

Runoff Curve Numbers for 10 Small Forested Watersheds in the Mountains of the Eastern United States

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Abstract: Engineers and hydrologists use the curve number method to estimate runoff from rainfall for different land use and soil conditions; however, large uncertainties occur for estimates from forested watersheds. This investigation evaluates the accuracy and consistency of the method using rainfall-runoff series from 10 small forested-mountainous watersheds in the eastern United States, eight annual maximum series from New Hampshire, West Virginia, and North Carolina, and two partial duration series from Georgia. These series are the basis to compare tabulated curve numbers with values estimated using five methods. For nine of 10 watersheds, tabulated curve numbers do not accurately estimate runoff. One source of the large uncertainty is a consistent decrease in storm-event curve numbers with increasing rainfall. A calibrated constant curve number is suitable for only two of 10 watersheds; the others require a variable watershed curve number associated with different magnitude rainfalls or probabilities of occurrence. Paired watersheds provide consistent curve numbers, indicating that regional values for forested-mountainous watersheds (locally calibrated and adjusted for storm frequency) may be feasible. DOI: 10.1061/(ASCE)HE.1943-5584.0000436. © 2012 American Society of Civil Engineers.

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Introduction

The Natural Resources Conservation Service (NRCS) curve number procedure is widely used to estimate runoff resulting from rainfall events. The curve number explicitly lumps the effects of land use and cover, soil type, and hydrologic condition into a single coefficient (NRCS 2001). The method uses a simplified representation of

event water storage within the watershed including: (a) the watershed retains the initial rainfall before runoff begins; (b) a curve number represents the maximum potential retention; and (c) the ratio of runoff to rainfall is linearly related to the ratio of the event abstraction (rainfall less runoff) to the maximum potential retention.

The NRCS [formerly the Soil Conservation Service (SCS)] developed the curve number method in 1954 to design flood control projects on agricultural watersheds (Rallison and Miller 1982) and subsequently to estimate runoff from urban areas (SCS 1975). Although useful for estimating runoff from agricultural and urban watersheds and moderately useful for rangelands, the curve number method often results in inaccurate estimates of runoff from many forested watersheds (Hawkins 1984, 1993; Ponce and Hawkins 1996; Schneider and McCuen 2005; McCutcheon et al. 2006).

The investigation reported in this paper is motivated by the need to understand the limitations of the curve number method in the forested-mountainous watersheds of the eastern United States. Numerous studies establish ad hoc representation of the perennial stream flows in these forests (Hibbert and Cunningham 1967; Douglass and Hoover 1988; Bailey et al. 2003; USDA 2004; Kochenderfer 2006; McCutcheon et al. 2006). Yet, the accuracy of the curve number method for estimating forested watershed runoff has not been determined (McCutcheon et al. 2006). This study focuses on the utility of the curve number method for 10 watersheds with the goals of evaluating: (a) the relative accuracy of various procedures for determining watershed curve numbers from rainfall-runoff measurements; and (b) the applicability of the method in estimating runoff from forested watersheds.

Literature Review

The SCS developed the curve number method to apply equitably the 1954 Watershed Protection and Flood Prevention Act, PL-566

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(16 U.S.C 1001 *et seq.*). The SCS had begun development of a rainfall-runoff relationship that did not depend upon streamflow monitoring within the watershed (Mockus 1949; Andrews 1954), and this work served as the initial basis for the generalized SCS runoff equation using a curve number index.

The SCS derived curve numbers from approximately 199 experimental watersheds at 23 locations nationwide, using measurements of annual maximum rainfall and runoff collected between 1928 and 1954 and thousands of infiltrometer tests. The watersheds ranged in size from 0.0971 ha to 18,600 ha (0.24 acres to 46,080 acres) and had a single soil group and cover complex in most cases. Unfortunately, most of the information compiled for the initial development of the curve number method has not been preserved (NRCS 2001; Woodward et al. 2002; Hawkins et al. 2009).

The curve number method uses a short-term event water budget for a watershed to estimate the storm runoff $Q = P^* - F$ where $P^* = P - I_a$ = effective rainfall; F = the retention of water on the watershed during the event; P = rainfall; and I_a = the watershed initial abstraction. This approach is appropriate for an event of sufficiently limited duration, during which other components of the water budget (e.g., evapotranspiration) are negligible (Yuan et al. 2001; Hawkins et al. 2009). The curve-number-based estimate of runoff is the typical response to an annual maximum rainfall of a given probability of occurrence (Ponce 1996).

The ratio of runoff to rainfall used to derive the runoff equation is $Q/P^* = F/S$ with S as the maximum potential retention of water or as a curve number $CN = 100/(1 + S/\alpha)$, where $\alpha = 254$ mm (10 in.) (Ponce and Hawkins 1996). The SCS conceived of the maximum potential retention S as a constant for each watershed (Hawkins et al. 2009) as long as the land cover, use, and hydrologic condition do not change. However, maximum potential retention S varies between storms because of soil moisture variation and other watershed and rainfall factors (Rallison and Cronshey 1979; Hjelmfelt 1980, 1983, 1991; Hjelmfelt et al. 1982; Rallison and Miller 1982; Mack 1995; Ponce 1996; Ponce and Hawkins 1996; NRCS 2001; Yuan et al. 2001; Hawkins et al. 2009). Hawkins (1993) noted that maximum potential retention S or the curve number CN varied as event rainfall increased. As Titmarsh et al. (1995) and McCutcheon et al. (2006) noted, some watersheds require a variable curve number that is different for different design probabilities.

Despite large uncertainties, the SCS originally estimated the initial abstraction I_a as a constant 20% of the maximum potential retention S . Later defined as $\lambda = I_a/S$, the NRCS (2001) determined the initial abstraction ratio λ with a smaller subset of the rainfall-runoff measurements available in 1954. This subset of daily rainfall and runoff was reportedly measured on watersheds smaller than 4 ha (10 acres). Half of these events led to initial abstraction ratios λ of 0.095 to 0.38, the full range is 0.013 to 2.20. Victor Mockus, a pioneer of the curve number method (Ponce 1996), accepted that other ratios are possible if supported by additional data. Subsequent studies in the United States and other countries document initial abstraction ratios λ between 0.00 and 0.38 (Ponce and Hawkins 1996), with 0.05 the most likely (Woodward et al. 2002).

Tabulated curve numbers are medians (NRCS 2001), which were readily determined graphically from observed rainfall and runoff in 1954. Alternatively, the NRCS (2001) uses the geometric mean to determine a watershed curve number if the values calculated from rainfall and runoff measured for each event are log-normally distributed (Yuan 1933). Yet, no one seems to have established the log-normality of curve number distributions. Thus, the major strength of the geometric mean is quantification of uncertainty with the standard deviation and confidence intervals.

Bonta (1997) used the arithmetic mean curve number but did not justify this choice with evidence that watershed curve numbers are normally distributed. Besides these central tendencies for curve numbers, Hawkins (1993) used a nonlinear least squares fit to determine curve numbers from a series of rainfall and runoff and introduced an asymptotic curve number for some watershed responses.

Many questioned the physical basis of the method soon after Victor Mockus originally conceptualized the curve number equation in 1954 (Ponce 1996; Garen and Moore 2005). Subsequent studies (e.g., Hjelmfelt 1980, 1991; Ponce and Hawkins 1996; King et al. 1999; Jacobs et al. 2003; Garen and Moore 2005; Michel et al. 2005; McCutcheon et al. 2006) examined the accuracy of the curve number method and identify specific weaknesses and limitations that are not widely recognized and that are rarely noted in textbooks. A chief limitation is the failure to account for the temporal variation in rainfall and runoff (Ponce and Hawkins 1996; King et al. 1999). Lacking an accounting for rainfall variation, the method fails to represent runoff rates, paths, and source areas upon which erosion and water quality simulations depend.

Methods

This study uses rainfall and streamflow measurements on 10 small, forested-mountainous watersheds in the Appalachian Mountains to evaluate curve number estimates of runoff in the eastern United States. The U.S. Forest Service and University of Georgia subtracted baseflow from streamflow measurements to derive watershed series of runoff (McCutcheon et al. 2006). Fig. 1 shows the locations of the watersheds, and Table 1 summarizes watershed characteristics. The ten watersheds range in size from 12.26 to 144.1 ha (30.29 to 356.1 acres) and in elevation from 488 to 1,591 m (1,601 to 5,221 ft).

Eight U.S. Forest Service experimental watersheds are used, including four within the Coweeta Hydrologic Laboratory in North Carolina (Coweeta 2, 28, 36, and 37), two within the Fernow Experimental Forest in West Virginia (Fernow 3 and 4), and two within the Hubbard Brook Experimental Forest in New Hampshire (Hubbard Brook 3 and 5). The U.S. Forest Service originally instrumented these watersheds starting in 1934, 1951, and 1958, respectively, to study how forest management affects the hydrologic cycle and water resources in the Appalachian Highlands (USDA 2004).

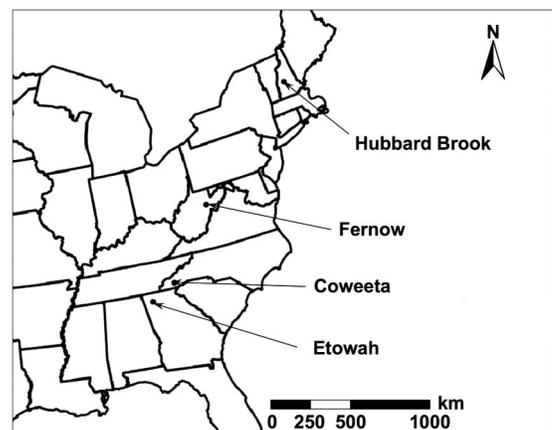


Fig. 1. Watersheds used to evaluate the curve number method for forested-mountainous watersheds of the Appalachian Highlands in the eastern United States

Table 1. Ten Small Forested Watersheds in the Mountains of the Eastern United States

Watershed	Period of record (years)	Area (ha)	Hydrologic soil group	Dominant aspect	Elevation range (m)	Channel length (m)	Mean slope (%)	Mean rainfall (mm yr ⁻¹)
Coweeta 2	68	12.3	B	South-southeast	709–1,004	392	60.2	1812
Coweeta 28	29	144.1	B	East	964–1,551	3,923	52.2	2340
Coweeta 36	59	46.6	B	East-southeast	1,021–1,542	1,327	65.3	2015
Coweeta 37	37	108.0	B	East-northeast	1,033–1,591	1,257	70.6	2015
Fernow 3	53	34.3	C	South	730–860	714	20.6	1450
Fernow 4	53	38.7	C	East-southeast	740–865	683	20.6	1450
Hubbard Brook 3	48	42.4	A: 39.9% B: 39.9% C: 20.2%	Southwest	527–732	961	21.4	1370
Hubbard Brook 5	43	21.9	A: 48.8% B: 48.8% C: 2.4%	Southeast	488–762	1,265	27.5	1370
Etowah 2	<2	28.0	B: 49.4% C: 50.6%	East-southeast	451–524	541	10.1	1448 ^a
Etowah 3	<2	31.0	B: 51.7% C: 48.3%	Southeast	518–710	600	12.6	1448 ^a

Note: Adapted from McCutcheon (2006).

^aSource: <http://pubs.usgs.gov/wri/wri934076/stations/02389000.html>.

This study also used rainfall and runoff measured on two small, forested watersheds in the mountainous Etowah River basin of northern Georgia. Although the other eight watersheds have sufficient records to define series of annual maximum rainfall and runoff, partial duration series of 21 months for Etowah 2 and 3 are all that are available to provide a sufficient number of events for analysis.

The Coweeta Hydrologic Laboratory is located in the Blue Ridge Physiographic Province of the southern Appalachian Mountains near Otto, North Carolina. Of the 17 instrumented watersheds at Coweeta, this study evaluated four that encompass the range in elevation, vegetation, soil depth, rainfall, and other climatic factors and hence, hydrologic response found in the Coweeta Hydrologic Laboratory (Swank and Crossley 1988). Soils are inceptisols and ultisols (Typic Hapludults and Humic Hapludults), with depths averaging 7 m (23 ft) at low-to-mid elevations (Coweeta 2 and 28) and <2 m (<6 ft) at higher elevations (Coweeta 36 and 37). Forest cover includes mixed oak, cove hardwood, oak-pine, and northern hardwood communities (Day et al. 1988). Coweeta 2 and 36 are reference watersheds that were uncut since 1927. Coweeta 28 is a multiple-use demonstration treatment of commercial harvest with clearcutting and thinning until 1964 but uncut since then. Measurement continued during the regrowth period until 1972 (Swank and Crossley 1988). Coweeta 37 was clearcut in 1963, allowed to regrow, and monitored until 1973.

The Fernow Experimental Forest lies in the Allegheny Mountain section of the unglaciated Allegheny Plateau. Almost all Fernow soils (including the sandstone, shale, and limestone soils) are well-drained medium textured loams and silt loams characterized by stoniness. Average soil depth to bedrock typically ranges from 91 to 152 cm (36 to 60 in.), and humus depth averaged approximately 6 cm (2 in.). The trees covering Fernow are in the central hardwood forest floristic province (Reinhart et al. 1963; Kochenderfer 2006). Of the 10 experimental watersheds, Fernow 4 is a reference on which loggers last harvested the trees circa 1905 to 1910. The U.S. Forest Service cut the trees on Fernow 3 by the diameter-limit method and clear-cutting at various times between 1958 and 1972 (McCutcheon et al. 2006).

The Hubbard Brook Experimental Forest, located in the White Mountain National Forest, was subject to extensive glaciation during the last ice age. This investigation used measurements from two of nine instrumented watersheds. Hubbard Brook 3 is a relatively undisturbed reference watershed, whereas a whole-tree harvest

occurred on Hubbard Brook 5 between October 1983 and May 1984. Soils are predominantly well-drained spodosols derived from glacial till with a sandy loam texture. The average of the highly variable soil depth, including unweathered till, is 2 m (6 ft) from surface to bedrock. Average humus depth at Hubbard Brook is 6.9 cm (2.7 in.). The second-growth forest is even-aged and consists of 80 to 90% northern hardwoods, the remainder is spruce-fir (USDA 2004; McCutcheon et al. 2006).

The Etowah River basin in northern Georgia is located in the Blue Ridge Physiographic Province. This study uses rainfall and runoff from two forested-mountainous watersheds within the northern portion of the Etowah basin in the Chattahoochee National Forest. Etowah 2 and Etowah 3 soils are fine loams, sandy loams, and sands. The Etowah forest cover consists of hardwoods and pines.

Curve Number Estimation

Tabulated curve numbers for each watershed are determined by using Table 2 for woods land use, hydrologic soil group (defined for each watershed), and a good hydrologic condition (i.e., protected from grazing with litter and shrubs covering the soil). For watersheds with soils classified into more than one hydrologic soil group, the procedure calculates an area-weighted-average curve number (Table 1).

This study compared tabulated curve numbers with watershed curve numbers determined by five procedures using gaged rainfall and runoff. These procedures include the median (NRCS 2001), geometric mean (NRCS 2001), arithmetic mean (Bonta 1997), nonlinear, least squares fit (Hawkins 1993), and standard asymptotic fit (Sneller 1985; Hawkins 1993).

Table 2. Curve Numbers for Woods Nationwide With Different Hydrologic Conditions and Soil Groups

Land use	Hydrologic condition	Hydrologic soil group			
		A	B	C	D
Woods	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30	55	70	77

Note: Initial abstraction is 20% of the maximum potential retention. Adapted from NRCS (2001).

By using measured rainfall-runoff ($P - Q$) pairs, the event maximum potential retention S is (Hawkins 1993)

$$S = 5(P + 2Q - \sqrt{4Q^2 + 5PQ}) \quad (1)$$

This study defined a series of annual maximum events for Fernow and Hubbard Brook on the basis of the annual maximum peak flow and the annual maximum event runoff volume for Coweeta. The Etowah watersheds had only 21 months of rainfall-runoff measurements; hence, this study compiled a partial duration series of all storms with ≥ 25 mm (1 in.) of rainfall.

For both the median and arithmetic mean, this study calculated the curve numbers for events from maximum potential retention S [Eq. (1)]. The geometric mean is found by first taking the logarithm of the event maximum potential retention S found by using Eq. (1), $\log S$; finding the arithmetic mean of the series, $\overline{\log S}$; and then estimating the geometric mean maximum potential retention, $10^{\overline{\log S}}$. The curve number is then $CN = 100 / (1 + 10^{\overline{\log S}} / \alpha)$ in which $\alpha = 254$ mm (10 in.).

The fourth method uses a nonlinear, least squares fit to find the curve number that minimizes the sum of squared differences between observed and estimated runoff for each series. Use of the logarithm of observations linearized the nonlinear equation.

The standard asymptotic method first ranks the rainfall series and then the runoff series; the procedure then matches rainfall and runoff having the same frequency of occurrence to compute corresponding curve numbers. Frequency matching does not necessarily pair the event runoff with the rainfall that caused the response.

Sneller (1985) and Hawkins (1993) identified three types of watershed responses (standard, violent, and complacent). The standard response occurs when the rainfall-runoff ratio becomes constant for increasing rainfall. In these cases, the curve number as a function of rainfall P [$CN(P)$] decreases to an asymptotic constant CN_∞ (Fig. 2) or $CN(P) = CN_\infty + (100 - CN_\infty) \exp(-kP)$ with $k =$ the fitting coefficient or rate constant that describes the curve number approach to the asymptotic constant CN_∞ . Sneller (1985) found the standard response on 80% of 70 watersheds investigated. Hawkins (1993) found 70% of 37 watersheds investigated to have a standard response. A violent response occurs when runoff begins after rainfall exceeds a threshold, observed in 10% of watersheds (Hawkins 1993), and is described as $CN(P) = CN_\infty [1 - \exp(-kP)]$. The fitting constant k is different for each watershed response, especially for standard versus violent. The complacent response occurs when the curve number does not approach an asymptotic limit and runoff is linearly dependent on rainfall $Q = CP$, where $C =$ empirical coefficient approximated

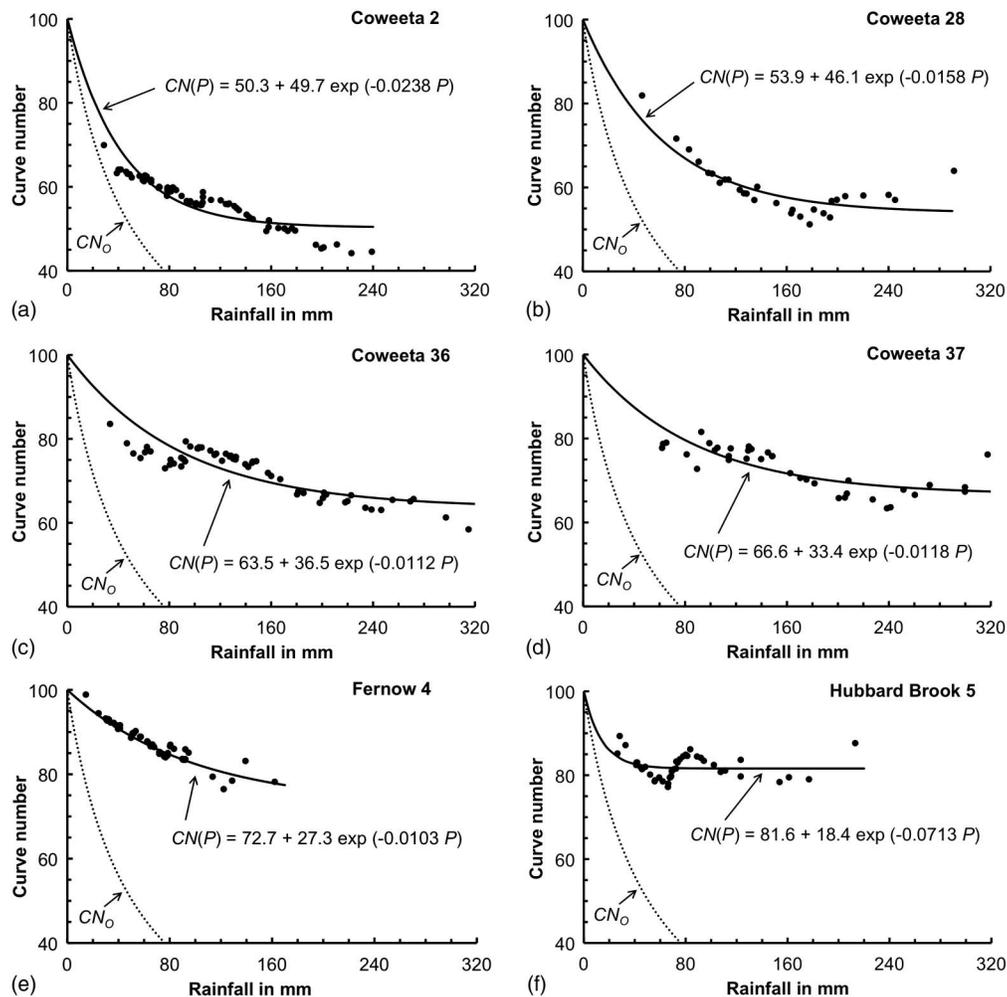


Fig. 2. Asymptotic curve numbers for selected watersheds using frequency matching of independently ranked rainfall and runoff series; $CN(P)$ is the curve number as a function of rainfall volume and $CN_o = 100 / (1 + 0.01969P)$ defines a threshold below which no runoff occurs until rainfall P in mm exceeds an initial abstraction of 20% of the maximum potential retention

by the percentage imperviousness in a watershed but that is normally estimated by using rainfall-runoff measurements. This response occurred on 16% of watersheds, which Hawkins (1993) attributed to channel and riparian imperviousness contributing to runoff, even during large storms. Sneller (1985) provides guidance on determining which of the three responses is appropriate for each watershed.

Statistical Analysis

This investigation estimated agreement by comparing observed series of runoff Q_i with the estimates \hat{Q}_i using the Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970)

$$E = 1 - \frac{\sum_{i=1}^n (Q_i - \hat{Q}_i)^2}{\sum_{i=1}^n (Q_i - \bar{Q})^2} \quad (2)$$

where n = number of storm events; and \bar{Q} = mean runoff for the series. An additional measure of goodness of fit is the coefficient of determination (Aitkin 1973)

$$D = 1 - \frac{\sum_{i=1}^n (Q_i - \hat{Q}_i)^2}{\sum_{i=1}^n (Q_i - \bar{Q})^2} \quad (3)$$

where \hat{Q}_i = improved estimate obtained by removing bias (i.e., regressing estimated runoff against observed runoff Q_i).

Both the Nash-Sutcliffe efficiency and coefficient of determination describe the degree of association between the observed and estimated runoff. A negative coefficient of efficiency can occur for biased estimates and indicates that the mean observed runoff is a better estimate than that calculated by using the curve number runoff equation. The Nash-Sutcliffe efficiency for unbiased estimates (assuming a linear relationship) ranges between 0 and 1, corresponding to the absence of correlation and perfect correlation, respectively. Compared to observed, biased estimated runoff occurs when the efficiency is less than the coefficient of determination

(Aitkin 1973). Although a good measure of the association between the observed and the calculated runoff, the coefficient of determination does not reveal systematic error (Aitkin 1973). Both the efficiency and coefficient of determination are always less than unity, and large values approaching unity indicate accurate estimates of runoff (Hope and Schulze 1981; McCuen et al. 2006; Jain and Sudheer 2008).

Statistical testing also compared observed with estimated runoff using the two-tailed, paired Student t -test. The null and alternative hypotheses determine whether differences are significantly different from zero at the 5% level of significance. This study also used Duncan (1955) multiple comparison tests to determine significant differences between observed and estimated runoff. While the curve number precision is reported to the nearest tenth of a unit, it is important to recognize that the accuracy is limited to (at best) the nearest unit.

Results

Table 3 presents tabulated and estimated watershed curve numbers. Tabulated curve numbers range from 41 (Hubbard Brook 5) to 70 (Fernow 3 and 4). For the central tendencies, Fernow 4 has the maximum estimated curve number, whereas Coweeta 2 has the minimum. Least squares fits range from 40 (Etowah 3) to 84 (Fernow 4), and asymptotic fits range from 38 (Etowah 3) to 83 (Hubbard Brook 3).

Geometric-mean curve numbers are generally larger (seven of 10 watersheds) than values estimated by the other procedures. The median provides the largest curve number for two of the other watersheds (Etowah 2 and Hubbard Brook 5), whereas the arithmetic mean is largest for Etowah 3. The arithmetic mean is smaller than the geometric mean but larger than the median for four of the 10 watersheds. For all 10 watersheds, these three central tendencies are larger than those estimated by using the nonlinear least squares and the asymptotic fits, except for the Hubbard Brook watersheds

Table 3. Tabulated and Estimated Curve Numbers with Uncertainty Ranges or Standard Error for Ten Forested-Mountainous Watersheds in the Eastern United States

Watershed	Tabulated	Median	Geometric mean	Arithmetic mean	Nonlinear least squares	Asymptotic (r^2 , SE)
Coweeta 2	55 (35–74)	58.0 (32.3–88.7)	58.2 (30.8–81.3)	57.4 (32.2–82.6)	45.8 (32.5–59.1)	50.3 (0.74, 0.708)
Coweeta 28	55 (35–74)	60.6 (37.3–88.8)	61.2 (34.4–82.6)	60.3 (48.6–72.0)	56.5 (45.0–68.0)	53.9 (0.76, 1.42)
Coweeta 36	55 (35–74)	71.5 (55.2–99.1)	75.1 (37.8–93.7)	72.5 (51.0–94.0)	68.1 (56.8–79.4)	63.5 (0.63, 1.46)
Coweeta 37	55 (35–74)	71.7 (50.7–99.2)	75.3 (62.3–81.9)	73.1 (53.9–92.3)	70.2 (60.5–79.9)	66.6 (0.60, 1.50)
Fernow 3	70 (51–85)	83.9 (62.5–99.2)	88.7 (48.4–98.7)	85.1 (68.2–102 ^a)	82.6 (74.3–90.9)	73.1 (0.90, 1.93)
Fernow 4	70 (51–85)	84.2 (71.5–98.5)	89.8 (49.4–98.4)	86.5 (71.8–101 ^a)	84.0 (76.9–91.1)	72.7 (0.91, 2.04)
Hubbard Brook 3	46 (27 ^b –66)	83.7 (57.4–98.7)	84.9 (55.9–96.0)	82.6 (63.3–102 ^a)	81.9 (72.1–91.7)	82.7 (0.001, 0.302)
Hubbard Brook 5	41 (23 ^b –61)	84.1 (58.2–97.2)	84.0 (55.0–95.7)	81.7 (61.9–102 ^a)	80.9 (70.9–90.9)	81.6 (0.15, 0.566)
Etowah 2	62.6 (43–80)	67.3 (39.9–85.4)	66.3 (42.7–73.9)	65.6 (46.1–85.1)	55.0 (45.1–64.9)	62.6 (0.26, 2.25)
Etowah 3	62.2 (42–79)	61.4 (34.3 ^b –77.3)	62.0 (37.7 ^b –74.2)	71.1 (52.8–89.4)	40.4 (33.1 ^b –47.7)	37.5 ^b (0.85, 3.89)

Note: This investigation expresses the uncertainty for (1) NRCS tabulated curve numbers based on $I_a = 0.2S$ using Table 10-1 for antecedent runoff conditions I and III, which Hjelmfelt (1991), NRCS (2001), and Hawkins et al. (2009) note approximately define the 90% confidence interval; (2) median as the range of curve numbers determined from each storm event; (3) the geometric and arithmetic means as the 95% confidence interval; (4) nonlinear least squares fit curve numbers as plus or minus the standard error, which is the square root of the minimum objective function $\sum_{i=1}^n (Q_i - \hat{Q}_i)^2$ divided by n (number of observations of rainfall and runoff) without correction for degrees of freedom in large samples, where Q_i is the observed runoff for rainfall-runoff pair i and \hat{Q}_i is the runoff for rainfall-runoff pair i computed from the curve number runoff equation (Hawkins et al. 2009); and (5) the asymptotic curve number as r^2 the Pearson correlation coefficient (McCutcheon et al. 2006) and SE, the standard error of the asymptotic curve number, which is the same as the standard error of the nonlinear least squares fit except \hat{Q}_i is the runoff computed from the curve number equation using the curve number (as function of rainfall P) for a standard watershed response $CN(P) = CN_\infty + (100 - CN_\infty) \exp(kP)$ in which CN_∞ is the asymptotic curve number and k is a fitting coefficient (Hawkins 1993).

^aCurve numbers greater than the limit of 100 are an unrealistic artifact of the calculation of the 95% confidence interval for the arithmetic mean, reported here solely to quantify estimates of uncertainty consistently.

^bNRCS (2001, Table 9-1, footnote 6, p. 9-3) recommends that curve numbers less than 30 be approximated as 30 and composite curve numbers (Hubbard Brook and Etowah) of less than 40 as 40 for all runoff calculations; however, this study reports values less than 30 or 40 to fully define uncertainty consistently.

Table 4. Multiple Comparisons Using Duncan Grouping of Runoff

Watershed	Duncan grouping						
Coweeta 2	A	A	A	A, B	A, B, C	B, C	C
Mean	24.51	24.26	23.62	20.62	18.47	15.52	11.33
Number	68	68	68	68	68	68	68
Method	GMQ	MQ	AMQ	TQ	OBQ	ASQ	LSQ
Coweeta 28	A	A	A	A	A	A	A
Mean	56.13	54.86	54.36	50.29	46.74	43.69	40.13
Number	29	29	29	29	29	29	29
Method	GMQ	MQ	AMQ	OBQ	LSQ	TQ	ASQ
Coweeta 36	A	A, B	A, B	A	A	B, C	C
Mean	79.76	74.17	71.88	70.36	64.77	55.63	39.88
Number	59	59	59	59	59	59	59
Method	GMQ	AMQ	MQ	OBQ	LSQ	ASQ	TQ
Coweeta 37	A	A	A	A	A	A, B	B
Mean	98.30	92.96	89.66	89.66	86.11	69.60	52.07
Number	37	37	37	37	37	37	37
Method	GMQ	AMQ	OBQ	MQ	LSQ	ASQ	TQ
Fernow 3	A	A, B	A, B	A, B	B	C	C
Mean	45.72	39.37	38.35	37.34	35.53	22.40	19.00
Number	53	53	53	53	53	53	53
Method	GMQ	AMQ	OBQ	MQ	LSQ	ASQ	TQ
Fernow 4	A	A, B	A, B	A, B	B	C	C
Mean	43.08	37.19	36.20	34.04	33.27	18.90	16.23
Number	53	53	53	53	53	53	53
Method	GMQ	AMQ	OBQ	MQ	LSQ	ASQ	TQ
Hubbard Brook 3	A	A	A	A	A	A	B
Mean	43.69	41.66	40.39	40.13	39.88	38.86	5.08
Number	48	48	48	48	48	48	48
Method	GMQ	MQ	OBQ	ASQ	AMQ	LSQ	TQ
Hubbard Brook 5	A	A	A	A	A	A	B
Mean	42.67	42.42	39.12	38.61	38.35	37.34	3.68
Number	43	43	43	43	43	43	43
Method	MQ	GMQ	OBQ	AMQ	ASQ	LSQ	TQ
Etowah 2	A	A	A	A	A	A	A
Mean	8.15	7.59	7.19	6.07	5.72	5.72	4.78
Number	14	14	14	14	14	14	14
Method	MQ	GMQ	AMQ	OBQ	ASQ	TQ	LSQ
Etowah 3	A	A	A	A	A	A	A
Mean	4.75	4.67	4.55	4.47	4.45	3.33	2.08
Number	17	17	17	17	17	17	17
Method	TQ	GMQ	AMQ	ASQ	MQ	LSQ	OBQ

Note: The ranked means of observed and estimated runoff (mm) with the same Duncan grouping letter (A, B, or C) are not significantly different at a 5% level of significance. Number refers to rainfall-runoff pairs. Method of determining runoff from a specific curve number is abbreviated as follows: geometric mean curve number (GMQ), median curve number (MQ), arithmetic mean curve number (AMQ), tabulated curve number (TQ), observed runoff (OBQ), asymptotic curve number (ASQ), and nonlinear-least-squares-fit curve number (LSQ).

where all five estimated curve numbers are comparable (Table 3). Nevertheless, the runoff estimated by the three central tendencies and least squares fit is never significantly different from the observed runoff. The asymptotic curve number estimates of runoff did not vary significantly from observed for seven of 10 watersheds (Table 4).

The uncertainties defined in Table 3 are not exactly comparable for all methods of determining the curve number but are similar, overall, except for the asymptotic curve numbers. The 90% confidence intervals for tabulated curve numbers typically are 34 curve

number units to 39 curve number units, whereas the ranges vary from 27 (Fernow 4) to 56 (Coweeta 2). The 95% confidence interval for the geometric mean is 20 (Coweeta 37) to 56 (Coweeta 36), whereas the arithmetic mean confidence interval varies from 23 (Coweeta 28) to 50 (Coweeta 2). Larger confidence intervals indicate poorer confidence in the expected watershed curve numbers. The Coweeta watersheds tend to have the greatest and least uncertainty in curve numbers based on central tendencies, indicating that the uncertainty ranges are not substantially different among the four locations in North Carolina, West Virginia, New Hampshire, and Georgia.

Much of the uncertainty in Fig. 2 is caused by rainfall-magnitude effects; curve numbers consistently decrease with increasing rainfall for all 10 watersheds (Hawkins 1993). Fig. 3 compares observed with estimated runoff to illustrate this trend, and Fig. 4 illustrates the bias in these runoff estimates.

Table 5 lists the Nash-Sutcliffe efficiency and the coefficient of determination for each of the six methods and 10 watersheds. From the negative Nash-Sutcliffe efficiencies, a simple average of the observed series of runoff provides a better estimate than calculations using NRCS-tabulated curve numbers for Etowah 2 and Hubbard Brook 3 and 5. Bias in tabulated curve numbers used to estimate runoff (when the efficiency and coefficient of determination are different) occurs for six of the 10 watersheds (Coweeta 36 and 37, Fernow 3 and 4, and Hubbard Brook 3 and 5). The Duncan multiple comparison tests in Table 4 confirm the significance of these biases.

Neither the coefficients of efficiency nor determination indicate that estimated runoff using tabulated curve numbers is well correlated (defined as >0.8 for this investigation only) with observations (Table 5). However, the central tendencies estimate runoff that is not substantially biased (coefficients and efficiency and determination are quite similar in magnitude) but also not well correlated (<0.8 for this investigation only) with observations. The limited correlation is seemingly caused by the large uncertainty shown in Table 3 and Figs. 3 and 4. For the five methods of calculating curve numbers from gaged watersheds, Coweeta 36 and 37 and Hubbard Brook 3 and 5, show little bias, as is evident from the similar magnitude of the Nash-Sutcliffe efficiency and the coefficient of determination. On the basis of the differences between the coefficients of efficiency and determination, three of 10 watershed runoff estimates indicate bias using the nonlinear least squares fit; five of 10 based on the asymptotic curve number indicate bias. However, the Duncan multiple comparison tests of significant differences in observed and estimated runoff are not fully consistent with all indications of bias in Table 5. None of the runoff estimates based on a nonlinear, least squares fit curve numbers are significantly different from observations. Runoff estimated from asymptotic curve numbers is significantly different for Coweeta 36 and Fernow 3 and 4. Nevertheless, none is as noticeable as the biases of the tabulated curve numbers for Coweeta 36 and 37, Fernow 3 and 4, and Hubbard Brook 3 and 5.

On the basis of the Nash-Sutcliffe efficiency, the median ranked first among curve numbers based on the central tendency for seven of 10 watersheds (Table 6), but neither the efficiencies nor these curve numbers are substantially different. The multiple comparison tests of central tendencies in Table 4 ranked the geometric mean first for seven watersheds; the geometric mean is ranked first or second for all watersheds, but none of the differences between estimated and observed runoff was significant for the central tendencies and least squares fit. In a choice between the median and geometric mean, the geometric mean curve number is the better choice (NRCS 2001) because the calculation of the 95 or 90% confidence intervals allow a probabilistic definition of the great uncertainty observed in event curve numbers for a watershed (Table 3).

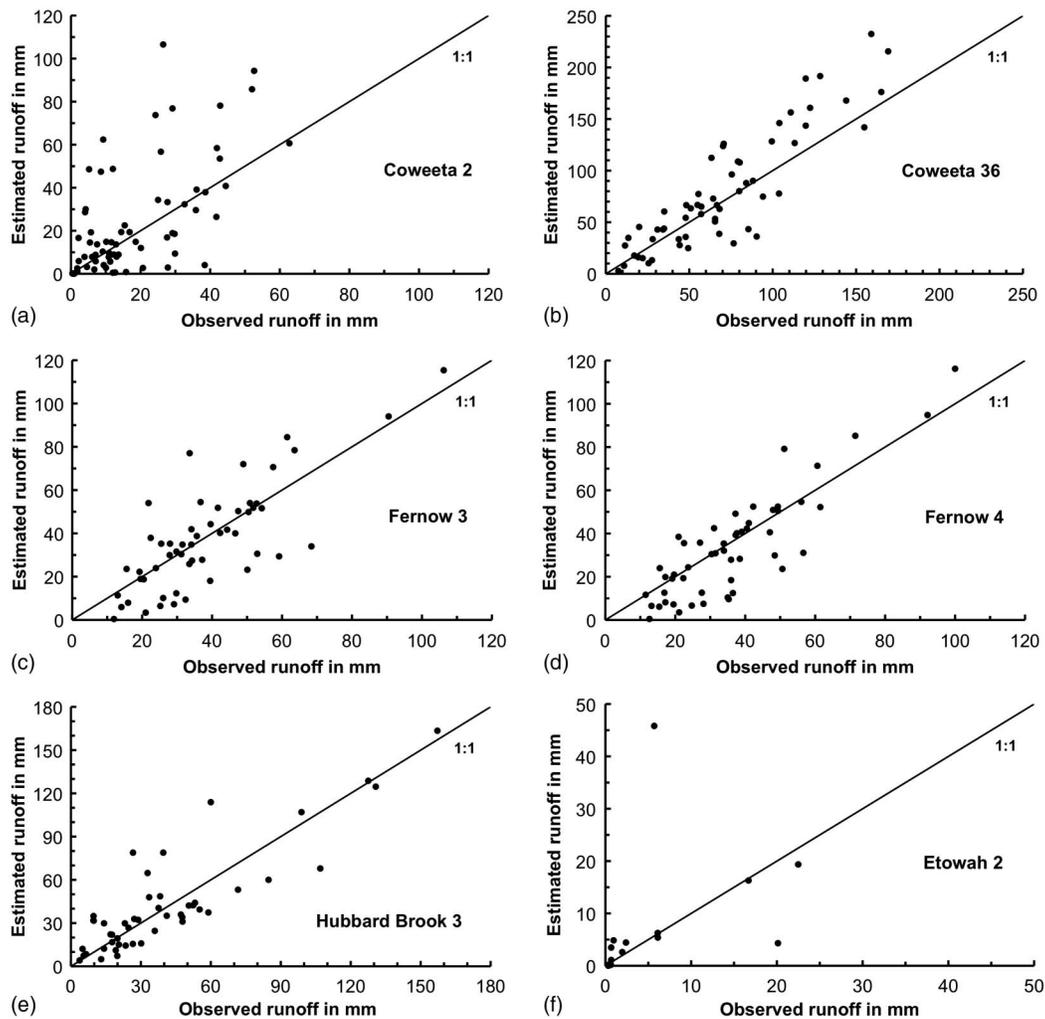


Fig. 3. Relationship between measured and estimated runoff; this investigation-based estimated runoff is on the arithmetic mean curve number of 57.4 for Coweeta 2; median curve number of 71.5 for Coweeta 36; median curve number of 83.9 for Fernow 3; median curve number of 84.2 for Fernow 4; median curve number of 83.7 for Hubbard Brook 3; and median curve number of 67.3 for Etowah 2

The range of curve numbers, which is the best expression of uncertainty to associate with the median (Table 3), is not intrinsically probabilistic (Hjelmfelt 1980, 1991).

Tables 3 and 6 suggest that calibrated curve numbers from paired or adjacent watersheds are similar for all locations. By using the Nash-Sutcliffe efficiency to rank the five methods to calculate curve numbers for gaged watersheds, Table 6 lists the maximum ranked method and the calibrated curve numbers selected for each of the 10 watersheds. The paired Student *t*-test established that, with one exception, none of the estimated runoff based on the best-ranked curve number is statistically different from that observed at a 5% level of significance, but the robustness of this test was not established.

The Duncan multiple comparison tests in Table 4 establishes that the estimated runoff based on the tabulated curve number is significantly different from the observed runoff for Coweeta 36 and 37, Fernow 3 and 4, and Hubbard Brook 3 and 5. The multiple comparison tests also reveal no significant difference (5% level of significance) in using the median, geometric mean, and arithmetic mean curve numbers to estimate runoff for all 10 watersheds.

For these 10 forested-mountainous watersheds, Tables 3–5 indicate that the distribution of curve numbers is approximately lognormal because the runoff estimated from the median and geometric mean curve numbers are not significantly different

(Yuan 1933). Yet, the arithmetic mean curve number falls between the median and geometric mean for four of the 10 watersheds and is similar to the median or geometric mean for the other six, indicating that an appropriate distribution is not uniquely identifiable.

Table 7 shows that the rainfall records should be suitable to determine standard asymptotic curve numbers because the maximum rainfalls recorded are greater than $58.496/k$. The only exceptions are Fernow 3 and 4, which are complacent. As indicated by Fig. 2, none of the 10 watersheds investigated exhibit violent responses.

Discussion

Tabulated curve numbers for woods provide runoff estimates for six of the 10 forested watersheds that are significantly smaller than observed (Table 4). For the Etowah and Hubbard Brook watersheds, the accuracy of tabulated curve numbers is so poor that the average of observed runoff provides better estimates or coefficients of determination and efficiency indicate bias. Tabulated curve number estimates are modestly correlated (Nash-Sutcliffe efficiency = 0.56) with observed runoff for only Coweeta 28. Smaller Nash-Sutcliffe efficiencies compared to coefficients of determination for at least six watersheds (Coweeta 36 and 37, Fernow 3 and 4, and Hubbard Brook 3 and 5) indicate that estimated

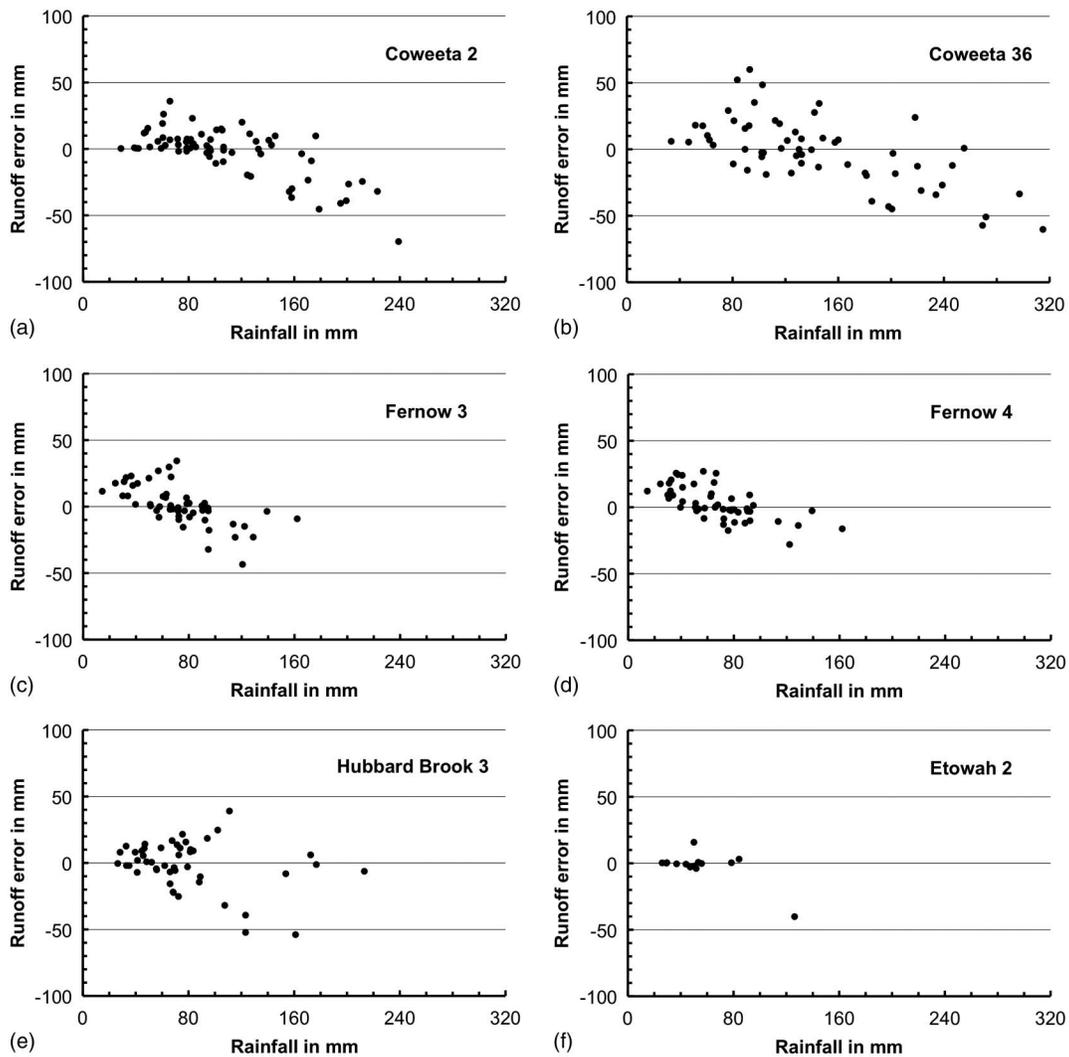


Fig. 4. Error (measured minus estimated runoff) as a function of rainfall; estimated runoff is based on the arithmetic mean curve number of 57.4 for Coweeta 2; median curve number of 71.5 for Coweeta 36; median curve number of 83.9 for Fernow 3; median curve number of 84.2 for Fernow 4; median curve number of 83.7 for Hubbard Brook 3; and median curve number of 67.3 for Etowah 2

Table 5. Nash-Sutcliffe Efficiency (E) and Coefficient of Determination (D) for Watershed Curve Numbers

Watershed	Tabulated		Median		Geometric mean		Arithmetic mean		Nonlinear least squares		Asymptotic	
	E	D	E	D	E	D	E	D	E	D	E	D
Coweeta 2	0.373	0.377	0.362	0.382	0.361	0.382	0.365	0.381	0.173	0.349	0.329	0.366
Coweeta 28	0.556	0.640	0.605	0.630	0.601	0.629	0.606	0.630	0.586	0.637	0.498	0.644
Coweeta 36	0.457	0.774	0.773	0.789	0.744	0.790	0.768	0.789	0.772	0.787	0.714	0.784
Coweeta 37	0.390	0.764	0.778	0.778	0.762	0.779	0.776	0.779	0.774	0.777	0.737	0.773
Fernow 3	0.217	0.621	0.611	0.613	0.557	0.608	0.609	0.611	0.603	0.614	0.323	0.620
Fernow 4	0.268	0.756	0.724	0.743	0.662	0.734	0.722	0.740	0.723	0.743	0.366	0.755
Hubbard Brook 3	-0.454	0.637	0.732	0.748	0.731	0.748	0.729	0.748	0.724	0.748	0.729	0.748
Hubbard Brook 5	-0.593	0.516	0.678	0.707	0.679	0.707	0.674	0.708	0.668	0.709	0.674	0.708
Etowah 2	-0.096	0.108	0.059	0.134	0.036	0.129	0.017	0.125	-0.715	0.053	-0.096	0.108
Etowah 3	0.099	0.141	0.101	0.140	0.099	0.141	0.100	0.140	-0.339	0.011	-0.500	0.008

runoff using tabulated curve numbers only marginally correlates to observed runoff and may be biased (Aitkin 1973; McCuen et al. 2006). When a tabulated curve number consistently underestimates runoff from undeveloped forest, the effect of urbanization will be consistently overestimated, and drainage oversized, perhaps explaining part of the annual overdesign costs estimated to be

as great as \$2 billion per year in the United States (Schneider and McCuen 2005).

Causes of inaccurate runoff estimates using tabulated curve numbers in these forested watersheds are unclear. The original information used to estimate the tabulated curve numbers for woods is no longer available (Hawkins et al. 2009). Thus, this study

Table 6. Representative Curve Numbers, Uncertainty, Degrees of Freedom, and Paired Student *t*-tests

Watershed	Procedure ^a	CN (range) ^b	Degrees of freedom	<i>t</i> -statistic	Probability < <i>t</i>
Coweeta 2	Arithmetic mean	57.4 (32.2–82.6)	67	–2.138	0.036
Coweeta 28	Arithmetic mean	60.3 (48.6–72.0)	28	–0.950	0.350
Coweeta 36	Median	71.5 (55.2–99.1)	58	–0.502	0.617
Coweeta 37	Median	71.7 (50.7–99.2)	36	0.020	0.984
Fernow 3	Median	83.9 (62.5–99.2)	52	0.505	0.616
Fernow 4	Median	84.2 (76.5–98.9)	52	1.655	0.104
Hubbard Brook 3	Median	83.7 (57.4–98.7)	47	–0.473	0.639
Hubbard Brook 5	Geometric mean	84.0 (80.8–86.7)	42	–1.165	0.250
Etowah 2	Median	67.3 (39.9–85.4)	13	–0.656	0.524
Etowah 3	Median	61.4 (34.3–77.3)	16	–0.866	0.400

Note: CN = curve number; the uncertainty is the range or 95% confidence interval.

^aProcedure selected based on the ranking of the coefficients of efficiency (*D*, Table 4).

^bUncertainty for the median is the range and 95% confidence interval for geometric and arithmetic means.

Table 7. Standard Asymptotic Watershed Responses for Frequency-Matched Rainfall and Runoff Series

Watershed	P_{\max} (mm)	k (mm ⁻¹)	$2.303k^{-1}$ (mm)
Coweeta 2	239	0.02382	96.7
Coweeta 28	291	0.01575	146
Coweeta 36	315	0.01122	205
Coweeta 37	318	0.01177	196
Fernow 3	162	0.01142	202
Fernow 4	162	0.01031	223
Hubbard Brook 3	213	0.08283	27.8
Hubbard Brook 5	213	0.07126	32.3
Etowah 2	126	0.06016	38.3
Etowah 3	150	0.01988	116

Note: P_{\max} is maximum observed rainfall for period of record, and k is a fitting coefficient.

could not compare the uncertainties observed here for forested watersheds and the uncertainties associated with the wooded watershed or watersheds used to derive the tabulated curve numbers.

Attributing these estimation errors to procedural mistakes and misclassification is not plausible. Specifically, a concern in using the curve number method, in general, is that many soils may be misclassified, especially those in Groups B and C (Neilsen and Hjelmfelt 1998). However, misclassification cannot explain the large discrepancies in runoff estimation. For example, if the higher elevation Coweeta 36 and Coweeta 37 soils are hypothetically in Group C (as opposed to Group B), a curve number of 70 would better agree with curve numbers of 72 to 75 determined from rainfall-runoff observations. As recently as 2005, the Monongahela National Forest changed the Fernow soil hydrologic group from B to C, resulting in a curve number change from 55 to 70 (McCutcheon et al. 2006). However, even a change to Group D (77) would not match curve number estimates of 84 to 89 from the Fernow and Hubbard Brook rainfall-runoff observations. Moreover, Group D is inconsistent with the National Engineering Handbook (NRCS 2001) guidance, especially for steep mountain forests in which shallow water tables and waterlogged soils are rare. In addition, in U.S. national forests, in general, and in experimental forests, in particular, a good hydrologic condition is maintained and expected. As a result, neither the selection of the soil hydrologic group nor hydrologic condition could explain the bias in tabulated curve number for woods.

One approach for reducing these uncertainties is to understand the relation between the magnitude of curve numbers for a watershed and hydrologic responses. At Coweeta, curve numbers are substantially smaller for the low-to-mid elevation watersheds (Coweeta 2 and 28) compared to the two higher elevation watersheds

(Coweeta 36 and 37). These large differences in hydrologic responses reflect physical differences between watersheds, i.e., soil depth and annual evapotranspiration are much larger on the lower elevation watersheds (Swift et al. 1988), which increases the potential for soil moisture storage and controls subsurface flow during storm events (Hibbert and Troendle 1988; Hewlett and Hibbert 1966). Only approximately 10% of annual discharge occurs as storm runoff on lower elevation Coweeta watersheds compared to more than 30% on higher elevation watersheds (Hewlett 1967; Swift et al. 1988), which is consistent with the relative hydrologic response shown by this curve number analysis.

This investigation attributes the large ranges and 95% confidence intervals, in part, to the dependency of the curve number on rainfall magnitude. All 10 forested-mountainous watershed curve numbers displayed asymptotic curve numbers that are less than the median, geometric mean, and arithmetic mean, all associated with a 2-year return interval. Although this rainfall-magnitude dependency explains much of the uncertainty, other sources of uncertainty (e.g., antecedent moisture, rainfall intensity and duration, slope, watershed size, soil depth and other characteristics, and the season of the year and tree harvesting) are also likely to be important for some watersheds.

Only the two Fernow watersheds have a complacent response (Hawkins 1993). Fernow event curve numbers vary substantially with rainfall magnitude and do not approach an asymptotic curve number for the 53 years of record, thus strongly suggesting that curve numbers be determined for each design period of importance (McCutcheon et al. 2006). As a result, the asymptotic curve number is less likely than curve numbers based on the central tendencies to serve as a unique watershed curve number to translate design rainfalls into runoff for ungaged watersheds.

Another method to reduce uncertainties is to calibrate curve numbers by using locally gaged rainfall and runoff. For these forested-mountainous watersheds, the central tendencies and non-linear least squares estimates are equally capable of estimating runoff with, at most, a 5% error (Table 4). Thus, a single watershed curve number, with large uncertainty might be sufficient to represent the runoff response of Coweeta 28 and 37 and the Hubbard Brook watersheds. Coweeta 28 and 37 have among the largest ranges of annual maximum rainfall and are less sensitive to the smaller rainfall events that introduce greater uncertainty (e.g., Etowah) by increasing curve numbers in watersheds with a standard response (Hawkins 1993). The Hubbard Brook watershed responses, by contrast, quickly approach an asymptote, which is similar to the means and median, making these watersheds amenable to a single watershed curve number. The partial duration series of 14 to 17 events recorded on Etowah in less than two years

of monitoring may be too few to determine reliable curve numbers for gaged watersheds.

At Hubbard Brook, use of a single calibrated watershed curve number (with large uncertainty) is feasible but not for the two Fernow watersheds in which each design storm may require a separate curve number. The Etowah partial duration series seem to involve too few storms to determine whether the reliability of the curve number method is adequate to estimate runoff. Forested watershed response at Coweeta, Fernow, and Etowah may require separate curve numbers for 2-, 10-, and 100-year return intervals (Titmarsh et al. 1995; McCutcheon et al. 2006).

Any evaluation of the curve number method on a watershed or event basis should anticipate inconsistencies because of the formulation of the curve number method. The SCS only intended the tabulations (Table 2) to represent the typical response of wooded watersheds nationwide that have the same soil hydrologic group and soil cover and condition (Ponce 1996). As demonstrated in this paper, actual runoff responses for different watersheds and from storm to storm vary widely from the typical responses used by the SCS to derive the curve numbers for woods.

Establishing that the curve numbers for woods (Table 2) are not representative for forest runoff, in general, is currently infeasible. The variability from the typical runoff response from woods is unknown because the records and documentation for the development of curve number tables are no longer available (Hawkins et al. 2009). In addition, this investigation never intended these 10 experimental watersheds to be representative of woods (open forests with limited tree density) or forests nationwide despite many extrapolations from Coweeta, Fernow, and Hubbard Brook to understand the hydrology of the Appalachian Highlands and elsewhere. Because of the missing records, the likelihood of updating the NRCS curve number table (NRCS 1998, 2001) seems remote despite recommendations by Rallison and Miller (1982) and Schneider and McCuen (2005). Unfortunately, these curve numbers for select Appalachian Highland watersheds are not consistent enough to develop a limited supplement similar to past additions to the original tabulations (NRCS 2001, Chapter 9, Tables 9-3 and 9-4). More importantly, these results establish that regional curve numbers for forested-mountainous watersheds are necessary (and feasible from the close agreement obtained for the five paired watersheds).

Because of the high degree of uncertainty associated with event curve numbers for a given watershed, this investigation was unable to completely distinguish advantages in calculating curve numbers to estimate runoff that was not significantly different from observations. One exception was the asymptotic curve number that was only effective for 70% of the watersheds (Coweeta 2, 28, and 37, Hubbard Brook 3 and 5, and Etowah 2 and 3) in estimating runoff (Table 4), and even then, the significance testing was not robust enough (because of large uncertainty) to also distinguish poor goodness-of-fit and bias. Because of frequency matching, the asymptotic curve numbers were more precise than the curve numbers derived by the other four methods for which this study did not use frequency matching to determine watershed curve numbers. The estimated runoff may not have been significantly different from observed because of the uncertainty, but the Etowah watersheds had negative efficiencies so that the curve number runoff equation was not as good as a simple average of observed runoff during the 21 months of observation. For the Fernow watersheds and perhaps Coweeta 28, the difference in the coefficients of efficiency and determination indicated bias, even with the insignificant difference between estimated runoff and observed. Thus, this study finds that the asymptotic curve number is not reliable, generally, as a single watershed curve number to replace the geometric

mean or median for estimating runoff from forested- mountainous watersheds of the Appalachian Highlands. Nevertheless, when multiple curve numbers for a watershed must be associated with design rainfalls of different return intervals, the asymptotic fit is indispensable.

Runoff estimation using the nonlinear least squares fit was consistent with observations (Table 4), but the average observed runoff from the Etowah watersheds was better, and some bias was possible for Coweeta 2. Thus, only the central tendencies provided runoff estimates generally free of bias.

That the 95% confidence intervals for the arithmetic mean for the Fernow and Hubbard Brook watersheds exceeded 100 favored the NRCS (2001) procedures of using the median or geometric mean. Of these two, the geometric mean is procedurally superior in allowing probabilistic estimates of confidence intervals to interpret the determination of a single watershed curve number.

Conclusions and Practical Implications

Although the curve number method is widely used for estimating runoff from ungaged watersheds, substantial uncertainties are present when applied to forested watersheds of the mountainous eastern United States. Runoff estimates using tabulated curve numbers are unreliable to estimate runoff for nine of the 10 forested-mountainous watersheds investigated. Curve number selection for the forests of the Appalachian Highlands requires independent calibration to watersheds representative of regional landscape and hydrologic characteristics.

For some watersheds, the geometric mean curve number derived from an annual maximum series of observed rainfall and runoff from gaged watersheds (NRCS 2001) provides locally consistent estimates with a probabilistic basis. For some watersheds, each appropriate design storm required a different curve number.

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References

- Aitkin, A. S. (1973). "Assessing systematic errors in rainfall-runoff models." *J. Hydrol.*, 20(2), 121–136.
- Andrews, R. G. (1954). *The use of relative infiltration indices in computing runoff*, U.S. Soil Conservation Service, Fort Worth, TX.
- Bailey, A. S., Hornbeck, J. W., Campbell, J. C., and Eagar, C. (2003). Hydrometeorological database for Hubbard Brook experimental forest: 1955–2000, *General Technical Report NE-305*, U.S. Dept. Agriculture, Forest Service, Northeastern Research Station, Newton Square, PA.

- Bonta, J. V. (1997). "Determination of watershed curve number using derived distributions." *J. Irrig. Drain. Div.*, 123(1), 28–36.
- Day, F. P., Jr., Phillips, D. L., and Monk, C. D. (1988). "Forest communities and patterns." *Forest hydrology and ecology at Coweeta*, W. T. Swank and D. A. Crossley, Jr., eds., Ecological Studies 66, Springer-Verlag, New York, 141–149.
- Douglass, J. E., and Hoover, M. D. (1988). "History of Coweeta." *Forest hydrology and ecology at Coweeta*, W. T. Swank and D. A. Crossley, Jr., eds., Ecological Studies 66, Springer-Verlag, New York.
- Duncan, D. B. (1955). "Multiple range and multiple F tests." *Biometrics*, 11(1), 1–42.
- Garen, D. C., and Moore, D. S. (2005). "Curve number hydrology in water quality modeling: Uses, abuses, and future directions." *J. Am. Water Resour. Assoc.*, 41(2), 377–388.
- Hawkins, R. H. (1984). "A comparison of predicted and observed runoff curve numbers." *Water today and tomorrow, Symp. Proc.*, ASCE, Reston, VA, 702–709.
- Hawkins, R. H. (1993). "Asymptotic determination of runoff curve numbers from data." *J. Irrig. Drain. Eng.*, 119(2), 334–345.
- Hawkins, R. H., Ward, T. J., Woodward, D. E., and Van Mullen, J. A., eds. (2009). *Curve number hydrology: State of the practice*, ASCE, Reston, VA.
- Hewlett, J. D. (1967). "A hydrologic response map for the state of Georgia." *Water Resour. Bull.*, 3(3), 4–20.
- Hewlett, J. D., and Hibbert, A. R. (1966). "Factors affecting the response of small watersheds to precipitation in humid areas." *Proc., National Science Foundation Advanced Science Seminar: Int. Symp. on Forest Hydrology*, W. B. Sopper and H. W. Lull, eds., Pergamon Press, New York, 275–290.
- Hibbert, A. R., and Cunningham, G. B. (1967). "Streamflow data processing opportunities and application." *Proc., National Science Foundation Advanced Science Seminar: Int. Symp. on Forest Hydrology*, W. B. Sopper and H. W. Lull, eds., Pergamon Press, New York, 725–736.
- Hibbert, A. R., and Troendle, C. A. (1988). "Streamflow generation by variable source area." *Forest hydrology and ecology at Coweeta*, W. T. Swank and D. A. Crossley, Jr., eds., Ecological Studies 66, Springer-Verlag, New York, NY, 111–127.
- Hjelmfelt, A. T. (1980). "Empirical investigation of curve number techniques." *J. Hydraul. Eng. Div.*, 106(9), 1471–1476.
- Hjelmfelt, A. T. (1983). "Curve number: A personal interpretation." *Proc., Specialty Conf. on Advances in Irrigation and Drainage: Surviving External Pressures*, J. Borrelli, V. R. Hasfurther, and R. D. Burman, eds., ASCE, Reston, VA, 208–215.
- Hjelmfelt, A. T. (1991). "An investigation of the curve number procedure." *J. Hydraul. Eng.*, 117(6), 725–737.
- Hjelmfelt, A. T., Kramer, L. A., and Burwell, R. E. (1982). "Curve numbers as random variables." *Rainfall-runoff relationship*, V. P. Singh, ed., Resources Publications, Littleton, CO, 365–370.
- Hope, A. S., and Schulze, R. E. (1981). "Improved estimates of stormflow volume using the SCS curve number method." *Rainfall-runoff relationship*, V. P. Singh, ed., Resources Publications, Littleton, CO, 419–428.
- Jacobs, J. M., Myers, D. A., and Whitfield, B. M. (2003). "Improved rainfall/runoff estimates using remotely sensed soil moisture." *J. Am. Water Resour. Assoc.*, 39(2), 313–324.
- Jain, S. K., and Sudheer, K. P. (2008). "Fitting of hydrologic models: A close look at the Nash Sutcliffe index." *J. Hydrol. Eng.*, 13(10), 981–986.
- King, K. W., Arnold, J. G., and Bingner, R. L. (1999). "Comparison of Green-Ampt and curve number methods on Goodwin Creek watershed using SWAT." *Trans. ASAE*, 42(4), 919–925.
- Kochenderfer, J. N. (2006). "Fernow and the Appalachian hardwood region." *The Fernow watershed acidification study*, M. B. Adams, D. R. DeWalle, and J. L. Hom, eds., Springer, Dordrecht, Netherlands, 17–39.
- Mack, M. J. (1995). "HER—Hydrologic evaluation of runoff; The soil conservation service curve number technique as an interactive computer model." *Comput. Geosci.*, 21(8), 929–935.
- McCuen, R. H., Knight, Z., and Cutter, A. G. (2006). "Evaluation of the Nash-Sutcliffe efficiency index." *J. Hydrol. Eng.*, 11(6), 597–602.
- McCutcheon, S. C. (2006). "Rainfall-runoff relationships for selected eastern U.S. forested mountain watersheds: Testing of the curve number method for flood analysis." *Technical Rep.*, West Virginia Division of Forestry, Charleston, WV.
- Michel, C., Andréassian, V., and Perrin, C. (2005). "Soil conservation service curve number method: How to mend a wrong soil moisture accounting procedure?" *Water Resour. Res.*, 41(2), W02011.
- Mockus, V. (1949). "Estimation of total (and peak rates of) surface runoff for individual storms." *Interim survey report, Grand (Neosho) River watershed*, Appendix B: Exhibit, U.S. Dept. Agriculture, Washington, DC.
- Nash, J. E., and Sutcliffe, J. V. (1970). "River flow forecasting through conceptual models. Part I—A discussion of principles." *J. Hydrol.*, 10(3), 282–290.
- National Resources Conservation Service (NRCS). (1998). "Urban hydrology for small watersheds, version 2.1." *Technical Release-55*, U.S. Dept. of Agriculture, Washington, DC.
- National Resources Conservation Service (NRCS). (2001). "Section 4: Hydrology." *National engineering handbook*, U.S. Dept. of Agriculture, Washington, DC.
- Neilsen, R. D., and Hjelmfelt, A. T. (1998). "Hydrologic soil group assignment." *Proc., Int. Water Resources Engineering Conf.*, S. R. Abt, J. Young-Pezeshk, and C. C. Watson, eds., ASCE, Reston, VA, 1995.
- Ponce, V. M. (1996). "Notes of my conversation with Vic Mockus." (<http://mockus.sdsu.edu/>) (Jan. 17, 2011).
- Ponce, V. M., and Hawkins, R. H. (1996). "Runoff curve number: Has it reached maturity?" *J. Hydrol. Eng.*, 1(1), 11–19.
- Rallison, R. E., and Cronshey, R. G. (1979). "Discussion of runoff curve numbers with varying site moisture." *J. Irrig. Drain. Div.*, 105(IR4), 439–441.
- Rallison, R. E., and Miller, N. (1982). "Past, present and future SCS runoff procedure." *Rainfall-runoff relationships*, V. P. Singh, ed., Water Resources Publications, Littleton, CO, 353–364.
- Reinhart, K. G., Eschner, A. R., and Tremble, G. R., Jr. (1963). "Effect on streamflow of four forest practices." *Research Paper NE-1*, U.S. Dept. of Agriculture, Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA.
- Schneider, L. E., and McCuen, R. H. (2005). "Statistical guideline for curve number generation." *J. Irrig. Drain. Eng.*, 131(3), 282–290.
- Sneller, J. A. (1985). "Computation of runoff curve numbers for rangelands from Landsat data." *Technical Report HL85-2*, U.S. Dept. of Agriculture, Agricultural Research Service, Hydrology Laboratory, Beltsville, MD.
- Soil Conservation Service (SCS). (1975). "Urban hydrology for small watersheds." *Technical Release 55*, U.S. Dept. of Agriculture, Washington, DC.
- Swank, W. T., and Crossley, D. A. (1988). "Introduction and site description." *Forest hydrology and ecology at Coweeta*, W. T. Swank and D. A. Crossley, Jr., eds., Ecological Studies 66, Springer-Verlag, New York, 3–16.
- Swift, L. W., Jr., Cunningham, G. B., and Douglass, J. E. (1988). "Climatology and hydrology." *Forest hydrology and ecology at Coweeta*, W. T. Swank and D. A. Crossley, Jr., eds., Ecological Studies 66, Springer-Verlag, New York, 35–55.
- Titmarsh, G. W., Cordery, I., and Pilgrim, D. H. (1995). "Calibration procedures for rational and USSCS design flood methods." *J. Hydraul. Eng.*, 121(1), 61–70.
- USDA. (2004). "Experimental forests and ranges of the USDA forest service." *General Technical Report NE-321*, Forest Service, Northern Research Station, Newtown Square, PA.
- Woodward, D. E., Hawkins, R. H., and Quan, Q. D. (2002). "Curve number method: Origins, applications and limitations." *Proc., Second Federal Interagency Hydrologic Modeling Conference: Hydrologic Modeling for the 21st Century*, Subcommittee on Hydrology of the Advisory Committee on Water Information, Las Vegas, NV.
- Yuan, P. T. (1933). "Logarithmic frequency distribution." *Ann. Math. Stat.*, 4(1), 30–74.
- Yuan, Y., Mitchell, J. K., Hirschi, M. C., and Cooke, R. A. C. (2001). "Modified SCS curve number method for predicting subsurface drainage flow." *Trans. ASAE*, 44(6), 1673–1682.