Return Period Adjustment for Runoff Coefficients Based on Analysis in Undeveloped Texas Watersheds

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Abstract: The rational method for peak discharge (Q_p) estimation was introduced in the 1880s. The runoff coefficient (C) is a key parameter for the rational method that has an implicit meaning of rate proportionality, and the C has been declared a function of the annual return period by various researchers. Rate-based runoff coefficients as a function of the return period, $C(T)$, were determined for 36 undeveloped watersheds in Texas using peak discharge frequency from previously published regional regression equations and rainfall intensity frequency for return periods T of 2, 5, 10, 25, 50, and 100 years. The $C(T)$ values and return period adjustments $C(T)/C(T=10\text{ year})$ determined in this study are most applicable to undeveloped watersheds. The return period adjustments determined for the Texas watersheds in this study and those extracted from prior studies of non-Texas data exceed values from well-known literature such as design manuals and textbooks. Most importantly, the return period adjustments exceed values currently recognized in Texas Department of Transportation design guidance when $T > 10$ years. **DOI: 10.1061/(ASCE)IR.1943-4774.0000571.** *© 2013 American Society of Civil Engineers.*

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Introduction

The rational method, which was introduced by Kuichling (1889), is typically used to compute the peak discharge, Q_p (in m^3/s in SI units or ft^3/s in English units) for the design of drainage structures. The equation for the method is

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

where C = runoff coefficient (dimensionless); I = rainfall intensity (mm/h or in./h) over a critical period of storm time (typically taken or conceptualized as the time of concentration, T_c, of the watershed); A = drainage area (hectares or acres); and m_o = dimensional correction factor ($1/360 = 0.00278$ in SI units or 1.008 in English units). From inspection of Eq. (1), it is evident that C is an expression of rate proportionality between I and Q_p, i.e., a rate-based runoff coefficient (Dhakal et al. 2013).

Typical whole watershed C values (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 many textbooks and design manuals [e.g., hydraulic design manual of the Texas Department of Transportation (TxDOT)]. 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 the 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 observed rainfall and runoff data for the selected C_{lit} values was provided in the ASCE and WPCF (1960) manual.

A substantial and community-recognized criticism of the rational method arises because observed C values vary from storm to storm (Schaake et al. 1967; Pilgrim and Cordery 1993). The ASCE and WPCF (1960) manual (p. 49), in describing tabulations of C, states that "[t]he coefficients on these two tabulations [of C values] are applicable for storms having 5- to 10-year return periods [0.2 to 0.1 annual exceedance probabilities]. Less frequent, higher intensity storms will require the use of higher coefficients because infiltration and other losses have a proportionately smaller effect on runoff." A logical extension of these observations is that return period adjustments for C values of the rational method are useful for practical circumstances.

Schaake et al. (1967) found that the average percentage increase of the coefficient for the 10-year return period $C(10)$ was only 10%, compared to the coefficient for the 1-year return period $C(1)$, and they proposed adoption of a single value of C for design applications. The C has been considered a function of annual return period by various researchers (Jens 1979; Pilgrim and Cordery 1993; Hotchkiss and Provaznik 1995; Titmarsh et al. 1995; Young et al. 2009). Considering C as a function of the return period T (Jens 1979; Pilgrim and Cordery 1993), the rational formula can be expressed as

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$$Q(T) = m_o C(T) I(T) A = m_o C_{\mathrm{lit}} C_f(T) I(T) A \qquad (2)$$

where $Q(T)$ = peak discharge (m^3/s or ft^3/s); $C(T) = C$ as function of return period T that is measured in years; $I(T)$ = rainfall intensity (mm/h or in./h) as function of T; C_{lit} = literature-based C; and $C_f(T)$ = frequency factor or multiplier as function of return period T (the return period adjustment) [Denver Regional Council of Governments (DRCG) 1969; Jens 1979). Eq. (2) implies a conversion of $I(T)$ to $Q(T)$ where T denotes the same return period for both I and Q. Thus, an assumption of probability equivalence is implicitly expressed in the rational method. Eq. (2) also represents the probabilistic interpretation of the rational formula commonly used in design practices (French et al. 1974; Pilgrim and Cordery 1993).

Relatively few studies have been done to determine rational C values using frequency-based analysis of data (Young et al. 2009). Schaake et al. (1967) examined the rational method using experimental rainfall and runoff data collected from 20 small urban watersheds with drainage areas less than 0.6 km^2 (0.23 mi^2) in Baltimore, Maryland. Schaake et al. (1967) used watershed lag time (the time from the center of mass of excess rainfall to the hydrograph peak) to compute average rainfall intensity and used a frequency-matching approach to compute rate-based C values. Hotchkiss and Provaznik (1995) estimated C for 24 rural watersheds in south-central Nebraska using event-paired and frequency-matched data. Young et al. (2009) estimated the C of different return periods for 72 rural watersheds in Kansas with drainage areas less than 78 km^2 (30 mi^2). The peak discharge $Q(T)$ for each T was estimated using annual peak frequency analysis of observed streamflow records and rainfall intensity obtained from rainfall intensity-duration-frequency tables (Young et al. 2009).

$C(T)$ values considered in this study were not computed from statistical analysis of observed pairings of rainfall and runoff data; instead, the $C(T)$ values for 36 undeveloped Texas watersheds were computed using Q_p and I values from previous publications. The Q_p values were computed from regional regression equations (Asquith and Slade 1997), and the I values were computed from an empirical equation with county-specific coefficients (TxDOT 2002) for respective counties of the same 36 undeveloped Texas watersheds. A return period of 10 years ($T = 10$) was used as a base value to compute frequency factors as $C_f(T) = C(T)/C(10)$ where all terms are as previously defined. Using a 10-year return period as a base value to compute frequency factors $C_f(T)$ is consistent with the literature (French et al. 1974; Pilgrim and Cordery 1993; Young et al. 2009). Results of $C(T)$ and frequency factors $C_f(T)$ were analyzed and compared with results from previous studies.

Study Watersheds

The 36 watersheds in Texas considered here have been previously considered by the authors (Asquith et al. 2004). The 36 watersheds consist of 20 rural watersheds and 16 suburban watersheds in or near one of four Texas cities (Austin, Dallas, Fort Worth, or San Antonio). Locations and geographic distribution of the streamflow-gauging stations associated with these watersheds are shown in Fig. 1.

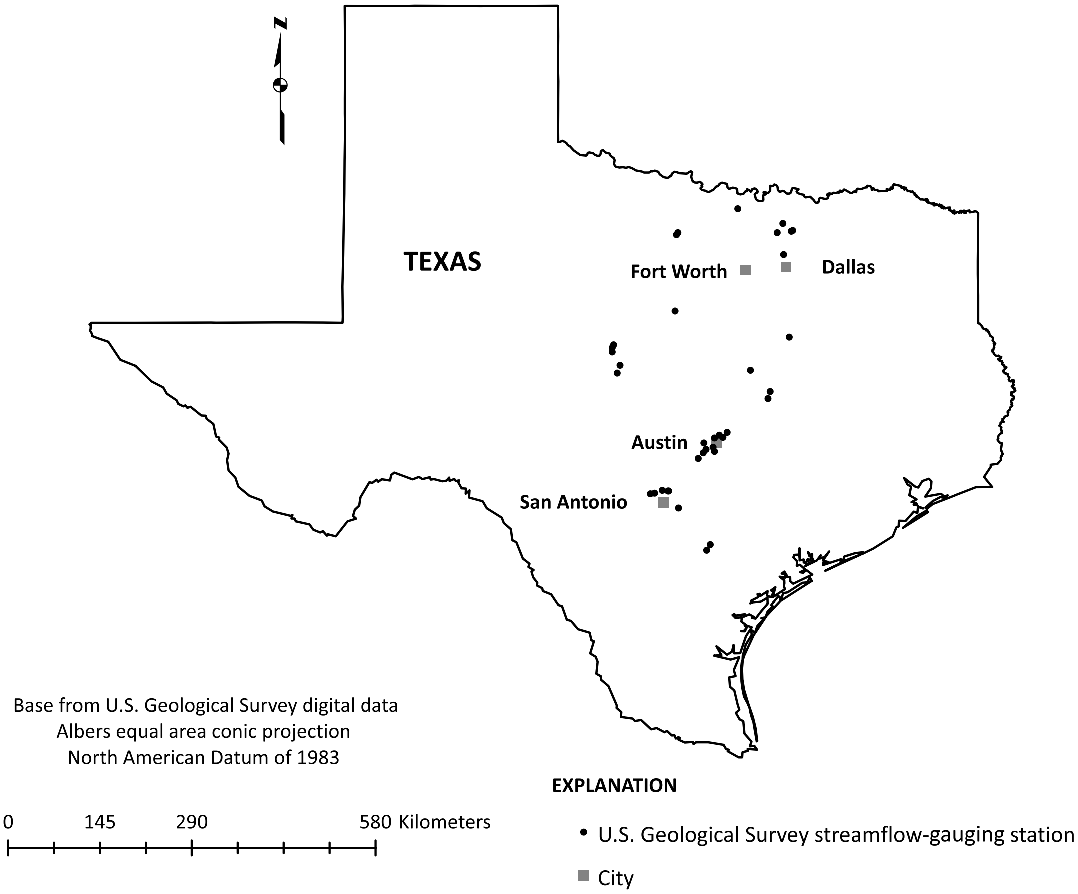

Fig. 1. Locations of USGS streamflow-gauging stations in Texas associated with 36 undeveloped watersheds considered for this study (some stations overplot)

All of the Texas watersheds considered in this study were previously classified as undeveloped (Asquith et al. 2004) as part of a binary classification scheme that characterized watersheds throughout the state as developed or undeveloped. The classification scheme of developed and undeveloped watersheds accommodates 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 was purposeful and reflects the uncertainty in precise watershed development conditions for the time period of available data (Asquith and Roussel 2007). This same binary classification was successfully used to prepare regression equations to estimate the shape parameter and the time to peak for regional analysis of unit hydrographs for Texas watersheds (Asquith et al. 2006). Based on 1992 National Land Cover Data (NLCD) (Vogelmann et al. 2001), the primary land uses of these watersheds are forest, shrubland, grassland, and cultivated cropland.

The drainage area of study watersheds range from approximately 2.3 to 320 km^2 (0.9 to 123.6 mi^2); the median and mean values are 20.7 km^2 (8 mi^2) and 56.7 km^2 (21.9 mi^2), respectively. The stream slopes of study watersheds range from approximately 0.0022 to 0.0196 dimensionless; the median and mean values are both 0.0089.

Many practitioners would argue that the application of the rational method is not appropriate for the range of watershed areas presented in this study. ASCE and WPCF (1960) 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." (ASCE and WPCF 1960, page 32). Pilgrim and Cordery (1993) stated that the rational method is one of the three methods widely used to estimate peak flows for small- to medium-sized basins. According to Pilgrim and Cordery, "[i]t 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." (Pilgrim and Cordery 1993, page 9.14) Young et al. (2009) stated that the rational method may be applied to much larger drainage areas than typically assumed in some design manuals, provided that the watershed is unregulated. Thompson (2006) stated that watershed drainage area does not appear to be an applicable factor for discriminating among appropriate hydrologic technologies (such as the rational method, regional regression equations, and site-specific flood frequency relations), and other methods for discrimination between procedures for making design-discharge estimates should be investigated.

A geospatial database of properties was previously developed by Roussel et al. (2005) for the 36 watersheds. For this paper, basin-shape factor, main channel length, and channel slope from the database were used to estimate time of concentration T_c, which is equal to travel time for overland flow determined by using the Kerby (1959) method, plus travel time for channel flow determined by using the Kirpich (1940) method. This combination of methods to compute T_c is discussed by Roussel et al. (2005) and Fang et al. (2008). The Kirpich equation (1940) was developed from the Natural Resources Conservation Service (NRCS) data for rural watersheds with drainage areas less than about 0.45 km^2 (0.17 mi^2). For their studies of watersheds in Texas with drainage areas as large as 440 km^2 (170 mi^2), Fang et al. (2007) and Fang et al. (2008) demonstrated that the Kirpich equation provides reliable estimates of T_c. Furthermore, these researchers determined that their estimates of T_c are consistent with those from other empirical equations developed for large watersheds as well as with estimates using the NRCS velocity method (Viessman and Lewis 2003). The T_c estimated using the Kirpich equation reasonably approximates the average T_c estimated from observed rainfall and runoff data (Fang et al. 2007).

Runoff Coefficients for Different Return Periods

The rate-based $C(T)$ values for the 36 undeveloped watersheds in Texas and corresponding frequency factors were determined for various return periods using Eq. (3) (Pilgrim and Cordery 1993)

$$C(T) = \frac{Q(T)}{m_0 I(T_c, T) A} \tag{3}$$

where $C(T)$ = runoff coefficient (dimensionless); $Q(T)$ = peak discharge; and $I(T_c, T)$ = rainfall intensity for time of concentration T_c and return period T. In this study, $Q(T)$ values for each of the 36 undeveloped Texas watersheds were estimated by regional regression equations for Texas (Asquith and Slade 1997). The equations are based on contributing drainage area, main channel slope, and other watershed characteristics. The $I(T_c, T)$ values were estimated using Texas county-specific empirical coefficients from tables to estimate $I(T)$ from the TxDOT (2002). Specific details follow.

The T_c for each watershed in Texas was determined using the Kerby-Kirpich equation (Roussel et al. 2005; Fang et al. 2008). Considering the respective county in Texas in which each watershed is located, the rainfall intensity, $I(T_c, T)$, for each return period was estimated using rainfall intensity-duration-frequency (IDF) relations (TxDOT 2002) with duration T_c:

$$I(T_c, T) = \frac{e}{(T_c + f)^g} \tag{4}$$

where $I(T_c, T)$ is from a TxDOT design manual (TxDOT 2002); and e, f, and g = coefficients for specific frequencies and Texas counties (TxDOT 2002).

By using $Q(T)$ from Asquith and Slade (1997) and Eq. (3), $C(T)$ for each watershed and for each return period of T = 2, 5, 10, 25, 50, and 100 years was computed. The $C(T)$ versus T for three undeveloped Texas watersheds are presented as illustrative examples in Fig. 2. For these three watersheds, $C(T)$ increases with increasing T. The value of $C(100)$ is 0.6 for USGS streamflow-gauging station 08139000 Deep Creek subwatershed number 3 (Sub. 3) near Placid, Texas, 1.05 for USGS station 08178645 East Elm Creek at San Antonio, Texas, and 1.3 for USGS station 08187000 Escondido Creek subwatershed number 1 (Sub. 1) near Kenedy, Texas. The occurrence of $C(T) > 1$ is inherently related to general uncertainties of $Q(T)$ and $I(T_c, T)$ as well as to the assumption of frequency equivalence between rainfall intensity and peak discharge.

Several studies (French et al. 1974; Pilgrim and Cordery 1993; Young et al. 2009) have shown that values of $C(T) > 1$ (unity) are possible when rate-based C was determined from observed peak discharge and rainfall intensity. Analysis of observed rainfall and runoff data in 90 Texas watersheds has shown that only the volumetric runoff coefficient, C_v, as the ratio of total runoff depth to total rainfall depth, is <1 for all storm events (Dhakal et al. 2012).

Statistical summaries of $C(T)$ for 36 undeveloped watersheds are listed in Table 1, and corresponding boxplots of the distribution are shown in Fig. 3. The median values of $C(T)$, as well as the curves shown in Fig. 2, show that $C(T)$ increases with the increasing return period for undeveloped watersheds in Texas. Ratios of $C(T)/C(10)$ or frequency factors $C_f(T)$ are derived for the Texas

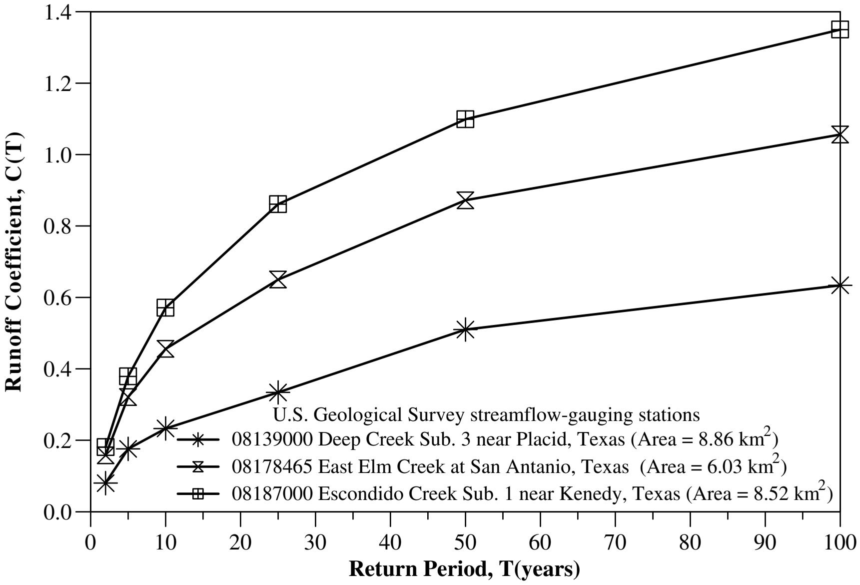

Fig. 2. Relation between runoff coefficient $C(T)$ and T-year return periods for three undeveloped Texas watersheds identified by USGS streamflow-gauging station associated with each watershed

Table 1. Statistical Summary of Rational Method Runoff Coefficient $C(T)$ for T-year Return Periods for 36 Undeveloped Watersheds in Texas

	Return periods (years)					
Statistical parameters	2	5	10	25	50	100
Minimum	0.08	0.14	0.18	0.24	0.30	0.34
Maximum	0.39	0.64	0.77	0.97	1.14	1.44
25th percentile	0.12	0.29	0.39	0.48	0.50	0.55
Median	0.15	0.32	0.43	0.62	0.77	0.94
75th percentile	0.22	0.37	0.50	0.70	0.91	1.12
Mean	0.18	0.33	0.44	0.59	0.73	0.86
Standard deviation	0.075	0.091	0.110	0.163	0.238	0.319

watersheds, and statistical summaries of the ratios are listed in Table 2; the mean and median values are of special importance for representation of frequency.

Discussion

Comparing $C(T)$ and $C_f(T)$ for Texas Watersheds with Other Studies

Young et al. (2009) estimated median $C(T)$ from observed data for 72 rural watersheds in Kansas, and these values are shown in Fig. 3

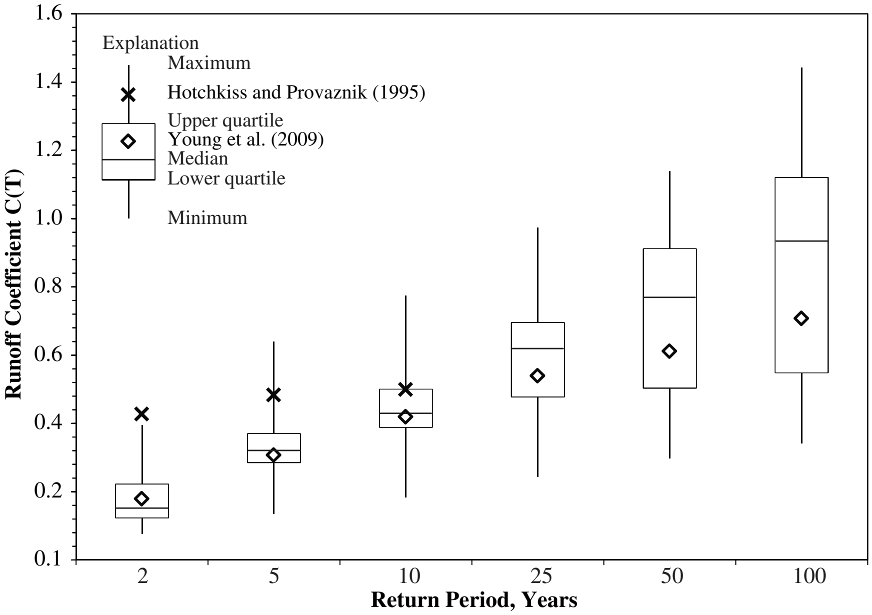

Fig. 3. Boxplots depicting distribution of runoff coefficient $C(T)$ for different T-year return periods for 36 undeveloped watersheds in Texas, with mean $C(T)$ values from observed data for 24 rural watersheds in south-central Nebraska (data from Hotchkiss and Provaznik 1995) and estimated median $C(T)$ values from observed data for 72 rural watersheds in Kansas (data from Young et al. 2009)

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Table 2. Statistical Summary of Frequency Factor $C(T)/C(10)$ or Return Period Adjustment for 36 Undeveloped Watersheds in Texas

Statistical parameters	$C(2)/C(10)$	$C(5)/C(10)$	$C(25)/C(10)$	$C(50)/C(10)$	$C(100)/C(10)$
Minimum	0.25	0.63	1.10	1.14	1.16
Maximum	0.69	0.89	1.55	2.45	3.14
25th percentile	0.30	0.68	1.23	1.34	1.47
Median	0.35	0.72	1.42	1.66	1.93
75th percentile	0.51	0.85	1.49	2.06	2.54
Mean	0.41	0.75	1.36	1.68	1.98
Standard deviation	0.14	0.09	0.14	0.39	0.578

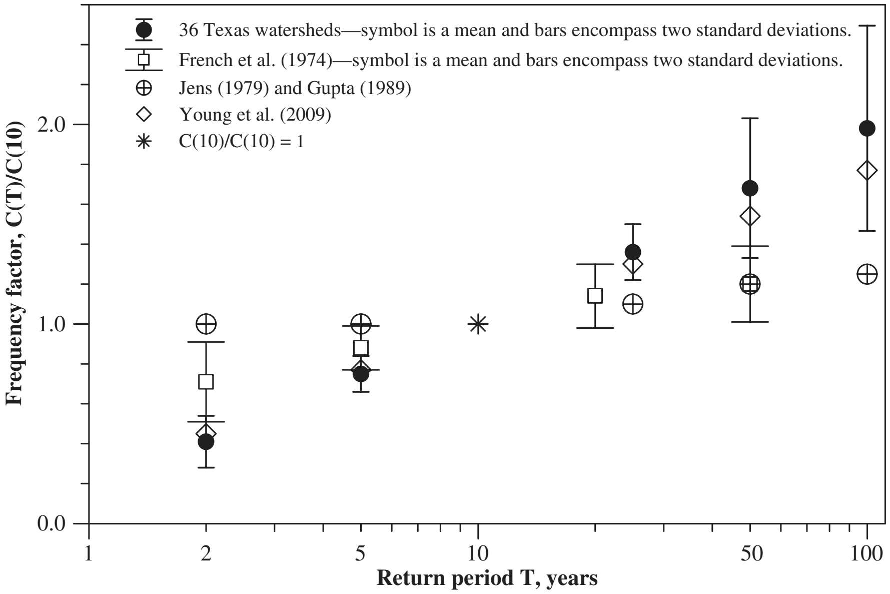

Fig. 4. Relation between frequency factors $C(T)/C(10)$ and T-year return periods for 36 undeveloped watersheds in Texas, with relations between frequency factors and return periods for: 37 rural watersheds in New South Wales, Australia (French et al. 1974); Denver watersheds (data from DRGC 1969; Jens 1979; later published in textbooks such as Gupta 1989; Viessman and Lewis 2003, and in design manuals such as TxDOT 2002); and 72 rural watersheds in Kansas (data from Young et al. 2009)

for comparison. The results of $C(T)$ for Texas watersheds reported in Table 1 and Fig. 3 are consistent with results reported by Young et al. (2009). The mean values of $C(T)$ derived from observed data for 24 rural watersheds in south-central Nebraska (Hotchkiss and Provaznik 1995) are shown in Fig. 3. Literature-based C values for the Nebraska watersheds are 0.35 for $T < 10$ years (Hotchkiss and Provaznik 1995). The mean $C(T)$ values reported by Hotchkiss and Provaznik (1995) for the Nebraska watersheds are larger than not only median $C(T)$ values determined for the Texas and Kansas watersheds but are also larger than C_{lit} values. French et al. (1974) depicted $C(10)$ values in New South Wales, Australia, for 37 rural watersheds with drainage area up to 250 km^2 (96 mi^2).

Along with the results for the 36 Texas watersheds considered here, Fig. 4 depicts the relations between frequency factors and return periods (1) from French et al. (1974), (2) for Denver watersheds (DRGC 1969; Jens 1979) and later published in textbooks such as Gupta (1989), Viessman and Lewis (2003), and in design manuals such as TxDOT (2002), and (3) from Young et al. (2009). The frequency factors $C_f(T)$ determined by French et al. (1974) and by Young et al. (2009) exceed the textbook values from Gupta (1989) and Viessman and Lewis (2003) and exceed TxDOT (2002) values when $T > 10$ years. The Texas frequency factors $C_f(T)$ are similar to those determined for Kansas watersheds by Young et al. (2009). Lastly, the Texas frequency factors $C_f(T)$ are larger than those from watersheds in New South Wales, Australia (French et al. 1974) for $T > 10$ years and are smaller for $T < 10$ years.

The frequency factors $C_f(T)$ specified for Denver watersheds (DRCG 1969; Jens 1979) and later published in other textbooks (e.g., Gupta 1989; Viessman and Lewis 2003) and design manuals (e.g., TxDOT 2002) are listed in Table 3. Typically, a frequency factor $C_f(T)$ of 1.0 is used when $T < 10$ years (Table 3). The frequency factors $C_f(T)$ extracted from the Federal Highway

Table 3. Frequency Factors or Return Period Adjustments Suggested for Multiplication on Literature-Based Rational Method Runoff Coefficient C from Different Sources

	Frequency factor $C_f(T)$, $C(T)/C(10)$ or return period adjustment				
Return period, T (years)	Design manuals and textbooks[a]	0% IMP[b]	65% IMP[b]	Young et al. (2009)	Undeveloped Texas watersheds
2	1.0	0.48	0.69	0.45	0.41
5	1.0	0.77	0.87	0.77	0.75
10	1	1	1	1	1
25	1.1	1.22	1.15	1.30	1.36
50	1.2	1.40	1.22	1.54	1.68
100	1.25	1.60	1.30	1.77	1.98

[a] $C_f(T)$ from the Denver material (DRCG 1969; Jens 1979) and later published in other textbooks (e.g., Gupta 1989; Viessman and Lewis 2003) and design manuals (e.g., TxDOT 2002).

[b] From Jens (1979).

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Administration (FHWA) curve (Jens 1979) for percent impervious (IMP) area equal to 0% and 65% and from the study by French et al. (1974) and Young et al. (2009) are listed in Table 3 for comparison. Of special note is the observation that the Texas frequency factors, $C(2)/C(10)$ and $C(5)/C(10)$, as well as those from French et al. (1974) and Young et al. (2009), are less than 1.0 (Tables 2 and 3) but are equal to 1.0 in ASCE and WPCF (1960) [and subsequently presented by Gupta (1989); Viessman and Lewis (2003); and TxDOT (2002)]. This means that the $C(T)$ for $T < 10$ year (more frequent storms) of Texas, Kansas, and Australia is less than C_{lit} commonly recommended in the literature. The frequency factors $C_f(T)$ were extracted from the FHWA curve (Jens 1979) for percent impervious areas of 65% because they are approximately the same as frequency factors $C_f(T)$ values presented in design manuals [e.g., TxDOT (2002)] and textbooks (Gupta 1989; Viessman and Lewis 2003). The frequency factors $C_f(T)$ presented in design manuals and textbooks are seemingly more appropriate for urban watersheds with a relatively large percentage of impervious area.

The larger frequency factors $C_f(T)$ determined for Texas watersheds and those determined for Kansas watersheds (Young et al. 2009) are for undeveloped watersheds with impervious cover less than a few percent. The larger frequency factors $C_f(T)$ of Texas are similar to frequency factors $C_f(T)$ extracted from the FHWA curve (Jens 1979) for 0% impervious areas (Table 3). These larger $C_f(T)$ values from Jens (1979) were originally proposed by Bernard (1938). The frequency factors $C_f(T)$ from the FHWA curve (Jens 1979) for 100% impervious area is approximately 1.1 for T of 25, 50, and 100 years. If it is assumed that $C = 1$ for 100% impervious areas, then frequency factors $C_f(T)$ should be 1.0 for 100% impervious area for any T. Therefore, variable frequency factors $C_f(T)$ as a function of percent of impervious area (Jens 1979) are a reasonable conjecture and supported by Young et al. (2009) as well as by this study for undeveloped Texas watersheds. When frequency factors $C_f(T)$ are applied, and if any resulting $C(T)$ values are >1, Jens (1979), Gupta (1989), and TxDOT (2002) indicated that $C(T)$ should be set equal to 1. Such a truncation is generally consistent with fundamental interpretation of the rational method.

C for 100-year Return Period

In an adaptation of the rational method, Bernard (1938) proposed that C varied in a functional manner with the T-year return period when related to the maximum or limiting C values (called $C_{\max}$)

$$C = C_{\max}(T/100)^x \tag{5}$$

where x = exponent and ranges from 0.15 to 0.23 for undeveloped watersheds (Bernard 1938). Bernard (1938) assumed the $C_{\max}$ value corresponds to $C(100)$. In relation to Eq. (5), Jens (1979) proposed $C_{\max} = C(100) = 1.0$ for watersheds with any percentage of impervious area for application of Eq. (5) for the FHWA manual (Jens 1979). $C(100)$ for the 36 Texas watersheds ranges from 0.34 to 1.44 with mean and median values of 0.86 and 0.94 (Table 1). $C(100)$ values for three Texas watersheds also are presented as illustrative examples shown in Fig. 2. Stubchaer (1975) applied the calibrated Santa Barbara Unit Hydrograph (SBUH) method on a 157-hectare urban watershed and developed $C(T)$ using the frequency analysis of rainfall and simulated runoff from the SBUH. The $C(100)$ value determined for the watershed is 0.65 (Stubchaer 1975). The $C(100)$ values for watersheds with different percentages of impervious cover from the DRCG manual (DRCG 1969) range from 0.20 to 0.96, and from Chow et al. (1988), they range from 0.36 to 0.97; $C(100)$ values are consistently < 1.

Summary

The runoff coefficients $C(T)$ for different annual return periods (T) were developed through the rational method for 36 undeveloped Texas watersheds using previously published regional regression equations of peak discharge for different values for T and selected watershed characteristics and an empirical equation for rainfall intensity in each watershed using previously published county-specific coefficients for different values of T. The return period adjustments [frequency factor $C_f(T) = C(T)/C(10)$] determined for 36 Texas watersheds in this study and those extracted from prior studies of non-Texas watersheds exceed values from well-known literature such as design manuals and textbooks. Most importantly, the return period adjustments reported herein exceed values currently recognized in TxDOT design guidance when $T > 10$ years. The relations between return period adjustments determined for Texas watersheds and return period adjustments from the literature are shown in Fig. 4. The frequency factors $C(2)/C(10)$ and $C(5)/C(10)$ for the Texas watersheds (Table 2) as well as from French et al. (1974) and Young et al. (2009) are not equal to 1 as assumed in ASCE and WPCF (1960) and published by Gupta (1989) and Viessman and Lewis (2003) and in a commonly used design manual (TxDOT 2002) (Table 3 and Fig. 4) but rather are <1.

The frequency factors determined for the 36 Texas watersheds and the 72 Kansas watersheds (Young et al. 2009), which are larger than those mostly found in the literature, are for undeveloped watersheds with relatively small percent impervious areas. The frequency factors found in the literature are generally smaller than those determined for the 36 Texas watersheds. The frequency factors from the literature are appropriate for urban watersheds with relatively large percentages of impervious area (DRCG 1969; Stubchaer 1975; Jens 1979; Gupta 1989; Viessman and Lewis 2003; TxDOT 2002). Such frequency factors are consistent with those proposed by Jens (1979). When the Texas frequency factors are applied, if any resulting $C(T)$ values are greater than unity, Jens (1979), Gupta (1989), and TxDOT (2002) indicated that each of those $C(T)$ values should be equal to 1. Such a truncation is generally consistent with fundamental interpretation of the rational method.

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Notation

The following symbols are used in this paper:

A = watershed area in hectares or acres;
$C_f(T) = C(T)/C(10)$, = frequency factor or return period adjustment for return period T;
$C_{\max}$ = maximum runoff coefficient for return period 100 years;
$C(T)$ = rate-based runoff coefficient for return period T;
C_v = volumetric runoff coefficient as ratio of total runoff depth and total rainfall depth;
I = average rainfall intensity (mm/h or in./h) with duration equal to time of concentration;
m_o = dimensional correction factor (1.008 in English units, $1/360 = 0.00278$ in SI units);
Q_p = peak runoff rate in m^3/s or ft^3/s;

$Q(T)$ = peak discharge for return period T;
Q_T = regional regression equation for natural basins developed for TxDOT;
T = annual return period in years; and
T_c = time of concentration.

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