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A derived flood frequency distribution for correlated rainfall intensity and duration

N.K. Goel[a], R.S. Kurothe[b], B.S. Mathur[a], R.M. Vogel[c,*]

[a]Department of Hydrology, University of Roorkee, Roorkee 247667, India
[b]Central Soil and Water Conservation Research and Training Institute, Research Centre, Vasad, District Anand, Gujarat 388306, India
[c]Department of Civil and Environmental Engineering, Tufts University, Medford, MA 02155, USA

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Abstract

A derived flood frequency distribution (DFFD) combines a stochastic rainfall model with a deterministic rainfall–runoff model to obtain a physically based probability distribution of flood discharges. Previous DFFD studies have either assumed that rainfall intensity and duration are independent or negatively correlated. This study is more general than previous studies because it accommodates both positive and negative correlations between rainfall intensity and duration. Rainfall–runoff processes are modeled using a ϕ-index infiltration model and a geomorphoclimatic instantaneous unit hydrograph. Applications to four Indian watersheds and one US watershed demonstrates that (1) the correlation of rainfall intensity and duration has an important impact on the DFFD and (2) the DFFD provides a potentially useful alternative for estimating flood flow quantiles at ungaged sites.

Keywords: 1821 Floods; 1833 Hydroclimatology; 1860 Runoff and streamflow; 1869 Stochastic processes; 1854 Precipitation

1. Introduction

Very few methods exist for the estimation of the probability distribution function (PDF) of flood discharges for catchments without discharge measurements. Yet estimation of flood quantiles at ungaged sites is one of the most common and important problems in hydrology. The location of most flood problems is rarely coincident with a streamflow gage, hence physically based methods such as the derived flood frequency distribution (DFFD) are needed which relate storm characteristics and watershed information to the PDF of flood discharges. Flood frequency problems are even more challenging in underdeveloped regions where streamflow networks are sparse.

Methods for estimation of the PDF of flood discharges at ungaged sites include: (1) transfer of streamflow records from a nearby river basin using a drainage area scaling relationship, followed by fitting a PDF and (2) use of regional flood frequency methods such as the index-flood or regional regression methods (see Stedinger et al., 1993). Each of these approaches has attendant problems. Transfer of flows from a nearby watershed is only reliable when an adequate length of good flow records exist *and* if the nearby basin is hydrologically similar to the basin in question. Regional flood frequency models are not available for all regions of the world. Furthermore, regional hydrologic models do not usually take into account the site-specific nature of the intensity and

* Corresponding author. Fax: +1-617-627-3994.
E-mail address: rvogel@tufts.edu (R.M. Vogel).

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Nomenclature

A	area of the watershed (km^2)
i_e	effective rainfall intensity (cm/h)
i_r	areal rainfall intensity (cm/h)
L_Ω	length of the highest order stream (km)
m_v	mean number of independent storms per year
P_{NR}	probability of null runoff
q_P	peak of the IUH (1/h)
Q_P	peak discharge from the catchment (m^3/s)
R_L	Hortons stream length ratio
t_b	time base of the IUH (h)
t_e	effective rainfall duration (h)
t_r	point/areal storm duration (h)

Greek symbols

α_Ω	kinematic wave parameter for the highest order stream ($m^{-1/3}\ s^{-1}$)
β	inverse of mean areal storm intensity (h/cm)
δ	inverse of mean storm duration (1/h)
ϕ	spatially averaged potential loss rate; ϕ-index (cm/h)
ρ	correlation coefficient between i_r and t_r

duration of rainfall for the basin in question. Physically based derived flood frequency distribution models offer a promising alternative to these approaches for estimating the PDF of flood flows at an ungaged site. Essentially, a DFFD uses readily available catchment information relating to rainfall intensity and duration, along with a rainfall–runoff model whose parameters do not require calibration. DFFD methods are unique because they integrate our theoretical knowledge of both the deterministic hydrologic processes and the stochastic rainfall processes.

DFFD models are an analytic combination of a stochastic rainfall model and a deterministic rainfall–runoff watershed model. DFFD models usually have three components: (1) a stochastic rainfall model, (2) infiltration model and (3) effective rainfall–runoff model. Kurothe et al. (1997) developed a DFFD model using a bivariate exponential rainfall model with negatively correlated intensity and duration, constant loss rate (ϕ-index) infiltration model and a geomorphoclimatic instantaneous unit hydrograph (GcIUH) as the effective rainfall–runoff model. The form of the bivariate exponential distribution was not appropriate for most rainfall data, which exhibits a positive correlation between rainfall intensity and duration. In this study, a different form of bivariate exponential distribution (Nagao and Kadoya, 1971) has been adopted which does not pose any restriction on the sign of the correlation coefficient. Raines and Valdes (1993), Kurothe (1995) and Kurothe et al. (1997) review physically based flood frequency models. Avoiding the repetition of a literature review, the following section derives the DFFD for the generalized case of correlated rainfall intensity and duration.

2. Stochastic rainfall model

The stochastic rainfall model used in earlier DFFD models is a bivariate exponential PDF of storm rainfall intensity i_r and duration t_r. In most of the previous studies, these random variables were assumed to be independent of each other. The joint PDF of i_r and t_r can be expressed as

$$f_{I_r,T_r}(i_r,t_r) = \beta\delta \exp(-\beta i_r - \delta t_r) \quad (1)$$

where the marginal PDFs of intensity and duration are exponential with parameters β and δ, representing the inverse of the mean storm intensity and the mean storm duration, respectively. The assumption of independence will affect the output of a DFFD model. Rainfall records can exhibit either positive or negative correlation between i_r and t_r. For negatively correlated i_r and t_r the joint PDF

$$f_{I_r,T_r}(i_r,t_r) = \beta\delta[(1+\beta\gamma i_r)(1+\delta\gamma t_r) - \gamma] \times \exp(-\beta i_r - \delta t_r - \beta\delta\gamma i_r t_r) \quad (2)$$

was introduced by Gumbel (1960) and Bacchi et al. (1994). The parameter γ ranges from 0 to 1 and describes the correlation coefficient $\rho(i_r,t_r)$ between intensity and duration which is defined by

$$\rho(i_r,t_r) = -1 + \int_0^\infty \frac{1}{1+\gamma x} \exp(-x)\,dx \quad (3)$$

This model is only valid for correlation coefficients ranging from 0 ($\gamma = 0$) to -0.404 ($\gamma = 1$). Using the PDF of i_r and t_r in Eq. (2), the ϕ-index as an infiltration model and the GcIUH as an effective rainfall–runoff model, the cumulative flood frequency distribution of streamflow was derived by Kurothe et al. (1997). One objective of this paper is to extend that work to the case of generalized (positive or negative) correlation between i_r and t_r. Another objective is to demonstrate the ability of the DFFD to reproduce the PDF of observed flood flows at an ungaged site.

For the development of a DFFD for the generalized case of correlated rainfall intensity and duration, the joint PDF given by Nagao and Kadoya (1971) is employed here. This PDF does not pose any restrictions on the correlation coefficient. The joint PDF is

$$f_{I_r,T_r}(i_r, t_r) = \frac{\beta\delta}{1-\rho} \exp(-\beta_1 i_r - \beta_2 t_r) \times I_0\left[\frac{2(\rho\beta\delta i_r t_r)^{1/2}}{1-\rho}\right] \tag{4}$$

where the marginal PDFs of i_r and t_r are exponential with parameters β and δ, ρ is the correlation coefficient between i_r and t_r, $I_0(\,)$ is the modified Bessel function of order zero, and

$$\beta_1 = \frac{\beta}{1-\rho} \tag{5a}$$

$$\beta_2 = \frac{\delta}{1-\rho} \tag{5b}$$

The function $I_0(\,)$ may be expressed as (Gradshteyn and Ryzhik, 1965):

$$I_0(z) = \sum_{k=0}^{\infty} \frac{(z/2)^{2k}}{(k!)^2} \tag{6}$$

Combining Eqs. (4) and (6) leads to

$$f_{I_r,T_r}(i_r, t_r) = \sum_{k=0}^{\infty} \eta_k (i_r t_r)^k \exp(-\beta_1 i_r - \beta_2 t_r) \tag{7}$$

where

$$\eta_k = \frac{\rho^k (\beta\delta)^{k+1}}{(1-\rho)^{2k+1}(k!)^2} \tag{8}$$

The PDF introduced by Nagao and Kadoya (1971) in Eq. (4) was also used by Cordova and Rodriguez-Iturbe (1985) in their study of probabilistic structure of storm surface runoff to account for correlation between i_r and t_r.

An even more flexible stochastic model of rainfall was suggested recently by Lambert and Kuczera (1998) who introduce a generalized exponential model which can be adapted to account for the seasonal nature of rainfall. The bivariate exponential distribution has been documented to be a realistic model for rainfall intensity and duration by many previous investigators (see for example Cordova and Bras, 1981).

2.1. Probability of rainfall excess

Estimation of rainfall excess requires knowledge of the spatial and temporal variation in soil moisture. Index methods, using only one or two parameters, provide an approximation to the infiltration process and are often used in practice. The most common infiltration index is the ϕ-index, defined as the (constant) infiltration rate to be subtracted from the rainfall rate resulting in rainfall excess. The ϕ-index is normally estimated from concurrent rainfall and runoff records, however when such records are unavailable, it is possible to relate values of ϕ to the hydraulic conductivity of the prevailing catchment soil types.

Effective rainfall intensity i_e and duration t_e for a spatially averaged potential loss rate ϕ are given by

$$i_e = i_r - \phi \qquad i_r > \phi \tag{9a}$$

$$t_e = t_r \qquad i_r > \phi \tag{9b}$$

$$i_e = 0 \qquad i_r \le \phi \tag{9c}$$

$$t_e = 0 \qquad i_r \le \phi \tag{9d}$$

When $i_r \le \phi$, no runoff is generated. In terms of the joint distribution of i_e and t_e this situation is represented by a spike at $i_e = 0$ and $t_e = 0$ which is the probability of null runoff (P_{NR}) and is given by

$$P_{NR} = P(i_e = 0, t_e = 0) = \int_0^{\infty}\left[\int_0^{\phi} f_{I_r,T_r}(i_r, t_r)\,\mathrm{d}i_r\right]\mathrm{d}t_r \tag{10}$$

Substitution of $f_{I_r,T_r}(i_r, t_r)$ from Eq. (7) into Eq. (10)

leads to

$$P_{NR} = \sum_{k=0}^{\infty} \eta_k \int_0^{\infty} t_r^k \exp(-\beta_2 t_r)\, dt_r \times \int_0^{\phi} i_r^k \exp(-\beta_1 i_r)\, di_r \tag{11}$$

Completion of the integration in Eq. (11) with respect to t_r yields

$$P_{NR} = \sum_{k=0}^{\infty} \eta_k \frac{k!}{\beta_2^{k+1}} \int_0^{\phi} i_r^k \exp(-\beta_1 i_r)\, di_r \tag{12}$$

The integral in Eq. (12) has the solution

$$\int_0^{\phi} i_r^k \exp(-\beta_1 i_r)\, di_r = \frac{k!}{\beta_1^{k+1}} - \exp(-\beta_1 \phi) \sum_{n=0}^{k} \frac{k!}{n!} \frac{\phi^n}{\beta_1^{k-n+1}} \tag{13}$$

Using Eqs. (5), (8) and (13) we obtain

$$P_{NR} = 1 - \exp\left[\frac{-\beta\phi}{1-\rho}\right] \sum_{k=0}^{\infty} \frac{\rho^k \beta^{k+1}}{(1-\rho)^k k!} \times \sum_{n=0}^{k} \frac{k!}{n!} \frac{\phi^n (1-\rho)^{k-n+1}}{\beta^{k-n+1}} \tag{14}$$

2.2. The joint PDF of rainfall intensity and duration

The PDF of i_e and t_e can be derived as a function of the PDF of i_r and t_r by using the general relationship

$$f_{I_e,T_e}(i_e, t_e) = f_{I_r,T_r}[g_1^{-1}(i_e, t_e), g_2^{-1}(i_e, t_e)] \left| \frac{\partial(i_r, t_r)}{\partial(i_e, t_e)} \right| \tag{15}$$

where $g_1^{-1}(i_e, t_e)$ and $g_2^{-1}(i_e, t_e)$ are the inverse functions of i_r and t_r. Substitution of Eqs. (7) and (9) into Eq. (15) leads to

$$f_{I_e,T_e}(i_e, t_e) = \sum_{k=0}^{\infty} \eta_k [(i_e + \phi) t_e]^k \times \exp[-\beta_1 (i_e + \phi) - \beta_2 t_e] \tag{16}$$

Eqs. (14) and (16) completely define the distribution of i_e and t_e.

3. Derivation of cumulative density function of peak discharge

The stochastic rainfall model discussed above is used to derive the cumulative distribution function (CDF) of peak discharge. Considering a triangular IUH, Henderson (1963) describes the peak discharge Q_P at the outlet of a catchment as

$$Q_P = \frac{2 i_e t_e A}{t_b}\left[1 - \frac{t_e}{2 t_b}\right] \quad \text{for } t_e < t_b \tag{17}$$

$$Q_P = i_e A \quad \text{for } t_e \geq t_b \tag{18}$$

where A is the area of the catchment and t_b is the time base of the IUH. For a triangular IUH:

$$q_P t_b = 2 \tag{19}$$

Using Eq. (19), Eqs. (17) and (18) can be expressed as

$$Q_P = i_e t_e A q_P \left[1 - \frac{q_P t_e}{4}\right] \quad \text{for } t_e < \frac{2}{q_P} \tag{20}$$

$$Q_P = i_e A \quad \text{for } t_e \geq \frac{2}{q_P} \tag{21}$$

Rodriguez-Iturbe et al. (1982) express the GcIUH peak as

$$q_P = \frac{0.871 (i_e A R_L)^{2/5} \alpha_\Omega^{3/5}}{L_\Omega} \tag{22}$$

where i_e is the effective rainfall intensity (cm/h), A the area of the watershed (km^2), R_L the Horton's stream length ratio, α_Ω the kinematic wave parameter of the highest order stream (m$^{-1/3}$ s^{-1}), and L_Ω the length of the highest order stream (km). Using Eq. (22), Eqs. (20) and (21) can be written as

$$Q_P = 0.871 K_1 A i_e^{7/5} t_e \left[1 - \frac{0.871 K_1 i_e^{2/5} t_e}{4}\right] \quad \text{for } t_e < \frac{2}{0.871 K_1} i_e^{-2/5} \tag{23}$$

$$Q_P = i_e A \quad \text{for } t_e \geq \frac{2}{0.871 K_1} i_e^{-2/5} \tag{24}$$

where

$$K_1 = \frac{(A R_L)^{2/5} \alpha_\Omega^{3/5}}{L_\Omega}$$

Solving Eq. (23) for t_e we obtain

$$t_e = \frac{2}{0.871K_1} i_e^{-2/5} \left[1 - \left[1 - \frac{Q_P}{Ai_e} \right]^{1/2} \right] \qquad (25)$$

Defining $t_e = t_e^*$ and $Q_P/A = Q_P^*$ Diaz-Granados et al. (1983, 1984) evaluated the CDF of Q_P as

$F_{Q_P}(Q_P$

Table 1
Model parameters of Davidson and four Indian watersheds

Parameters	Kharanala	Pausar	Tairhia	Lakhora	Davidson
β (h/cm)	7.85	4.69	6.33	5.35	2.46
δ (1/h)	0.113	0.124	0.075	0.124	0.19
m_v	64	70	62	65	24
ϕ-index (cm/h)	0.015	0.015	0.015	0.015	1.125
A (km^2)	42.7	67.4	101.0	151.4	104.6
R_L	2.00	2.15	2.64	1.96	2.41
L_Ω (km)	7.57	8.05	14.06	12.66	8.80
α_Ω (m$^{-1/3}$ s^{-1})	0.26	0.13	0.14	0.13	1.00
ρ	0.101	0.204	0.122	0.095	NA

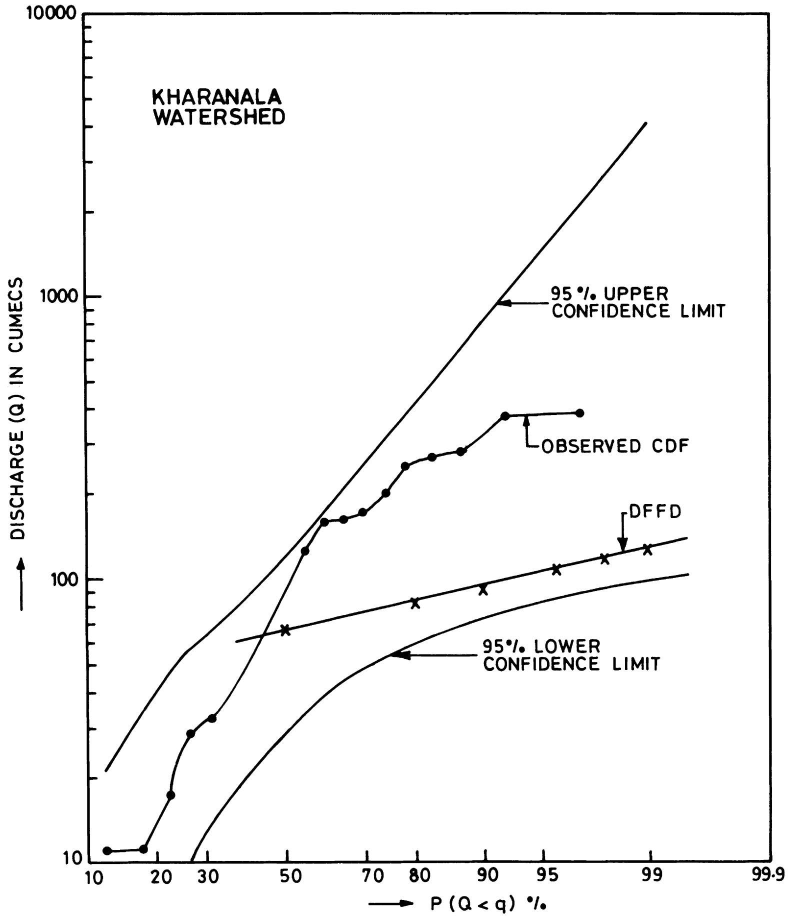

Fig. 1. Comparison of DFFD models with 95% confidence intervals associated with observed flood discharges for the Kharanala watershed.

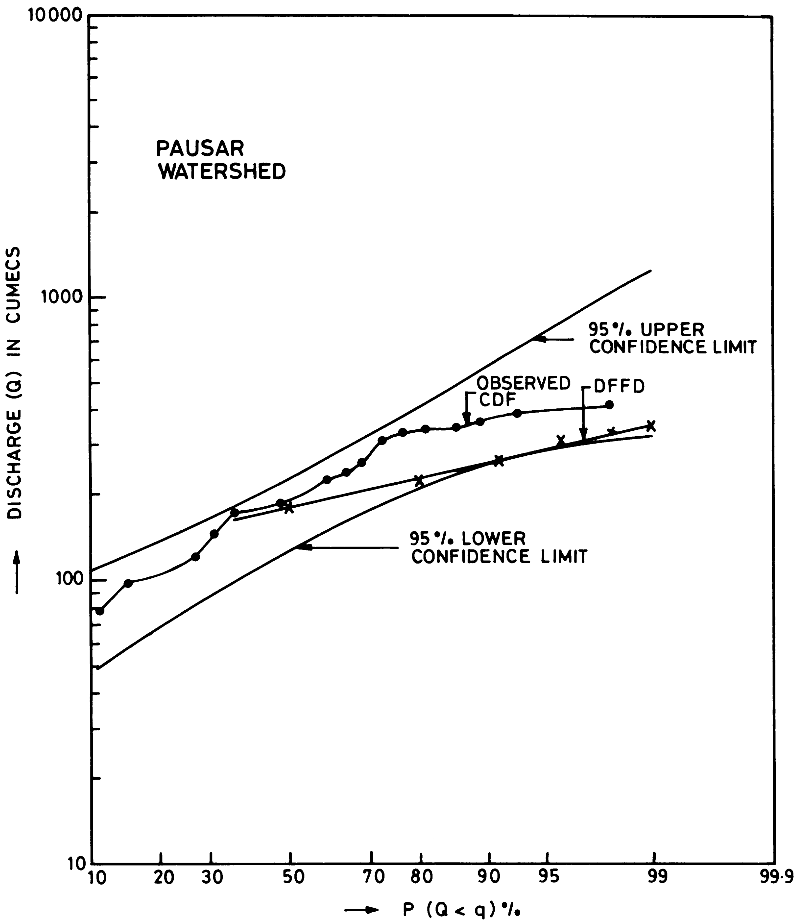

Fig. 2. Comparison of DFFD models with 95% confidence intervals associated with observed flood discharges for the Pausar watershed.

region is a wet pocket of the State with a yearly precipitation of 1676 mm. The watershed area is 104.6 km^2. The mean catchment slope is approximately 0.33 m/m. This watershed has been considered previously by Diaz-Granados et al. (1983) and Kurothe et al. (1997).

5. Results

5.1. The accuracy of DFFD models

The DFFD model introduced here was applied to each of the five catchments summarized in Table 1. For the four Indian watersheds, the CDF of flood discharges is illustrated in Figs. 1–4, along with 95% confidence intervals assuming a lognormal distribution of flood discharge. The confidence intervals were constructed by fitting a lognormal distribution to the flood discharge observations at each site and estimating 95% confidence limits about the true distribution. The confidence intervals reflect our uncertainty regarding the underlying CDF of flood discharges at each site, and hence provide a useful and informative basis for evaluating the results of the DFFD models.

The DFFD models are not calibrated to at-site data, hence one would not expect the derived CDFs to reproduce the observed CDF of flood discharges. Nevertheless, one would expect each DFFD to be enclosed by the 95% confidence intervals. Although the DFFD models are not always able to reproduce the

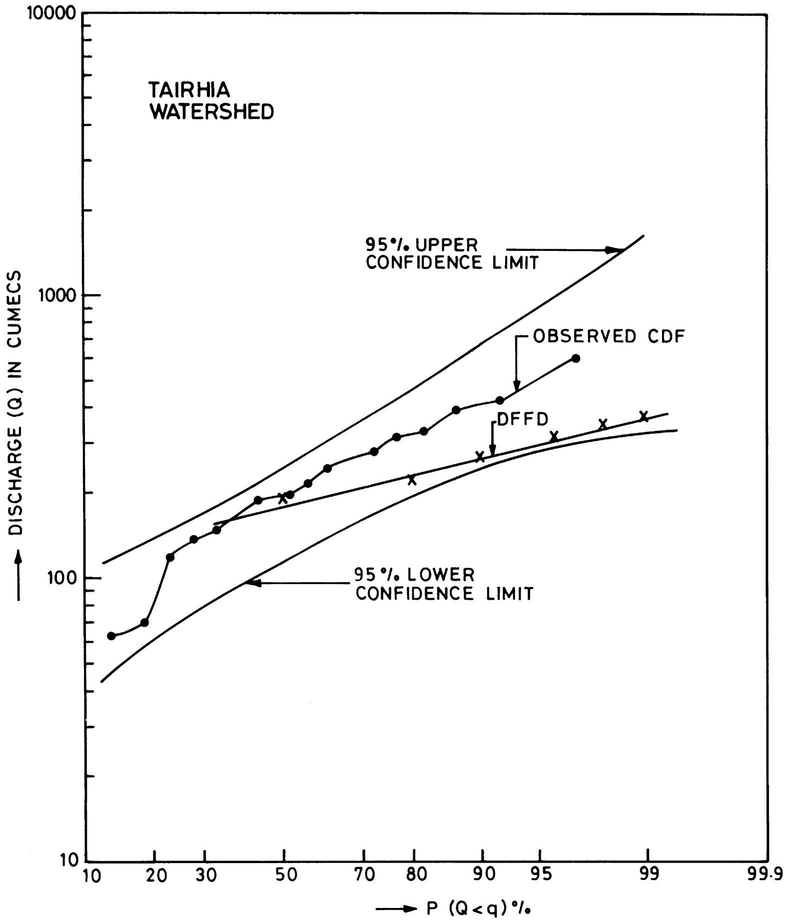

Fig. 3. Comparison of DFFD models with 95% confidence intervals associated with observed flood discharges for the Tairhia watershed.

observed CDF of flood discharges in Figs. 1–4, they are enclosed by the 95% confidence intervals, for the most part, in the upper tail of the distribution. Future research relating to the use of DFFD models would benefit from calibration of the models to observations and subsequent regionalization of the key model parameters such as the infiltration index which we are unable to measure from field observations.

5.2. The impact of correlation

Cordova and Rodriguez-Iturbe (1985) showed that assumptions regarding the correlation of rainfall intensity and duration can have a significant impact on the moments of flood discharges. Therefore, one would expect that such correlation should also influence flood flow quantiles. This section evaluates the impact of correlation on the magnitude of flood flow quantiles using the DFFD models introduced here.

5.3. Davidson watershed

Diaz-Granados et al. (1983) applied their model to the Davidson catchment and produced a reasonable fit to observed data by using 50% contributing area and a ϕ-index of 0.72 cm/h. The model parameters for this watershed are listed in Table 1. A contributing area of 52.3 km and ϕ-index of 0.72 cm/h are assumed here. Other parameters were held constant. The value of the correlation coefficient ρ was varied from -0.5 to $+0.4$ in steps of 0.1.

The computed discharges corresponding to various

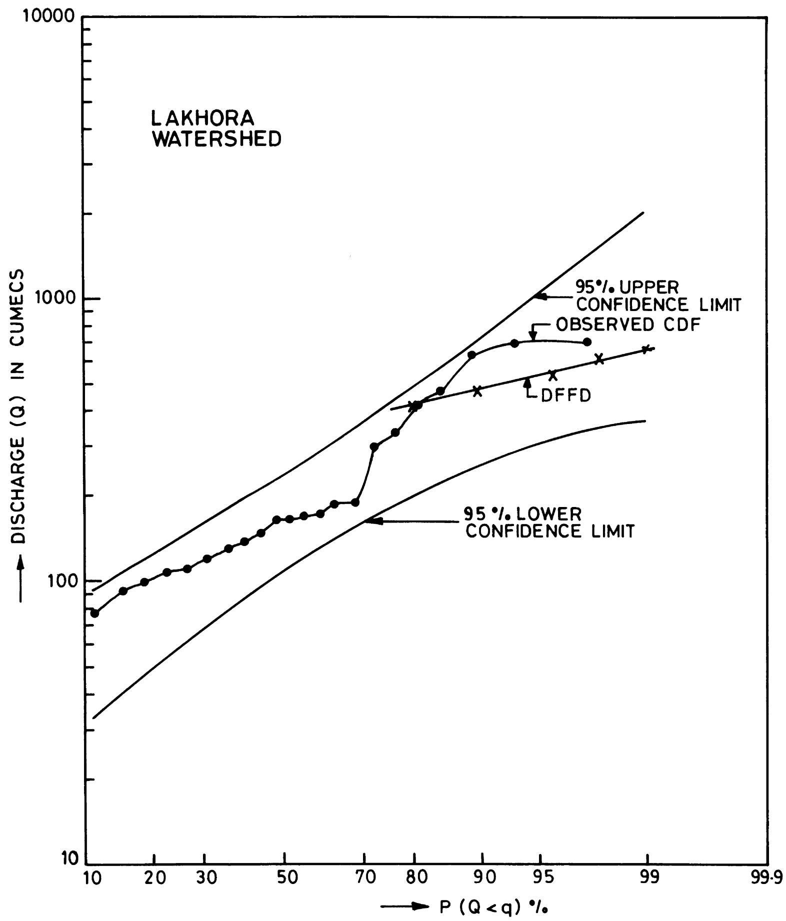

Fig. 4. Comparison of DFFD models with 95% confidence intervals associated with observed flood discharges for the Lakhora watershed.

return periods for different values of ρ are given in Table 2 and illustrated in Fig. 5. A positive correlation coefficient of 0.4 results in a quantile of about 347 m^3/s for the 100-year return period event as compared to about 338 m^3/s when a DFFD model with independent rainfall intensity and duration ($\rho = 0$) is used. The under estimation is only 2.7% in this case. As the return period decreases the percentage under-estimation

Table 2
Effect of correlation coefficient on quantiles (Davidson watershed)

Return period (years)	Correlation coefficient, ρ									
	−0.5	−0.4	−0.3	−0.2	−0.1	0.0	0.1	0.2	0.3	0.4
2	76	81	87	93	98	104	109	113	116	118
5	111	120	130	140	149	157	163	168	170	172
10	133	147	162	176	188	198	204	209	212	213
25	156	178	201	223	240	251	262	263	265	267
50	168	196	229	257	278	292	300	304	306	307
100	175	211	252	292	317	332	341	345	347	347

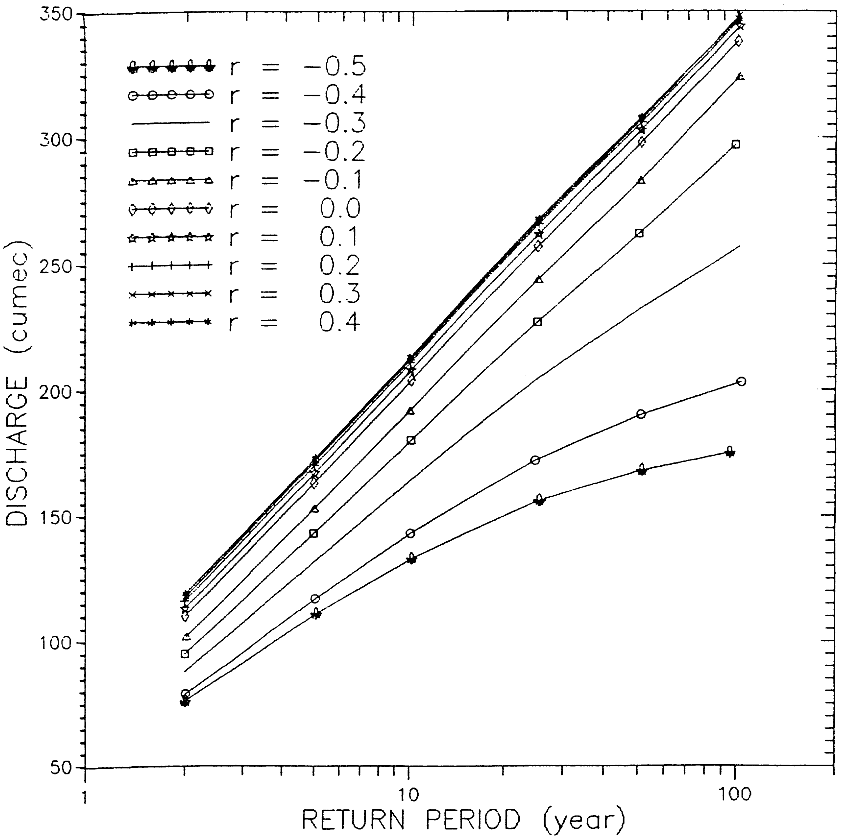

Fig. 5. Impact of correlation on flood quantiles for the Davidson watershed.

increases. Under-estimation is about 8% for the 2-year return period flood. Computed discharges are 110 and 119 m^3/s for $\rho = 0$ and $\rho = 0.4$, respectively. It may be concluded that quantiles estimated by DFFD models for the independent case ($\rho = 0$) are lower than the flood quantiles estimated by the proposed model, which accounts for the positive correlation between these variables.

On the contrary, negative correlation coefficient has a significant and opposite effect on the quantiles. Bacchi et al. (1994) have reported negative correlation coefficients as high as −0.5. Therefore, Table 2 presents the effect of negative correlation coefficients up to −0.5. The 100-year return period quantile of 175 m^3/s for $\rho = -0.5$ value is over-estimated to 338 m^3/s, an increase of over 50%. The percentage over-estimation decreases with decrease in the return period. However, the percentage over estimation is still over 30%.

5.4. Indian watersheds

Clay soils are predominant in these watersheds. Approximately 65% of the drainage area is cultivated and the remainder is covered by tropical dry deciduous forest. The model parameters of these watersheds are listed in Table 1. The correlation coefficient between rainfall intensity and duration ranges from $\rho = 0.1$ to $\rho = 0.204$.

Flood quantiles for the independent case $\rho = 0$ and the positive at-site correlations are compared for the four Indian watersheds in Table 3 for the 2, 5, 10, 25, 50 and 100-year return periods. The under-estimation varies from 3.4 to 9.5%. As the positive correlation coefficient increases the percentage under-estimation

Table 3
Effect of positive correlation on quantiles of four Indian watersheds

Return period (years); watershed size (km^2)	Quantiles (m^3/s)		Under-estimation (%)
Kharanala; 42.7	$\rho = 0$	$\rho = 0.101$	
2	63	66	4.76
5	77	80	3.90
10	88	91	3.41
25	101	106	4.95
50	112	117	4.46
100	122	127	4.10
Pausar; 67.4	$\rho = 0$	$\rho = 0.204$	
2	168	184	9.52
5	205	222	8.29
10	233	251	7.73
25	270	290	7.41
50	298	319	7.05
100	325	349	7.38
Tairhia; 101.0	$\rho = 0$	$\rho = 0.122$	
2	185	195	5.41
5	226	238	5.31
10	257	270	5.06
25	298	312	4.70
50	329	344	4.56
100	359	376	4.74
Lakhora; 151.4	$\rho = 0$	$\rho = 0.095$	
2	313	335	7.03
5	386	411	6.48
10	442	469	6.11
25	515	545	5.83
50	570	604	5.96
100	624	663	6.25

tends to increase. It can also be seen from the table that as the size of the watershed increases the percentage under-estimation tends to increase. Kharanala ($42.7\ km^2$) and Lakhora ($151.4\ km^2$) watersheds have a correlation coefficient of approximately 0.1 but the under-estimation is greater in Lakhora watershed. A similar trend is observed in Pausar watershed. In general the percentage under-estimation (in each design quantile) decreases as the return period increases.

6. Conclusions

We have documented that a physically based derived flood frequency distribution (DFFD) model offers a promising alternative to the conventional approaches for estimating the PDF of flood flows at an ungaged site. DFFD methods are unique because they are the only analytic approach to flood frequency analysis which integrates our stochastic knowledge regarding the structure of rainfall and our deterministic knowledge regarding the rainfall–runoff process. The DFFD is really just an analytic combination of a stochastic rainfall model and a rainfall–runoff watershed model. The stochastic rainfall model used in this study is able to account for any observed correlation between rainfall intensity and duration. Earlier studies required storm duration and intensity to be either independent or negatively correlated. This study documents the under-estimation in design quantiles which can result from assuming that storm duration and intensity are either independent or negatively correlated, when a positive correlation exists. Overall the results of application of a DFFD to four Indian watersheds and one watershed in the United States indicate that cross correlation of rainfall duration and intensity has an important impact on the estimated quantiles.

This study has employed the geomorphoclimatic instantaneous unit hydrograph (GcIUG) introduced by Rodriguez-Iturbe et al. (1982) as the rainfall–runoff model. Shamseldin and Nash (1998) provide a critical review of the geomorphological unit hydrograph (GUH) along with its inherent assumptions and constraints. Shamseldin and Nash (1998) argue that the GUH is really an empirical model because its shape and scale factors must still be related empirically to catchment characteristics.

The application of DFFD models in hydrology is still in its infancy. To enable more widespread usage of these methods several issues must still be addressed. Hypothesis tests and goodness-of-fit tests for DFFD models need to be applied, much like goodness-of-fit tests which have been applied to traditional flood frequency models. Such tests have led to the widespread and nearly global acceptance of the generalized extreme value model for at-site flood frequency analysis (Vogel and Wilson, 1996). To enable application of DFFD models at ungaged sites, regional hydrologic investigations are required to evaluate the regional structure of both the stochastic rainfall model and the rainfall–runoff model parameters.

With the recent proliferation of geographic information systems and large databases of hydrologic and climatic data, the regionalization of DFFD models to most regions of the world is now possible. Still comparisons are required to evaluate DFFD models with other regional hydrologic modeling approaches such as regional hydrologic regression and index flood methods.

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