Rate-Based Estimation of the Runoff Coefficients for Selected Watersheds in Texas

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Abstract: The runoff coefficient, C, of the rational method is an expression of rate proportionality between rainfall intensity and peak discharge. Values of C were derived for 80 developed and undeveloped watersheds in Texas using two distinct methods. First, the rate-based runoff coefficient, C_{rate}, was estimated for each of about 1,500 rainfall-runoff events. Second, the frequency-matching approach was used to derive a runoff coefficient, C_r, for each watershed. Published C values, C_{lit}, or literature-based runoff coefficients were compared to those obtained from the methods investigated here. Using the 80 Texas watersheds, comparison of the two methods shows that about 75% of literature-based runoff coefficients are greater than C_r and the watershed-median C_{rate}, but for developed watersheds with more impervious cover, literature-based runoff coefficients are less than C_r and C_{rate}. An equation applicable to many Texas watersheds is proposed to estimate C as a function of impervious area. **DOI: 10.1061/(ASCE)HE.1943-5584.0000753.** © *2013 American Society of Civil Engineers.*

CE Database subject headings: Water discharge; Runoff; Hydrology; Watersheds; Texas; Coefficients.

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Introduction

The search for a reliable method for estimation of peak discharges for small and ungauged undeveloped (rural) watersheds has led to various engineering-design methods (French et al. 1974). These various methods often are applicable for developed (suburban to urban) watersheds (Chow et al. 1988). The rational method likely is the applied method used most often by hydraulic and drainage engineers to estimate design discharges for small watersheds. These design discharges are used to size a variety of drainage structures for small undeveloped and developed watersheds throughout the United States (Viessman and Lewis 2003).

The rational method (Kuichling 1889) computes the peak discharge, Q_p (in m^3/s in SI units or ft^3/s in English units), by using

$$Q_p = m_0 CIA \tag{1}$$

where C = runoff coefficient (dimensionless), I = rainfall intensity (mm/h or in./h) over a critical period of storm time (typically taken as the time of concentration, T_c), A = drainage area (hectares or acres), and m_o = dimensional correction factor ($1/360 = 0.00278$ in SI units; 1.008 in English units). Steady-state conditions are needed for the application of the rational method (French et al. 1974). From inspection of the equation, it is evident that C is an expression of rate proportionality between rainfall intensity and peak discharge (flow rate). The theoretical range of values for C is between 0 and 1. The typical *whole watershed C* values (that is, C values representing the integrated effects of various surfaces in the watershed and other watershed properties) are listed for different general land-use conditions in various design manuals and textbooks. Examples of textbooks that include tables of C values are Chow et al. (1988) and Viessman and Lewis (2003). Published C values, C_{lit}, were sourced from ASCE and the Water Pollution Control Federation (WPCF) in 1960 (ASCE and WPCF 1960). The C_{lit} values were obtained from a response survey, which received "71 returns of an extensive questionnaire submitted to 380 public and private organizations throughout the United States." No justification based on analyses of observed rainfall intensity and peak discharge data for the C_{lit} values is apparent in ASCE and WPCF (1960)—a few analyses of observed relations between rainfall intensity and peak discharge were considered by Kuichling (1889). In short, the authors of this paper conclude that C_{lit} values appeared heuristically determined; therefore, a comparison of rate-based C values derived from observed rainfall and runoff data to the C_{lit} values is made.

Estimation of reliable values of C presents a substantial difficulty in the rational method and a major source of uncertainty in many small watershed projects (Pilgrim and Cordery 1993). Furthermore, the concept of *runoff coefficient* for a watershed is fraught with ambiguities. The volumetric runoff coefficient, C_v, is the ratio of total runoff to rainfall (Merz et al. 2006; Dhakal et al. 2012). Because C is an expression of rate proportionality [Eq. (1)], such a coefficient is termed a *rate-based runoff coefficient*, C_{rate}. It is important to stress that although the C_{lit} found in ASCE and WPCF (1960) is intended for use in the rate-based rational method, C_{lit} appears not to be derived from any observed data.

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When observed rainfall and runoff data are available, C_{rate} is computed through the rational method (Pilgrim and Cordery 1993) as

$$C_{\text{rate}} = \frac{Q_p}{m_0 I(t_{av}) A} \tag{2}$$

where $I(t_{av})$ = average rainfall intensity over time period t_{av}, which is the rainfall intensity averaging time period (a critical time period), rather than the entire rainfall event duration (Kuichling 1889; Schaake et al. 1967). Here, t_{av} should be a period of time for a storm that contributes runoff that produces the observed Q_p. Kuichling (1889) argued against using the entire rainfall event duration, t_w, to obtain the average rainfall intensity, I_w, because I_w is generally not appropriate due to the fact that rainfall durations of real storms often are greater than the characteristic time of the small watersheds that he considered. Thus, a lasting contribution of Kuichling (1889) was the introduction of the concept of the time of concentration, T_c, of a watershed. This time also is termed a *critical storm duration* because it uses an average rainfall intensity that produces reliable peak discharge estimates. T_c is influenced in part by drainage area, which is a major criterion used to assess the applicability of the rational method (Chow et al. 1988). In particular, TxDOT (2002) recommends the use of the rational method for watersheds with very small drainage areas of <0.8 km^2 (81 ha).

Other investigators have reported C values derived from the analysis of observed rainfall and runoff data for various watersheds throughout the world. Schaake et al. (1967) examined the rational method using experimental rainfall and runoff data collected from 20 small urban watersheds of <0.6 km^2 (60.75 ha) in Baltimore, Maryland. Those authors used watershed lag time to compute average rainfall intensity and used a frequency-matching approach.

Hotchkiss and Provaznik (1995) estimated C_{rate} for 24 rural watersheds in south-central Nebraska using event-paired and frequency-matched data. Young et al. (2009) estimated C_{rate} for 72 rural watersheds in Kansas with drainage areas of <78 km^2 for different return periods. The peak discharge for each return period was estimated using annual peak frequency analysis of the gaged peak discharges and rainfall intensity obtained from rainfall intensity-duration-frequency tables (Young et al. 2009).

In this paper, two methods were used to estimate C_{rate} for 80 selected watersheds in Texas. Both methods rely on the analysis of observed rainfall and runoff data. First, C_{rate} was estimated using Eq. (2); $I(t_{av})$ was computed as the maximum intensity for a moving time window of duration T_c before and up to the time to peak, T_p. T_c was derived for the study watersheds using the Kerby-Kirpich approach (Roussel et al. 2005; Fang et al. 2008). About 1,500 rainfall-runoff events from 80 Texas watersheds were analyzed to determine event-specific, watershed-median, and watershed-mean C_{rate} values. Second, the frequency-matching approach (Schaake et al. 1967) was used to derive a representative C, referred to as C_r, for each of the 80 watersheds. The paper also compares C values from the two different methods and those published in the literature. Finally, an equation of C as a function of the percentage of impervious area is proposed for the 80 watersheds.

Study Area and Rainfall-Runoff Database

Watershed data from a larger data set accumulated by researchers from the USGS Texas Water Science Center, Texas Tech University, the University of Houston, and Lamar University (Asquith et al. 2004) were used for this study. A total of 10 watersheds out of about 90 represented by USGS streamflow-gauging stations in the source database (Asquith et al. 2004) were not used in this study because less than four rainfall and runoff events were recorded for each of these watersheds. The locations of 80 USGS streamflow-gauging stations representing 80 watersheds in Texas are shown in Fig. 1. Incidentally, these data also were used by Asquith and Roussel (2007), Cleveland et al. (2006), Fang et al. (2007, 2008), and Dhakal et al. (2012). The rainfall-runoff data set consists of about 1,500 rainfall-runoff events that occurred between 1959 and 1986. The number of events available for each watershed varied from 4 to 50, with median and mean values of 16 and 19 events, respectively. Values of rainfall depths for about 1,500 events ranged from 3.56 mm (0.14 in.) to 489.20 mm (19.26 in.), with median and mean values of 57.66 mm (2.27 in.) and 66.8 mm (2.63 in.), respectively.

The drainage areas of the watersheds in the study range from approximately 0.2–320 km^2; the median and mean values are 17.0 km^2 and 37.3 km^2, respectively. The stream slope of study watersheds range from approximately 0.0022–0.0196 dimensionless numbers; the median and mean values are 0.0076 and 0.0081, respectively. The percentage of impervious area (*IMP*) values of the study watersheds range from approximately 0 to 73; the median and mean values are 18.0 and 28.2, respectively.

There has been discussion in the literature concerning the size of watersheds for which the application of the rational method is appropriate. For application of the rational formula, Kuichling (1889, pp. 40–41) stated: "For large areas, on the other hand, a more elaborate analysis becomes necessary in order to find under what condition the absolute maximum discharge will occur, although the method of procedure above indicated will remain the same." Kuichling (1889) did not suggest a specific large area limit. ASCE and WPCF (1960, p. 32), made the following statement when the rational method was introduced for design and construction of sanitary and storm sewers: "Although the basic principles of the rational method are applicable to large drainage areas, reported practice generally limits its use to urban areas of less than 5 square miles." Pilgrim and Cordery (1993, p. 9.14) explained that the rational method is one of three methods widely used to estimate peak flows for small to medium-sized basins, and wrote that "it is not possible to define precisely what is meant by 'small' and 'medium' sized, but upper limits of 25 km^2 (10 mi^2) and 550 km^2 (200 mi^2), respectively, can be considered as general guides." Young et al. (2009) stated that the rational method might be applied to much larger drainage areas than typically assumed in some design manuals, so long as the watershed is unregulated. The results of this study will indicate further that there is no demonstrable relation between runoff coefficient and drainage area.

For any watershed (regardless of its size), some of the required attributes to apply the Kuichling method are time of concentration (T_c), main channel length (L_c), and channel slope (S_c). For each of the 80 Texas watersheds, a geospatial database was developed by Roussel et al. (2005) containing L_c and S_c for each watershed, along with drainage area, basin width, longitude, latitude, and 39 other watershed characteristics. In this paper, L_c and S_c are used to estimate time of concentration T_c by Kirpich (1940) for channel flow, plus travel time for overland flow using Kerby (1959). A combination of the methods of Kirpich (1940) and Kerby (1959) is discussed by Roussel et al. (2005) and Fang et al. (2008). The Kirpich equation (1940) was developed from the Soil Conservation Service (SCS) data for rural watersheds with drainage areas less than 0.45 km^2, and it is presented here:

$$T_c = 3.978 L_c^{0.77} S_c^{-0.385} \tag{3}$$

where L_c = channel length in km and S_c = channel slope in m/m. Fang et al. (2007, 2008) demonstrated that for watersheds with

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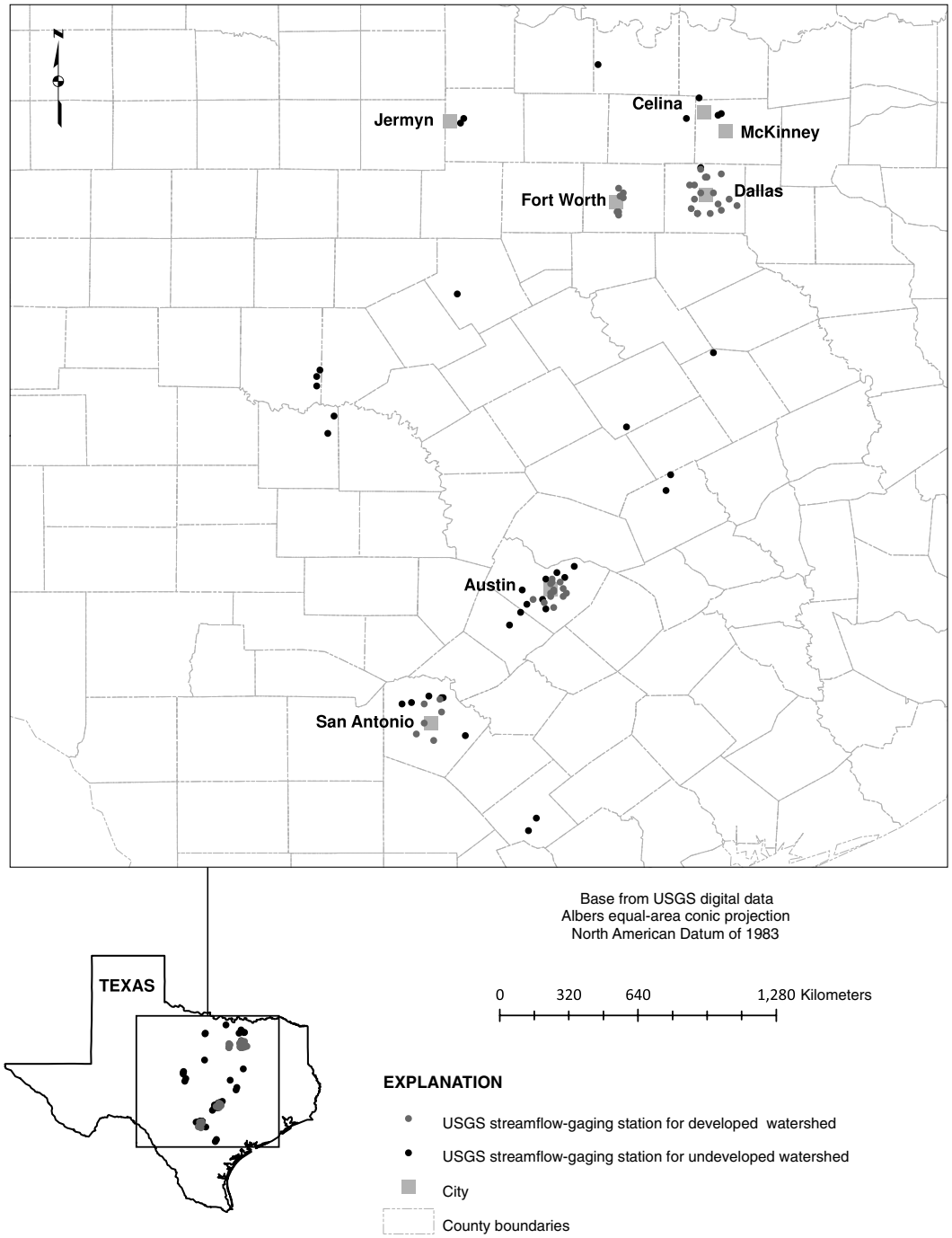

Fig. 1. Map showing USGS streamflow-gauging stations representing 80 developed and undeveloped watersheds in Texas (base from U.S. Geological Survey digital data)

relatively large drainage areas (more than 50 km^2), the Kirpich equation provides as reliable an estimate of T_c as the other empirical equations developed for large watersheds and the SCS velocity method (Viessman and Lewis 2003). The value of T_c estimated using the Kirpich equation reasonably approximates the average value of T_c estimated from observed rainfall and runoff data (Fang et al. 2007). For the study watersheds, T_c ranged from 1.1 h to 16.7 h, with median and mean values of 2.8 h and 3.8 h, respectively.

Each of the 80 Texas watersheds was previously classified as either developed or undeveloped (Roussel et al. 2005; Cleveland et al. 2008). The classification scheme of developed and undeveloped watersheds is consistent with the characterization of watersheds in more than 220 USGS reports of Texas data from which the original data for the rainfall and runoff database were obtained (Asquith et al. 2004). Although this binary classification seems arbitrary, it does take into account the uncertainty in watershed development conditions for the time period of available data (Asquith and Roussel 2007). This binary classification was used by Asquith et al. (2006) in a regionalization study of unit hydrographs for the Texas watersheds (Asquith et al. 2004). Using the binary classification scheme for the 80 Texas watersheds, there are 44 developed watersheds in four metropolitan areas in Texas (Austin, Dallas, Fort Worth, and San Antonio) and 36 undeveloped watersheds. The 36 undeveloped watersheds consist of 16 watersheds near these four cities and 20 rural watersheds.

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Runoff Coefficients Estimated from Event Rainfall-Runoff Data

Rate-Based C Derived for Individual Rainfall-Runoff Events

For this study, the intensity I in Eq. (2) is the maximum rainfall intensity before the time to peak, T_p, of a runoff hydrograph and is calculated as the maximum intensity found by a moving time window of duration t_{av} through the 5-min interval rainfall hyetograph for the storm event. For data processing, only the largest Q_p for each storm event (in the case of multiple peaks in the overall hydrograph) was used.

The computation of C_{rate} is illustrated here by an example. In Fig. 2, the I and C_{rate} values are shown as functions of t_{av} for two storm events gaged by the USGS: one on September 22, 1969, at USGS streamflow-gauging station 08048550 Dry Branch at Blandin Street, Fort Worth, Texas (hereinafter *Dry Branch*); and the second on April 25, 1970, at 08058000 Honey Creek near McKinney, Texas (hereinafter *Honey Creek*). As shown in Fig. 2, as t_{av} increases, I decreases and C_{rate} increases. For example, for the storm event at Dry Branch, as t_{av} increases from 5 min to 3.5 h, I decreases from about 119 mm/h (4.7 in./h) to about 16.3 mm/h (0.64 in./h) and C_{rate} increases from 0.04 to 0.30. For the Dry Branch and Honey Creek watersheds, T_c is estimated as 1.8 h and 1.5 h, respectively. These T_c values are derived via the Kerby-Kirpich method (Roussel et al. 2005; Fang et al. 2008); the corresponding C_{rate} values for the Dry Branch and Honey Creek watersheds are 0.23 and 1.70, respectively. Following the analysis leading to Fig. 2, one C_{rate} value was determined using I corresponding to a moving time window T_c for each of about 1,500 events from the 80 Texas watersheds.

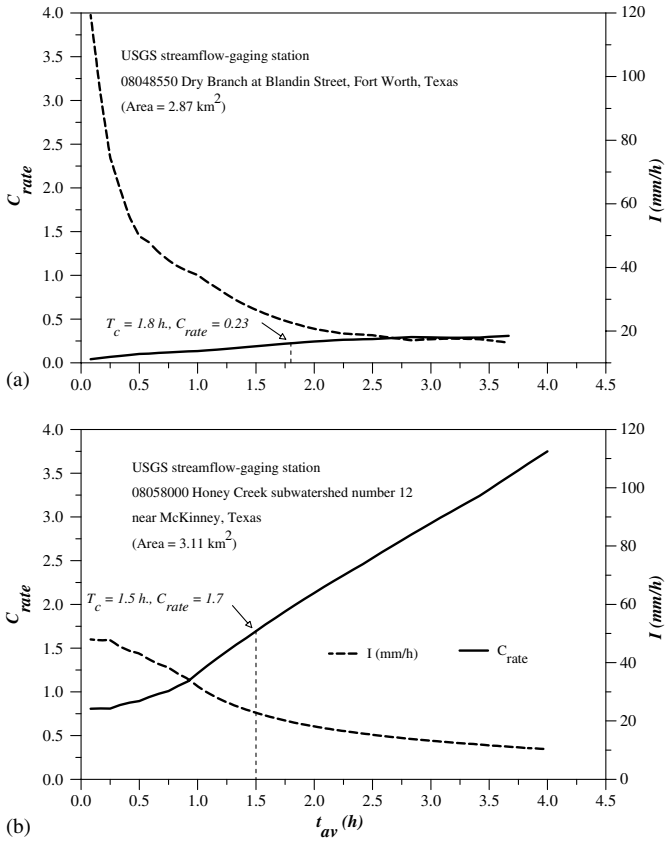

Fig. 2. Average rainfall intensity I and runoff coefficient C_{rate} as a function of t_{av} for two storm events: (a) on September 22, 1969, at USGS streamflow-gauging station 08048550 Dry Branch at Blandin Street, Fort Worth, Texas; (b) on April 25, 1970, at USGS streamflow-gauging station 08058000 Honey Creek subwatershed number 12, near McKinney, Texas

Because T_c was computed using the Kerby-Kirpich approach, the mean value of C_{rate} is 0.31 for events where $T_p < T_c$. In contrast, for events where $T_p \geq T_c$, the mean value of C_{rate} is 0.50 (see Table 1). From inspection of the frequency distributions of C_{rate} shown in Fig. 3, estimates of C_{rate} are significantly greater (Welch-Satterthwaite t-test; p-value <0.0001) for storm events when $T_p \geq T_c$ than those from events when $T_p < T_c$. Therefore, values of C_{rate} depend on the duration of the rainfall event, which supports the idea proposed by Kuichling (1889) that as T_c is reached, discharge for a watershed becomes a maximum (a peak) because the entire area is contributing runoff to the outlet. For cases considered in this research, the maximum value of C_{rate} sometimes exceeded 1 (and went up to 4.48 when $T_p \geq T_c$). For 124 of the approximately 1,500 events, the calculated C_{rate} was greater than 1.

The occurrence of $C_{\text{rate}} > 1$ is related to unknown errors in T_c used to calculate I (see Fig. 2), rainfall characteristics, fundamental measurement errors of rainfall and runoff data, or other unusual hydrologic factors. Several studies (French et al. 1974; Pilgrim and Cordery 1993; Young et al. 2009) have shown that values of C_{rate} greater than 1 are possible when rate-based C was determined from the observed peak flow rate and computed rainfall intensity over a critical period of storm time. If the time of concentration were exactly correct for the watershed, and if the rainfall were spatially and temporally homogeneous and isolated (i.e., no preceding rainfall), then C_{rate} would have to be less than or equal to 1, but the rainfall normally varies in time and in space. Averaging the temporal and spatial variability of rainfall leads to lower rainfall intensities, and consequently lower predicted peak discharge values. Thus, when using average rainfall as a predictor of Q_p, the C value necessarily will be higher than if the rainfall were truly uniform in space and time.

Most of the C_v values derived from about 1,500 rainfall events in Texas watersheds (Dhakal et al. 2012) are between 0 and 1. Rate-based runoff coefficient C_{rate} and volumetric-based runoff coefficient C_v are defined differently and were determined using different approaches from observed rainfall and runoff data. The use of rate-based runoff coefficients is appropriate if one wants to determine peak discharge using the rational method, and the volumetric runoff coefficient can be used to estimate fractional rainfall loss using the constant fraction method (McCuen 1998) or for hydrologic modeling and runoff volume design purposes for a stormwater quality control basin (USEPA 1983; Guo and Urbonas 1996; Mays 2004).

Frequency distributions of C_{rate} values computed for about 1,500 events from the 80 Texas watersheds are shown in Fig. 3, and summary statistics are listed in Table 1. Recalling that T_c was computed using the Kerby-Kirpich approach, the mean value of C_{rate} is 0.31 for events where $T_p < T_c$. In contrast, for events where $T_p \geq T_c$, the mean value of C_{rate} is 0.50 (see Table 1). From inspection of the frequency distributions of C_{rate} shown in Fig. 3, estimates of C_{rate} are significantly greater (Welch-Satterthwaite t-test; p-value <0.0001) for storm events when $T_p \geq T_c$ than those from events when $T_p < T_c$. Therefore, values of C_{rate} depend on the duration of the rainfall event, which supports the idea proposed by Kuichling (1889) that as T_c is reached, discharge for a watershed becomes a maximum (a peak) because the entire area is contributing runoff to the outlet. For cases considered in this research, the maximum value of C_{rate} sometimes exceeded 1 (and went up to 4.48 when $T_p \geq T_c$). For 124 of the approximately 1,500 events, the calculated C_{rate} was greater than 1.

Watershed Mean and Median Runoff Coefficients

Watershed mean and median values of C_{rate} for the 80 Texas watersheds were calculated for all observed storms in the same watershed (regardless of whether T_p was less than or greater than T_c). The computed watershed means of C_{rate} ranged from 0.07 to 1.79, the watershed medians of C_{rate} ranged from 0.07 to 1.73, and the average values of the individual watershed mean and median C_{rate} were 0.44 and 0.40, respectively (see Table 2). Standard deviations from the watershed-means C_{rate} ranged from 0.03 to 0.87. Frequency distributions of the watershed mean and median of C_{rate}

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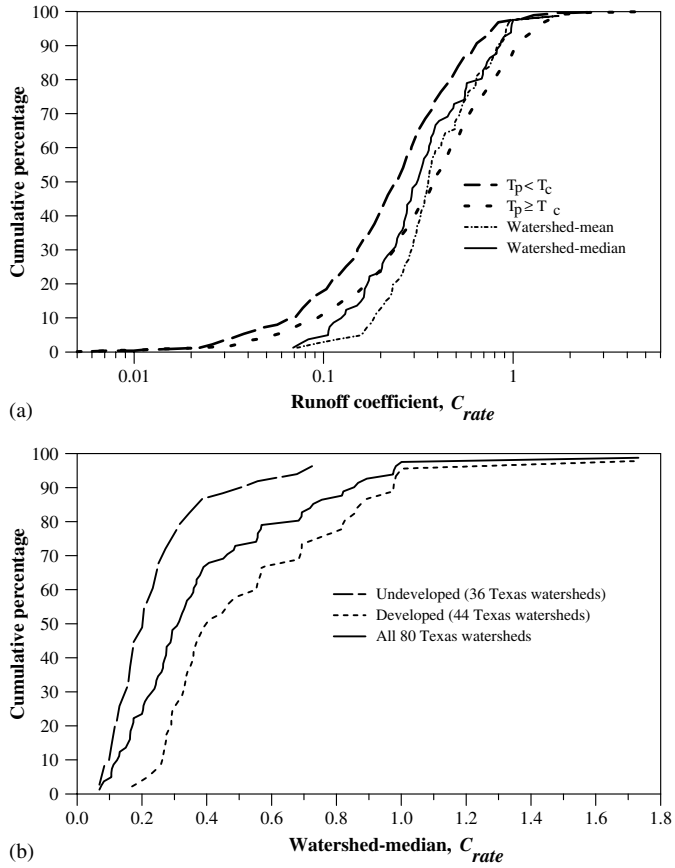

Fig. 3. Cumulative distributions of runoff coefficient (C_{rate} values): (a) for rainfall-runoff events when the time to peak (T_p) was less than the time of concentration (T_c), and for rainfall-runoff events when the time to peak (T_p) was greater than or equal to the time of concentration (T_c), the watershed-average (mean), and the watershed-median; (b) the watershed-median C_{rate} for developed and undeveloped Texas watersheds

Table 1. Statistical Summary of C_{rate} Calculated from Observed Rainfall-Runoff Event Data

Analysis	$T_p \geq T_c$[a]	$T_p < T_c$[b]	All events
Minimum	0.01	0.01	0.01
Maximum	4.48	2.68	4.48
25th percentile	0.21	0.13	0.17
Median	0.38	0.24	0.32
75th percentile	0.68	0.40	0.56
Mean	0.50	0.31	0.43
Standard deviation	0.42	0.27	0.39

[a]For 952 events.
[b]For 548 events.

are shown in Fig. 3; these distributional locations (means) are similar at a significance level of 0.01 (paired t-test; p-value = 0.04).

The amount of developed land in a watershed influences various runoff characteristics of a watershed. To study the relation between C_{rate} and the binary watershed development classification, statistical summaries of watershed median C_{rate} were computed (Table 3). The watershed median C_{rate} for developed watersheds ranged from 0.17 to 1.73, and for undeveloped watersheds, the watershed median C_{rate} ranged from 0.07 to 0.73. Of the developed watersheds, only two had a watershed-median $C_{rate} > 1$.

Table 2. Statistical Summary of Watershed-Median, Watershed-Mean, and Standard Deviation Values of C_{rate} for 80 Texas Watersheds

Analysis	Watershed-median C_{rate}	Watershed-mean C_{rate}	Standard deviation
Minimum	0.07	0.07	0.03
Maximum	1.73	1.79	0.87
25th percentile	0.20	0.27	0.16
Median	0.31	0.36	0.22
75th percentile	0.55	0.56	0.37
Mean	0.40	0.44	0.27
Standard deviation	0.29	0.27	0.15

Table 3. Statistical Summary of Watershed-Median C_{rate} for Developed and Undeveloped Watersheds

Analysis	Undeveloped[a]	Developed[b]
Minimum	0.07	0.17
Maximum	0.73	1.73
25th percentile	0.13	0.30
Median	0.20	0.40
75th percentile	0.28	0.71
Mean	0.24	0.53
Standard deviation	0.16	0.31

[a]For 36 undeveloped watersheds.
[b]For 44 developed watersheds.

The corresponding frequency distributions of the watershed-median C_{rate} for developed and undeveloped watersheds are shown in Fig. 3(b). The watershed-median value of C_{rate} for developed watersheds is 0.40; and for undeveloped watersheds, the watershed-median value of C_{rate} is 0.20 (Table 3). The C_{rate} values of the developed watersheds are significantly larger than those from the undeveloped watersheds (Fig. 3), as anticipated (Welch-Satterthwaite t-test; p-value <0.0001).

Runoff Coefficients from Frequency-Matching Approach

The frequency-matching approach assumes that return periods of rainfall and runoff events are the same (Hawkins 1993). Specifically, the T-year storm produces the T-year peak discharge. An alternative viewpoint is that the frequency-matching approach forces the largest rainfall intensity to produce the largest peak discharge within a given data set. The authors observed that this assumption is implicit in circumstances of practical application of the rational method. Many design engineers assume that the T-year storm produces the T-year discharge. Although not a physical requirement, this assumption generally is appropriate in small watersheds.

The maximum rainfall intensities and the observed peak discharges were independently ranked from largest to smallest for each of the 80 Texas watersheds. The frequency-matched C was computed from the rank-ordered pairs of the observed peak discharge and the maximum rainfall intensity for each storm event using

$$C_{rj} = \frac{Q_{pj}}{m_0 I_j A} \tag{4}$$

where C_{rj} = runoff coefficient corresponding to the maximum rainfall intensity I_j, the observed peak discharge Q_{pj} of the jth rank-order of I_{max}-Q_p data pairs, and drainage area A. A plot of runoff

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coefficients, C_{rj}, versus the maximum rainfall intensity was prepared for each watershed. For most of the watersheds, C_{rj} increases until it acquires an approximate constant value as judged by an analyst. This constant value is referred to as C_r. For example, the plot for USGS streamflow-gauging station 08042650 North Creek Surface Water Station 28A near Jermyn, Texas (hereinafter *North Creek near Jermyn*), is presented in Fig. 4(a); $C_r = 0.20$ for this watershed as indicated by the line in Fig. 4(a).

The C_r also can be estimated from the slope of the regression line obtained from the plots of the rank-ordered $Q_{pj}/(0.00278 * A)$ or Q_{pj^*} values versus the rank-ordered I_j. For example, the regression equation for North Creek near Jermyn is $Q_{pj^*}(\mathrm{m^3/s/ha}) = 0.19 * I_j(\mathrm{mm/h})$ [Fig. 4(b)]. The slope of the regression line in Fig. 4(b) is representative of C_r based on Eq. 4. Using the slope of the line, $C_r = 0.19$ for North Creek near Jermyn. For most of the 80 Texas watersheds, C_r values obtained using analyst judgment or the regression slope method have approximately the same value, and C_r values ranged from 0.10 to 1.2 (one outlying C_r value of 1.2 was the only C_r value greater than 1). The mean and medians for C_r were 0.42 and 0.37, respectively. A statistical summary of C_r is listed in Table 4.

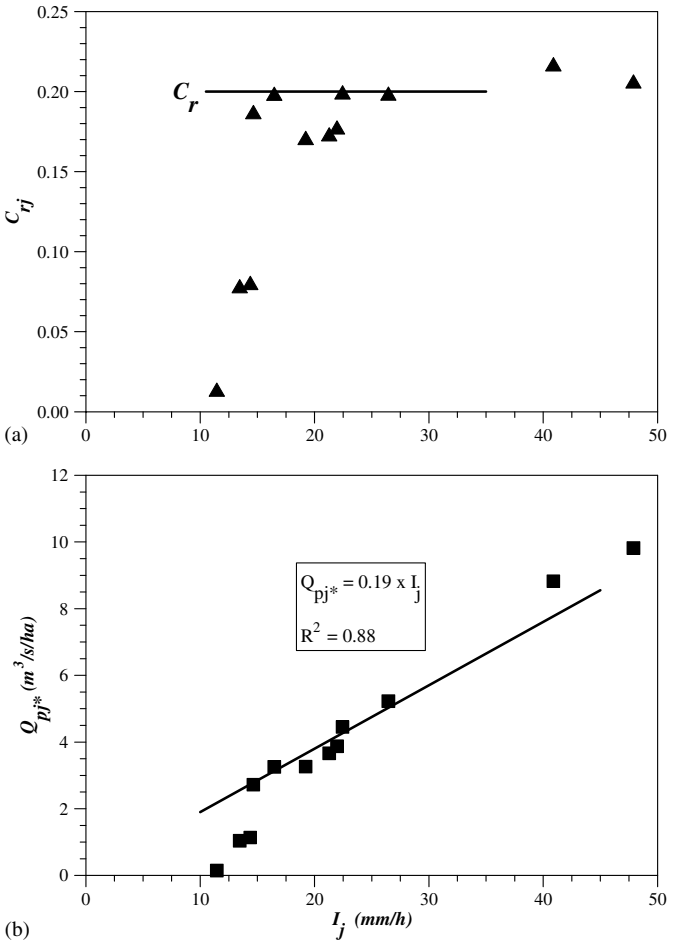

Fig. 4. (a) Runoff coefficient (C_r) values derived from the rank-ordered pairs (triangles) of observed peak discharge and maximum rainfall intensity (mm/h) during each storm event at versus the maximum rainfall intensity (I_j) USGS streamflow-gauging station 08042650 North Creek Surface Water Station 28A, near Jermyn, Texas; (b) the rank-ordered pairs (squares) of the observed peak discharge versus the maximum rainfall intensity for the same station

Table 4. Statistical Summary of C_r and Differences among C_r, C_{rate}, and C_{lit} for 80 Texas Watersheds

Analysis	C_r	$C_r - C_{\mathrm{rate}}$[a]	$C_r - C_{\mathrm{lit}}$	$C_{\mathrm{rate}} - C_{\mathrm{lit}}$[a]
Minimum	0.09	−0.53	−0.44	−0.46
Maximum	1.20	0.52	0.66	1.19
25th percentile	0.25	−0.02	−0.17	−0.24
Median	0.37	0.03	−0.11	−0.14
75th percentile	0.54	0.06	0.02	−0.01
Mean	0.42	0.02	−0.06	−0.07
Standard deviation	0.23	0.14	0.21	0.27

[a]Watershed-median C_{rate}.

Comparison of C_r to Watershed Median C_{rate} and Literature-Based C_{lit}

For the 80 Texas watersheds, the distributions of C_r and watershed median C_{rate} follow the same shape [Fig. 5(a)] and are not statistically different at the 0.05 significance level (paired t-test; p-value = 0.27). The difference between C_r and the watershed median C_{rate} for each watershed was calculated, and a statistical summary of the differences is listed in Table 4. The median value of $C_r - C_{\mathrm{rate}}$ is 0.03. The minimum and maximum differences are −0.53 and 0.52, respectively, and quartiles of the differences between C_r and the watershed-median C_{rate} are considered acceptably small (less than 0.06). About 74% of C_r and the watershed-median C_{rate} values differ by less than ±0.1.

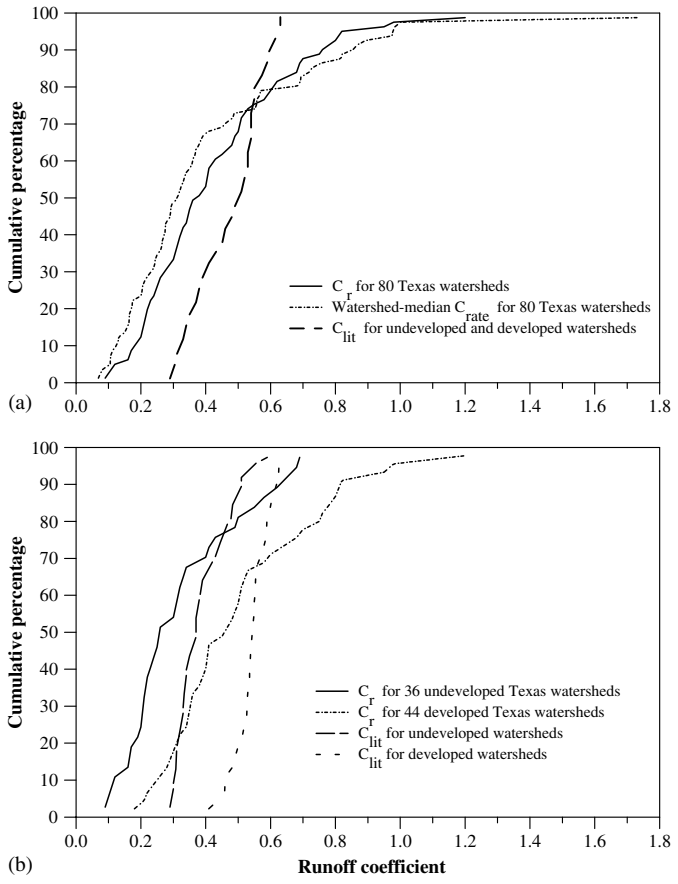

Fig. 5. Cumulative distributions of (a) C_r, watershed-median C_{rate} and C_{lit}; (b) distributions of C_r and C_{lit} for developed and undeveloped watersheds

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The frequency distributions of literature-based C_{lit} from land-use data (Dhakal et al. 2012) for developed and undeveloped watersheds are shown in Figs. 5(a and b). The differences between C_r and C_{lit} or between C_{rate} and C_{lit} are larger than the differences between C_r and C_{rate}. When the runoff coefficient is less than 0.55, C_{lit} is greater than C_r; otherwise, C_{lit} is smaller than C_r [Fig. 5(a)]. About 75% of C_{lit} values are greater than C_r [Fig. 5(a)]. For typical applications of the rational method in urban (developed) watersheds, using the typically smaller C_{lit} value for the watershed would underestimate Q_p for design purposes. The difference between watershed-median C_r and C_{lit} or between C_{rate} and C_{lit} for each watershed was calculated, and a statistical summary of the differences is listed in Table 4. The median (50th percentile) of $C_r - C_{lit}$ and $C_{rate} - C_{lit}$ are −0.11 and −0.14, respectively, compared to the smaller mean differences between C_r and C_{lit} and C_{rate} and C_{lit} (−0.06 or −0.07, respectively).

C_r and C_{lit} for Developed and Undeveloped Watersheds

C_r and C_{lit} were grouped into two categories of developed and undeveloped watersheds (Roussel et al. 2005). Statistical summaries of C_r and C_{lit} for developed and undeveloped watersheds are listed in Table 5; C_r and C_{lit} frequency distributions are shown in Fig. 5(b). The median value of C_r for undeveloped watersheds is 0.26, and the median value for the developed watershed is 0.45. These median values are similar to those for watershed-median C_{rate} (Table 3). The median and mean values of C_{lit} are larger than those of C_r for both developed and undeveloped watersheds (Table 5). About 68% and 78% of C_{lit} are larger than C_r for developed and undeveloped watersheds, respectively (Fig. 5).

C_r in Relation to Impervious Area

For this study, the percentage of impervious area for each watershed was computed using 1992 National Land Cover Data for Texas (Vogelmann et al. 2001). C_r for 45 Texas watersheds with *IMP* greater than 10% are plotted in Fig. 6. Schaake et al. (1967) developed the regression equation $C = 0.14 + 0.65IMP + 0.05S$ (referred to herein as the *Schaake et al. equation*) for urban drainage areas in Baltimore, Maryland, to relate C_r (for a return period of five years) to the relative imperviousness of the drainage area and channel slope of the watershed. C_r was calculated using the Schaake et al. equation for the 45 Texas watersheds with watershed imperviousness greater than 10%. For comparison purposes, with C_r values for 45 Texas watersheds with *IMP* greater than 10%, C_r values calculated using the Schaake et al. equation also are plotted

Table 5. Statistical Summary of C_r and C_{lit} for Developed and Undeveloped Watersheds

	C_r		C_{lit}	
Analysis	Undeveloped watersheds	Developed watersheds	Undeveloped watersheds	Developed watersheds
Minimum	0.09	0.18	0.29	0.37
Maximum	0.69	1.20	0.59	0.63
25th percentile	0.20	0.34	0.33	0.52
Median	0.26	0.45	0.37	0.54
75th percentile	0.42	0.62	0.44	0.58
Mean	0.32	0.50	0.39	0.54
Standard deviation	0.17	0.23	0.08	0.06

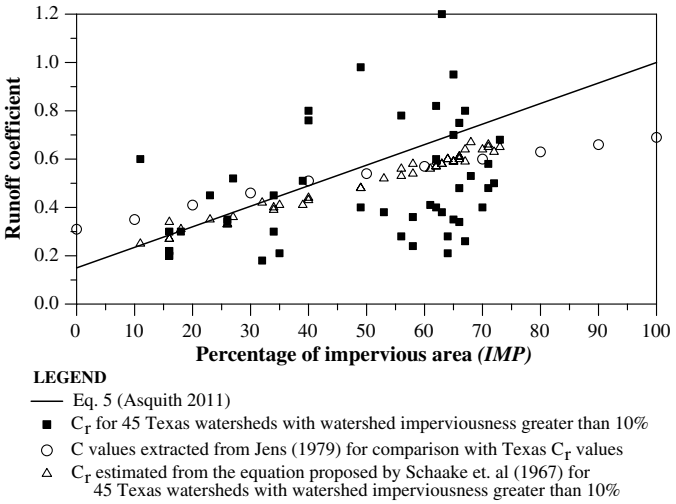

Fig. 6. Runoff coefficients versus the percentage of impervious area (*IMP*)

in Fig. 6, along with C values extracted from Jens (1979), and Eq. (5) from Asquith (2011).

The results of these three studies [this study, Schaake et al. (1967), and Jens (1979)] are consistent—the value of C increases with increasing *IMP*. Asquith (2011) proposes a single equation to estimate C for Texas watersheds as a function of *IMP*

$$C = 0.85IMP + 0.15 \tag{5}$$

This equation was used to estimate the runoff coefficient C^* (C-star) for the unified rational method (URAT) developed for a Texas Department of Transportation (TxDOT) research project summarized in Cleveland et al. (2011). Eq. (5), plotted in Fig. 6, is consistent with the general pattern of the data.

Several studies (Jens 1979; Pilgrim and Cordery 1993; Hotchkiss and Provaznik 1995; Titmarsh et al. 1995; Young et al. 2009) have demonstrated that C is highly dependent on the return period T. In this study, rate-based runoff coefficients were not derived for any return period because the observed data do not include all events that would constitute the complete annual series needed for the frequency analysis. Return-period-based $C(T)$ values were computed by the authors using regional regression equations for Q_p and I for the 36 undeveloped Texas watersheds in the database and presented as a separate paper (Dhakal et al. 2013).

Correlation between C and Watershed Area

To evaluate the C values for the 80 Texas watersheds, C_r and the watershed-median C_{rate} were used to estimate the peak discharge rates (Q_p) for each of about 1,500 rainfall-runoff events using the rational Eq. (1). The observed versus the modeled Q_p are shown in Fig. 7. The peak relative error (QB) between the observed and the modeled peak discharges was estimated to analyze the model results (Cleveland et al. 2006)

$$QB = \frac{P_i - O_i}{O_i} \tag{6}$$

where P_i are the modeled peak discharge values and O_i are the observed peak discharge values. Cleveland et al. (2006) suggested the following range of QB for the acceptance of model performance

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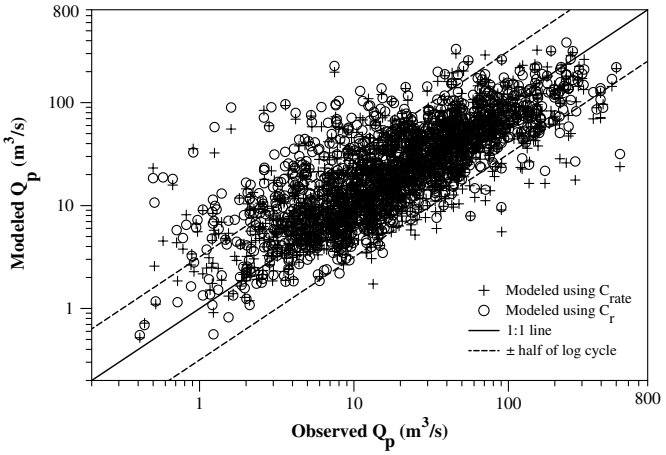

Fig. 7. Modeled peak discharges (Q_p) from rational Eq. (1) using C_r and watershed-median C_{rate} for about 1,500 rainfall-runoff events in 80 Texas watersheds against observed peak discharges

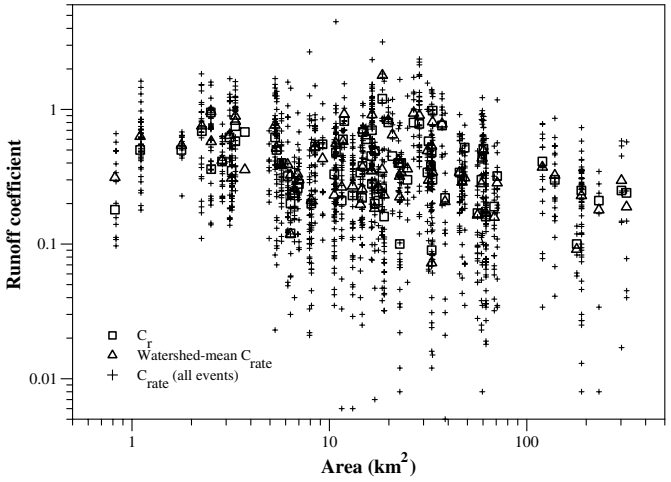

Fig. 8. Rate-based runoff coefficient C_{rate} for all events, watershed-mean C_{rate}, and C_r versus drainage area (km^2) in 80 Texas watersheds

$$-0.25 \le QB \le 0.25 \quad (7)$$

Median QB values derived using C_r and the watershed-median C_{rate} are 0.11 and 0.00, respectively. Similarly, the use of C_r and the use of the watershed-median C_{rate} resulted in about 56% and 59% of storms with QB less than ±50%, respectively. About 87% of the modeled Q_p values from both cases are within about half of a log cycle from the equal value line (Fig. 7). The differences between the observed and modeled Q_p are generally within about a third of a log cycle, which is an uncertainty similar to that reported for regional regression equations of peak discharge in Texas by Asquith and Roussel (2009).

The observation that about 87% of the modeled Q_p values from both cases are within about half of a log cycle from the equal value line supports the conclusion by ASCE and WPCF (1960), Pilgrim and Cordery (1993), and Young et al. (2009) that the rational method may be applied to much larger drainage areas than typically indicated (assumed) in some design manuals, so long as streamflows in the watershed are unregulated (Young et al. 2009). ASCE and WPCF (1960) state, "Although the basic principles of the rational method are applicable to large drainage areas, reported practice generally limits its use to urban areas of less than 5 square miles. Development of data for application of hydrograph methods is usually warranted on larger areas." Kuichling (1889, pp. 40–41) made a similar statement for application of the rational formula to large watershed areas.

C_{rate} for all events, the watershed-mean C_{rate}, and C_r versus watershed area (km^2) are displayed in Fig. 8. Of note in Fig. 8 is that the runoff coefficients are subject to substantial variability. That is, based on visual examination, there appears to be no relation between watershed drainage area and runoff coefficient. To apply a quantitative test, Pearson correlation coefficients between the watershed-mean C_{rate} and C_r and the watershed area are −0.27 and −0.26, with p-values of 0.012 and 0.018, respectively. Therefore, at the 95% confidence level ($n = 80$ observations), Pearson correlation coefficients between C_{rate} and C_r and the watershed area are statistically significant but correlations are weak (determination coefficient $r^2 \approx 0.07$) and C exhibits high variability (Fig. 8). Only about 7% of the variance is described by the correlation. Although statistically significant, the contribution of the correlation to the description of the variability of C_{rate} and C_r is not useful in an engineering context.

Of the 80 study watersheds, drainage area exceeds 40 km^2 for 17. The choice of 40 km^2 is completely arbitrary for the purposes of examining the runoff coefficient for relatively large watersheds. For this group of largest watersheds, the average values of the watershed-mean C_{rate} and C_r are 0.27 and 0.29, respectively. The standard deviations of the watershed-mean C_{rate} and C_r are 0.11 and 0.12, respectively. In comparison, the literature-based C_{lit} from land-use data (Dhakal et al. 2012) for these watersheds ranged from 0.30 to 0.55, with an average value of 0.42 and a standard deviation of 0.10. By inference, the literature-based C_{lit} might be too large (Fig. 5), so estimates derived from the application of C_{lit} to relatively large watersheds might lead to overly conservative estimates of discharge. Therefore, the literature-based C values [e.g., published by ASCE and WPCF (1960) and current textbooks and design manuals] should not be used for watersheds with large drainage areas.

Although published values for C are not appropriate for relatively large watersheds, the rational method can be applied if reasonable estimates of the runoff coefficient can be derived. One source would be observations of the runoff coefficient from hydrologically similar watersheds. Another would be derivation from observations of rainfall and runoff from the watershed of interest. The published limits [5 square miles, ASCE and WPCF (1960); 200 acres, TxDOT (2002)] on the maximum drainage area for application of the rational method seem to be arbitrary.

The authors do not advocate any specific limits that should be imposed on drainage area for application of the rational method. Therefore, it remains the responsibility of the end user to use appropriate engineering judgment when applying the rational method and the assumptions associated with the method, such as steady-state conditions.

Summary

The runoff coefficient, C, of the rational method is an expression of rate proportionality between rainfall intensity and peak discharge. Two methods were used to estimate C. Both methods used about 1,500 observed rainfall and runoff events data from 80 Texas watersheds to derive C. For the first method, the rate-based runoff coefficient, C_{rate}, was estimated for each rainfall-runoff event by the ratio of event peak discharge in a time series to the corresponding largest average rainfall intensity, I, in the same time series,

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averaged over the time window length. Time of concentration, T_c, was used as the time window length to estimate I. The T_c values estimated using the Kerby-Kirpich method were used for the 80 watersheds studied. The rate-based C depends on the rainfall intensity averaging time t_{av} used for the study, because based on Eq. (2), estimates of the runoff coefficient based on observed data cannot be decoupled from the selection of the time-response characteristics. Watershed-mean and watershed-median values of C_{rate} were derived. The distributions of the watershed-mean and watershed-median C_{rate} are similar. Finally, the C_{rate} values for the developed watersheds are consistently higher than those for undeveloped watersheds. For the second method, a frequency-matching approach similar to the procedure used by Schaake et al. (1967) was used to sort peak discharges and average rainfall intensities independently and then to compute the rate-based C from the rational formula. A constant runoff coefficient C_r for the watershed was derived from the plot of the rate-based C versus I. The C_r values for the developed watersheds are consistently greater than those for the undeveloped watersheds; about 74% of C_r and the watershed-median C_{rate} differ by less than ± 0.1 (Table 4). The values of C_r and C_{rate} were compared to the literature based runoff coefficients (C_{lit}) developed from land-use data for these study watersheds (Dhakal et al. 2012). About 75% of the C_{lit} values are greater than C_r (Fig. 5). For typical applications of the rational method in developed (urban) watersheds, watershed C_{lit} is less than C_r (Fig. 5); using smaller C_{lit} would underestimate Q_p for design purposes. An equation was proposed to estimate the rate-based C as a function of *IMP* for Texas watersheds, and predictions from the equation are consistent with the results from Schaake et al. (1967) and Jens (1979).

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Notation

The following symbols are used in this paper:

A = drainage area in hectares or acres;
C_{lit} = literature-based runoff coefficient developed from land-use data;
C_r = runoff coefficients from the frequency-matching approach;
C_{rate} = rate-based runoff coefficient;
C_{rj} = runoff coefficient estimated from the ratio of the jth rank-ordered peak discharge and the maximum rainfall intensity data pairs;
C_v = volumetric runoff coefficient;
C^* = runoff coefficients as a function of percentage of impervious area from Eq. (5);
I = average rainfall intensity (mm/h or in./h) with the duration equal to time of concentration;
I_j = the maximum rainfall intensity of the jth order;
I_w = average rainfall intensity from the entire rainfall event duration;
IMP = percentage of impervious area expressed as a decimal (50% = 0.5) for a watershed area;
j = jth term in the sequence of ordered peak discharge and the maximum rainfall intensity data pairs;
L_c = channel length in km;
m_o = the dimensional correction factor ($1/360 = 0.00278$ in SI units; 1.008 in English units);
O_i = observed peak discharge for computing *QB*;
P_i = modeled peak discharge for computing *QB*;
Q_p = peak discharge in m^3/s or ft^3/s;
Q_{pj} = peak discharge of the jth rank-order of maximum rainfall intensity and peak discharge data pairs in m^3/s;
Q_{pj^*} = Q_{pj} divided by 0.0028 times the drainage area in $m^3/s/h$;
QB = peak relative error between the observed and simulated peak discharges;
S_c = channel slope in m/m;
T_c = time of concentration;
T_p = time to peak;
t_{av} = rainfall intensity averaging time period; and
t_w = rainfall event duration.

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