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Intercomparison of Rainfall Estimates of Three Distributions for Computation of PFD using Rational Formula and SUH Approach

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ABSTRACT

Peak flood discharge (PFD) for a given return period is considered as one of the most important parameters for planning and design of hydraulic structures, river protection works, and development of integrated water resources management projects. This can be achieved by adopting various methods such as flood frequency analysis, rational formula, envelope curves and Synthetic Unit Hydrograph (SUH) approach. Out of which, rational formula is applied for estimation of PFD for ungauged catchments with catchment area less than 25 km^2 while SUH approach is adopted for ungauged catchments with catchment area more than 25 km^2. This paper aims to investigate the study on intercomparison of probability distributions for estimation of extreme (i.e., 1-day maximum) rainfall for computation of PFD by adopting rational formula and SUH approach for the Vadhavan Port Project (VPP). The annual 1-day maximum rainfall series is extracted from the daily rainfall data observed at Dahanu site during the period 1969 to 2019 and also used for estimation of rainfall. The probability distributions viz., Extreme Value Type-1, 2-parameter Log Normal and Log Pearson Type-3 (LP3) adopted in extreme value analysis of rainfall is evaluated through diagnostic test using root mean square error and accordingly LP3 is adjudged as the best fit for estimation of rainfall. The 1-day maximum rainfall obtained from LP3 is considered to compute the rainfall intensity by applying one-third rule of IMD (India Meteorological Department) and also used for computation of PFD through rational formula. In SUH approach, the areal rainfall, physiographic and SUH parameters of the ungauged catchments are considered for computation of PFD. The study suggests the 25-year, 50-year and 100-year return period PFDs at six locations within the study area using rational formula and SUH approach could be considered for design purposes while designing civil and hydraulic structures within the study area of VPP.

Keywords: Log Pearson Type-3, Mean Square Error, Rainfall, Rational Formula, Synthetic Unit Hydrograph, Peak Flood Discharge

INTRODUCTION

Estimation of peak flood discharge (PFD) and design flood hydrograph is of utmost importance in hydrological studies particularly for ungauged basins that are often characterized bysmall contributing areas and short concentration times (Mlynskiet al., 2018). Also, PFD for a given return period is considered as one of the important parameters in many civil engineering projects such as design of flood relief, construction of bridges and culverts, design of hydraulic structures viz., dams, weirs and barrages. However, runoff prediction in ungauged basins is a challenging problem for hydrologists because of the difficulty in obtaining adequate historical data that is needed for calibrating the advanced hydrological models (Duan et al., 2006). This can be achieved by adopting various methods viz., empirical equation, rational formula, envelope curves, flood frequency analysis and synthetic unit hydrograph (SUH) approach (Gopinath and Radhakrishnan, 2011).

In India, most of the river basins are either sparsely gauged or ungauged at all where the lack of hydrological and catchment information makes obstruction for watershed planning. For gauged catchments, flood frequency analysis is widely adopted for estimation of PFD that involves fitting probability distribution to the annual maximum series of discharge data whereas envelop curve is used when the catchment characteristics are available. For ungauged catchments, empirical equation and rational formula is applied for estimation of PFD for the catchments with catchment area less than 25 km^2 whereas SUH approach is adopted for the catchments with catchment area more than 25 km^2. Duringthe past, number of studies on estimation of PFD for ungauged catchments has been carried out by different researchers.

Ramirez (2000) carried out the study on estimation of PFD by using SUH for 20 watersheds located in the Appalachian Highlands. Jena et al. (2005) adopted the SUH for estimation of PFD for water resources project in

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Baitarani basin, Odisha. Khaleghi et al. (2011) determined the shape and dimensions of outlet runoff hydrographs for Kasilian basin by employing geomorphological model with Snyder, soil conservation services (SCS), triangular, Rosso and geomorphologic instantaneous unit hydrograph (GIUH) methods while Sabzevari et al. (2013) estimated the surface and subsurface runoff hydrographs for Kasilian catchment using GIUH. Kumari and Goel (2015) adopted the SUH approach for flood estimation for rivers of Saurashtra Region contributing into Gulf of Khambhat. Gharib et al. (2017) made an attempt to simulate the flood hydrograph of Tangrah catchment, a tributary of Madarsoo basin in Golestan province in northeastern Iran through semi-distributed version of the modified Clark method. Kim and Mun-Ju Shin (2018) developed the relationship between the parameters such as runoff coefficient, intensity of rainfall and curve number, and then utilized the relationship to calculate the peak flow using the rational formula for ungauged catchments. Petroselli et al. (2020) compared the design peak flow estimation methods for ungauged basins in Iran. Andrea et al. (2020) carried out the study on comparison of peak flood estimation methods for ungauged basins in Iran.

This paper presents the procedures adopted in extreme value analysis (EVA) of rainfall, estimation of PFD using rational formula and SUH approach, and derivation of flood hydrograph with illustrative example and the results obtained thereon.

MATERIALS AND METHODS

Out of a number of probability distributions, the Extreme Value Type-1 (EV1), 2-parameter Log Normal (LN2) and Log Pearson Type-3 (LP3) are widely applied for rainfall estimation and hence used in the present study. Table 1 presents the cumulative distribution function (CDF) and quantile estimator of EV1, LN2 and LP3 distributions adopted in estimating the extreme rainfall.

In Table 1, F(x) is the CDF of x, ξ is the location parameter, α is the scale parameter, β is the shape parameter, $\mu(y)$ and $\sigma(y)$ are the mean and standard deviation of the log transformed (y) data of the variable (x) and φ^{-1} is the inverse of standard normal distribution (Rao and Hamed, 2000).The parameters are determined by method of moments (MoM) and used to estimate the extreme (i.e., 1-day maximum) rainfall (x(T)) for different return period (T). The lower and upper confidence limits (LCL and UCL) of the estimated extreme rainfall (ER) can be obtained by using LCL=ER-1.96(SE) and UCL=ER+1.96(SE) wherein SE is the standard error on the estimated ER. The selection of best fit amongst EV1, LN2 and LP3 distributions adopted in EVA of rainfall is evaluated through diagnostic test using root mean square error (RMSE). Theoretical description of RMSE (Chen and Adams, 2006) is given as below:

$$\text{RMSE} = \sqrt{(1/N)\sum_{i=1}^{N}\left(x(i)-x(i)^{*}\right)^{2}} \quad (1)$$

Here, x(i) is the observed data for i^{th} sample, $x(i)^*$ is the estimated data for i^{th} sample and N is the sample size. The distribution with minimum RMSE is considered as better suited for estimation of rainfall.

Table 1.CDF and quantile estimator of EV1, LN2 and LP3

Probability distribution	CDF (F(x) or F(y))	Quantile estimator (x(T))
EV1 (ξ, α)	$F(x)=\exp\left(-\exp-\left(\frac{x-\xi}{\alpha}\right)\right)$, $\alpha>0, -\infty \le x \le \infty$	$x(T)=\xi-\alpha\ln[-\ln(1-(1/T))]$
LN2 ($\mu(y)$, $\sigma(y)$)	$F(y)=\varphi\left(\frac{y-\mu(y)}{\sigma(y)}\right)$, $0<x<\infty, \sigma(y)>0$	$x(T)=\exp\ (\mu(y)+\sigma(y)\varphi^{-1}(1/T))$ with y=ln(x)
LP3 (ξ, α, β)	$F(x)=\begin{cases} G\left(\beta,\frac{\ln(x)-\xi}{\alpha}\right) & ,\alpha>0 \\ 1-G\left(\beta,\frac{\ln(x)-\xi}{\alpha}\right) & ,\alpha<0 \end{cases}$	No explicit expression of quantile function is available

Approaches for estimation of PFD

For the present study, rational formula and SUH approach is applied for estimation of PFD though many approaches available (Bhatt and Tiwari, 2010; Dawod and Koshak, 2011). The procedures adopted in rational formula and SUH approach are given as below.

Rational formula

Rational formula (Gericke and Du Plessis, 2012) is adopted for estimation of PFD for ungauged catchments with catchment area less than 25 km^2, which is defined by:

$$q = (0.028)CiA \quad (2)$$

Here, q is the PFD (m^3/s), C is runoff coefficient, 'i' is the rainfall intensity (cm/hour) and A is the catchment area (ha). The rainfall intensity is obtained from the estimated rainfall by applying one-third rule of IMD (India Meteorological Department), which is given as below:

$$P(t)=P(24)(t/24)^{1/3} \quad (3)$$

Here, P(24) is the estimated 1-day maximum rainfall (cm), P(t) is the t-hour rainfall (cm) and t is the duration (hour).

SUH approach

A systematic and sustained collection of hydrometeorological data for selected catchments in different climatic zones is required for estimation of PFD.

Based on the data collected, the physiographic parameters viz., catchment area, length of the longest stream, length of the longest stream closer to the center 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 characteristics, the SUH parameters were determined from the empirical equations to derive the 1-hour SUH based on CWC (1992) flood estimation report for West Coast Region Konkan and Malabar Coasts Subzone-5(a) and 5 (b). In the process, the ordinates of the UH are adjusted in such a way that the total volume of direct runoff is adjusted to 1 cm depth over the catchment (Natakusumah et al., 2011; Sathe et al., 2012). The empirical equations used in determination of SUH parameters for developing UH are given in Table 2.

Table 2. Empirical equations used in determination of SUH parameters

$q_p=0.918(L/S)^{-0.431}$	$t_p=1.561(q_p)^{-1.081}$	$W_{50}=1.925(q_p)^{-1.090}$
$W_{75}=1.019(q_p)^{-1.044}$	$WR_{50}=0.579(q_p)^{-1.107}$	$WR_7=0.347(q_p)^{-1.054}$
$T_B=7.380(t_p)^{0.734}$	$Q_p=q_p*A$	$T_m=t_p+0.5$

Here,

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

Application

Study area and data used

This paper presents a study on intercomparison of probability distributions for estimation of extreme rainfall for computation of PFD for the Vadhavan Port Project (VPP), which is located near Dahanu town of Palghar district. The Dahanu town is located at a distance of 111 km from Mumbai, which is surrounded by Dahanu (Khonda), Danda and Savta creeks. The main Dahanu Creek branches into a smaller Savta Creek and a larger Danda creek. The depth at the center of the main creek is around 4 to 5 m during low tide. Further, the Danda creek having two arms, which are extends 2 to 3 km inland and it is terminate near Kompada village. The Savta creek is itself a small seasonal river, which originates near Santoshi hill about 10 to 12 km east of Dahanu. In the dry season, during high tide, sea water in the Savta creek extends to about 1.5 to 2 km inside. The Dandi creek (about 10 km long) originates from Dandi village and flows between Dandi and Navapur villages and also runs around Tarapur town. The Tarapur is an industrial cluster of Boisar/ Tarapur MIDC town and also houses a Nuclear Power Plant. The mouth of Dandi creek is narrow and shallow and not navigable during low tide. It carries total effluents load from industrial and domestic sectors. The index map of the study area of VPP is shown in Figure 1 while the locations of interest are presented in Table 3. From Figure 1, it can be found that the locations of interest viz., A, B and C are in Savta of Dahanu creek while D and E are in Danda of Dahanu creek, and F in Dandi creek.

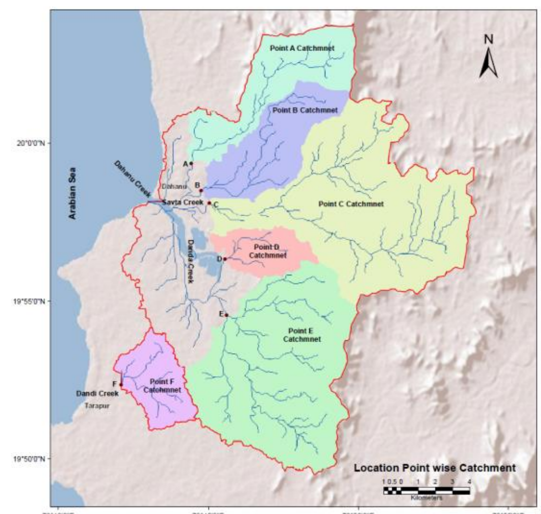

Figure 1. Index map of the study area of VPP

Table 3. Details of locations of interest of the catchments within study area

Location of interest	Geographical coordinates		Catchment area (km^2)
	Latitude (N)	Longitude (E)	
A	19° 59′ 24.80″	72° 44′ 19.53″	30.88
B	19° 58′ 33.75″	72° 44′ 37.36″	27.82
C	19° 57′ 49.95″	72° 45′ 06.00″	93.00
D	19° 56′ 31.80″	72° 45′ 19.43″	12.53
E	19° 54′ 37.46″	72° 45′ 31.60″	82.05
F	19° 52′ 27.52″	72° 41′ 50.25″	16.40

RESULTS AND DISCUSSION

EVA of rainfall

In this paper, the daily rainfall data observed at Dahanu site during the period 1969 to 2019 is used for EVA. The annual 1-day maximum rainfall (AMR) series is derived from the daily rainfall data and applied in EVA. Figure 2 presents the time series plot of the observed AMR of Dahanu. The descriptive statistics such as average, standard deviation, coefficient of skewness and coefficient of the observed AMR are determined as 209.2 mm, 84.0 mm, 1.649 and 3.674 respectively. By applying the procedures of EV1, LN2 and LP3 distributions, as detailed in text book titled 'Flood Frequency Analysis' by Rao and Hamed (2000), the parameters of the distributions are determined by MoM and also used for estimation of extreme rainfall (ER). Table 4 gives the ER estimates with lower and upper confidence (LCL and UCL) limits (ER±1.96SE) for different return periods for Dahanu. From EVA results, it is found that the estimated ER by LP3 is higher than those values of EV1 and LN2 for the return periods from 20-year and above.

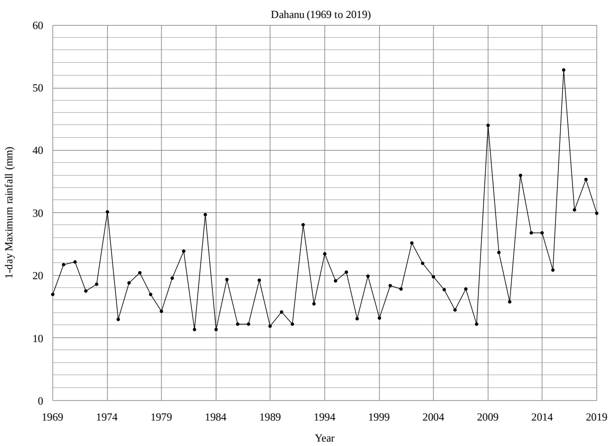

Figure 2. 1-day maximum rainfall of Dahanu for the period 1969 to 2019

Table 4. Estimated 1-day maximum rainfall with 95% confidence limits using EV1, LN2 and LP3 for Dahanu

Return period (year)	1-day maximum rainfall (cm) with 95% confidence limits								
	EV1			LN2			LP3		
	ER	LCL	UCL	ER	LCL	UCL	ER	LCL	UCL
2	19.5	17.4	21.7	19.6	17.8	21.6	19.0	17.0	20.9
5	27.0	23.4	30.5	26.4	23.6	29.6	26.1	22.9	29.3
10	31.9	27.1	36.7	30.9	27.1	35.3	31.4	26.6	36.3
20	36.6	30.5	42.7	35.2	30.3	40.9	37.0	29.7	44.3
25	38.1	31.6	44.6	36.6	31.3	42.8	38.9	30.6	47.2
50	42.7	34.9	50.5	40.8	34.3	48.4	45.0	33.2	56.9
75	45.4	36.9	53.9	43.2	36.0	51.8	48.9	34.6	63.2
100	47.3	38.2	56.3	44.9	37.2	54.3	51.7	35.5	67.9

The selection of suitable distribution for estimation of rainfall is evaluated through diagnostic test using RMSE. By using Eq. (1), the RMSE values of EV1, LN2 and LP3 are computed as 29.73 mm, 31.09 mm and 25.21 mm respectively. From these values, it is observed that the RMSE of LP3 is minimum than those values of EV1 and LN2. Hence, the LP3 is considered as the best suitable distribution for rainfall estimation, which is further used for flood estimation. Figure 3 presents the plots of estimated 1-day maximum rainfall with 95% confidence limits using LP3 and observed AMR of Dahanu wherein it is found that about 95% of the observed AMR are within the confidence limits of the estimated rainfall.

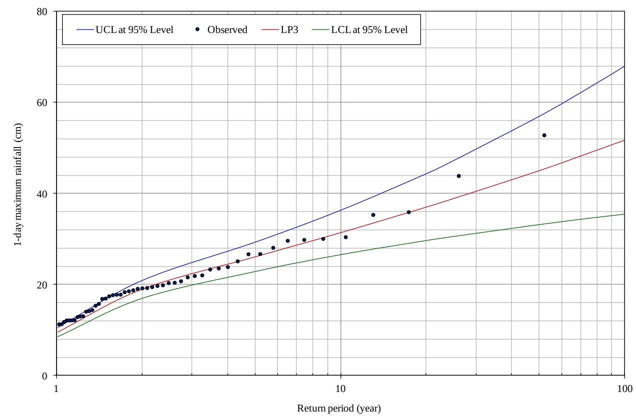

Figure 3. Estimated 1-day maximum rainfall with 95% confidence limits using LP3 and observed AMR of Dahanu

Estimation of PFD using rational formula

In this paper, the study area consist six locations of interest (Table 3) of VPP is considered for estimation of PFD. From the analysis of catchment characteristics, the design storm duration is considered as 1-hour for Danda of Dahanu creek (D) and Dandi creek (F). By applying the one-third rule of IMD, the 1-hour rainfall is computed from the estimated 1-day maximum rainfall using LP3 and also considered as an input for flood estimation.

Table 5. Estimated PFD (m^3/s) using rational formula

Location of interest	Name of the catchment	Catchment area		Peak flood discharge (m^3/s)		
		(ha)	(km^2)	25-year	50-year	100-year
D	Danda of Dahanu creek	1253	12.53	189.2	219.1	251.5
F	Dandi creek	1640	16.40	247.6	286.8	329.2

By considering topography and general land use character of the catchments, the value of runoff coefficient (C) is considered as 0.40 while computing PFD at the locations D and F. As the catchment areas of Danda of Dahanu creek (D) and Dandi creek (F), as given in Table 3, are less than 25 km^2, the PFD at these locations is estimated by rational formula and are given in Table 5. From these values, it is found that the estimated PFD at Dahanu creek is less than those values of Dandi creek.

Estimation of PFD using SUH approach

Determination of SUG parameters

The 24-hour maximum rainfall is obtained by multiplying the estimated 1-day maximum rainfall of Dahanu with a factor of 1.15, which is used to derive the 1-hour distributed rainfall by using the conversion factor, as given in Figure 4. By using Survey of India Toposheets, DEM (Digital Elevation Model) of National Remote Sensing Centre (NRSC) and Google earth of the region of the study area, the catchments of three locations of interest (A, B and C) in Savta and one location (E) in Danda of Dahanu creek are delineated and also used for estimation of PFD. The physiographic and SUH parameters of the catchments are determined by using empirical equations and are presented in Table 6. By using the SUH parameters, the SUH of four locations of interest (viz., A, B, C and E) of the study area are derived and also presented in Figure 5.

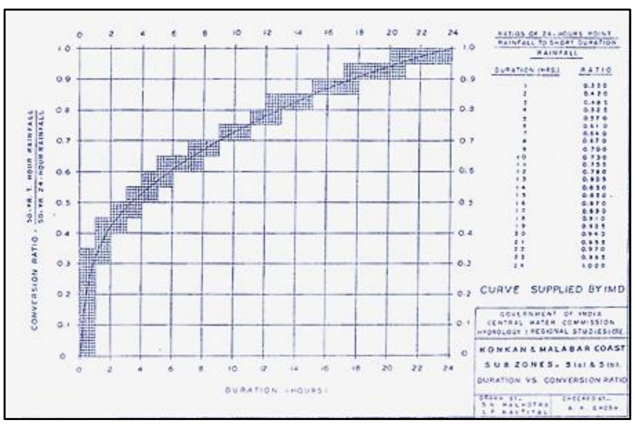

Figure 4. Ratio for conversion of 24-hour point rainfall to short duration rainfall (CWC, 1992)

Estimation of PFD and development of flood hydrograph

By considering the procedures, as described in CWC (1992) flood estimation report for West Coast Region Konkan and Malabar Coasts Subzone-5(a) and 5(b), the design storm duration, base flow, loss rate and areal rainfall involved in computation of the ordinates of the flood hydrograph of the catchments are computed and are presented in Table 7. By using the physiographic and SUH parameters, the 25-year, 50-year and 100-year return period PFDs at different locations (viz., A, B, C and E) of the study area are computed and also presented in Table 8 while the flood hydrographs are shown in Figure 6.

Table 6. Physiographic and SUH parameters of the catchments

Parameters	Savta of Dahanu creek			Danda of Dahanu creek
	A	B	C	E
Physiographic parameters				
Catchment Area (km^2)	30.88	27.82	93.00	82.05
Length (km)	15.638	15.330	21.566	14.331
L_c (km)	9.144	6.396	9.380	5.551
Slope (m/km)	8.949	6.662	3.669	2.560
SUH parameters				
q_p (m^3/s)	0.721	0.641	0.428	0.437
t_p (hour) (say)	2.50	2.50	3.50	3.50
W_{50} (hour)	2.75	3.13	4.85	4.75
W_{75} (hour)	1.43	1.62	2.47	2.42
WR_{50} (hour)	0.83	0.95	1.48	1.45
WR_{75} (hour)	0.49	0.55	0.85	0.83
T_B (hour) (say)	15.00	15.00	19.00	19.00
Q_p (m^3/s)	22.28	17.82	39.76	35.82
Q (m^3/s)	85.85	77.34	258.54	228.10

Table 7. Parameters involved in computation of PFD by SUH and derivation of flood hydrograph

Location of interest	Parameter			Areal rainfall (mm)		
	Design storm duration (hour)	Base flow (m^3/s)	Loss rate (cm/ hour)	25-year	50-year	100-year
A	3.00	4.63	0.19	20.62	23.88	27.41
B	3.00	4.17	0.19	20.73	24.00	27.55
C	4.00	13.95	0.19	21.03	24.35	27.96
E	4.00	12.31	0.19	21.24	24.59	28.23

Table 8. Estimated PFD at various locations within the study area using SUH approach

Location of interest	Peak Flood Discharge (m^3/s)		
	25-year	50-year	100-year
Savta of Dahanu creek (A)	407.6	472.8	543.4
Savta of Dahanu creek (B)	331.1	384.0	441.3
Savta of Dahanu creek (C)	749.7	869.9	1000.2
Danda of Dahanu creek (E)	682.6	792.1	910.7

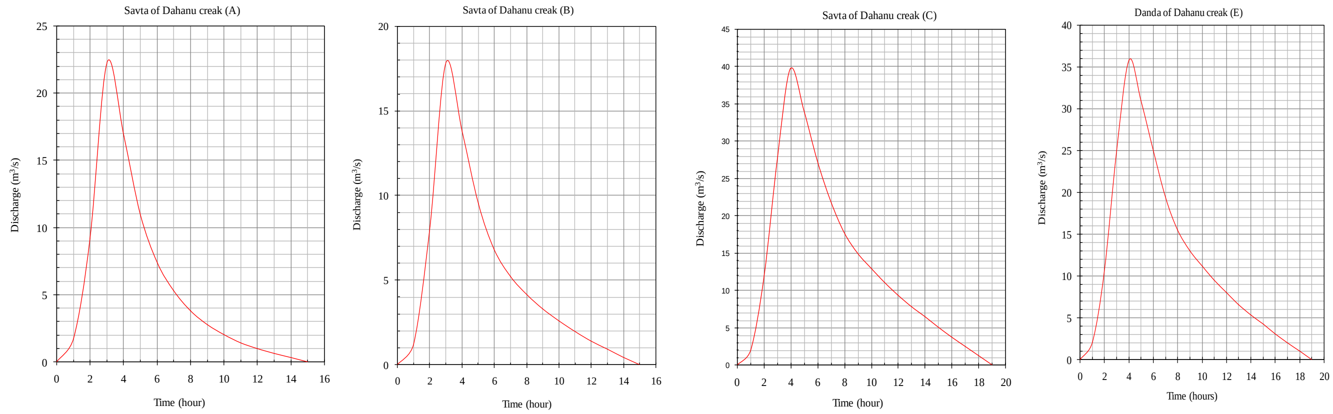

Figure 5. SUH for the ungauged catchments with catchment area more than 25 km^2 in the study area of VPP

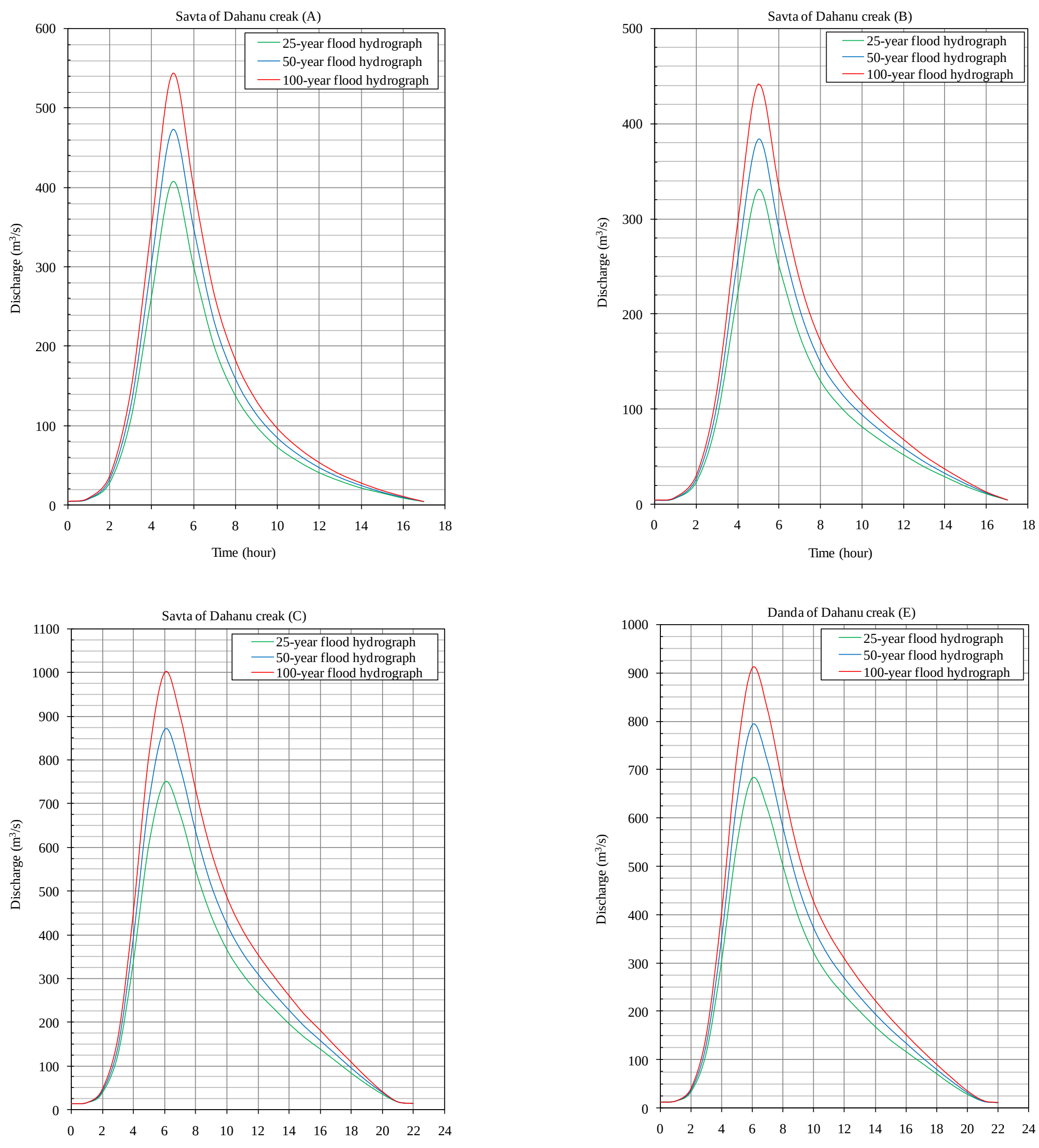

Figure 6. Flood hydrographs for the ungauged catchments with catchment area more than 25 km^2 in the study area of VPP

CONCLUSIONS

The paper presented a study on intercomparison of rainfall estimates of three distributions for computation of PFD using rational formula and SUH approach at various locations within the study area of the Vadhavan Port Project (VPP). For this purpose, rainfall estimation using the AMR series observed at Dahanu was carried out by adopting EV1, LN2 and LP3 distributions, which are evaluated through diagnostic test using RMSE. The 1-day maximum rainfall given by the selected distribution was used to compute the rainfall intensity through one-third rule of IMD and considered as an input while computing the 25-year, 50-year and 100-year return period PFD at two different locations, viz., one in Danda of Dahanu creek (D) and other in Dandi creek (F) by applying rational formula wherein runoff coefficient was considered as 0.40. By using the 1-hour distributed rainfall, physiographic and SUH parameters, the 25-year, 50-year and 100-year return period PFD at four locations of interest, viz., three different locations (A, B and C) in Savta of Dahanu creek and one in Danda of Dahanu creek (E) was estimated by using SUH approach. Based on the results of the data analysis, some of the conclusions were drawn from the study and are given as below.

- Diagnostic test results using RMSE confirmed that the LP3 is better suited distribution for rainfall estimation at Dahanu. From the fitted curves of the estimated rainfall, it was observed that about 95% of the observed AMR data are within 95% confidence limits of the estimated 1-day maximum rainfall using LP3.
- The 1-hour distributed rainfall derived from 24-hour maximum rainfall (i.e., 1-day maximum rainfall is multiplied with a factor of 1.15) using LP3 was considered for flood estimation using SUH approach.
- The 25-year, 50-year and 100-year return period PFD computed by using rational formula at Dandi creek was comparatively higher than those values of Danda creek.
- The 25-year, 50-year and 100-year return period PFD at location C in Savta of Dahanu creek was higher than those values estimated at the locations A and B.

The study suggested that the estimated PFDs at various locations of interest within the study area and the derived hydrographs could be used for the purpose of designing hydraulic structures, river protection works and development of integrated water resources management activities within the study area of VPP.

DECLARATIONS

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Conflict of interest

The authors hereby confirm that there is no conflict of interest.

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