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Estimation of Peak Flood for the Ungauged Catchments Using Synthetic Unit Hydrograph Approach

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Abstract- Estimation of Peak Flood (PF) for a given return period is considered as one of the most important parameters for planning and design of hydraulic structures, river protection works, development of integrated water resources management projects, etc. This can be achieved by adopting various approaches viz., flood frequency analysis, rational method, empirical equation, envelope curve and Synthetic Unit Hydrograph (SUH) approach. In this paper, SUH approach is adopted for estimation of PF for the ungauged catchments wherein rainfall depth (i.e., 24-hour maximum rainfall) becomes an important parameter. This can be determined through Extreme Value Analysis (EVA) by fitting Gumbel probability distribution to the Annual Maximum Rainfall (AMR) series that is derived from the daily rainfall data. Parameters of the distribution are determined by maximum likelihood method and used for estimation of rainfall. Goodness-of-Fit tests viz., Anderson-Darling and Kolmogorov-Smirnov are applied for checking the adequacy of fitting Gumbel distribution to the AMR series. The rainfall depth is computed by multiplying the estimated 1-day maximum rainfall with 1.15 and used as an input for estimation of PF. The paper presents the procedures adopted in estimation of PF for the ungauged catchments of Suketi Khad using SUH approach and the results obtained thereof.

Keywords- Extreme value analysis, Gumbel distribution, Maximum likelihood method, Peak flood, Synthetic unit hydrograph

I. INTRODUCTION

Estimation of Peak Flood (PF) for a given return period is considered as one of the most important parameters for planning and design of hydraulic structures, river protection works, development of integrated water resources management projects, etc [1-2]. This can be achieved by adopting various approaches viz., flood frequency analysis, rational method, empirical equation, envelope curve and Synthetic Unit Hydrograph (SUH) approach [3]. Out of which, flood frequency analysis method involves fitting probability distribution to the annual maximum series of stream flow data is adopted for estimation of PF for the gauged catchments. Likewise, rational method is used for estimation of PF for ungauged catchments with catchment area less than 25 km^2.

A SUH approach is adopted for estimation of PF for gauged as well as ungauged catchments with catchment area more than 25 km^2 [4]. For ungauged catchments, stream flow data is generally not available for estimation of PF. For such cases, the 24-hour maximum rainfall is an important parameter for estimation of PF. This can be determined through Extreme Value Analysis (EVA) that involves fitting probability distribution to the Annual 1-day Maximum Rainfall (AMR) series that is derived from the daily rainfall data.

This research paper is arranged in the following manner. The introduction on estimation of PF is presented in Section-I. The studies conducted by various researchers on PF estimation is presented in Section-II. The methodology adopted in EVA of rainfall and estimation of PF using SUH approach is presented in Section-III. The study area and data used in this paper is given in Section-IV. The results of the data analysis and its related discussions are presented in Section-V. The conclusions and recommendations made from the study are presented in Sections VI and VII respectively.

II. LITERATURE REVIEW

During the past, number of studies on estimation of PF for ungauged catchments has been carried out by different researchers. Ramirez [5] conducted the study on estimation of PF using SUH approach for 20 watersheds that were located in the Appalachian Highlands. Jena et al. [6] adopted the SUH approach for estimation of design flood for water resources project in Baitarani basin, Odisha. Natakusumah et al. [7] applied SUH approach for the derivation of flood hydrograph of the Cibatarua river basin. Priyanka Kumari and Goel [8] adopted SUH approach for flood estimation for rivers of Saurashtra Region contributing into Gulf of Khambhat. Kim and Mun-Ju Shin

[9] estimated the relationship between the runoff coefficient, intensity of rainfall, and curve number, and then utilized the relationship to calculate the peak flow using the rational method for ungauged catchments. Reddy et al. [10] conducted the study on flood estimation at ungauged catchments of western catchments of Karnataka, West coast of India by adopting five different methods such as CWC (Central Water Commission) approach, Snyder method, SCS (Soil Conservation Service) method, Gamma distribution and hybrid model. They also found that the hybrid model satisfies the UH criterion whereas traditional methods of Snyder, SCS, CWC-SUH and CWC dimensionless methods require manual adjustments of the characteristics points and have a significant degree of subjectivity and trial and error. Andrea et al. [11] carried out the study on comparison of design peak flow estimation methods for ungauged basins in Iran. They found that the CWC-SUH approach gives better results than other methods. However, the outcomes of the results of various studies reported therein didn't suggest for applying a particular method for estimation of PFD for the ungauged catchments.

This paper details on a study on estimation of PF for the ungauged catchments using SUH approach with illustrate example. The procedures adopted in EVA of rainfall and estimation of PF using SUH approach is briefly described in the ensuing sections.

III. METHODOLOGY

Gumbel (or Extreme Value Type-1) Distribution

Out of a number of probability distributions, the family of Extreme Value Distributions (EVDs) includes Generalized Extreme Value, Extreme Value Type-1 (Gumbel), Extreme Value Type-2 (Frechet) and Generalized Pareto is widely adopted for EVA of rainfall. EVDs arise as limiting distributions for the sample of independent, identically distributed random variables, as the sample size increases. In the group of EVDs, Gumbel distribution has no shape parameter as when compared to other distributions and also simpler; and hence used for EVA of rainfall. The Cumulative Distribution Function (CDF) of the Gumbel distribution [12] for the variable 'x' (i.e., AMR), is given as below:

$$F(x) = e^{-e^{-(x-\alpha)/\beta}}, \beta > 0 \quad \dots (1)$$

where, α is the location parameter and β is the scale parameter of the Gumbel distribution. The parameters are computed by maximum likelihood method and used to estimate the Extreme Rainfall (x(T)) for different return periods (T) from

$$x(T) = \hat{\alpha} + Y(T)\hat{\beta} \quad \dots (2)$$

Here, Y(T)=-ln(-ln(1-(1/T))) is called as a reduced variate for a given return period T (in year).

$$\hat{\alpha} = -\hat{\beta}\ln\left[\sum_{i=1}^{N} \exp\left(-x(i)/\hat{\beta}\right) \Big/ N\right] \quad \dots (3)$$

$$\hat{\beta} = \overline{R} - \left[\sum_{i=1}^{N} x(i)\exp\left(-(x(i)/\hat{\beta}\right) \Big/ \sum_{i=1}^{N} \exp\left(-x(i)/\hat{\beta}\right)\right] \quad \dots (4)$$

$$SE(x(T)) = \left(\hat{\beta}/\sqrt{N}\right)\left(1.15894 + 0.19187\,Y(T) + 1.1Y(T)^2\right)^{0.5} \quad \dots (5)$$

where, x(i) is the observed AMR of i^{th} sample, $\bar{x}$ is the average of the AMR, N is the sample size and x(T) is the estimated Extreme Rainfall (ER) for a given return period (T). The lower and upper confidence limits (LCL and UCL) of the estimated ER are obtained from the equations viz., LCL=ER-1.96(SE) and UCL=ER+1.96(SE). Here, SE is the Standard Error of the estimated ER [13].

Goodness-of-Fit Tests

GoF tests viz., AD and KS tests statistic are applied for checking the adequacy of fitting Gumbel distribution to the series of AMR data. Theoretical descriptions of GoF tests statistic are given as below:

$$AD = (-N) - (1/N)\sum_{i=1}^{N}\begin{Bmatrix}(2i-1)\ln(Z(i)) + \\ (2N+1-2i)\ln(1-Z(i))\end{Bmatrix} \quad \dots (6)$$

$$KS = \mathop{Max}_{i=1}^{N}\left(F_e(x(i)) - F_D(x(i))\right) \quad \dots (7)$$

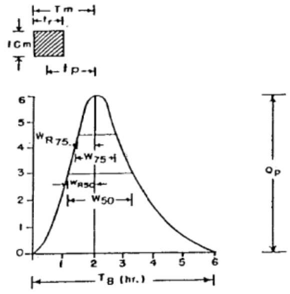
where, Z_i=F(x(i))=(i-0.44)/(N+0.12) for i=1,2,3, …,N with x(1)<x(2)<….<x(N), $F_e(x(i))$ is the empirical CDF of x(i), $F_D(x(i))$ is the derived CDF of x(i) using Gumbel distribution. Here, x(1) and x(N) indicates the smallest and highest values in the AMR series. The theoretical values AD and KS tests statistic for different sample size (N) at 5% or 1% significance level are available in the technical note on 'Goodness-of-Fit Tests for Statistical Distributions' by Charles Annis [14].

Test criteria: If the computed values of GoF tests statistic by Gumbel distribution are less than its theoretical values at the desired significance level (either at 5% or 1%), then the distribution is found to be acceptable for EVA of rainfall at that level.

SUH Approach

A systematic and sustained collection of hydro-meteorological data for selected catchments in different climatic zones is required for estimation of PF. Based on the data collected, the physiographic parameters viz., catchment area, length of the longest stream, length of the longest stream closer to the centre of gravity to the point of study and equivalent stream slope are computed by delineating the catchments of the study area using ArcGIS software. By using the physiographic parameters, the SUH parameters were determined from the empirical equations (Table 1) to derive the 1-hour SUH based on CWC [16] Flood estimation report for Western Himalayas-Zone 7. In the process, the ordinates of the unit hydrograph are adjusted in such a way that the total volume of direct runoff is adjusted to 1.00 cm depth over the catchment.

Table 1. Empirical equations used in determination of SUH parameters

$q_p = 1.048\left(t_p\right)^{-0.178}$ $t_p = 2.498\left(LL_c / S\right)^{0.156}$ $W_{50} = 1.954\left(LL_c / S\right)^{0.099}$ $W_{75} = 0.972\left(LL_c / S\right)^{0.124}$ $WR_{50} = 0.189\left(W_{50}\right)^{1.769}$ $WR_{75} = 0.419\left(W_{75}\right)^{1.246}$ $T_B = 7.845\left(t_p\right)^{0.453}$ $Q_p = q_p * A$ and $T_m = t_p + 0.5$	 Parameters of SUH (Snyder, 1938)[15]

where,

A	:	Catchment area (km^2)
L	:	Length of the longest main stream along the river course (km)
L_c	:	Length of the longest stream from centre of gravity (km)
S	:	Equivalent stream slope (m/km)
t_p	:	Time to peak or the basin lag (hour)
t_r	:	Unit rainfall duration (hour)
q_p	:	Peak discharge (m^3/s) of UH per unit area (km^2)
T_B	:	Time base of the UH (hour)
T_m	:	Time from the start of rise to peak of UH (hour)
T_D	:	Design storm duration (hour)
Q_p	:	Peak discharge of UH (m^3/s)
W_{50}	:	Width of UH at 50% of Q_p (hour)
W_{75}	:	Width of UH at 75% of Q_p (hour)
WR_{50}	:	Width of rising limb of UH at 50% of Q_p (hour)
WR_{75}	:	Width of rising limb of UH at 75% of Q_p (hour)

The steps involved in derivation of design flood hydrograph using SUH approach [17] are summarized and are presented as given below:

i) Preparation of catchment area plan of the ungauged catchment.
ii) Determination of physiographic parameters i.e. the catchment area, the length of the longest stream (L) and equivalent stream slope (S).
iii) Determination of 1-hour SUH parameters viz., q_p, Q_p, t_p, T_m, W_{50}, W_{75}, WR_{50}, WR_{75} and T_B.
iv) Derivation of 1-hour SUH.
v) Estimation of design storm duration (T_D or T_B) i.e., T_D=1.1t_p
vi) Estimation of point rainfall to areal rainfall to obtain the value of T_D.
vii) Distribution of areal rainfall during T_D to obtain rainfall increments for unit duration intervals.
viii) Estimation of effective rainfall units after subtraction of prescribed design loss rate for this zone from rainfall increments.
ix) Estimation of base flow.
x) Computation of design PF and derivation of design flood hydrograph of the catchment.

IV. STUDY AREA AND DATA USED

In this paper, a study on estimation of PF for the ungauged catchments of Suketi Khad using SUH approach was carried out. The Suketi Khad is one of the main tributary of Suketi River Basin (SRB), which is located in the Mandi district of Himachal Pradesh, India. It encompasses a central intermountain valley and surrounding mountainous terrain in the Lower Himachal Himalaya. The SRB encompasses an area of 1710 km^2 with an altitude ranging from 754 m to 2052 m. Geographically, the study area falls between the longitudes 76° 48' 30" to 77° E and latitudes 31° 29' to 31° 45' N. From the topography of the SRB [18], it was noted that the Hind Khad, Khansa Khad, Ratti Khand and Kummai Khad are the Sub-Catchments (SCs) of Suketi Khad that contributes flow to the SRB. Figure 1 shows the location map of the SCs of Suketi Khad upto Kangi Bridge. For EVA of rainfall, the daily rainfall data observed at Sundernagar site for the period 1969 to 2018 was used. The AMR data series was derived from the daily rainfall data and used for EVA. Figure 2 presents the time series plot with descriptive statistics of the AMR data of Sundernagar site.

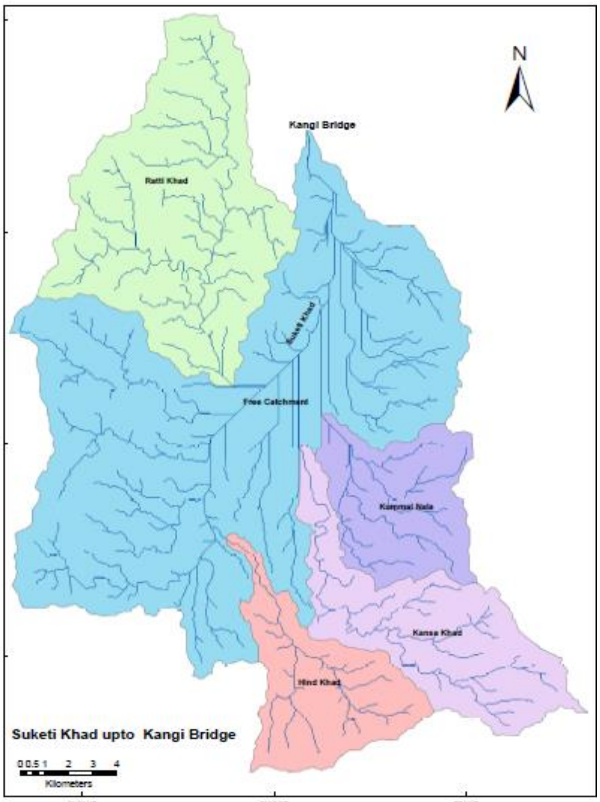


Figure 1. Location map of SCs of Suketi Khad upto Kangi Bridge

V. RESULTS AND DISCUSSIONS

EVA of Rainfall

By applying the procedures of Gumbel distribution, as described above, the parameters of the distribution were determined and used for estimation of ER. Table 2 gives the ER estimates with 95% confidence limits (ER±1.96SE) for different return periods for Sundernagar site whereas the plots are presented in Figure 3. The 24-hour maximum rainfall was computed by multiplying the estimated 1-day maximum rainfall with 1.15 and also presented in Table 2.

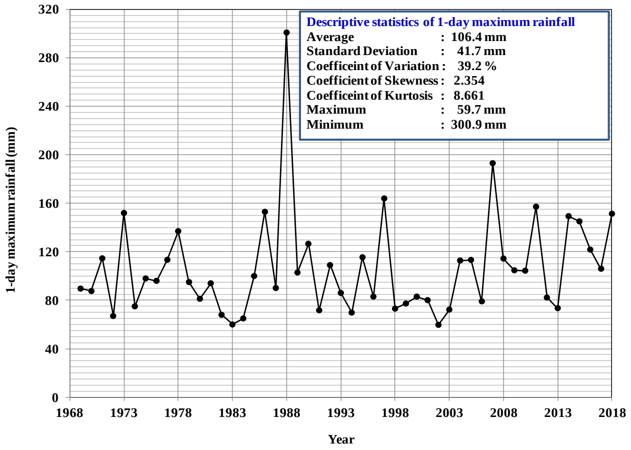


Figure 2. Time series plot with the descriptive statistics of the observed AMR of Sundernagar

Table 2. Estimated 1-day and 24-hour maximum rainfall (mm) with 95% confidence limits for different return periods by Gumbel distribution for Sundernagar

Return period (year)	1-day maximum rainfall	Confidence limits at 95% level		24-hour maximum rainfall
		Lower	Upper	
2	99.4	91.0	107.9	114.3
5	128.9	115.9	141.8	148.2
10	148.4	131.7	165.0	170.7
20	167.0	146.7	187.4	192.1
25	173.0	151.4	194.5	199.0
50	191.2	165.9	216.6	219.9
75	201.9	174.3	229.4	232.2
100	209.4	180.3	238.5	240.8
200	227.4	194.6	260.3	261.5
500	251.3	213.4	289.2	289.0
1000	269.3	227.5	311.1	309.7

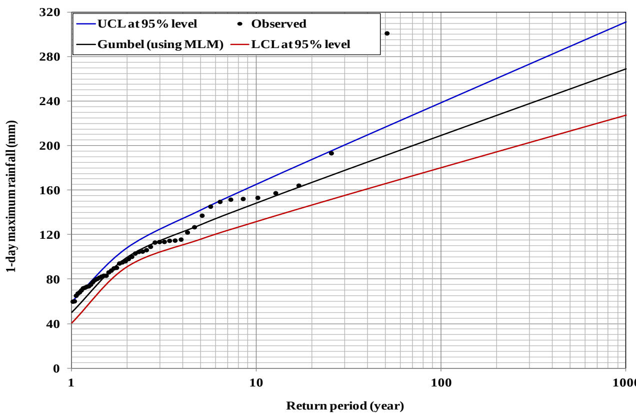


Figure 3. Plots of estimated 1-day maximum rainfall with 95% confidence limits for different return periods by Gumbel distribution and observed AMR of Sundernagar

Analysis Based on GoF Tests

By using the procedures of GoF tests, as described above, AD and KS tests statistic values of Gumbel distribution were computed as 0.455 and 0.082 respectively. From GoF tests results, it is noted that the computed values are less than its theoretical values (i.e., 0.757 for AD and 0.178 for KS) at 5% level and at this level both GoF tests are supported the use of Gumbel distribution for EVA of rainfall.

Estimation of PF using SUH Approach

The 24-hour maximum rainfall of Sundernagar site, as given in Table 2, was used for estimation of PF by SUH approach based on CWC (1994) Flood estimation report for Western Himalayas-Zone 7. By using Survey of India Toposheets, DEM (Digital Elevation Model) of National Remote Sensing Centre (NRSC) and Google Earth of the region of the SCs of Suketi Khad viz., Hind Khad, Kansa Khad, Ratti Khad and Kummai Khad were delineated and presented in Figure 1. Also, the catchment characteristics of SCs of Suketi Khad were extracted with the aid of ArcGIS software and are presented in Table 3. The physiographic and SUH parameters of the SCs were determined by using the empirical equations (Table 3) and used for estimation of PF.

Derivation of SUH

By using the SUH parameters, as given in Table 3, the SUH of SCs of Suketi Khad were derived and presented in Figure 4.

Derivation of Flood Hydrograph

By considering the procedures described in CWC (1994) guidelines, various factors viz., design storm duration, correction factor for estimation of point rainfall and areal rainfall for design storm duration, loss rate (i.e., 2 mm for all SCs) and base flow involved in computation of the ordinates of the flood hydrograph of SCs are presented in Table 4.

Table 3. Physiographic and SUH parameters of SCs of Suketi Khad

Parameters	Hind Khad	Kansa Khad	Ratti Khad	Kummai Khad
Physiographic parameters				
Catchment Area (km^2)	36.77	51.56	93.24	35.19
Length (km)	12.64	27.04	20.38	11.64
L_c (km)	8.17	16.96	8.89	6.76
Slope (m/km)	38.55	36.18	11.39	37.20
SUH parameters				
q_p (m^3/s)	0.87	0.83	0.82	0.87
t_p (hour)	2.91	3.71	3.85	2.81
t_r (hour)	3.00	4.00	4.00	3.00
W_{50} (hour)	2.15	2.51	2.57	2.10
W_{75} (hour)	1.10	1.33	1.37	1.07
WR_{50} (hour)	0.73	0.96	1.00	0.70
WR_{75} (hour)	0.47	0.60	0.62	0.45
T_D (hour) (T_D=1.1*t_p)	3.20	4.08	4.23	3.09
T_B (hour)	13.00	15.00	15.00	13.00
Q_p (m^3/s)	31.86	42.78	76.88	30.69
Q (m^3/s)	102.22	143.34	259.21	97.83

By using the values and physiographic and SUH parameters, as given in Table 3, the 25-year, 50-year, 75-year and 100-year return period PFs for SCs of Suketi Khad were computed and are presented in Table 5. The estimated PFs were used to derive the flood hydrographs for the said SCs and presented in Figures 5 to 8.

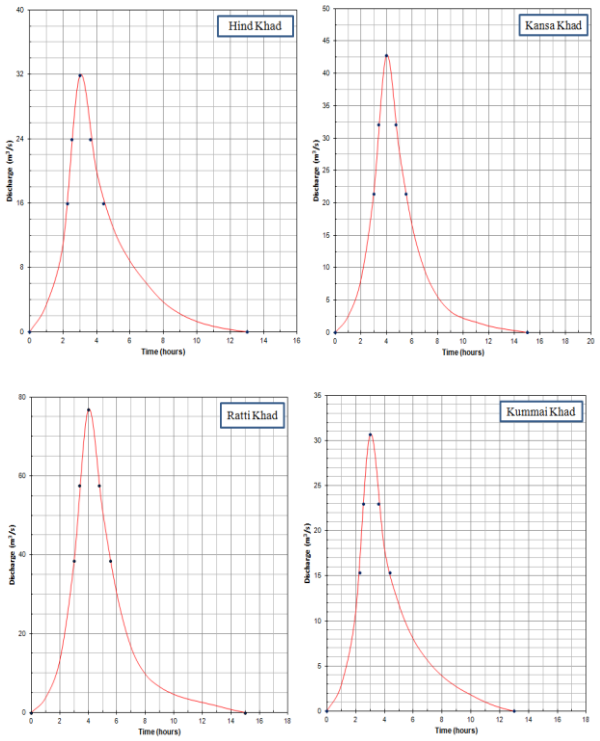


Figure 4. SUH of SCs of Suketi Khad

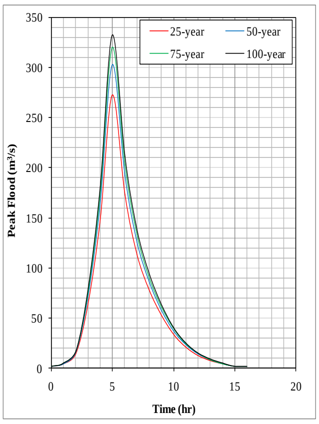


Figure 5. Flood hydrograph for different return periods of Hind Khad

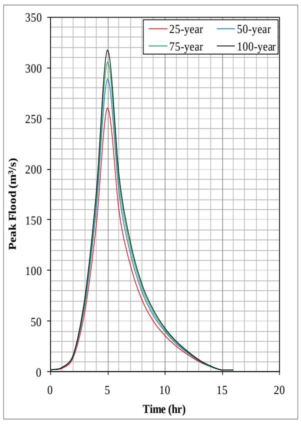


Figure 6. Flood hydrograph for different return periods of Kummai Khad

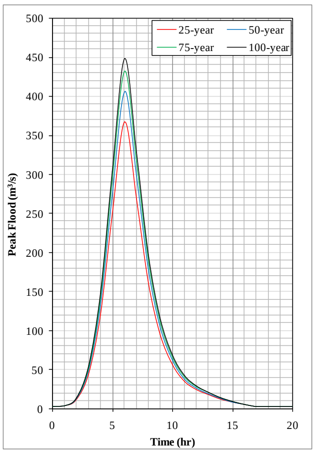


Figure 7. Flood hydrograph for different return periods of Kansa Khad

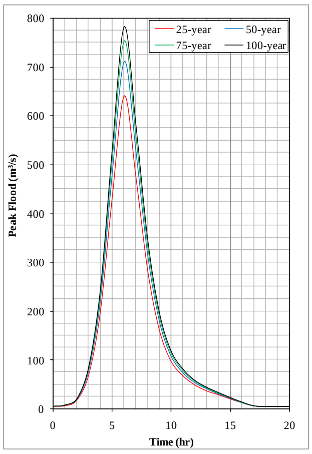


Figure 8. Flood hydrograph for different return periods of Ratti Khad

Table 4. Factors considered in computation of PF and derivation of flood hydrograph

Parameters	Hind Khad	Kansa Khad	Ratti Khad	Kummai Khad
Design storm Duration (T_D in hour)	3.00	4.00	4.00	3.00
Point rainfall (mm) for different return periods				
25-year	101.0	108.3	105.0	101.2
50-year	111.7	119.7	116.0	111.8
75-year	117.9	126.4	122.5	119.5
100-year	122.3	131.1	127.1	122.4
Base flow (m^3/s)	1.84	2.58	4.66	1.76

Table 5. Peak flood estimates for different return periods for SCs of Suketi Khad

Sl. No.	Name of the sub-catchment	Peak flood (m^3/s)			
		25-year	50-year	75-year	100-year
1	Hind Khad	272.9	302.6	320.2	332.5
2	Kansa Khad	367.3	405.9	431.8	448.6
3	Ratti Khad	640.6	711.6	753.4	782.6
4	Kummai Khad	260.3	289.0	305.7	317.5

VI. CONCLUSIONS

The paper presented a study on estimation of PF for ungauged catchments of Suketi Khad. For this purpose, EVA of daily rainfall of Sundernagar site by Gumbel distribution and estimation of PF for the ungauged catchments using SUH approach was carried out. On the basis of the results obtained from the study, some of the conclusions were drawn and summarized as given below:

- GoF tests results supported the use of Gumbel distribution for EVA of rainfall of Sundernagar site.
- From the fitted curves of the estimated rainfall, about 98% of the observed AMR are within 95% confidence limits of the estimated 1-day maximum rainfall.
- The computed 25-year, 50-year, 75-year and 100-year return period 24-hour maximum rainfall at Sundernagar site are 199.0 mm, 219.9 mm, 232.2 mm and 240.8 mm respectively.
- The design storm duration was considered as 3-hours for Hind Khad and Kummai Khad catchments whereas 4-hours for Kansa Khad and Ratti Khad catchments. The loss rate was considered as 2 mm for four SCs of Suketi Khad while computing PF.
- The estimated 25-year, 50-year, 75-year and 100-year return period PF at Kummai Khad by SUH approach are noted to be lower than the corresponding values of Hind Khad, Kansa Khad and Ratti Khad.

VII. RECOMMENDATIONS

The study recommended that the estimated PFs at the ungauged catchments viz., Hind Khad, Kansa Khad, Ratti Khad and Kummai Khad could be used for the purpose of planning and design of hydraulic structures, river protection works and development of integrated water resources management projects in the study region of Suketi Khad.

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