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A NEW APPROACH FOR THE DEVELOPMENT OF DESIGN FLOOD HYDROGRAPHS

Niranjan Pramanik[1] and Rabindra K. Panda[2]

Abstract*: Quite a good numbers of studies have been conducted to model the unit hydrographs using probability density functions in the past. However, a little focus has been made, so far, to determine the peaks and shapes of flood hydrographs, which is of vital importance in controlling reservoir operations and designing hydraulic structures. Appropriate shapes and peak magnitudes of flood hydrographs are highly probabilistic. The conventional method of flood frequency analysis is carried out to estimate the peak floods for different return periods without taking care of about the reliable shapes of the design hydrographs. The present study aimed at developing the peaks as well as the shapes for hydrographs of different return period using Weibull probability density function (PDF). The Weibull PDF was fitted to the direct stream flow hydrographs (DSFH) of 22 years at a site of Brahmani River, India. The time to attain peak and peak discharge of all the DSFHs were derived from the PDF and the best fitted shape and scale parameters were used for further analysis in the modeling of hydrograph shapes. Frequency analysis was employed to the best fitted parameters and their values corresponding to 20-, 50-, 100- and 200-year return periods were estimated. Those design parameters were used to develop the PDFs for respective return periods, which in turn represent the design flood hydrographs of different return periods. To validate the proposed approach, the estimated peaks of the design flood hydrographs obtained using PDF, were compared with the corresponding peak discharges obtained from the frequency analysis of the 22 years of annual maximum flow data. The results of the comparison showed that the PDF generated peak discharges of all the return periods were found to match closely with the design peak obtained from the frequency analysis. The study concludes that the suggested approach is purely analytical to capture the shapes and peaks of the flood hydrographs to a reliable extent and is having universal applicability.*

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Keywords*: Flood hydrographs; Probability density function; Frequency analysis*

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INTRODUCTION

Three important parameters of a hydrograph are peak discharge (Q_p), time base *(D)* and time to attain peak *(D_p)*, which need to be computed for effective water resources planning, design and management. Using the above-mentioned three parameters, hydrographs could be developed synthetically for partially gauged watersheds using some empirical relationships between them. Generally, peak discharge and runoff volume are considered for designing storage and other hydraulic structures without considering the shape of the hydrograph. Based upon the relationship between D_p and the time interval between the centroid of a flood hydrograph from

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the origin (D_c), flood hydrographs are categorized into three different shapes namely, positively skewed ($D_p < D_c$), symmetrical ($D_p = D_c$) and negatively skewed ($D_p > D_c$). Different flood hydrograph shapes may cause significant differences in cost and flood control policies of water resources planning and management projects.

To construct hydrograph synthetically, various empirical models and statistical techniques have been proposed by various researchers during the past. Most of the methods were used to develop the unit hydrographs. The synthetic unit hydrograph (SUH) method proposed by Snyder (1938) is a widely used technique to construct unit hydrographs, which assumes a triangular shaped hydrograph in which the watershed lag time, the time to attain the peak and the magnitude of peak discharge are estimated using empirical relations. However, very few studies have been reported to develop design flood hydrographs, which are most essential for design and planning of water resources systems. The shape and size of design flood hydrographs have been developed using statistical techniques using the historical stream flow hydrographs. Nezhikhovsky (1971) and Sokolo *et al*. (1976) applied a typical hydrograph (TH) concept to obtain the shape of the design flood hydrographs. They selected the highest peak hydrograph from a series of historical hydrographs as TH. The ratio between the peak discharge of a given return period to the peak discharge of the TH are estimated and are used as amplifier, which is multiplied with the ordinates of TH to develop the design flood hydrograph.

A good numbers of studies have been conducted to develop unit hydrographs using probability density functions in the past (Gray, 1961; Sokolov *et al*., 1976; Ciepielowski, 1987; Haktanir and Sezen, 1990; Yue *et al*., 2002; Bhunya *et al*., 2004). Mostly, Gamma and Beta PDF have been used to represent the shape of unit hydrographs (Koutsoyiannis and Xanthopoulos, 1989; Haktanir and Sezen, 1990; Haan *et al.,* 1994; Bhunya *et al*., 2003; Bhunya *et al*., 2004; Rai *et al*., 2008). The researchers have also discussed the flexibility of the PDFs to produce different shapes by changing their parameter values (Bhunya *et al*., 2008). Rai *et al*. (2008) evaluated nine probability density models in eighteen different watersheds to develop unit hydrographs (UH) and ranked their suitabilities based on the size of the watersheds. Yue *et al*. (2002) attempted to model the shape of stream flow hydrograph using two parameter Beta PDF by introducing shape mean and shape variance of the hydrographs. Very few studies related to the development of design flood hydrographs using PDF have been reported so far. Design flood hydrographs could also be constructed using the random parameters of the PDF with known time base. The PDF parameters from a series of stream flow hydrographs of several years could be used for frequency analysis and the computed parameter values of different return periods could be used for developing design flood hydrographs.

In the present study, the two-parameter Weibull PDF was used to develop design flood hydrographs. The major criterion for selection of the PDF is the resemblance of the shape of the PDF with the shape of the observed flood hydrograph. The suitability of the PDF to represent the shape of the hydrographs was obtained by comparing the PDF fitted hydrographs with the observed hydrographs. Further, to develop the design flood hydrographs, a new approach has been used in which the best fitted PDF parameters, time base, base flow and volume of the hydrographs of different return periods were estimated and were used to develop the design flood hydrographs using Weibull PDF. The peak discharge of the design flood hydrographs were compared with the discharge obtained from the frequency analysis of 22 years of annual maximum flow data.

WEIBULL PROBABILITY DENSITY FUNCTION

The two parameter Weibull PDF was first introduced by Rosin and Rammler (1933). Under certain values of its parameters, the function mimics like normal and exponential distribution functions. The expression for the hydrograph using this PDF is presented in Table I. Where, κ and λ are positive numbers and are treated as shape and scale parameters respectively. The above expression is valid for all t > 0. The Weibull functions return 0 for non-zero *t*. Scale parameter is responsible for shrinking and widening the hydrograph, whereas the skewness of the hydrographs is obtained with the certain combinations of κ and λ. For same scale parameter, more the value of shape parameter, bigger is the hydrograph size. The best fitted parameters are very difficult to estimate. However, approximate solutions have been suggested by many researchers to compute the optimal parameters using numerical methods. The expression for time to attain peak discharge (t_p) is also presented in Table 1. The equation of t_p is valid for all $\kappa > 1$.

Table 1. Probability density functions and their corresponding t_p and q_p

Name of the distribution	Probability distribution functions	Peak discharge (q_p)	Time to peak (t_p)
Weibull	$q_{(t,\kappa,\lambda)} = \frac{\kappa}{\lambda}\left(\frac{t}{\lambda}\right)^{\kappa-1} \exp-\left(\frac{t}{\lambda}\right)^{\kappa}$	$q_p = \frac{\kappa}{\lambda}\left(1-\frac{1}{\kappa}\right)^{1-\frac{1}{k}} \exp\left[-\left(1-\frac{1}{\kappa}\right)\right]$	$t_p = \lambda\left(\frac{\kappa-1}{\kappa}\right)^{\frac{1}{k}}$

METHODOLOGY

In the present study, the Weibull PDF described above was employed to fit the observed stream flow hydrographs of 22 years. Generally, continuous stream flow hydrographs at a site of a river are the delayed response of rainfall, whose shapes get affected by the duration and intensity of rainfall as well as human interference and presence of structures within the catchments. In this section, the entire process of computation of best fitted PDF curves for all observed hydrographs as well as the procedures followed to develop design hydrographs of 20-, 50-, 100- and 200-year return periods are presented.

Base flow separation

The portion of the daily stream flow hydrographs having the highest peak flow magnitude were selected from each year's stream flow record and were used for further analysis. The starting points of the rising limb and the end point on the recession limb while the flow reduces to base flow of the hydrographs were determined. Many techniques are practiced to separate the base flow from the stream flow hydrographs. Three commonly used graphical techniques namely constant discharge, constant slope and concave methods are practiced for this purpose. The graphical method of baseflow separation mentioned above may not be effective when separations are to be undertaken from a long continuous record of stream flows, rather than just a few storm period hydrographs. Therefore, a recursive digital filtering technique, which is a common tool in signal analysis and processing, was used for base flow separation in the present study (Rieger and Olive, 1984; Nathan and McMahon, 1990; Lim *et al*., 2005). The filtering operation takes into consideration, the sequential nature of the stream hydrograph for which the relative smoothness of the baseflow curve is more convincing than that obtained from the existing graphical methods. This technique removes the high-frequency quick flow signal to derive the low-frequency base flow signal. A digital filtering algorithm for base flow separation developed by Chapman and Maxwell (1996) was used in the present study. The mathematical expression of the filtering technique is presented by Equation 1.

$$Q_b(i) = \frac{k}{2-k} Q_b(i-1) + \frac{1-k}{2-k} Q(i) \tag{1}$$

Where $Q_b(i)$ and $Q_b(i-1)$ are the base flow, at time interval *i*, and *i-1* and the parameter *k* is the recession constant during periods of no direct runoff. The constant *k* is called the filter parameter and derived from the recession analysis using linear models (Eckhardt, 2005). Above equation computes base flow if $Q_b(i) \le Q(i)$. A web-based hydrograph analysis tool (WHAT) developed at Purdue University, USA were used to compute the base flow and thereby to extract direct stream flow for 22 years.

Dimensionless hydrographs and PDF fitting

The derived direct stream flow hydrographs (DSFH) of 22 years were transformed to dimensionless hydrographs before they are used for curve fitting using the PDF equation. The volumes (*V*) under the direct flood hydrographs were computed using the trapezoidal method and the ratio of duration of each hydrograph (*D*) to the volume were computed. The computed fraction (*D/V*) was multiplied with ordinates of each DSFH and the values in the abscissa of each DSFH were divided by *D* to convert DSFH to dimensionless form. The objective of this transformation of DSFH to dimensionless hydrographs was to constraint the volume and time base as unity. The observed dimensionless flood hydrographs were fitted with the Weibull PDF. The shapes generated by the PDF were then compared with the shape of the observed dimensionless hydrographs. Non-linear least square method with Marquardt optimization algorithm was used to compute the best fitted parameters for all selected distributions. Goodness of fit criteria namely root mean square error (RMSE), coefficient of determination (R^2), percentage error of peak discharge (EQ_P) and error of time to peak (ET_P) were used to evaluate the fitting performances. The expressions of EQ_P and ET_P are expressed using Equations 2 and 3 respectively.

$$EQ_P = \frac{\left|Q_{PO} - Q_{Ppdf}\right|}{Q_{PO}} \times 100 \tag{2}$$

$$ET_P = \left|ET_{PO} - ET_{Ppdf}\right| \tag{3}$$

Where, Q_{PO} = Observed peak discharge, Q_{Ppdf}= PDF generated peak discharge, ET_{PO} = Actual time to peak and ET_{Pdf}= PDF generated time to peak.

Development of design flood hydrographs

Flood hydrographs of 20-, 50-, 100- and 200-year return periods were developed using the design PDF parameters obtained from frequency analysis. To obtain the PDF parameters of different return periods, frequency analysis of the parameter values was performed using six probability distribution models namely, Generalized Extreme value (GEV), Generalized Pareto, Gamma, Exponential, Weibull and Extreme value-1 (EV-1). The Kolmogorov-Smirnov (K-S) test was made to select the best fit distribution. Maximum likelihood method, which is considered as the most efficient method was used for parameter estimation of the distribution functions. Both the shape and scale parameters of the Weibull PDF were used for frequency analysis and κ_T and λ_T were estimated.

The computed design parameters were used to develop the dimensionless design hydrographs, because all the design parameters were obtained from the frequency analysis of the shape and scale parameters of best-fitted dimensionless hydrographs. Other important parameters of the stream flow hydrographs like time base (D) and volume (V) of the hydrographs were used for frequency analysis and the quartiles corresponding to 20-, 50-, 100- and 200-year return periods were estimated. The base flow (BF) amount of each year was selected for 22 DSFHs and BF_T was estimated from the frequency analysis. The ratio V_T/D_T was multiplied with the ordinates of the dimensionless design hydrograph to convert the dimensionless design hydrographs to real valued design flood hydrographs. Finally, the BF_T values were added with the ordinates of the corresponding design flood hydrographs to develop the complete flood hydrographs for different return periods.

RESULTS AND DISCUSSION

Base flow separations and development of dimensionless hydrographs

The developed twenty-two numbers of DSFHs are presented in Figure 1. The date of occurrence of peak flow before and after base flow separation along with their magnitudes was estimated and is presented in Table 2. The date of occurrence of peak flow before and after the base flow separation is found to be the same for all hydrographs except for the year 1986. V, D_p, D and t_p were estimated and are presented in Table 3 for all hydrographs after the base flow separation. It is observed from Table 3 that the shape and size of the DSFHs varies irregularly making it highly probabilistic. For hydrographs with larger D, the peaks are found to be delayed. Using the estimated values of D/V and D as seen in Table 3, the DSFHs were converted to dimensionless hydrographs.

Computation of best-fitted PDF

The percentage deviation of peak flow (EQ_P) was determined for all 22 hydrographs The magnitude of over prediction was found to be higher than the magnitude of under prediction. The values of EQ_P were found to range between 19.59 % to -9.83 %. The values of the RMSE and R^2 for all the PDFs were computed. The Weibull PDF was found to be more flexible function to generate wide range of hydrograph shapes. So far as R^2 value is concerned, the average values of the R^2 from Weibull PDF were found to be 0.9181. Similarly taking into account the average RMSE, the average value in case of the Weibull was found to be 0.2345. The suitability of the PDF was chosen on the basis of the matching of the generated peak discharge with the design peak discharge.

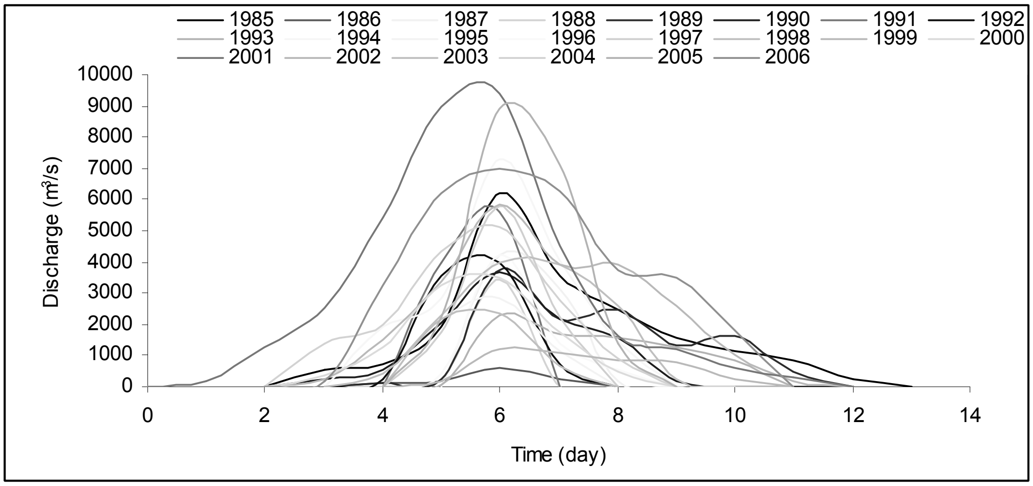

Fig. 1. The developed twenty two numbers of DSFHs.

Table 2. Time to attain peak and peak flow values before and after base flow separation

Year	Before base flow separation		After base flow separation	
	D_p *(day)*	Q_p (m^3/s)	D_p' (day)	Q_p' (m^3/s)
1985	4	7485.17	4	6142.83
1986	3	5056.6	2	3664.28
1987	1	4737.8	1	4209.54
1988	3	6216.8	3	5442.5
1989	3	4311.5	3	3726.7
1990	4	4595.2	4	3651.85
1991	2	9151	2	8096.3
1992	3	4892	3	4262.64
1993	2	3346	2	2262.64
1994	3	8952	2	7872.43
1995	2	3823	2	2835.45
1996	2	4652	2	4218.36
1997	2	7135	2	5783.5
1998	3	5173	3	3969.18
1999	3	8051.84	3	6829.9
2000	2	4527.34	2	3521.54
2001	5	9650	5	8979.79
2002	2	2097	2	1206.21
2003	2	3454.19	2	2372.92
2004	4	6115.78	4	5115.78
2005	1	10677.15	1	9566.34
2006	5	8026.77	5	7010.8

Q_p (m^3/s): Peak discharge; D_p' (day): Time to attain peak after the base flow separation; Q_p' (m^3/s): Peak discharge after base flow separation

Table 3. Estimated DSFH hydrograph parameters and scaling parameters (*D/V*, t_p) for DLSFH.

Year	*D* (day)	D_p (day)	*V* (m^3)	*(D/V)* × 10^{-3}	$t_p = (D_p/D)$
1985	11	4	18178	0.6051	0.3636
1986	5	3	1121.4	4.4587	0.6000
1987	4	1	7541	0.5304	0.2500
1988	5	3	5966.1	0.8381	0.6000
1989	9	3	12102.63	0.7436	0.3333
1990	10	4	10392	0.9623	0.4000
1991	3	2	9600.9	0.3125	0.6667
1992	5	3	8474.5	0.5900	0.6000
1993	7	2	7689.8	0.9103	0.2857
1994	6	3	17457.14	0.3437	0.5000
1995	4	2	6162.33	0.6491	0.5000
1996	5	2	6603.79	0.7571	0.4000
1997	4	2	9803.5	0.4080	0.5000
1998	8	3	13433.35	0.5955	0.3750
1999	8	3	22613.63	0.3538	0.3750
2000	6	2	9357.63	0.6412	0.3333
2001	11	5	43004.15	0.2558	0.4545
2002	7	2	4338.43	1.6135	0.2857
2003	4	2	5162.3	0.7748	0.5000
2004	7	4	11086.849	0.6314	0.5714
2005	4	1	19397.23	0.2062	0.2500
2006	9	5	32066.26	0.2807	0.5556

D: Duration of the hydrograph (day); D_p: Days to attain the peak flow condition; V: Volume under each DSFH (m^3); D/V: Factor for the ordinates to convert the DSFH to dimensionless hydrograph; t_p: Dimensionless time to attain the peak

Development of design flood hydrographs

The design flood hydrographs were developed using the design values of the shape and scale parameters of the PDF. As per the methodology described earlier, the shape and scale parameters of Weibull PDF of 22 years were subjected to frequency analysis. The parameters were fitted with continuous probability density functions like Generalized Extreme value (GEV), Generalized Pareto, Gamma, Exponential, Weibull and Extreme Value type-1 (EV-1). The distribution fitting results of all parameters of the PDF are presented in Table 4.

The return period (T) and probability of exceedance (P) of an event is related by the expression presented by Equation 4 given below. Therefore, the cumulative probability values (*F(x)*) of GEV and Generalized Pareto and EV-1 were obtained corresponding to each P, which in turn indicate the parameters of various return periods.

$$T = \frac{1}{P} = \frac{1}{1 - F(x)} \tag{4}$$

Where, *F(x)* is the cumulative probability density of an event.

The values of all the parameters (κ_T , λ_T) corresponding to 20-, 50-, 100- and 200-year return periods were estimated. The estimated design parameters of the Weibull PDF are presented in Table 5. The results of the frequency analysis showed GEV to fit best for *V, D* and *BF* based on their K-S statistics. The values of V_T, D_T and BF_T for 20-, 50-, 100-and 200-year return periods were estimated and are presented in Table 6.

Table 4. Fitting statistics of the PDF parameters

PDF Distributions	Weibull	
	κ	λ
GEV	**0.08326**	0.1127
Gen. Pareto	0.11948	0.1214
Gamma	0.1410	0.1328
Exponential (2P)	0.11258	0.1224
Weibull (3P)	0.11206	0.1248
EV-1	0.11508	**0.0966**

Note: Best fit distributions are marked by bold font

Table 5. Design parameters of Weibull PDF

Return Period (T)	Weibull	
	κ_T	λ_T
20	5.35	0.66
50	5.89	0.70
100	6.26	0.73
200	6.63	0.75

Table 6. Design volumes, duration, time to peak, base flow and ratio of V_T/D_T

Return Period (T)	V_T	D_T	BF_T	V_T/D_T
20	32000	10.34	1335	3094.778
50	35400	10.98	1380	3224.044
100	37500	11.37	1405	3298.153
200	39200	11.72	1420	3344.71

Using the above computed design parameters of various return periods, dimensionless design hydrographs were constructed. The dimensionless hydrographs were then converted to original design flood hydrographs by multiplying V_T/D_T with the ordinates and D_T with the abscissas. Figure 2 presents the developed flood hydrographs of 20-, 50-, 100- and 200-year return periods using Weibull. To obtain an appropriate shape of the hydrograph, a comparison of the PDF developed peak discharge with the design peak discharge (QP_{design}) obtained from the at-site flood frequency analysis of 22 years of annual maximum flow data were made. It is observed from the figure that Weibull-produced peak design discharges are closer to the corresponding QP_{design} for 100-year and 200-year return periods. The peak flow conditions for all the return periods was found to be the nearly same with the design PDF.

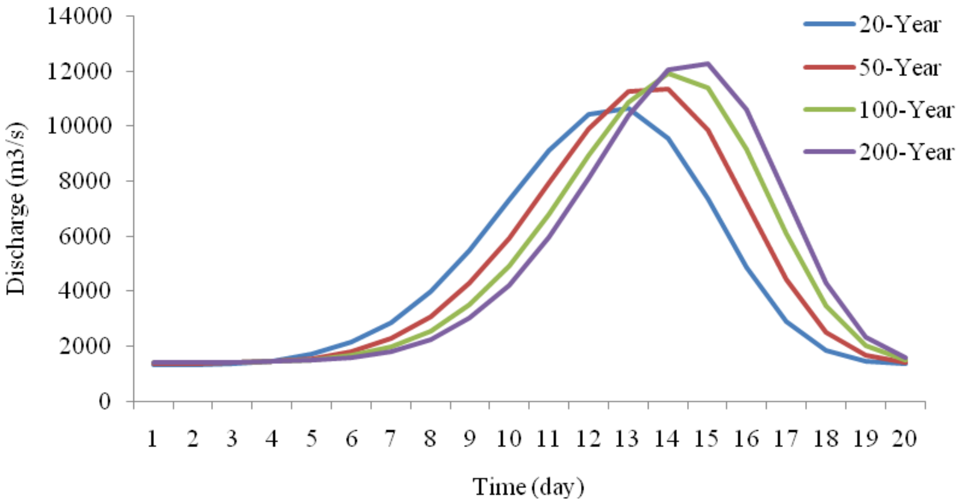

Fig. 2. The developed flood hydrographs for different return periods

CONCLUSIONS

The following conclusions were drawn from the results of the study:

1. Weibull PDF was found to produce hydrographs of flexible shapes ranging from positive to negatively skewed hydrographs and is capable of predicting the peak discharge accurately.
2. The novel approach used in the study for development of appropriate shape and magnitude of design flood hydrographs using the PDFs could be applied to any basin for designing the necessary hydraulic structures.

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