Estimation of Volumetric Runoff Coefficients for Texas Watersheds Using Land-Use and Rainfall-Runoff Data

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Abstract: The rational method for peak discharge (Q_p) estimation was introduced in the 1880s. Although the rational method is considered simplistic, it remains an effective method for estimating peak discharge for small watersheds. The runoff coefficient (C) is a key parameter for the rational method and can be estimated in various ways. Literature-based C values (C_{lit}) are listed for different land-use/land cover (two words, no hyphen) (LULC) conditions in various design manuals and textbooks; however, these C_{lit} values were developed with little basis on observed rainfall and runoff data. In this paper, C_{lit} values were derived for 90 watersheds in Texas by using LULC data for 1992 and 2001; the C_{lit} values derived from the two data sets were essentially the same. Also for this study, volumetric runoff coefficients (C_v) were estimated by using observed rainfall and runoff depths from more than 1,600 events observed in the watersheds. Watershed-median and watershed-average C_v values were computed, and both are consistent with data from the National Urban Runoff Program. In addition, C_v values were estimated by using rank-ordered pairs of rainfall and runoff depths (i.e., frequency matching). As anticipated, C values derived by all three methods (literature based, event totals, and frequency matching) consistently had larger values for developed watersheds than for undeveloped watersheds. Two regression equations of C_v versus percent impervious area were developed and combined into a single equation that can be used to rapidly estimate C_v values for similar Texas watersheds. **DOI: 10.1061/(ASCE)IR.1943-4774.0000368.** *© 2012 American Society of Civil Engineers.*

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Introduction

Estimation of peak discharge and runoff values for use in designing certain hydraulic structures (e.g., crossroad culverts, drainage ditches, urban storm drainage systems, and highway bridge crossings) is an important and challenging aspect of engineering hydrology (Viessman and Lewis 2003). Various methods are available to estimate peak discharges and runoff volumes from urban watersheds (Chow et al. 1988). The rational method is commonly used by hydraulic and drainage engineers to estimate design discharges, which are used to size a variety of drainage structures for small urban (developed) and rural (undeveloped) watersheds (Viessman and Lewis 2003). The rational method was developed in the United States by Emil Kuichling (1889) and introduced to Great Britain by Lloyd-Davies (1906). The peak discharge (Q_p in m^3/s in SI units or ft^3/s in English units) for the method is computed as follows:

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

where C = is the runoff coefficient (dimensionless); I = average rainfall intensity (in mm/hr or in./hr) for a storm with a duration equal to a critical period (typically assumed to be the time of concentration); A = drainage area (in hectares or acres); and m_o is a dimensional correction factor ($1/360 = 0.00278$ in SI units, 1.008 in English units).

The precise definition and subsequent interpretation of C varies. The C of a watershed can be defined either as the ratio of total depth of runoff to total depth of rainfall or as the ratio of peak rate of runoff to rainfall intensity for the time of concentration (Wanielista and Yousef 1993). Kuichling (1889) analyzed observed rainfall and discharge data for developed urban watersheds in Rochester, New York, and computed the percentage of rainfall discharged during the period of greatest flow as $Q_p/(IA)$, which is equal to C from Eq. (1). Kuichling concluded that the percentage of rainfall discharged for any given watershed is nearly equal to the percentage of impervious surface within the watershed, and this is the original meaning of C introduced by Kuichling (1889). According to Kuichling's definition, $C = 0$ for a strictly pervious surface and $C = 1$ for a strictly impervious surface.

Within the rational method, C is the variable least amenable to precise determination, and its estimation requires judgment on the part of the engineer [Joint Committee of the ASCE and the Water Pollution Control Federation (WPCF) 1960; Texas Department of Transportation (TxDOT) 2002]. Typical C values representing the integrated effects of many watershed conditions

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are listed for different land-use/land cover (LULC) conditions in various design manuals and textbooks (Chow et al. 1988; Viessman and Lewis 2003). These literature-based C values (C_{lit} in this paper) derive from the 1960 sanitary and storm-sewer design manual produced by a joint committee of the ASCE and the WPCF. Values of C_{lit} published by the joint committee were obtained from "71 returns of an extensive questionnaire submitted to 380 public and private organizations throughout the United States." The results represented decades of professional experience using the rational method to determine runoff volumes in storm sewer design applications (Joint Committee of the ASCE and the Water Pollution Control Federation 1960). The Joint Committee manual (1960) provided no observed rainfall and runoff data to justify the selected C_{lit} values; however, observed rainfall and runoff data were analyzed by Kuichling (1889).

In this paper, three methods were implemented to estimate C for 90 watersheds in Texas (see Fig. 1). The first method used LULC information for a watershed and published C_{lit} values for various land uses to derive a watershed-composite C_{lit}. The second method estimated volumetric runoff coefficient (C_v) values by the ratio of total runoff depth to total rainfall depth for individual storm events. Approximately 1,600 rainfall-runoff events measured in the 90 Texas watersheds were analyzed to determine event, watershed-median, and watershed-average C_v values. In this paper, the C_v determined from storm events is called the back-computed volumetric runoff coefficient (C_{vbc}). The third method computed probabilistic C_v values from the rank-ordered pairs of observed rainfall and runoff depths of a watershed and extracted a representative C_v for the watershed from the plot of C_v versus rainfall depths. In this paper, the C_v determined from the rank-ordered data is called the rank-ordered volumetric runoff coefficient (C_{vr}). The third method is similar to the procedure used by Schaake et al. (1967). The C values estimated by the three different methods were analyzed and compared. Regression equations of C_{vbc} and C_{vr} versus percent impervious area (IMP) are presented.

Watersheds Studied and Rainfall-Runoff Database

Watershed data taken from a larger data set (Asquith et al. 2004) accumulated by researchers from the USGS Texas Water Science Center, Texas Tech University, University of Houston, and Lamar University and previously used in a series of research projects funded by the TxDOT were used for this study. The data set comprises 90 USGS streamflow-gauging stations in Texas, each representing a different watershed (Fang et al. 2007, 2008). Location and distribution of the stations in Texas are shown in Fig. 1. There are 29, 21, 7, and 13 watersheds in the Austin, Dallas, Fort Worth, and San Antonio areas, respectively; the remaining 20 watersheds are small rural watersheds in Texas (see Fig. 1). The drainage area of the study watersheds ranged from approximately $0.8 - 440.3\ \mathrm{km}^2$ ($0.3 - 170\ \mathrm{mi}^2$), with median and mean values of $17.0\ \mathrm{km}^2$ ($6.6\ \mathrm{mi}^2$) and $41.1\ \mathrm{km}^2$ ($15.9\ \mathrm{mi}^2$), respectively. There are 33, 57, and 80 study watersheds with drainage areas less than $13\ \mathrm{km}^2$ ($5\ \mathrm{mi}^2$), $26\ \mathrm{km}^2$ ($10\ \mathrm{mi}^2$), and $65\ \mathrm{km}^2$ ($25\ \mathrm{mi}^2$), respectively. The stream slope of study watersheds ranged from approximately 0.0022–0.0196, with median and mean values of 0.0075 and 0.081, respectively. The IMP of study watersheds ranged from approximately 0.0–74.0, with median and mean values of 18.0 and 28.4, respectively.

Many would argue that application of the rational method is not appropriate for the range of watershed areas presented in this study. For example, watershed drainage area is a criterion used to select a hydrologic method (Chow et al. 1988) to compute peak discharge,

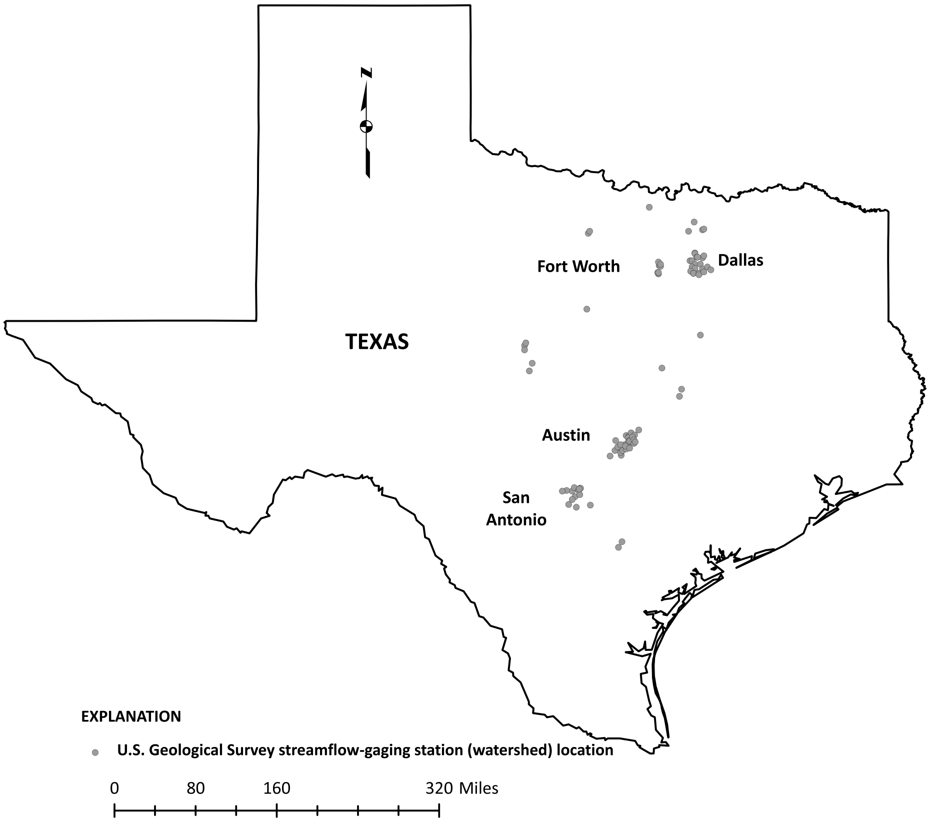

Fig. 1. U.S. Geological Survey streamflow-gauging stations associated with watersheds in Texas

according to TxDOT guidelines for drainage design. The TxDOT guidelines recommend the use of the rational method for watersheds with drainage areas less than 0.8 km^2 (200 acres) (TxDOT 2002). However, French et al. (1974) estimated values of the runoff coefficient in New South Wales, Australia, for 37 rural watersheds ranging in size up to 250 km^2 (96 mi^2). Young et al. (2009) determined runoff coefficients for 72 rural watersheds in Kansas with drainage areas up to 78 km^2 (30 mi^2). The Joint Committee of the ASCE and the WPCF (1960) issued the following statement when the rational method was introduced for the 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 five sq miles. Development of data for application of hydrograph methods is usually warranted on larger areas" (p. 32).

Chow et al. (1988) and Viessman and Lewis (2003) do not specify an area limit for application of the rational method. Pilgrim and Cordery (1993) stated that the rational method is one of three widely used to estimate peak flows for small- to medium-sized basins: "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" (p. 9.14). Results of this study will further indicate that there is no demonstrable trend in runoff coefficient with drainage area.

The rainfall-runoff data set comprised approximately 1,600 rainfall-runoff events recorded during 1959–1986. The number of events varied by watershed; for some locations only a few events were available, whereas for others as many as 50 events were available (Cleveland et al. 2006). Rainfall depths for the 1,600 events ranged from 3.56 mm (0.14 in.) to 489.20 mm (19.26 in.), with median and mean values of 57.15 mm (2.25 in.) and 66.29 mm (2.61 in.), respectively. Maximum rainfall intensities, calculated by using time of concentration for the 1,600 events ranged from 0.01 mm/min (0.03 in./h) to 2.54 mm/min (6.01 in./h), with median and mean values of 0.25 mm/min (0.58 in./h) and 0.30 mm/min (0.72 in./h), respectively.

A geospatial database was developed from another TxDOT project (Roussel et al. 2005) containing boundaries for the 90 watersheds, delineated by using a 30-m digital elevation model (DEM). The geospatial database contains watershed drainage area; longitude and latitude of the USGS streamflow gauging station, which was treated as the outlet of the watershed; and 42 characteristics (e.g., main channel length, channel slope, basin width) of each watershed (Roussel et al. 2005). Each of the 90 watersheds was classified as either developed (urbanized) or undeveloped (Roussel et al. 2005; Cleveland et al. 2008). Forty-four developed watersheds located in four metropolitan areas in Texas (i.e., Austin, Dallas, Fort Worth, and San Antonio) were used for USGS urban studies from 1959 to 1986. Thirty-six undeveloped locations include 20 small rural watersheds and 16 watersheds in suburbs of the four metropolitan areas. The classification scheme of developed and undeveloped watersheds parallels and accommodates the disparate discussion and conceptualization in more than 220 USGS reports that provided the original data for the rainfall and runoff database (Asquith et al. 2004). Although this binary classification seems arbitrary, it was purposeful and reflects the uncertainty in watershed development conditions at the time the rainfall-runoff data were collected (Asquith and Roussel 2007). This binary classification was successfully used to develop regression equations to estimate the shape parameter and the time to peak for regional gamma unit hydrographs for Texas watersheds (Asquith et al. 2006).

Estimation of Runoff Coefficients Using LULC Data

The value of C is strongly dependent on land use and, to a lesser extent, on watershed slope (Schaake et al. 1967; ASCE 1992). For watersheds with multiple land-use classes, a composite (area-weighted average) runoff coefficient, C_{lit}, can be estimated as follows:

$$C_{\mathrm{lit}} = \frac{\sum_{i=1}^{n} C_i A_i}{\sum_{i=1}^{n} A_i} \tag{2}$$

where, i = ith subarea with particular land-use type; n = total number of land-use classes in the watershed; C_i = literature-based runoff coefficient for ith land-use class; and A_i = subarea size for ith land-use class in the watershed (TxDOT 2002). In this paper, watershed-composite C_{lit} values were derived for the 90 watersheds in Texas using LULC information and C_{lit} values from various publications. A geographic information system (GIS) was used for subareal extraction of different LULC classes within a particular watershed [Environmental Systems Research Institute [ESRI] 2004]. The 1992 and 2001 National Land-Cover Data (NLCD) for Texas were obtained from the USGS website.

Each watershed has different LULC classes distributed within its boundary. Of 16 LULC classes from the 2001 NLCD, 15 were used for the 90 watersheds studied; definitions of NLCD LULC classes are available at http://www.epa.gov/mrlc/definitions.html. Runoff coefficients were assigned for 12 of the 15 LULC classes or mixed classes as listed in Table 1, which includes sources and references for the selected C values. From all sources considered, C values were not available for most of the 15 NLCD LULC classes, but similar land-use types from the literature were identified to match the NLCD LULC classes (seeTable 1). A C value of 1.0 was assigned to open water, woody wetlands, and emergent herbaceous wetlands and is not shown in Table 1. For the other LULC classes, a range of C values were available from the aforementioned sources under similar LULC types, and the average values (listed in column three of Table 1) were taken as literature C values for the study before a sensitivity analysis was conducted.

By using 2001 NLCD and standard published mean C values (see Table 1) and Eq. (2), composite runoff coefficients, C_{lit}, for the 90 Texas watersheds were developed. Values of C_{lit} ranged from 0.29 to 0.63, with median and mean values of 0.50 and 0.47, respectively (see Table 2). Estimates of C_{lit} for a given watershed may differ, depending on the experience and judgment used in assigning them to LULC classes and estimating areas for land-use classes. For example, Harle (2002) determined C_{lit} for a subset of 36 watersheds from the 90 Texas locations by using standard C_{lit} tables published by TxDOT (2002). The average absolute difference between Harle's estimate of C_{lit} and this study's is 0.06, and the maximum absolute difference is 0.13.

The 1992 NLCD were used to examine the potential for temporal differences in composite C_{lit} estimates with 18 of 21 LULC classes applied to the 90 watersheds. This difference from the 15 LULC classes determined using 2001 NLCD occurred because more land-use codes were available for some land cover classes in the 1992 NLCD. Summary statistics of the composite runoff coefficients, C_{lit}, obtained using 1992 and 2001 NLCD are listed in Table 2. The average runoff coefficients for the 90 watersheds derived from two LULC data sets are the same (i.e., 0.47; see Table 2). The median absolute difference of C_{lit} derived from the two LULC data sets is 0.03, with a minimum difference of 0.00 and a maximum difference of 0.14. The writers concluded that no substantial difference exists between C_{lit} values derived from the 1992 and 2001 LULC data sets because the paired t-test gives a p-value

Table 1. Coefficient, C, Selected for Various Land Cover Classes from 2001 NLCD

NLCD classification	NLCD description	C	Land use or description in the source
21	Developed, open space	$0.4^{a,d}$	Residential: single family areas (0.3–0.5)
22	Developed, low intensity	0.55^{c}	50% of area impervious (0.55)
23	Developed, medium intensity	0.65^{c}	70% of area impervious (0.65)
24	Developed, high intensity	0.83^{b}	Business: downtown areas (0.7–0.95)
31	Barren land	$0.3^{b,d}$	Sand or sandy loam soil, 0–5% (0.15–0.25); black or loessial soil, 0–5% (0.18–0.3); heavy clay soils; shallow soils over bedrock: pasture (0.45)
41	Deciduous forest	0.52^{e}	Deciduous forest (Tennessee) (0.52)
42	Evergreen forest	$0.48^{f,g}$	Forest (UK) (0.28–0.68); Forest (Germany) (0.33–0.59)
43	Mixed forest	$0.48^{f,g}$	Forest (UK) (0.28–0.68); Forest (Germany) (0.33–0.59)
52	Shrub/scrub	0.3^{d}	Woodland, sandy and gravel soils (0.1); loam soils (0.3); heavy clay soils (0.4); shallow soil on rock (0.4)
71	Grassland/herbaceous	0.22^{c}	Pasture, grazing HSG A (0.1); HSG B (0.2); HSG C (0.25); HSG D (0.3)
81	Pasture/hay	0.35^{d}	Pasture, sandy and gravel soils (0.15); loam soils (0.35); heavy clay soils (0.45); shallow soil on rock (0.45)
82	Cultivated crops	0.4^{d}	Cultivated, sandy and gravel soils (0.2); loam soils (0.4); heavy clay soils (0.5); shallow soil on rock (0.5)

Note: Numbers in parentheses are ranges for runoff coefficients given in the source (literature); HSG = hydrologic soil group.
[a] ASCE (1992).
[b] TxDOT (2002).
[c] Schwab and Frevert (1993).
[d] Dunne and Leopold (1978).
[e] Mulholland et al. (1990).
[f] Law (1956).
[g] Institute of Hydrology (1976).

Table 2. Statistical Summary of C_{lit} Using 1992 and 2001 National Land-Cover Data

Statistical distribution parameter	Watershed-average[a] C_{lit} using 1992 NLCD (1)	C_{lit} using 2001 NLCD			Absolute difference (1)–(3)
		Watershed-minimum[a] (2)	Watershed-average[a] (3)	Watershed-maximum[a] (4)	
Minimum	0.32	0.13	0.29	0.38	0.00
Maximum	0.68	0.60	0.63	0.68	0.14
25% quartile	0.40	0.24	0.38	0.48	0.02
Median	0.47	0.41	0.50	0.58	0.03
75% quartile	0.52	0.50	0.55	0.60	0.05
Average	0.47	0.38	0.47	0.55	0.04
Standard deviation	0.09	0.14	0.10	0.09	0.03

[a] Watershed-average, -minimum, and-maximum C_{lit} values were derived using mean, minimum, and maximum C values, respectively, for each LULC from the literature (see Table 1).

of 0.88 (Ayyub and McCuen 2003), which is much larger than the level of significance (i.e., 0.05) for the 95% confidence level.

A sensitivity analysis was conducted to examine the effect of selected C values for different LULC classes from the literature on the watershed-composite runoff coefficient, C_{lit}. The minimum and maximum C values for each LULC class from the literature (see Table 1) were used to derive watershed-minimum and watershed-maximum C_{lit} values, respectively, for each watershed. The 2001 NLCD were used for the sensitivity analysis. The cumulative distributions of watershed-minimum, -average, and -maximum C_{lit} values obtained are shown in Fig. 2 (top), and the summary statistics of these C_{lit} values are listed in Table 2. Values of watershed-minimum C_{lit} ranged from 0.13 to 0.60, with median and mean values of 0.41 and 0.38, respectively (see Table 2). Values of watershed-maximum C_{lit} ranged from 0.38 to 0.68, with median and mean values of 0.58 and 0.55, respectively (see Table 2). The differences between watershed-maximum and watershed-minimum C_{lit} values for the 90 Texas watersheds ranged from 0.04 to 0.34, with median and mean differences of 0.14 and 0.17, respectively. The Joint Committee of the ASCE and the WPCF (1960) and design manuals (e.g., TxDOT 2002) and textbooks (e.g., Viessman and Lewis 2003) give a range of C values (not a single value) for different land-use types, and the range of published C values for the same land use is between 0.04 and 0.3, the same variations of C_{lit} for the 90 Texas watersheds. This indicates uncertainty and variation of peak discharge estimation with use of the rational method.

The amount of developed land in a watershed is a key factor governing the runoff. To study the relationship between the composite runoff coefficients and the development factor of the watersheds, statistical summaries of C_{lit} from the 2001 NLCD were obtained separately for the 90 watersheds (see Table 3), which were classified as developed or undeveloped (Roussel et al. 2005). The corresponding cumulative frequency distributions are shown in Fig. 2 (bottom). The median value of C_{lit} (watershed-average) was 0.37 for undeveloped watersheds and 0.54 for developed watersheds. The average values of C_{lit} for undeveloped and developed watersheds were 0.39 and 0.54, respectively (see Table 3). The C_{lit}

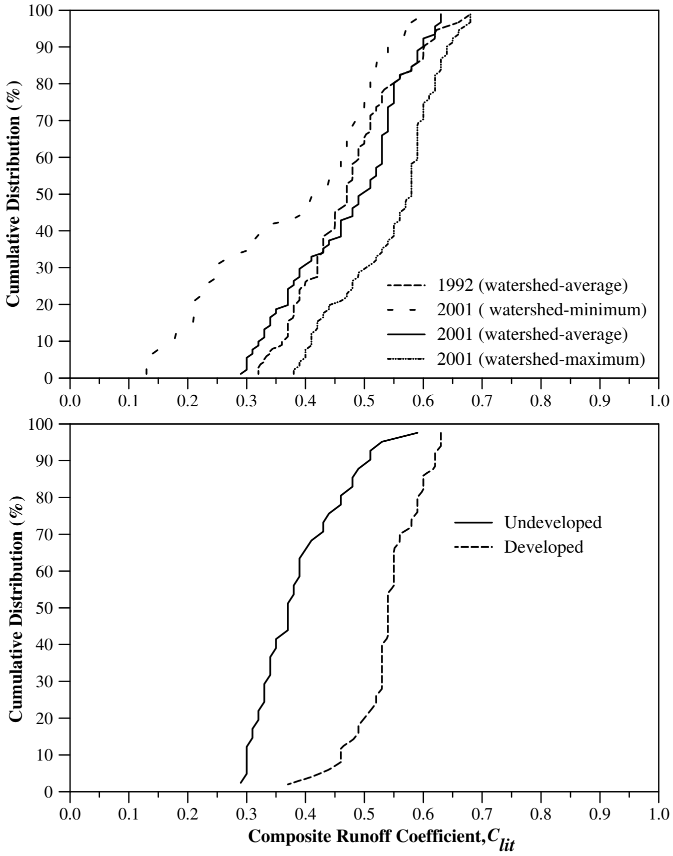

Fig. 2. Cumulative distributions of C_{lit} obtained by using 1992 and 2001 NLCD (top) and 2001 NLCD for developed and undeveloped watersheds (bottom)

Table 3. Statistical Summary of Watershed-Average C_{lit} Using 2001 NLCD for Undeveloped and Developed Watersheds

	Undeveloped	Developed
Minimum	0.29	0.37
Maximum	0.59	0.63
25% quartile	0.33	0.52
Median	0.37	0.54
75% quartile	0.43	0.58
Average	0.39	0.54
Standard deviation	0.07	0.06

values of developed watersheds are distinctly greater than those of undeveloped watersheds (p-value less than 0.0001 from the pooled t-test), as shown in Fig. 2 (bottom); the combination of LULC data and published C_{lit} values provides representative estimates of C_{lit} to reflect land-use development in a watershed.

Estimation of Back-Computed Volumetric Runoff Coefficients Using Observed Rainfall-Runoff Data

The concept of a rainfall-runoff event volumetric runoff coefficient (C_v) in hydrology dates to the beginning of the twentieth century. An example is Sherman (1932), who used the percentage of rainfall when he introduced the unit-hydrograph method. The C_v is defined as the portion of rainfall that becomes runoff during an event (Merz et al. 2006). Estimates of C_v from an individual event are usually determined by three steps: (1) separation into single events, (2) separation of observed streamflow into base flow and direct runoff, and (3) estimation of event C_v as the ratio of direct flow or runoff volume to event rainfall volume (Merz et al. 2006). The C_v is based on the integrated response of the watershed, i.e., the transformation of rainfall volume to runoff volume.

French et al. (1974) evaluated C_v for several rural catchments in New South Wales; Calomino et al. (1997) computed C_v for 66 events for an urban watershed [91.5% impervious area and total drainage area of 0.019 km^2 (1.89 ha)]. For the urbanized watershed studied by Calomino et al. (1997), event C_v ranged from 0.31 to 0.88, and C_v was strongly correlated to the total rainfall depth (P): $C_v = 0.57\ P^{0.042}$ ($R^2 = 0.96$). The Water Planning Division of the U.S. Environmental Protection Agency (USEPA) operated the National Urban Runoff Program (NURP), which had 20 projects to study pollutants from 76 U.S. urban watersheds, with drainage areas ranging from 0.004 to 115 km^2 (USEPA 1983). Researchers from NURP collected rainfall and runoff data from these watersheds, with the number of events ranging from five to 121. A runoff coefficient, R_v, defined as the ratio of runoff volume to rainfall volume, was determined for each of the NURP-monitored storm events. The median value of the runoff coefficients, the coefficient of variation, and the percent impervious area were reported for all watersheds used in the study (USEPA 1983).

In this study, estimates of volumetric runoff coefficient are called the back-computed volumetric runoff coefficient (C_{vbc}), and an individual-event C_{vbc} was obtained for the kth storm event by computing the ratio of total runoff depth, R_k (mm or in.), to the total rainfall depth, P_k (mm or in.), as follows:

$$C_{\text{vbc}}^k = \frac{\text{total event runoff}, R_k}{\text{total rainall for the event}, P_k} \tag{3}$$

The study database comprised 1,600 rainfall-runoff events with observed data collected from 90 watersheds in Texas (Fang et al. 2007). Therefore, 1,600 event runoff coefficients, C_{vbc}, were obtained using Eq. (3). Event C_{vbc} ranged from near 0.0 to 1.0, covering all possible values. The cumulative distributions of C_{vbc} are presented in Fig. 3, and summary statistics are listed in Table 4. For the 90 study watersheds in Texas, no substantial relationship between rainfall depth and C_{vbc} was detected (Pearson's correlation coefficient, $r = 0.2$ at the 0.1% level of significance because the p-value was less than 0.0001). For example, for 19 events with total rainfall depth less than 12.7 mm (0.5 in.), computed C_{vbc} ranged from 0.050 to 0.844. For 253 events with total rainfall depth between 76.2 mm (3 in.) and 101.6 mm (4 in.), the computed C_{vbc} ranged from 0.006 to 0.982. According to Fig. 3, C_{vbc} was less than 0.1 for 13% of events. Furthermore, C_{vbc} exceeded 0.9 for 1% of events. The regression relation between the runoff coefficient, C_{vbc}, and the total runoff depth, R, was $C_{\text{vbc}} = 0.374\ R^{0.699}$. The regression explained approximately 76% of the variance between the runoff depth and the runoff coefficient, and the regression coefficients were statistically significant at the 0.1% level of significance (p-value less than 0.0001).

The C_{vbc} values calculated for all events in the same watershed varied from one event to another (e.g., depending on antecedent moisture condition before a rainfall event). Statistical parameters of the range of C_{vbc} values, defined as the difference between maximum and minimum C_{vbc} values calculated for all events in the same watershed, are given in Table 4. The maximum and average values of the range of event C_{vbc} in the same watershed were 0.97 and 0.52, respectively, for 1,600 rainfall-runoff events in the 90 Texas watersheds. This finding is supported by previous studies by French et al. (1974) and the USEPA (1983). Variations of event

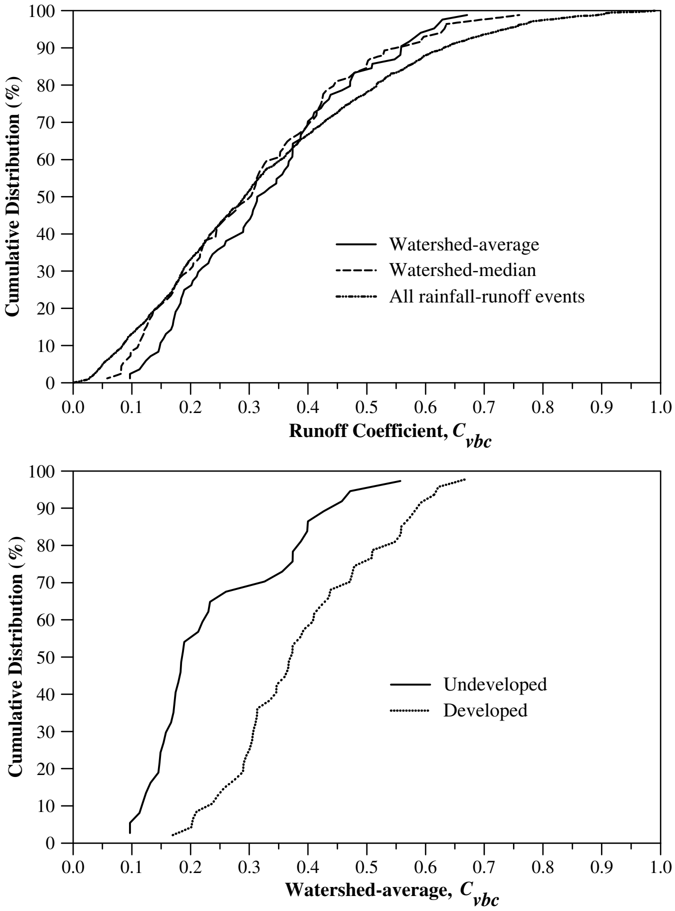

Fig. 3. Cumulative distributions of C_{vbc}: (top) watershed-average, watershed-median, and all rainfall-runoff events; (bottom) watershed-average C_{vbc} for developed and undeveloped watersheds

C_{vbc} in the same watershed determined from observed rainfall and runoff data are much larger than ranges of published C values for the same land-use type.

Watershed-average and watershed-median values of C_{vbc} were calculated from C_{vbc} values for all rainfall-runoff events observed in the same watershed and developed for 83 of the 90 watersheds in the Texas data set. Of the 90 watersheds, seven were excluded; fewer than four rainfall-runoff events were available for analysis in each of these seven watersheds. Computed watershed-average C_{vbc} ranged from approximately 0.1 to 0.67 and from approximately 0.06 to 0.76 for the watershed-median C_{vbc} (see Table 4). These values are similar to C_{lit} values estimated from LULC data, which ranged from 0.29 to 0.68 (see Fig. 2 and Table 2). Approximately 80% of the C_{vbc} watershed-median and watershed-average values were less than 0.5. Watershed-median R_v ranged from 0.02 to 0.93 for 76 watersheds studied in the National Urban Runoff Program (USEPA 1983). The average values of the watershed-average and watershed-median C_{vbc} were similar, 0.33 and 0.31, respectively (see Table 4). As shown in Fig. 3, the cumulative frequency distributions of the watershed-average and watershed-median C_{vbc} values were similar, and the maximum absolute difference of watershed-average and median C_{vbc} was less than 0.10.

Developed and undeveloped watershed classifications (Roussel et al. 2005) were used to sort the watershed-average C_{vbc} values for additional statistical analysis. The results are listed in Table 5, and cumulative distributions of C_{vbc} are shown in Fig. 3. The cumulative distributions are distinctly different: developed watersheds have greater C_{vbc} (watershed-average) in comparison to undeveloped watersheds (p-value less than 0.0001 from the pooled t-test). The median values of the watershed-average C_{vbc} for undeveloped and developed watersheds were 0.19 and 0.37, respectively (see Table 5).

For this study, the IMP was computed by using 1992 NLCD. Of the 90 study watersheds, 45 had percent impervious area greater than 15%. The watershed-median runoff coefficients C_{vbc} and R_v versus percent impervious area for the 45 developed watersheds in Texas and the 60 watersheds from NURP are shown in Fig. 4 (top). For 76 watersheds among those studied in NURP (USEPA 1983), two separate graphs of watershed-median runoff coefficient versus percent impervious area were developed and reported: one graph is for the 60 watersheds and another is for 16 watersheds.

According to the USEPA 1983, "The separate grouping is based on the fact that the relationship for these sites (16 watersheds) is internally consistent and significantly different (much lower) than the bulk of the project results" (pp. 6–60).

Polynomial regression lines were fit to the data for the 60 NURP watersheds and to the data for the combined group of 60 NURP and 45 Texas watersheds (watershed-median C_{vbc}) and are displayed in Fig. 4 (top). Coefficients of determination, R^2, for the two data sets were 0.79 and 0.57, respectively.

The regression equation obtained from data from the combined 60 NURP watersheds and the 45 Texas watersheds (watershed-median C_{vbc}) is

$$C_v = 1.843\text{IMP}^3 - 2.275\text{IMP}^2 + 1.289\text{IMP} + 0.036 \qquad (4)$$

where C_v = volumetric runoff coefficient and IMP = percent impervious area expressed as a fraction (50% = 0.5) of the watershed area. Urbanization alters the land surface and increases IMP. Although other watershed parameters, e.g., basin development

Table 4. Statistical Summary of C_{vbc} and R_v from NURP (USEPA 1983)

	C_{vbc} All events	Range of C_{vbc} [a]	Watershed-median C_{vbc}	Watershed-average C_{vbc}	Standard deviation C_{vbc}	Standard deviation R_v [b]
Minimum	0.00	0.02	0.06	0.10	0.04	0.02
Maximum	0.99	0.97	0.76	0.67	0.30	1.13
25% quartile	0.17	0.37	0.17	0.20	0.12	0.10
Median	0.29	0.53	0.30	0.31	0.16	0.16
75% quartile	0.47	0.66	0.42	0.42	0.19	0.28
Average	0.33	0.52	0.31	0.33	0.16	0.21
Standard deviation	0.21	0.22	0.17	0.15	0.05	0.18

[a] Difference between maximum and minimum C_{vbc} values calculated for all events in the same watershed.
[b] Estimated from median values and coefficients of variation of R_v for 60 NURP watersheds (USEPA 1983).

Table 5. Statistical Summary of Watershed-Average C_{vbc} for Undeveloped and Developed Watersheds

	Undeveloped	Developed
Minimum	0.10	0.17
Maximum	0.56	0.67
25% quartile	0.15	0.30
Median	0.19	0.37
75% quartile	0.36	0.48
Average	0.24	0.39
Standard deviation	0.12	0.13

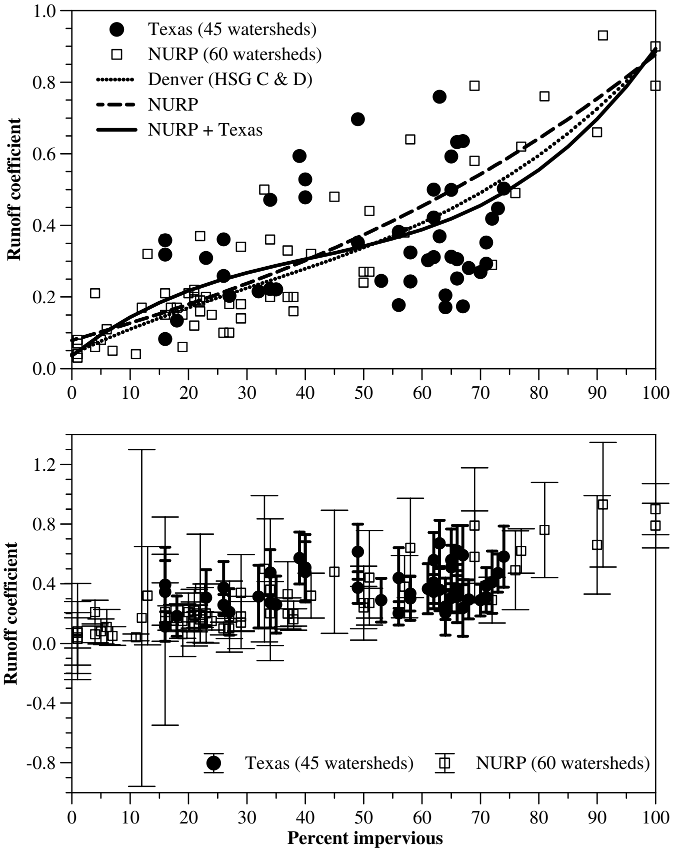

Fig. 4. Volumetric runoff coefficients from different studies versus percent impervious area including regression lines (top); runoff coefficients ±1 standard deviation for 45 Texas watersheds and 60 NURP watersheds (bottom)

factors (Sauer et al. 1983), can be used to quantify the degree of urbanization, IMP was used in this study to correlate it to C_v because Kuichling (1889) concluded that the runoff coefficient for any watershed he studied was nearly equal to the percent of impervious surface within the watershed.

For comparison, Urbonas et al. (1989) used watershed-median runoff coefficients from the group of 60 NURP watersheds and several runoff coefficients developed for watersheds in the Denver area to develop a polynomial regression equation between runoff coefficient and percent impervious area. The Urbonas et al. equation (not repeated here) was used by the Denver Urban Drainage and Flood Control District in its 2010 Drainage Criteria Manual (see from http://www.udfcd.org/downloads/down_critmanual.htm) to determine C for HSG Types C and D. The curve for the Urbonas et al. equation also is shown in Fig. 4 (top). Although the parameters differ between the three regressions shown, the curves are similar and have a maximum absolute difference of C_v less than 0.1.

Values of watershed-median C_{vbc} for the 45 Texas watersheds are generally consistent with those from the 60 NURP watersheds (see Fig. 4). Standard deviations from the watershed-average C_{vbc} were calculated for Texas watersheds and are shown in Fig. 4 (bottom) as solid circles with thick error bars. Standard deviations and coefficients of variation from watershed-averages, C_{vbc}, ranged from 0.04 to 0.30 and from 0.15 to 1.34, respectively, for 83 Texas watersheds, as shown in Table 4.

For the NURP data, watershed-median values and coefficients of variation were reported (USEPA 1983), but the watershed-average runoff coefficients, R_v, were not reported. To examine variations in runoff coefficient for the NURP data, reported watershed-median values were used as watershed-averages to estimate the standard deviations from reported coefficients of variation; the statistical distribution parameters of the estimated standard deviations for the NURP watersheds are listed in Table 4. The estimated maximum standard deviation from the NURP watershed data was greater than 1.0, which is impossible if R_v range from 0.0 to 1.0, possibly because watershed-median R_v was used. The NURP watersheds had a watershed-median R_v of 0.17 and a coefficient of variation of 6.64, which is much larger than 1.34, the maximum coefficient of variation for the 83 Texas watersheds. Fifteen NURP watersheds had estimated standard deviations greater than 0.3, the maximum standard deviation for the 83 Texas watersheds (see Table 4). The median standard deviations are approximately equal for both data sets. The NURP data (median R_v for the 60 watersheds) ±1 standard deviation are shown in Fig. 4 (bottom) as open squares with wide error bars. Standard deviations from watershed-average C_{vbc} for the 45 Texas watersheds were consistently less than those from the 60 NURP watersheds. The NURP data cover a greater range of IMP for watersheds (see Fig. 4), which are useful for developing the regression Eq. (4) and applying the regression to a wider range of watersheds.

Estimation of Volumetric Runoff Coefficients from Rank-Ordered Pairs of Observed Rainfall and Runoff Depths

Schaake et al. (1967) examined the rational method using observed rainfall and runoff data collected from 20 gauged urban watersheds in Baltimore. The size of the watershed drainage areas was 0.6 km^2 (150 acres) or smaller. Schaake et al. (1967) used a frequency-matching approach to prepare their data for analysis. The frequency-matching approach involved independently sorting observed rainfall intensity (i.e., average intensity over watershed lag time) and peak runoff rate before the runoff coefficient was computed by using the rational method. That is, the rainfall intensity and peak runoff rate were paired on the rank order and not the event order.

Schaake et al. (1967) concluded that the frequency of occurrence of the computed design peak runoff rate was the same as the frequency of the rainfall intensity selected by the designer. They developed a regression equation to relate rate-based C (determined from peak discharge and rainfall intensity) to the imperviousness of the watershed and the main channel slope. Hjelmfelt (1980) and Hawkins (1993) used a similar frequency-matching procedure, although they used rank-ordered rainfall and runoff depths for computing actual curve numbers from historical rainfall-runoff events.

For each of the 90 Texas watersheds in this study, the total rainfall depth and total runoff depth were ranked independently from greatest to least. As an example, the rank-ordered pairs of total rainfall depth (mm) and total runoff (mm) for 13 events at USGS gauge station 08,042,650 (North Trinity Basin, Texas) are presented in Fig. 5 (top). The volumetric runoff coefficient, C_v, was computed from the rank-ordered pairs of total runoff and rainfall depths as follows:

$$C_{\mathrm{vrj}} = \frac{R_j}{P_j} \tag{5}$$

where $C_{\mathrm{vrj}} = C_v$ corresponding to the total runoff depth, R_j, and the total rainfall depth, P_j, of the jth order of rainfall-runoff pairs (and r in C_{vrj} = rank-ordered).

A plot of runoff coefficient (C_{vrj}) versus total rainfall depth was prepared for each watershed. For example, the plot for USGS gauge station 08,042,650 is presented in Fig. 5 (bottom). For most of the study watersheds, C_{vrj} increased until an approximate constant value was acquired. This constant value was considered representative of C_{vr} for the watershed; for example, watershed-representative runoff coefficient $C_{vr} = 0.17$ for the North Trinity Basin watershed (see Fig. 5). In addition to Hawkins' procedure (Hawkins 1993), i.e., asymptotic determination of C_{vr} from C_{vrj} versus rainfall depth, watershed C_{vr} can be estimated from the slope of the regression line obtained from the plots of the rank-ordered total runoff depth versus the rank-ordered total rainfall depth, as shown in the top panel of Fig. 5. For example, for USGS station 08,042,650, the regression equation developed from rank-ordered runoff and rainfall data was $\text{Total runoff (mm)} = 0.167 \times \text{Total rainfall depth (mm)}$. Therefore, the C_{vr} was 0.167, which was equal to the slope of the regression equation. For most of the study watersheds, C_{vr} values obtained from both procedures were approximately the same. Table 6 shows the statistical distribution parameters of C_{vr} for 83 Texas watersheds (seven of 90 watersheds were excluded because of the limited rainfall-event data). Both the mean and median values of C_{vr} were 0.40. The values of C_{vr} ranged from 0.10 to 0.78. The cumulative distributions of the runoff coefficients C_{vr} and C_{lit} are shown in Fig. 6 (top). The median value of the absolute difference $|C_{vr} - C_{\mathrm{lit}}|$ was 0.14 (see Table 6). Upon examination of the cumulative frequency distributions of C_{lit} and C_{vr} for the 90 study watersheds [see Fig. 6 (top)], about 80% of the C_{lit} values exceeded the C_{vr} values.

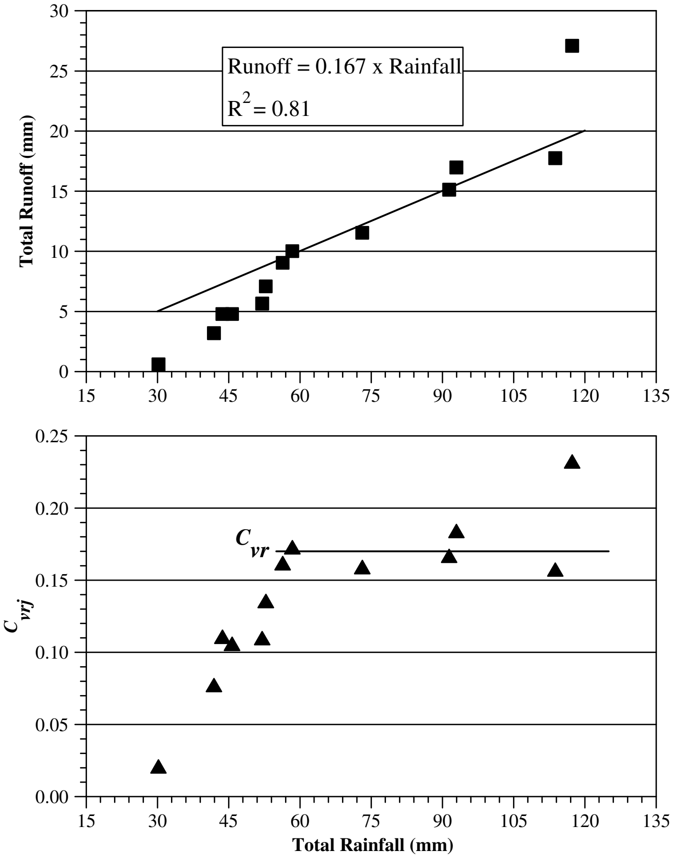

Fig. 5. The rank-ordered pairs of observed runoff and rainfall depths (top); runoff coefficients derived from the rank-ordered pairs of observed runoff and rainfall depths versus total rainfall depths (bottom); data are for USGS gauge station 08,042,650 (North Trinity Basin in Texas)

Table 6. Statistical Summary of C_{vr} and Absolute Difference (ABS) of C_{vr} with Watershed-Average C_{lit} for 83 Texas Watersheds

	C_{vr}	ABS $(C_{vr} - C_{\mathrm{lit}})$
Minimum	0.10	0.01
Maximum	0.78	0.40
25% quartile	0.24	0.07
Median	0.40	0.14
75% quartile	0.52	0.24
Average	0.40	0.16
Standard deviation	0.18	0.11

Watershed-representative runoff coefficients, C_{vr}, were grouped into two categories: those from developed watersheds and those

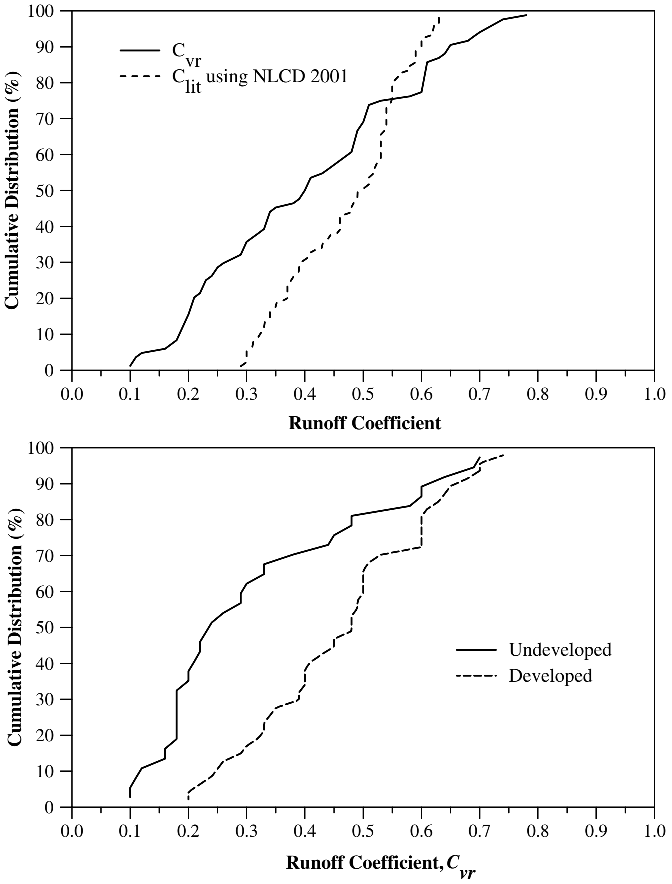

Fig. 6. Cumulative distributions of C_{vr} and C_{lit} (top); C_{vr} for developed and undeveloped watersheds (bottom)

from undeveloped watersheds (Roussel et al. 2005). The statistical summary of C_{vr} for the two groups is listed in Table 7, and the corresponding cumulative frequency distributions are presented in Fig. 6 (bottom). The median C_{vr} from undeveloped watersheds was 0.24, and the median value from developed watersheds was 0.48. On the basis of this observation, C_{vr} derived from rank-ordered rainfall-runoff data reflects the effects of watershed development, specifically the increase of percent impervious area (see Fig. 7). A statistical summary of the absolute differences, $|C_{vr} - C_{\mathrm{vbc}}|$ and $|C_{vr} - C_{\mathrm{lit}}|$, for the 45 developed watersheds in Texas is given in Table 7. Small average and median values of $|C_{vr} - C_{\mathrm{vbc}}|$ indicate that C_{vr} was similar to C_{vbc}, as both were derived from observed rainfall-runoff data. Average and median values of $|C_{vr} - C_{\mathrm{lit}}|$ were greater than those of $|C_{vr} - C_{\mathrm{vbc}}|$ (see Table 7), indicating that C_{vr} derived from rainfall-runoff data differs from C_{lit} derived from land-use data and published runoff coefficients (see Figs. 2 and 6).

The watershed-representative C_{vr} and watershed-median C_{vbc} from 45 developed Texas watersheds and the runoff coefficient, R_v, from 60 NURP watersheds were plotted against percent impervious area (see Fig. 7). Results from these data sets were consistent an overall increasing volumetric runoff coefficient with increased percent impervious area or degree of development. A polynomial regression line was fitted to the combined data from 60 NURP watersheds and to the watershed-representative C_{vr} for the 45 Texas developed watersheds (see Fig. 7). The R^2 for regression Eq. (6) was 0.57, which is the same as the R^2 for Eq. (4).

$$C_v = 1.469\mathrm{IMP}^3 - 1.940\mathrm{IMP}^2 + 1.315\mathrm{IMP} + 0.043 \qquad (6)$$

Table 7. Statistical Summary of C_{vr} for Undeveloped and Developed Watersheds and Absolute Difference (ABS) of C_{vr} with Watershed-Average C_{vbc} and C_{lit} for Developed Watersheds

	Undeveloped	Developed	ABS ($C_{vr} - C_{\mathrm{vbc}}$)	ABS ($C_{vr} - C_{\mathrm{lit}}$)
Minimum	0.10	0.20	0.00	0.01
Maximum	0.70	0.74	0.45	0.38
25% quartile	0.18	0.34	0.02	0.06
Median	0.24	0.48	0.04	0.12
75% quartile	0.44	0.60	0.12	0.18
Average	0.31	0.46	0.08	0.14
Standard deviation	0.18	0.15	0.10	0.10

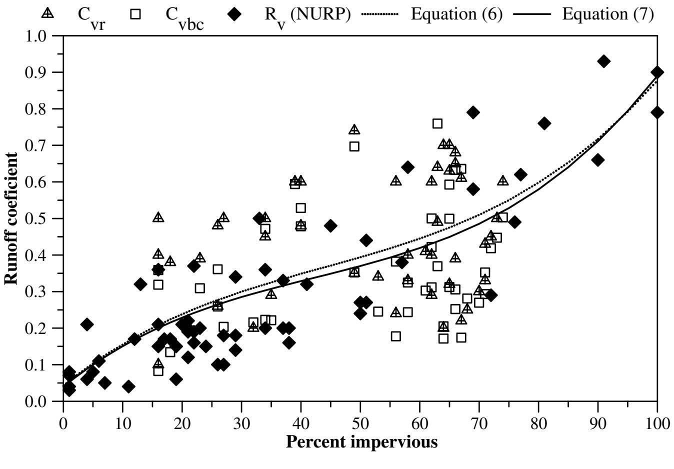

Fig. 7. Runoff coefficients C_{vr}, C_{vbc} (watershed-average), and R_v from 60 NURP watersheds versus percent impervious area, including lines for regression Eqs. (6) and (7)

Regression Eqs. (4) and (6) were combined by averaging their coefficients for general application in urban watersheds similar to the 45 developed Texas watersheds.

$$C_v = 1.66\mathrm{IMP}^3 - 2.11\mathrm{IMP}^2 + 1.30\mathrm{IMP} + 0.04 \qquad (7)$$

Eq. (7) can be used to estimate C_v for developed (urban) watersheds on the basis of impervious cover. Eq. (7) is plotted on Fig. 7, which also includes a curve for Eq. (6) and data points for C_{vbc}, C_{vr}, and R_v versus IMP. Fig. 7 and Eq. (7) indicate that C_v is not equal to 1.0 when IMP = 100%. This occurs because R_v estimated in the NURP study is for watersheds greater than 0.004 km^2 (1 acre) and C_v estimated in this study was for watersheds greater than 0.8 km^2 (200 acres); therefore, Eq. (7) does not apply to a very small, 100% impervious catchment such as a small parking lot. Further study is needed to correlate runoff coefficients for undeveloped watersheds (see Fig. 6) to soil types and other watersheds characteristics.

Discussion

Volumetric runoff coefficients, watershed-average C_{vbc} and C_{vr} for 83 Texas watersheds, watershed-average C_{lit} for 90 Texas watersheds, and watershed-median R_v for 60 NURP watersheds (USEPA 1983) were plotted against drainage area A in km^2 (see Fig. 8). Pearson's correlation coefficients between C_{vbc}, C_{vr}, C_{lit}, and R_v and A (km^2) were −0.20, −0.12, −0.27, and −0.26 with p-values of 0.060, 0.256, 0.009, and 0.044, respectively. Therefore, at the 90% confidence level, C_{vbc}, C_{lit}, and R_v had no substantial relationship with area (see Fig. 8); C_{vr} had no substantial relationship with area only at the 70% confidence level. Previously mentioned statistical analyses between volumetric C values and drainage area found no demonstrable relationship between volumetric C and drainage area, as Young et al. (2009) reported. This finding supports the conclusion by the Joint Committee of the ASCE and the 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 assumed in some design manuals, as long as the watershed is unregulated (Young et al. 2009). The published limits on drainage area for application of the rational method appear to be arbitrary. The writers do not advocate imposing a specific limit on drainage area for application of the rational

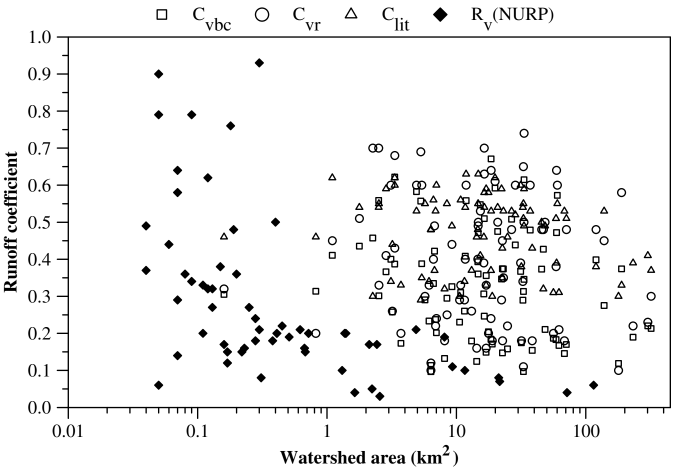

Fig. 8. Runoff coefficients C_{lit} (watershed-average), C_{vbc} (watershed-average), C_{vr}, and R_v plotted against watershed area (km^2)

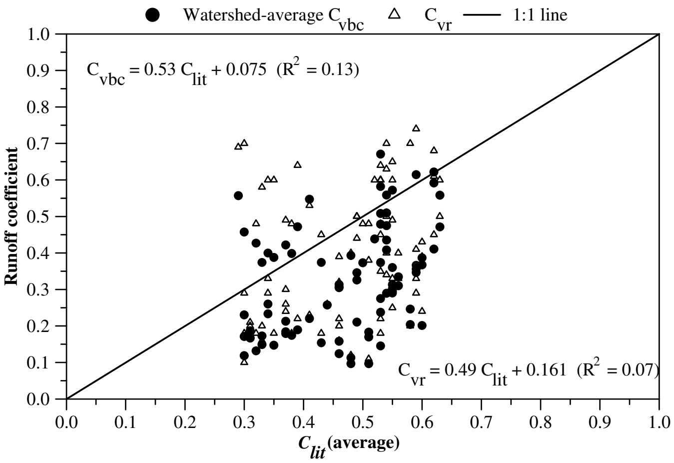

Fig. 9. Runoff coefficients C_{vbc} (watershed-average) and C_{vr} plotted against C_{lit} (watershed-average) for 83 Texas watersheds

method. Rather, the end user of the end-user of the rational method should be responsible for applying appropriate engineering judgment and experience when developing designs.

The writers explicitly are not advocating application of the rational method for larger watersheds because the steady-state assumption of the rational method for design purposes is questionable. However, extensive data analysis (Asquith 2011) suggests that inherent relations between runoff coefficient and drainage area are insubstantial if time of concentration of a watershed is reasonably estimated for determining rainfall intensity. The writers support the 1960 recommendation of the Joint Committee of the ASCE and the WPCF: "Development of data for application of hydrograph methods is usually warranted on larger areas" (p. 32).

The writers explicitly recognize that volumetric runoff coefficients may not have direct applicability in use of the rational method for engineering design purposes. Therefore, the writers did not apply the rational method with volumetric runoff coefficients (i.e., C_{vbc} and C_{vr}) to predict peak discharges for the 1,600 events or compare predicted and observed peak discharges. Such use is inconsistent with the assertion that rate-based values be used for runoff coefficients. In a subsequent paper, the writers determined rate-based rational runoff coefficients for these 90 Texas watersheds and applied the rational method to predict peak discharges and compare predicted and observed peak discharges.

Volumetric runoff coefficients estimated from observed rainfall and runoff data for the 83 Texas watersheds were plotted against C_{lit} (watershed-average) for the same watersheds (see Fig. 9). Regression equations between watershed-average C_{vbc}, and C_{vr} and C_{lit} were developed and are shown in Fig. 9, with Pearson's correlation coefficients of 0.36 and 0.26 at the 95% confidence level and p-values of 0.0007 and 0.01, respectively. Therefore, regression analyses indicate volumetric runoff coefficients determined from rainfall and runoff data weakly correlated to C_{lit}.

Summary

Volumetric runoff coefficients were estimated for 90 Texas watersheds by using three methods. The first method involved estimation of literature-based runoff coefficients (C_{lit}) using published values and GIS analysis of LULC classes to construct areally weighted values over a watershed. The C_{lit} was obtained independently from 1992 and 2001 NLCD and used minimum, average, and maximum published C values for different LULC classes. No substantial difference in watershed-average C_{lit} was obtained with the 1992 or 2001 version of the land-use data. For the study watersheds, watershed-average C_{lit} ranged from 0.29 to 0.68, with median and average values of approximately 0.5. Differences in watershed-maximum and watershed-minimum C_{lit} values for the 90 Texas watersheds ranged from 0.04 to 0.34, with median and mean differences of 0.14 and 0.17, respectively. When C_{lit} (watershed-average) was grouped into developed and undeveloped watersheds, the range of C_{lit} for developed watersheds was between 0.37 and 0.63, with a median value of 0.54. The median value of C_{lit} for developed watersheds exceeded that for undeveloped watersheds. This result occurred because even though published runoff coefficients resulted from a survey on engineering practices in the 1950s rather than from observed rainfall-runoff measurements, they, reflect the physical meaning of the original runoff coefficients introduced by Kuichling in 1889, i.e., they are related to the percent impervious area within the watershed. Therefore, published runoff coefficients remain useful for engineering design of drainage systems.

The second method used back-computed volumetric runoff coefficients (C_{vbc}) from observed rainfall-runoff measurements of more than 1,600 events and the ratio of total runoff depth to total rainfall depth for individual storm events. Event volumetric runoff coefficients covered all possible values from 0.0 to 1.0, with 10% of all values less than 0.08 and 10% of all values greater than 0.63 (see Fig. 3). The maximum and average values of the range of event C_{vbc} in the same watershed was 0.97 and 0.52 (see Table 4) for the 1,600 rainfall-runoff events in 90 Texas watersheds, respectively. Watershed-average and watershed-median values of C_{vbc} and estimated standard deviations were extracted. The distributions of watershed-average and watershed-median C_{vbc} were similar. Watershed-median values of C_{vbc} ranged from 0.06 to 0.76, with an average of 0.31. Watershed-median values of C_{vbc} for 45 developed watersheds in Texas with percent imperviousness greater than 15% were consistent with median values of runoff coefficient R_v reported for 60 NURP watersheds by the USEPA.

The third method involved the computation of runoff coefficients by the frequency-matching procedures of observed total rainfall-runoff depths from a watershed (Schaake et al. 1967). A single watershed-specific value of the runoff coefficient, C_{vr}, was developed from the plot of rank-ordered runoff coefficients versus rainfall depths. The values of C_{vr} ranged from 0.10 to 0.78, with a median value of 0.40. The C_{vr} values for the developed watersheds were consistently higher than those for the undeveloped watersheds. The distribution of C_{vr} was different from that of C_{lit}, with approximately 80% of C_{lit} values greater than C_{vr} values. This result might indicate that literature-based runoff coefficients overestimate peak discharge for drainage design when used with the rational method.

Runoff coefficients derived from observed rainfall and runoff data in the 90 Texas watersheds in this study were volumetric based (i.e., the ratio of total runoff to rainfall depth) and are useful in transforming rainfall depth to runoff depth per the curve number method (Soil Conservation Service 1963) and for watershed rainfall-runoff modeling such as the fractional loss model (McCuen 1998, p. 493). Current runoff coefficients given in textbooks and design manuals are neither volumetric nor rate-based (i.e., determined from peak discharge and rainfall intensity) because they were not derived from observed data; however, they are used for the rate-based rational method.

Regression Eqs. (4) and (6) were developed by using watershed-median C_{vbc} and watershed-representative C_{vr} data combined with median runoff coefficients, R_v, from 60 NURP watersheds. The coefficient of determination, R^2, for both equations was 0.57, and these equations were combined in Eq. (7), which can be used to estimate volumetric runoff coefficients for developed urban watersheds similar to the 45 developed watersheds in Texas. The published limits on drainage area for application of the rational method appear arbitrary. Results from this study support the conclusion by the Joint Committee of the ASCE and the 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 assumed in some design manuals.

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Notation

The following symbols are used in this paper:

A = watershed drainage area in hectares or acres;
A_i = subarea for ith land-cover classes in the watershed;
C = runoff coefficient;
C_i = literature-based runoff coefficient for ith land cover class;
C_v = volumetric runoff coefficient, portion of rainfall that becomes runoff, determined from regression equations;
C_{vbc} = watershed-average or median back-computed volumetric runoff coefficient;
C_{vbc}^k = back-computed volumetric runoff coefficient for kth event;
C_{lit} = literature-based runoff coefficient developed from land-use data;
C_{vrj} = runoff coefficient estimated from ratio of jth rank-ordered runoff and rainfall data pair;
C_{vr} = watershed representative runoff coefficient estimated from distribution of ratios of rank-ordered runoff and rainfall;
I = average rainfall intensity (mm/h or in./h) with duration equal to time of concentration;
IMP = percent of impervious area expressed as fraction ($50\% = 0.5$) for watershed;
m_o = dimensional correction factor (1.008 in English units, $1/360 = 0.00278$ in SI units);
no = total number of land-cover classes in watershed;
P_j = total rainfall depth of jth order of ranked runoff data series;
P_k = total rainfall depth of kth event;
Q_p = peak discharge or runoff rate in m^3/s or ft^3/s;
R_j = total runoff depth of jth order of ranked rainfall data series;
R_k = total runoff depth of kth event; and
R_v = runoff coefficient as ratio of runoff volume to rainfall volume determined by USEPA for NURP data.

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