the average interval in years between occurrence of a flood of specific magnitude and an equal or larger flood. The m th largest flood in a data series has been equaled or exceeded m times in the period of record N years and an estimate of its recurrence interval, T_P,(eqn3) (Table 3) as given by Weibull formula (Dalrymple T.(1960))

$P = m / n +1$, eqn… (1)

where, P is the probability of the event. 'm' is the rank and 'n' is the number of data points (years of data).

Since the only possibilities are that the event will or will not occur in any year, the probability that it will not occur in a given year is 1 –P. From the principles of probability, the probability J that at least one event that equals or exceeds the T year event will occur in any series of N years is:

$J = 1 – (1 – P) N$ eqn…(2)

Hence, $J = 1 – (1 –T) N$ is the probability that the event will occur during a span of N years (Linsley and Frazini, 1992).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 series. The data are then arranged in decreasing order of magnitude and the probability P of each event being equaled to or exceeded (plotting position) is calculated by the plotting-position formula (eqn… 1)

Where, m = order number of the event and N = total number of events in the data. The recurrence interval, T_p (also called the return period or frequency) is calculated as

$T_p = 1 / P$ eqn…(3)

A plot of discharge Q vs. Tp yields the probability distribution. For small return periods (i.e. for interpolation) or where limited extrapolation is required, a simple best-fitting curve through plotted points can be used as the probability distribution. A logarithmic scale for T_p is often advantageous. However, when larger extrapolations of T_p are involved, theoretical probability distribution have to be used. In frequency analysis of floods the usual problem is to predict extreme flood events. Towards this, specific extreme-value distributions are assumed and the required statistical parameters calculated from the available data. Using these, the flood magnitude for a specific period is estimated. Chow (1951) has shown that most frequency-

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distribution functions applicable in hydraulic studies can be expressed by the following equation known as the general equation of hydrologic frequency analysis:

$X = x + K\sigma$ eqn ….(4)

Where, X = value of the variant; Q of a random hydrologic series with a return period T_p;

x = mean of the variants; σ = standard deviation of the variant; K = frequency factor which depends upon the return period; T_p and the assumed frequency distribution. Some of the commonly used frequency distribution functions for the prediction of extreme flood values are:

Gumbel's extreme-value distribution, Log-Pearson Type III distribution, and Log normal distribution.

Only the Gumbel distribution is dealt here with emphasis on application.

3.2 Gumbel's Method

Gumbel defined a flood as the largest of the 365 daily flows 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 xo is

$P(X \geq xo) = 1 - e^{-e^{-y}}$ eqn…(5)

In which y is a dimensionless variable given by

$y = \alpha(x - a)$

$a = x - 0.45005\ \sigma x$ eqn…(6)

$\alpha = 1.2825 / \sigma x$

Thus, $y = (1.2825(x - x) / \sigma x) + 0.577$

Where x = mean and σx = standard deviation of the variant X.

In practice it is the value of X for a given P that is required and as such Eq. (5) is transposed as

$y_p = -\ln[-\ln(1 - P)]$ eqn…(7)

Noting that the return period $T_p = 1/P$ and designating

y_T = The value of y, commonly called the reduced variate, for a given

$y_T = -[\ln.\ln.(Tp/(Tp-1))]$ eqn… (7.1)

or

$y_T = -[0.834 + 2.303\ \log.\log.(T_p/(T_p-1))]$ .. eqn…(7.2)

Now rearranging Eq. (5), the value of the variants X with a return period Tp is

$X_T = x + K\sigma x$ eqn…(8)

X_T is estimated event magnitude

Where $K = (y_T - 0.577)/1.2825$ eqn…(9)

Note that eqn (9) is of the same form as the general equation of hydrologic frequency analysis, Eq. (4). Further eqns. (8) and (9) constitute the basic Gumbel's equations and are applicable to an infinite sample size (i.e. $N \rightarrow \propto$).Since practical annual data series of extreme events such as floods, maximum rainfall depths, etc., all have finite lengths of record, eqn (9) is modified to account for finite N as given below for practical use.

3.2.1 Gumbel's Equation for Practical Use

Equation (8) giving the values of the variate X with a recurrence interval Tp is used as

$X_T = x + K\ \sigma_{n-1}$ eqn… (10)

Where σ_{n-1} = standard deviation of the sample size N

K= frequency factor expressed as

$K = (y_T - y_n / S_n)$ eqn…(11)

In which y_T = reduced variate, a function of T and is given by

$y = - [\ln.\ln.(Tp/(Tp-1))]$ eqn… (12)

or

$y_T = -[0.834 + 2.303 \log.\log.(Tp/(Tp-1))]$

y_n = reduced mean, a function of sample size N

S_n = reduced standard deviation, a function of sample size N

These equations are using the following procedure to estimate the flood magnitude corresponding to a given return period based on an annual flood series.

1. The discharge data are compiled with the sample size N (Table 5). Here, the annual flood value is the variate X. For the given data, x and σ_{n-1} values are found. Using standard tables (Table 2) yn and S_n appropriate to given N are determined For a given T, K and y_T are found by using eq. (11 and 12) and required x_T is determined by eq. (10).

To verify whether the given data follow the assumed Gumbel's distribution, the following procedure was adopted.

The value of X_T for some return periods Tp < N are calculated by using Gumbel's formula and plotted as X_T vs T_p on a convenient paper such as a semi-log, log-log or Gumbel probability paper (Figure-2). The use of Gumbel probability paper results in a straight line for X_T vsT_p plot. Gumble's distribution has the property which gives

Tp = 2.33years for the average of the annual series when N is very large. Thus, the value of a flood with Tp = 2.33 years is called the mean annual flood. In graphical plots this gives a mandatory point through which the line showing variation of X_T with Tp must pass. For the given data, values of return periods (plotting positions) for various recorded values, x of the variate are obtained by the relation

$Tp= (N+1)/m$ and plotted on the graph described above. A good fit of observed data with the theoretical variation line indicates the applicability of Gumbel's distribution to the given data series by extrapolation of the straight line X_T vs T_p,values of X_T for $T_p > N$ can be determined easily.

4. Flood Discharge Computation and Analysis

The flood discharge values are arranged in descending order and the plotting position recurrence interval Tp for each discharge is obtained as

$$Tp = (N + 1) / m = 41 / m$$

Where m = order number. The discharge magnitude Q are plotted against the corresponding to Tp on a Gumbel extreme probability paper (Figure- 2).The statistics x and σ_{n-1} for the series are next calculated and are shown in Table 2.Using these the discharge X_T for some chosen recurrence interval is calculated by using Gumbel's formulae [Eqs. (12), (11) and (10)].From the standard tables of Gumbel's extreme value distribution, for N = 40, yn =0.5436

and $Sn = 1.1413$.Choosing Tp = 50 years, by eqn. (12)

$y_T = -[\ln.\ln(50/ 49)] = 2.056$, $K = (2.056 - 0.5485) /1.607 = 0.938$

$X_T = 3536.222 + (0.938 \times 1813.04) = 5236.8535$ m3/s

TABLE -2:
REDUCED MEAN (YN) AND REDUCED STANDARD DEVIATION (SN)

N	10	15	20	25	30	40	50	
yn	0.4952	0.5128	0.5236	0.5309	0.5362	0.5436	0.5485	
Sn	0.9457	1.0206	1.0628	1.0915	1.1124	1.1413	1.1607	
N	60	70	80	90	100	200	500	α
yn	0.5521	0.5548	0.5569	0.5586	0.5600	0.5672	0.5724	0.5772
Sn	1.1747	1.1854	1.1938	1.2007	1.2065	1.2360	1.2588	1.2826

TABLE-3
T_P FOR OBSERVED DATA FOR ARJUNWAD GAUGE STATION

Order No M	Flood Discharge (m3 / s)	Tp	Order Number M	Flood Discharge (m3 / s)	Tp
1	9381	41	11	4904	3.72
2	9505	20.50	12	4890	3.41
3	6500	13.66	13	4780	3.15
4	6300	10.25	14	4211	2.92
5	5938	8.20	15	3989	2.73
6	5270	6.83	16	3943	2.56
7	5079	5.85	17	3850	2.41
8	4997	5.12	18	3800	2.27
9	4954	4.55	19	3560	2.15
10	4950	4.10	20	3460	2.05

Order Number M	Flood Discharge (m3 / s)	Tp	Order Number M	Flood Discharge (m3 / s)	Tp

21	3362	1.95	31	2579	1.32
22	3357	1.86	32	2550	1.28
23	3345	1.78	33	2469	1.24
24	3284	1.70	34	2411	1.20
25	3193	1.64	35	2351	1.17
26	3085	1.57	36	2241	1.13
27	2936	1.51	37	1764	1.10
28	2928	1.46	38	1747	1.07
29	2868	1.41	39	1678	1.05
30	2843	1.36	40	1333	1.02

N = 40 years, x = 3536.22 m3 / s, σ n-1 = 1813.04m3 /s

Similarly , values of X_T are calculated for more Tp values

TABLE-4:
DESIGN DISCHARGE FOR RETURN PERIOD TP

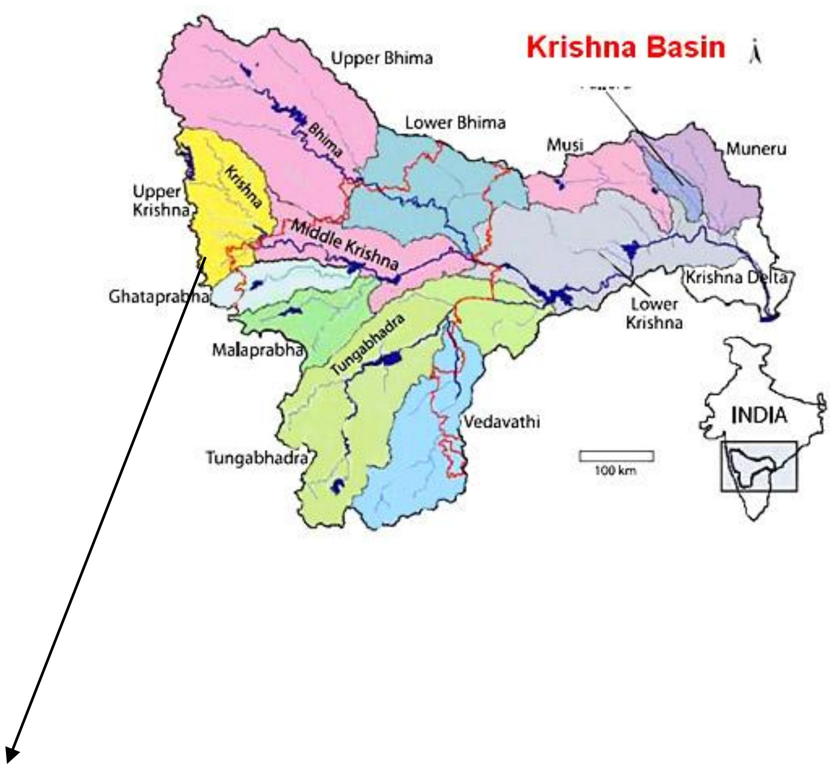
Tp (year)	Design discharge X_T (obtained by eq.10)						
	Arjunwad	Karad	Kurundwad	Warungi	Sadalgi	Terwad	Samdoli
2	4877.871	3348.624	8881.315	2505.167	1466.65	2714.33	1763.33
5	6306.547	4488.695	13236	3298.04	1809.966	3181.048	2153.237
10	5164.331	3577.217	9754.65	2664.145	1535.485	2807.911	1841.548
20	5469.647	3820.856	10685.47	2833.585	1608.856	2907.911	1924.862
50	5236.853	3635.089	9975.751	2704.39	1552.914	3161.50	1861.337
100	6246.716	4440.951	13054.545	3264.839	1795.589	3257.46	2136.909
200	6540.429	4675.331	13949.99	3427.843	1866.169	2276	2217.056

TABLE 5:
ANNUAL MAXIMUM DISCHARGE WITH CORRESPONDING WATER LEVEL (M.S.L.) FOR ARJUNWAD

Year	1965-66	66-67	67-68	68-69	69-70	70-71	71-72	72-73	73-74
Q max(cumecs)	Not established				3850	5079	2936	3989	4950
WL(m)					540.395	538.000	536.843	537.760	539.870
Year	1974-75	75-76	76-77	77-78	78-79	79-80	80-81	81-82	82-83
Q max(cumecs)	2469	5270	4890	3460	2579	4904	3800	3362	2241
WL(m)	536.404	540.460	541.070	537.817	536.321	539.767	539.895	538.195	536.213
Year	1983-84	84-85	85-86	86-87	87-88	88-89	89-90	90-91	91-92
Q max(cumecs)	3345	3284	3085	2868	2351	4997	4954	6500	5938
WL(m)	538.615	538.045	537.449	537.641	536.205	539.895	539.735	540.795	540.416
Year	1992-93	93-94	94-95	95-96	96-97	97-98	98-99	99-00	00-01
Q max(cumecs)	2928	2843	6300	2550	3560	4780	2411	3193	1747
WL(m)	537.316	537.060	541.175	535.670	539.125	540.995	535.618	537.773	534.482
Year	2001-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	
Q max(cumecs)	1764	1678	1333	4211	9381	7505	3943	3357	
WL(m)	533.590	534.323	532.785	539.455	543.680	542.125	539.885	538.345	

CONCLUSIONS

In the present study of flood frequency analysis, annual maximum series data pertaining to period 1962-2010 for the Karad, Sangli, Kholapur were analyzed using Gumble's distribution method for 2,10,20,50 100,200 year return period flood for each gauging station. 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 design floods for return period of 2 year were flood to be almost same as the observed data and verified with historical data. Arjunwad river gauging station is having very high design flood as compare to other gauging station in the study area. 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 6,246 m3/s. Knowing these design floods one can mark the high flood water level with the help of available river cross sectional area and can be used in flood studies and design of hydraulic structures within the basin and similar catchments.



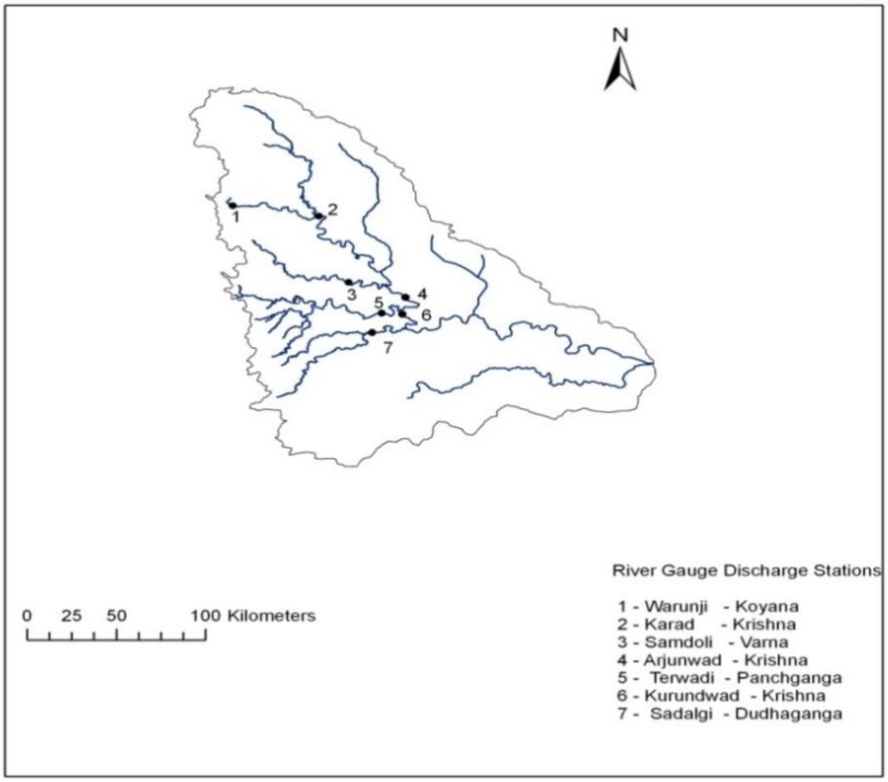


Figure 1 : Study Area

Figure.2: Flood probability analysis by Gumble's distribution

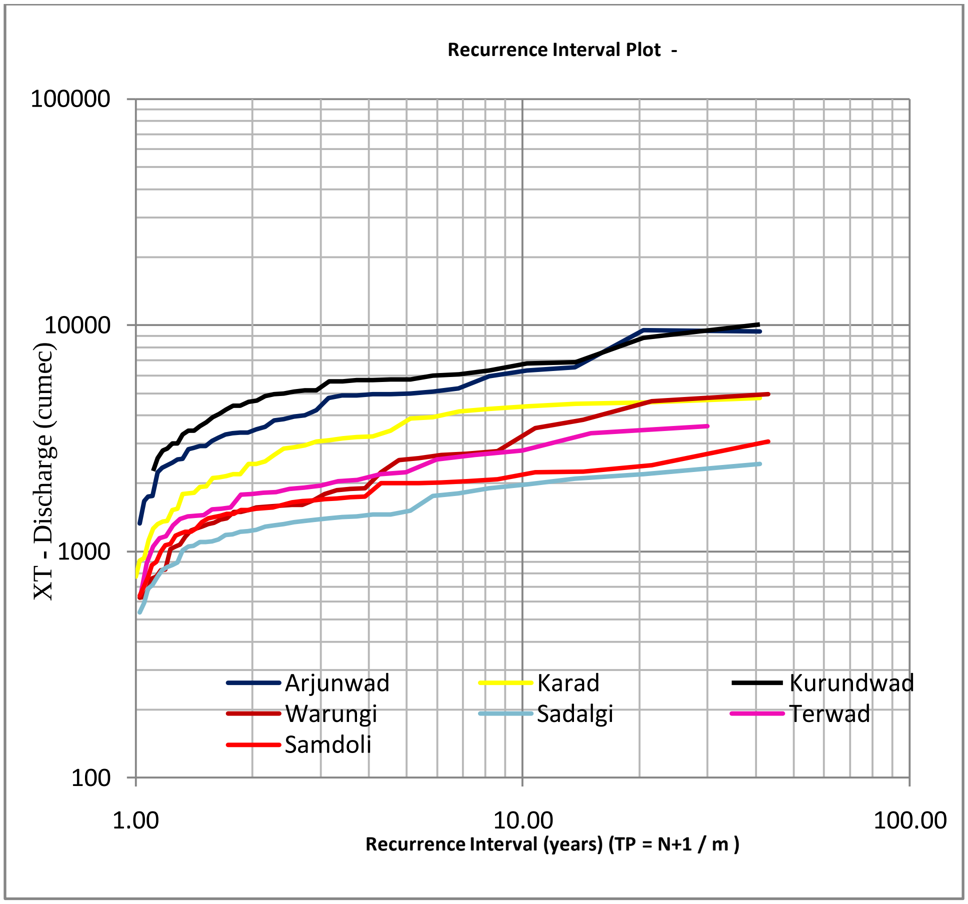
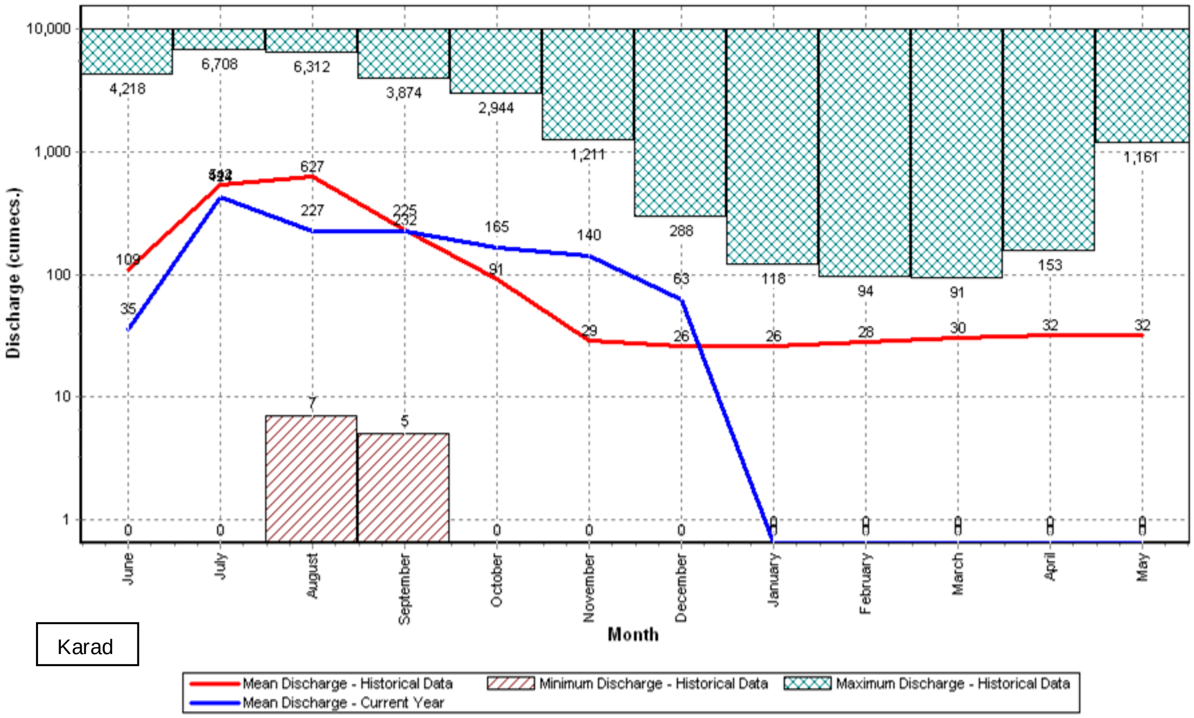
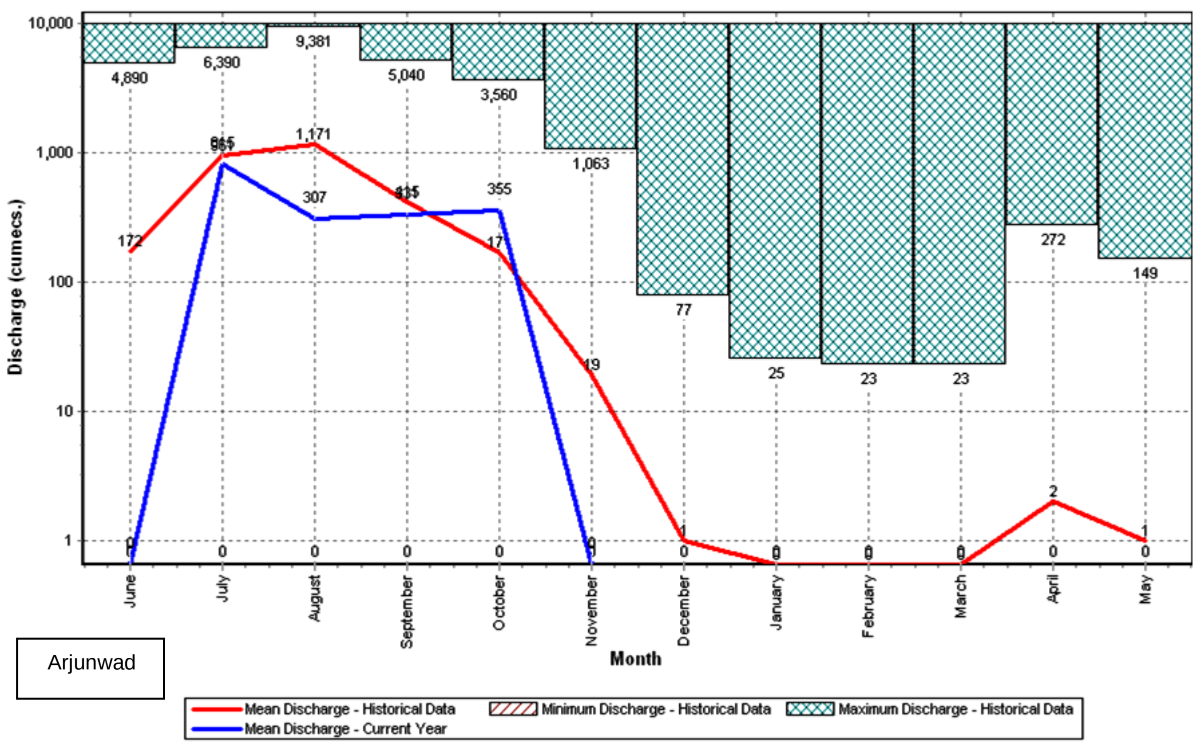


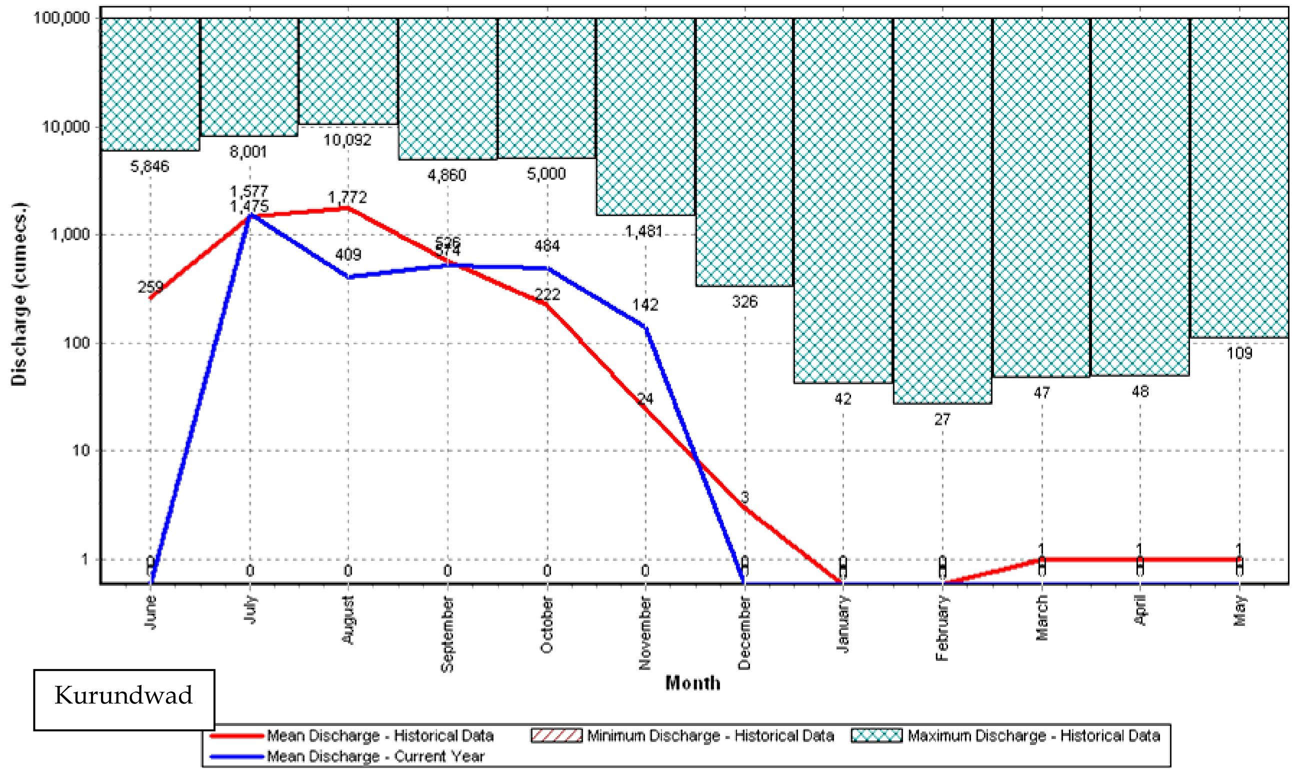
Figure 3: Time – Discharge analysis for year 2009 -10 for all seven Gauging stations

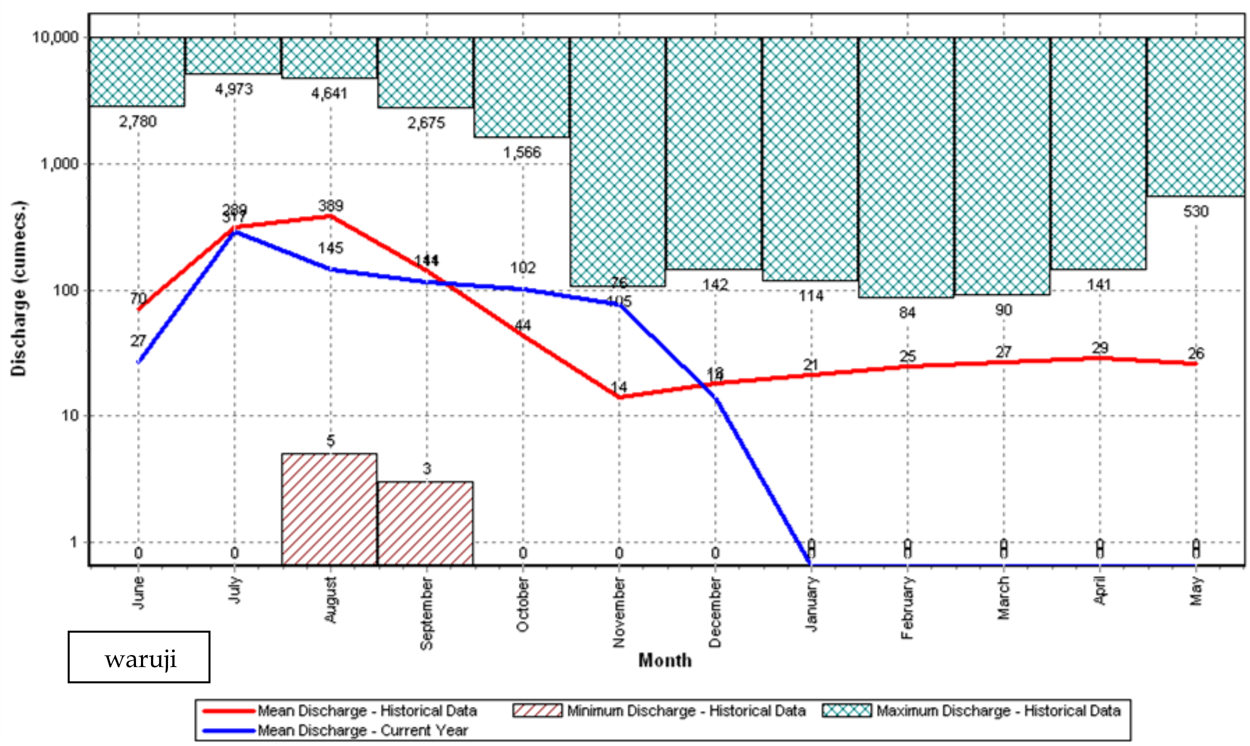


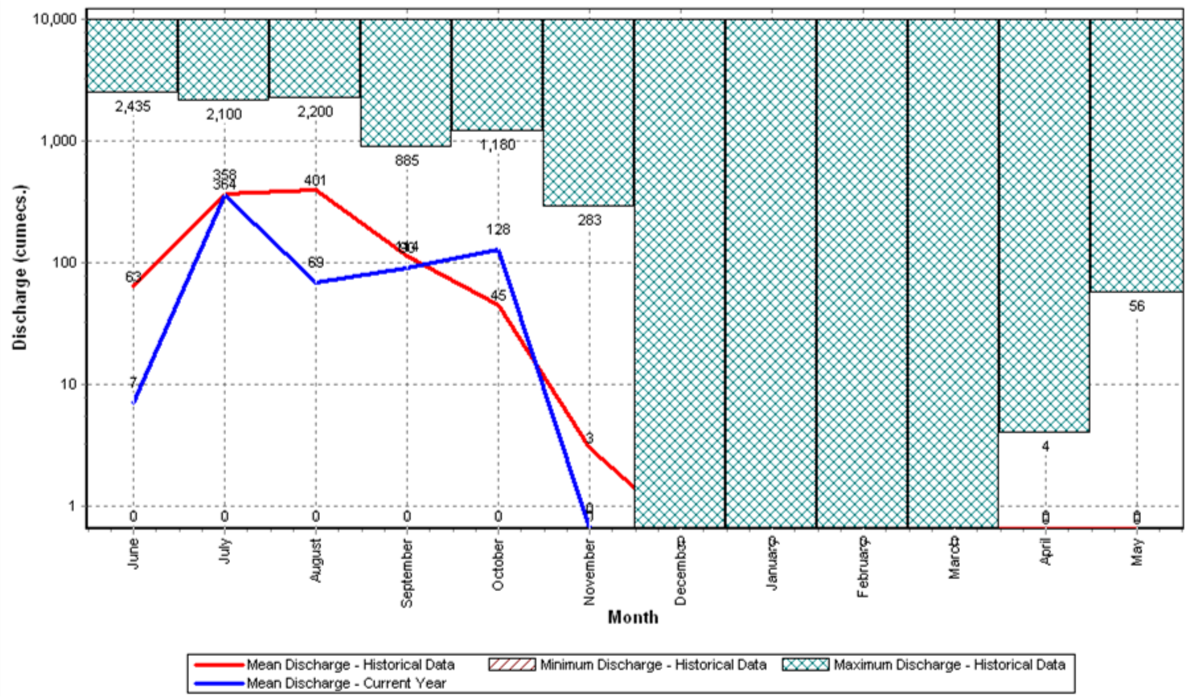
Karad

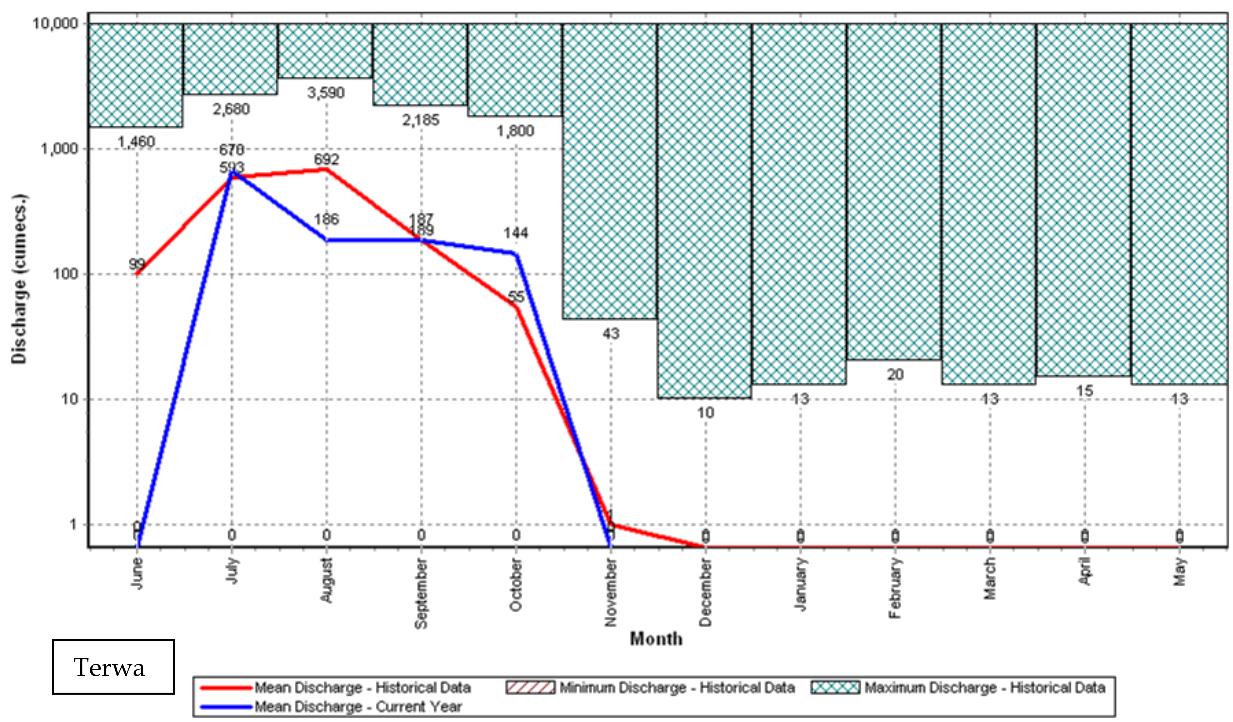


Arjunwad


Discharge (cumecs.)
100,000
10,000
1,000
100
10
1
June
July
August
September
October
November
December
January
February
March
April
May
Month
Kurundwad
Mean Discharge - Historical Data
Mean Discharge - Current Year
Minimum Discharge - Historical Data
Maximum Discharge - Historical Data


Discharge (cumecs.)
10,000
1,000
100
10
1
June
July
August
September
October
November
December
January
February
March
April
May
Month
waruji
Mean Discharge - Historical Data
Mean Discharge - Current Year
Minimum Discharge - Historical Data
Maximum Discharge - Historical Data


10,000
1,000
100
10
1
Discharge (cumecs.)
2,435
2,100
2,200
885
1,180
283
56
4
401
128
69
63
45
7
3
0
June
July
August
September
October
November
December
January
February
March
April
May
Month
Mean Discharge - Historical Data
Mean Discharge - Current Year
Minimum Discharge - Historical Data
Maximum Discharge - Historical Data


10,000
1,000
100
10
1
Discharge (cumecs.)
1,460
2,680
3,590
2,185
1,800
43
10
13
20
13
15
13
670
593
692
186
187
144
99
55
0
June
July
August
September
October
November
December
January
February
March
April
May
Month
Terwa
Mean Discharge - Historical Data
Mean Discharge - Current Year
Minimum Discharge - Historical Data
Maximum Discharge - Historical Data

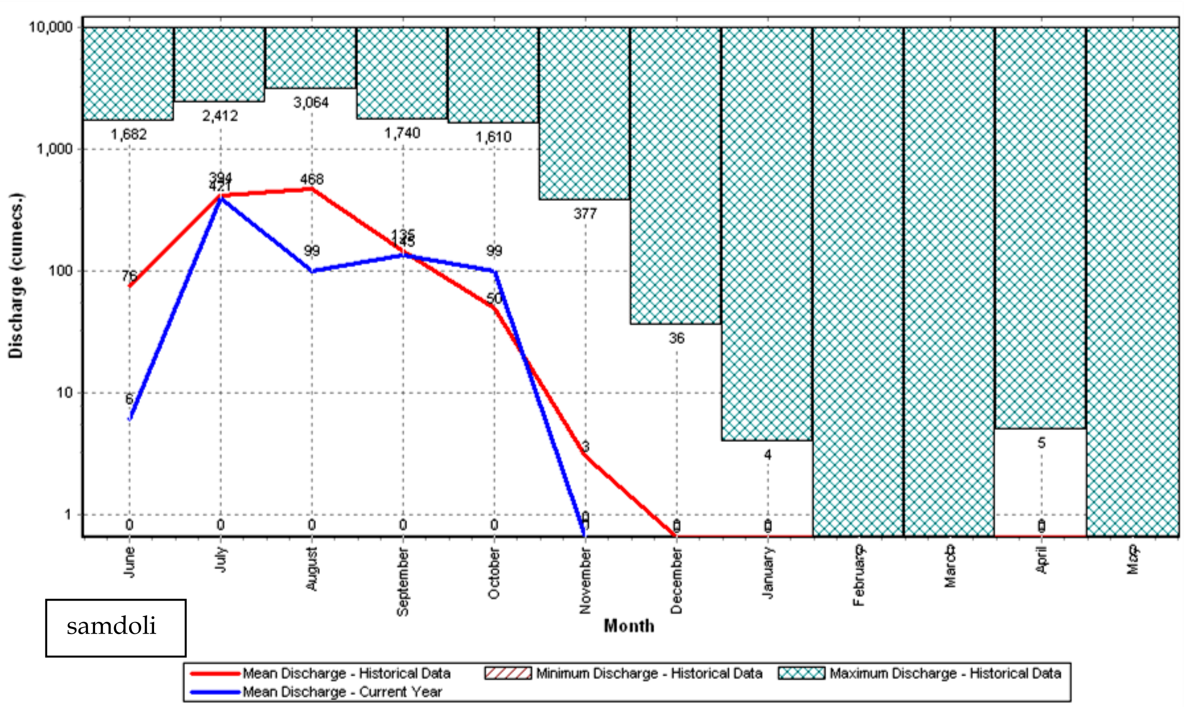
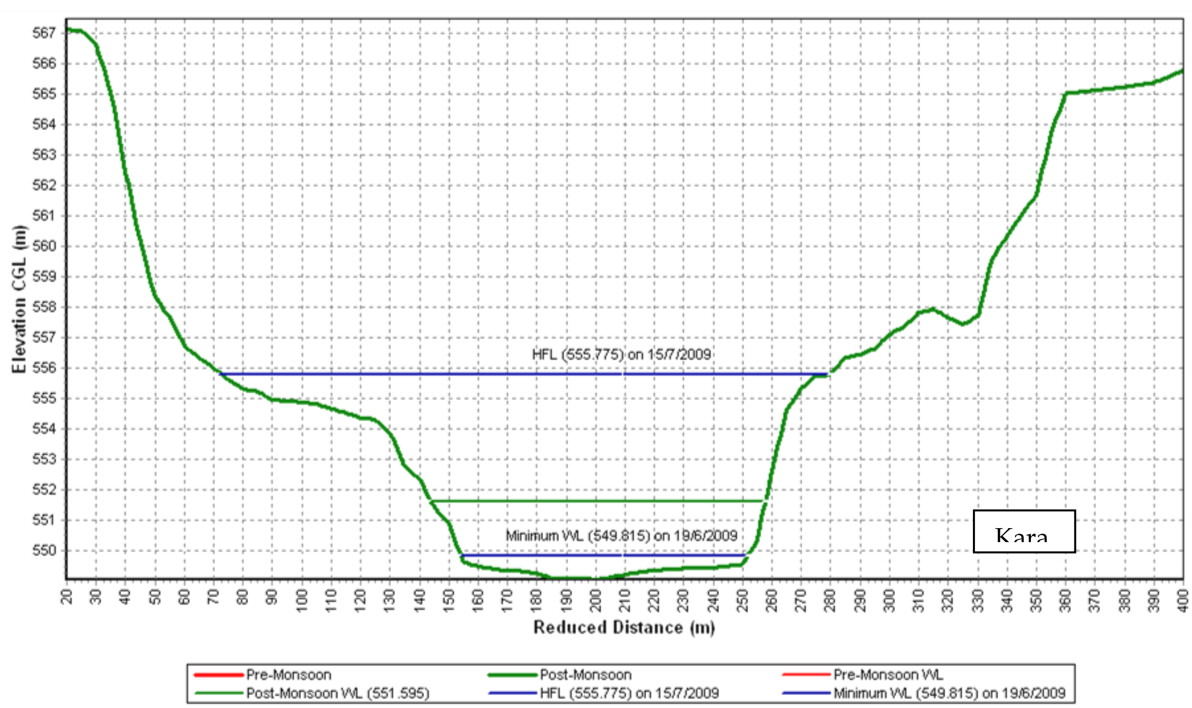
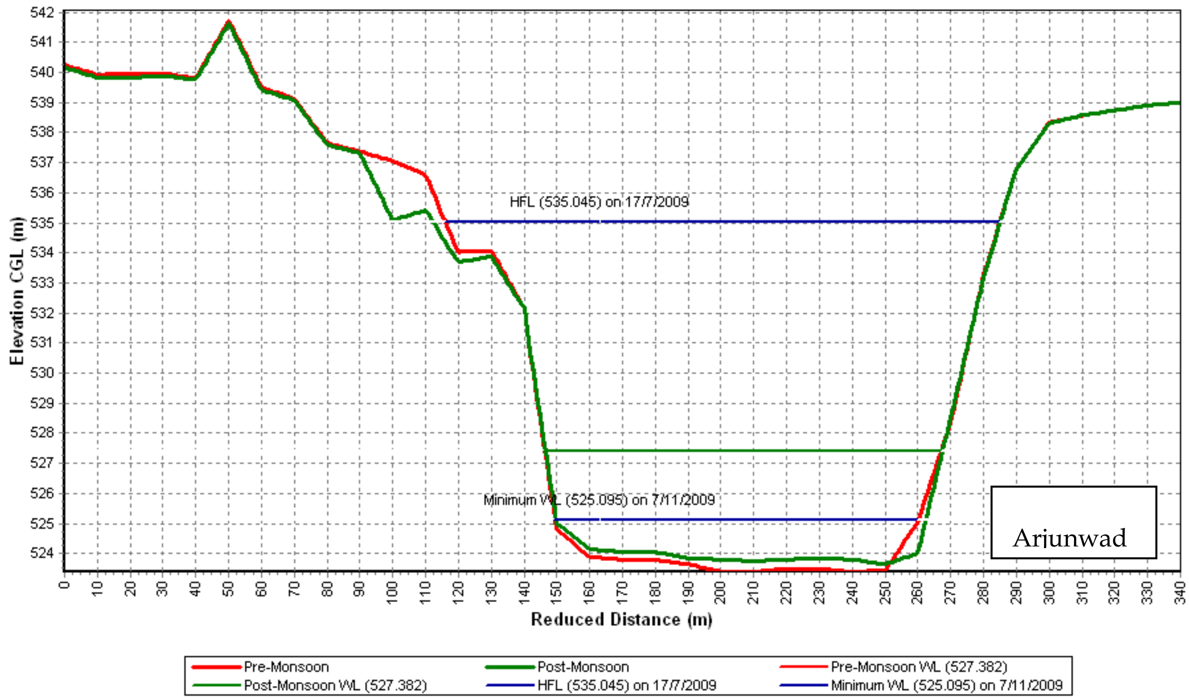
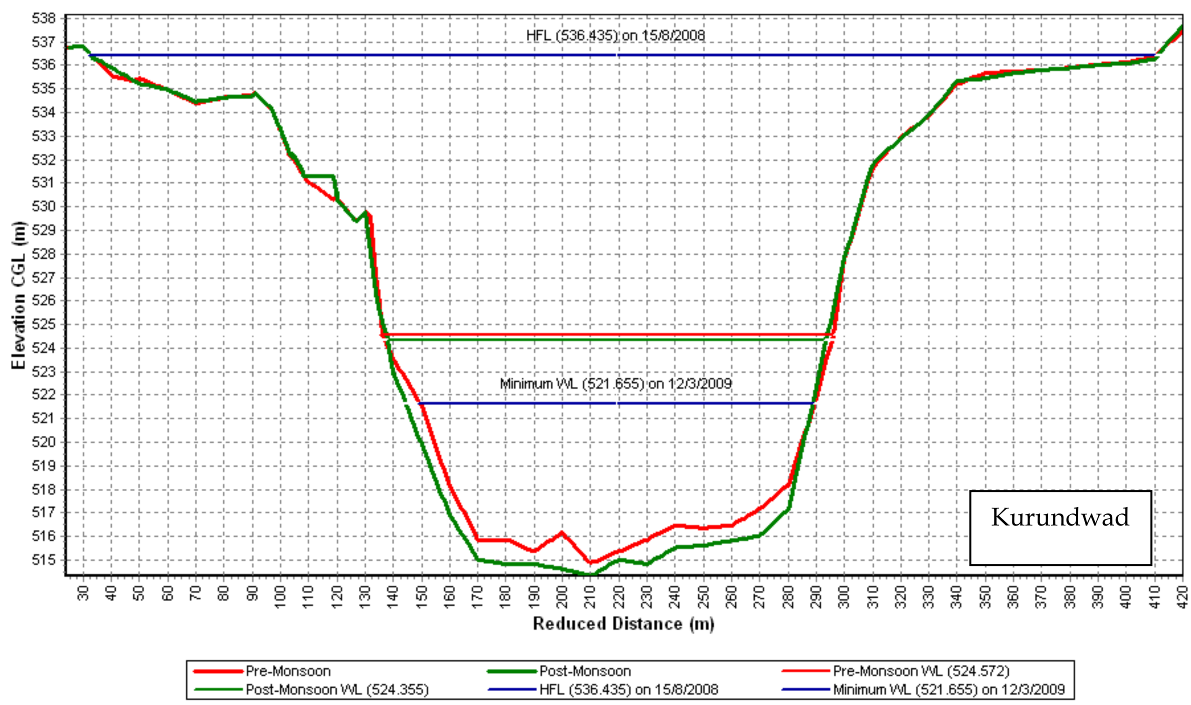
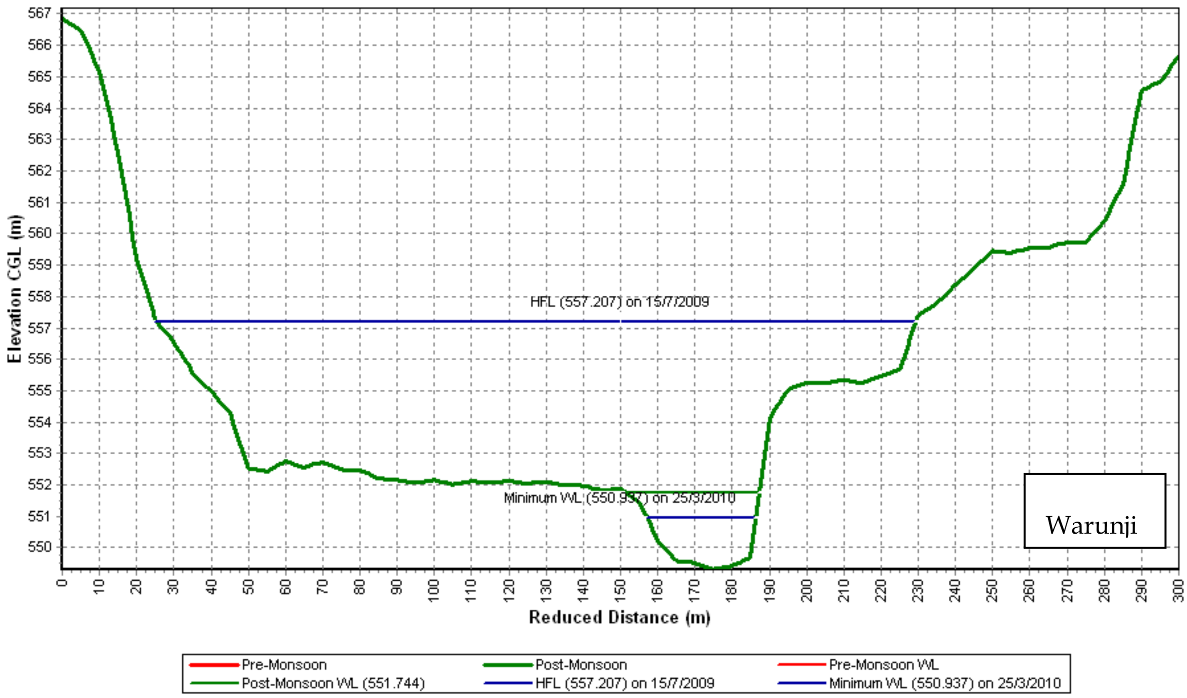


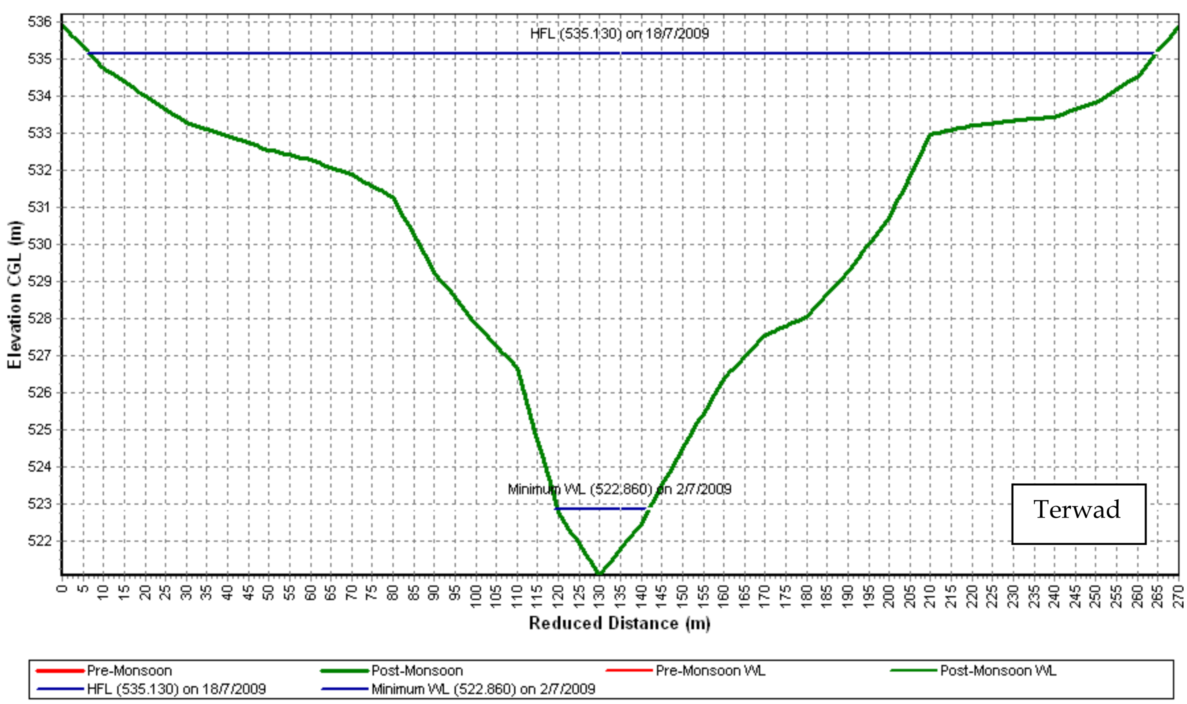
Figure 4 River cross section with high flood levels for river gauging station

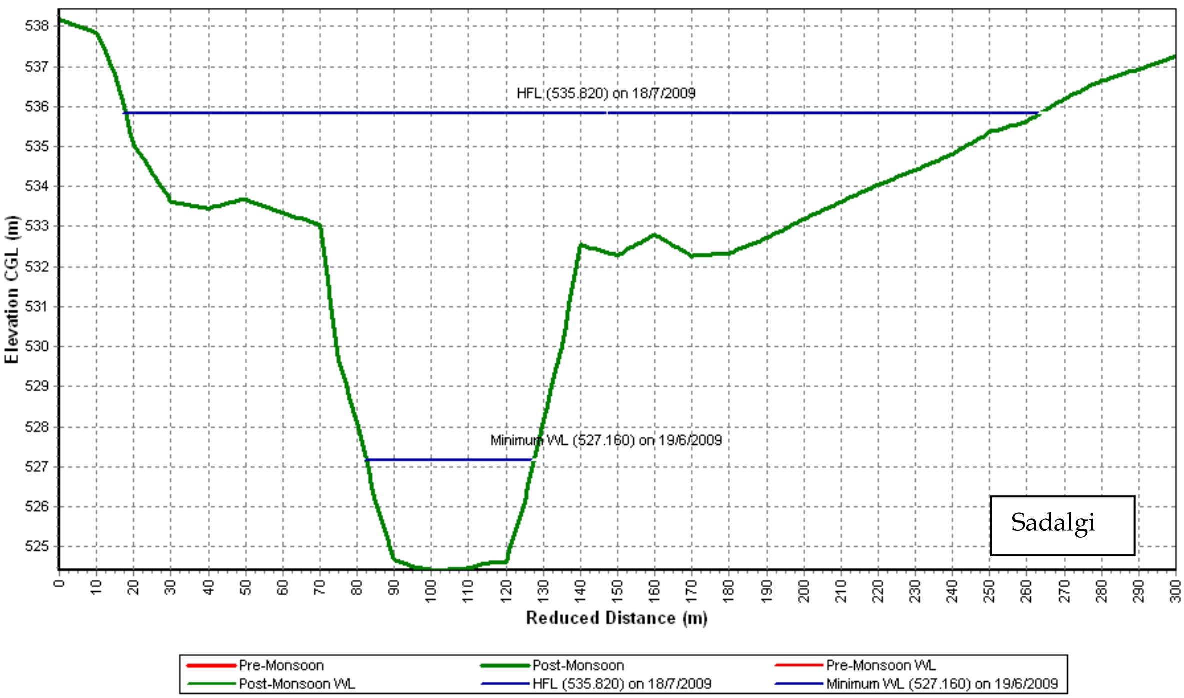


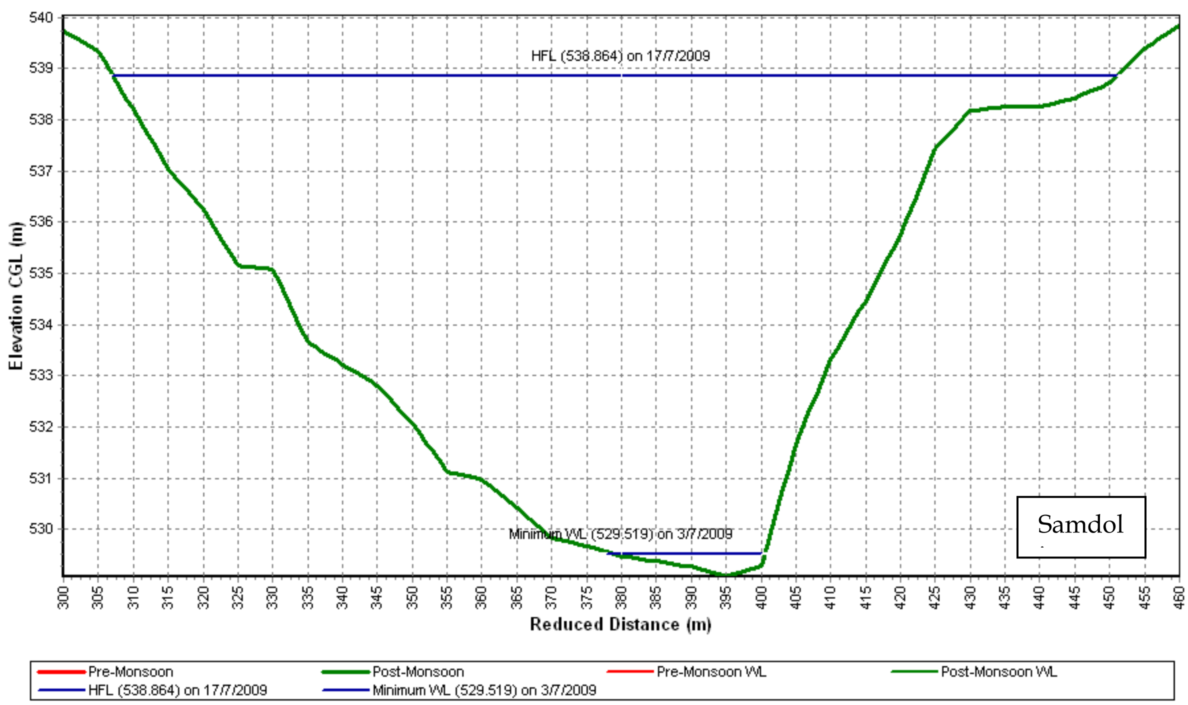

HFL (535.045) on 17/7/2009
Minimum WL (525.095) on 7/11/2009
Arjunwad
Elevation CGL (m)
Reduced Distance (m)
Pre-Monsoon
Post-Monsoon
Pre-Monsoon WL (527.382)
Post-Monsoon WL (527.382)
HFL (535.045) on 17/7/2009
Minimum WL (525.095) on 7/11/2009


HFL (536.435) on 15/8/2008
Minimum WL (521.655) on 12/3/2009
Kurundwad
Elevation CGL (m)
Reduced Distance (m)
Pre-Monsoon
Post-Monsoon
Pre-Monsoon WL (524.572)
Post-Monsoon WL (524.355)
HFL (536.435) on 15/8/2008
Minimum WL (521.655) on 12/3/2009


HFL (557.207) on 15/7/2009
Minimum WL (550.937) on 25/3/2010
Warunji
Elevation CGL (m)
Reduced Distance (m)
Pre-Monsoon
Post-Monsoon
Pre-Monsoon WL
Post-Monsoon WL (551.744)
HFL (557.207) on 15/7/2009
Minimum WL (550.937) on 25/3/2010


HFL (535.130) on 18/7/2009
Minimum WL (522.860) on 2/7/2009
Terwad
Elevation CGL (m)
Reduced Distance (m)
Pre-Monsoon
Post-Monsoon
Pre-Monsoon WL
Post-Monsoon WL
HFL (535.130) on 18/7/2009
Minimum WL (522.860) on 2/7/2009





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