Curve Numbers for Nine Mountainous Eastern United States Watersheds: Seasonal Variation and Forest Cutting

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Abstract: Many engineers and hydrologists use the curve number method to estimate runoff from ungaged watersheds; however, the method does not explicitly account for the influence of season or forest cutting on runoff. This study of observed rainfall and runoff for small, forested watersheds that span the Appalachian Mountains of the eastern United States showed that curve numbers calibrated for the growing season tended to be smaller than for the dormant season. Forest cutting tended to increase curve numbers. However, the increase in water yield following forest cutting on these watersheds only lasted 1 year to 11 years, thereby limiting the precision of the curve numbers estimated for these brief hydrologic effect periods. This study highlights the need to account for seasonal and forest cutting when estimating runoff from some forested watersheds. **DOI: 10.1061/(ASCE)HE.1943-5584.0000437.**

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Introduction

The curve number method (NRCS 2001, Chapter 10) estimates runoff with convenience and simplicity. Watershed moisture conservation for a short-term event, during which evapotranspiration is secondary, is the basis of the estimation of direct runoff Q from rainfall P

$$P = I_a + F + Q \quad (1)$$

where I_a = initial abstraction and F = watershed retention during the typical runoff response to a specified rainfall. Eq. (1) normally expresses all the volumes involved in the dimensions of depth, typically in millimeters or inches.

Both initial abstraction I_a and retention F vary with season and forest cutting. Increased initial abstraction I_a and retention F decrease runoff Q for the same event rainfall P. A deciduous forest with a full canopy maximizes evapotranspiration and interception of sunlight and rainfall P, resulting in increased initial abstraction I_a and reduced runoff Q. In contrast, a deciduous forest during the dormant season or after cutting has less evapotranspiration and rainfall interception by vegetation. Consequently, the influence of season and forest cutting should affect rainfall–runoff relationships and curve number calculations.

Mockus (1964) did not incorporate the effect of seasonal variation on runoff in the early uses of the curve number method, ignoring the influence of seasonal evapotranspiration and interception on initial abstraction, event retention, and watershed maximum potential retention. The curve number method is based upon an initial abstraction I_a equal to 20% of the maximum potential retention, which may not be appropriate for both dormant and growing seasons. Jacobs and Srinivasan (2005) found that runoff estimation with annually consistent curve numbers has limited application because some watershed responses vary substantially between seasons. In general, forests have greater evapotranspiration than nonirrigated agricultural or urban landscapes. Therefore, adjusting the curve number seasonally for forested watersheds may result in more accurate runoff estimation.

In addition to omitting seasonal effects, the original conceptualization of the curve number method did not account for the influence of forest management practices. Bosch and Hewlett (1982) reviewed the many studies of hydrologic responses to forest cutting in the United States, and most showed an initial increase in water yield following cutting, generally attributed to decreases in evapotranspiration. The effect of forest cutting on rainfall–runoff relationships has the potential to influence curve numbers in much the same way that seasonal affects do, yet these influences are not well established.

This study used records of rainfall and streamflow to calculate curve numbers for nine small, forested watersheds at four sites in the Appalachian Mountains of the eastern United States. This investigation compared curve numbers calculated for the growing and dormant seasons, as well as how curve numbers changed between the precutting and post-forest-cutting hydrologic effect periods.

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Methods

The Coweeta Hydrologic Laboratory in North Carolina, Fernow Experimental Forest in West Virginia, and Hubbard Brook Experimental Forest in New Hampshire are the source of long-term records of maximum annual precipitation and streamflow. Table 1 summarizes watershed attributes; Swank and Crossley (1988), Adams et al. (1994), and Likens and Bormann (1995), respectively, provide thorough descriptions. In addition to these long-term studies, this study used shorter, 21-month records from two small watersheds in the mountainous Etowah River basin of north Georgia in the analysis of seasonal effects only (Tedela et al. 2007).

Seasonal effects required defining the growing and dormant seasons for each of the reference watersheds (Coweeta 2 and 36, Fernow 4, Hubbard Brook 3, and Etowah 2 and 3). The period from the average spring leaf out (ranging from April 1 at Etowah to May 16 at Hubbard Brook) to fall senescence (ranging from September 16 at Hubbard Brook to November 1 at Etowah) was the basis for defining growing seasons. The comparisons were (1) with and (2) without a two-month seasonal transition period, which exhibited characteristics of both seasons and, when excluded, improved curve number calibrations (Tedela et al. 2007). For watersheds with multiyear observations, this study used the maximum annual series of rainfall and runoff, excluding events influenced by snow melt or frozen ground (NRCS 2001, Chapter 7, p. 7-1, Chapter 9, p. 9-1, Chapter 11, p. 11-6). For the brief records available from the two Etowah watersheds, this study analyzed partial duration series consisting of all storms with more than 25 mm of rainfall (Hawkins 1993). The USDA Forest Service and University of Georgia converted streamflow records to runoff using consistent hydrograph separation techniques (Hewlett and Hibbert 1967).

This investigation divided the observed rainfall and runoff series by season, resulting in a watershed series of curve numbers CN on the basis of

$$\mathrm{CN} = \frac{25{,}400}{5[P + 2Q - (4Q^2 + 5PQ)^{1/2}] + 254} \tag{2}$$

where the measured rainfall P and direct runoff Q from individual storm events are in millimeters. This study compared arithmetically averaged curve numbers for each season to estimate a mean for the growing season CN_g and for the dormant season CN_d, using the one-way analysis of variance (ANOVA) with a 0.05 level of significance.

This investigation used the paired-watershed approach to identify the influence of forest cutting on curve numbers during the hydrologic effect period. The comparison involved contrasting runoff from watersheds subjected to forest cutting (Coweeta 36, Fernow 3, and Hubbard Brook 5) versus that from the corresponding reference watersheds (Coweeta 37, Fernow 4, and Hubbard Brook 3) following a precutting (calibration) period. This study separated event rainfall and runoff pairs into precutting and post-forest-cutting hydrologic effect series, computed curve numbers for each event, and calculated arithmetic means. Similar to the analysis of seasonal effects, this analysis compared curve numbers for the precutting period CN_{pt} to curve numbers for the hydrologic effect period CN_{he}, using the one-way ANOVA with a 0.05 level of significance.

Results and Discussion

Seasonal Variation

Curve numbers computed for the growing season were smaller than for the dormant season for all watersheds, whether the two-month transition periods were included or excluded (Table 2). Coweeta 2 and Etowah 3 had the largest and smallest between-season differences in curve numbers, respectively. The difference in curve numbers between the dormant and growing season curve numbers for Etowah 3 was only 2.7 when transition periods were included and 5.2 when the transition periods were excluded (Table 2). The difference in curve numbers between the dormant and growing season curve numbers for Coweeta 2 was 14.1 when the transition periods were included and 11.6 when the transition periods were excluded (Table 2).

These seasonal differences in curve numbers at Coweeta are consistent with other studies of long-term soil moisture at this hydrologic laboratory. Helvey and Hewlett (1962) showed that average monthly water content in the top layers of soil is sinusoidal with the maxima at the end of the dormant season and minima at the end of the growing season. The annual cycle of soil moisture also correlates with the long-term average monthly streamflow. The watershed differences in curve numbers between Coweeta 2 and 36 are mainly due to much deeper soils and higher evapotranspiration on Coweeta 2 than 36.

Excluding the transitional months increased the difference in dormant and growing season curve numbers at half of the watersheds (Coweeta 36, Hubbard Brook 3, and Etowah 3), whereas the other three watersheds showed decreases. Thus, the exact definition

Table 1. Watershed Descriptions

Watershed	Treatment (water years)	Area (hectares)	Period of record (years)	Precutting period (water years)	Hydrologic effect period (water years)
Coweeta 2	Reference	12.3	68	—	—
Coweeta 36	Reference	46.6	59	—	—
Coweeta 37	Clear-cut (1963)	43.7	37	1944–1947, 1949–1951, 1953–1957, 1962 (13 years)[a]	1963–1973 (11 years)
Fernow 3	Diameter limit cutting (1958, 1963, 1968), Clear cut (1969–1970, 1972)	34.3	53	1951–1957 (7 years)	1969–1975 (7 years)
Fernow 4	Reference	38.7	53	—	—
Hubbard Brook 3	Reference	42.4	48	—	—
Hubbard Brook 5	Whole-tree harvest (1983)	21.9	43	1962–1982 (21 years)	1983 (1 year)
Etowah 2	Reference	28.0	< 2	—	—
Etowah 3	Reference	31.0	< 2	—	—

Note: (Swank and Crossley 1988; Adams et al. 1994; Likens and Bormann 1995; Tedela et al. 2007).
[a]Coweeta Hydrologic Laboratory did not measure streamflow during the 1948, 1952, and 1958–1961 water years.

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Table 2. Differences in Dormant and Growing Season Mean Curve Numbers and One-Way ANOVA Including and Excluding Transition Periods

Transition period	Watershed	CN_g (SE)	CN_d (SE)	$\lvert CN_g - CN_d \rvert$	**F**	p > **F**
Included						
	Coweeta 2	48.4 (2.4)	62.5 (1.8)	14.1	16.0	0.0002
	Coweeta 36	67.5 (1.8)	74.8 (2.0)	7.3	8.6	0.0048
	Fernow 4	80.9 (1.1)	89.7 (1.3)	8.8	17.3	0.0001
	Hubbard Brook 3	80.3 (2.1)	84.6 (1.9)	4.3	2.4	0.1312
	Etowah 2	65.3 (2.9)	72.3 (2.8)	7.0	1.9	0.1891
	Etowah 3	63.1 (3.4)	65.8 (1.9)	2.7	1.4	0.2630
Excluded						
	Coweeta 2	50.1 (3.2)	61.7 (3.2)	11.6	15.9	0.0003
	Coweeta 36	68.2 (2.9)	76.2 (2.4)	8.0	3.7	0.0620
	Fernow 4	81.5 (1.5)	89.3 (1.3)	7.8	14.6	0.0005
	Hubbard Brook 3	80.3 (2.1)	89.5 (1.2)	9.2	10.1	0.0032
	Etowah 2	64.3 (3.6)	69.8 (3.8)	5.5	2.6	0.1449
	Etowah 3	58.9 (4.4)	64.1 (1.7)	5.2	0.2	0.6750

Note: CN_g = curve number for growing seasons; CN_d = curve number for dormant seasons; SE = standard error; **F** = statistic calculated in the **F** test; and p = probability.

of the growing season did not have a consistent effect on curve numbers for pairs of watersheds or during the records of individual watersheds.

The one-way ANOVA showed that for three of the six watersheds in Table 2, the mean curve numbers for the growing season were significantly different from the dormant season values. If the transitions were included in the analysis, the dormant and growing season curve numbers for Coweeta 2, Coweeta 36, and Fernow 4 were significantly different, whereas the dormant and growing season curve numbers for Coweeta 2, Fernow 4, and Hubbard Brook 3 were significantly different with the transitions excluded from the analysis.

Neither of the Etowah watersheds showed a significant difference between seasonal curve numbers, probably because of the briefness of the 21-month records. The curve numbers for Coweeta 2 and Fernow 4 showed consistent responses with and without seasonal transitions, whereas results for Coweeta 36 and Hubbard Brook 3 were ambiguous.

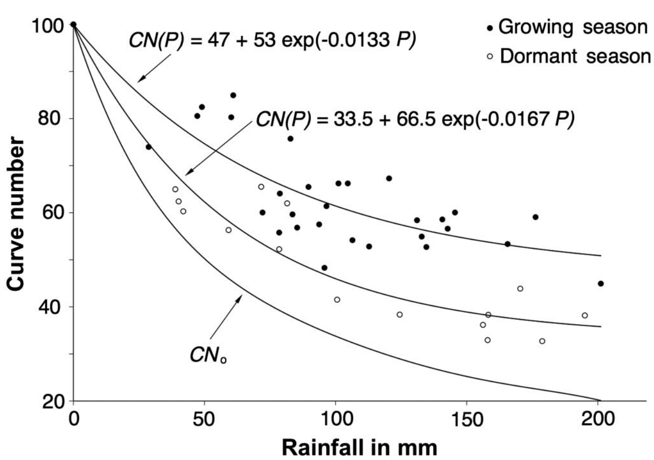

Fig. 1. Asymptotic curve numbers for growing and dormant seasons for Coweeta 2; for an initial abstraction of 20% of the maximum potential retention CN_0 represents a limit below which curve numbers are not valid for a given rainfall P in millimeters; the two equations for the curve number as a function of rainfall $CN(P)$ are the standard watershed response to dormant and growing season curve numbers for a rainfall P in millimeters

The asymptotic curve numbers (Hawkins 1993) for the growing and dormant seasons showed a distinct numerical difference for Coweeta 2 (Fig. 1). However, curve numbers and rainfalls for the other five watersheds were too uncertain to fit a standard asymptotic curve number equation and consequently are not shown.

Cutting Effects

Previous research evaluated the hydrologic responses to cutting mixed-hardwood forests in the Appalachians, on the basis of the analysis of 23 cutting experiments in the region (Douglass and Swank 1972; Swank et al. 1988), including some of the watersheds in this study. First-year increases in streamflow after cutting were a function of the percent reduction in stand basal area and an energy variable (insolation index) that represents energy theoretically received by watersheds with different slopes and aspects. These two variables explained 89% of the total variation in first-year increases in runoff. The duration of streamflow increases were highly variable and related to the rate of vegetation regrowth.

The paired-watershed analysis in this study also showed a wide range (1 year to 11 years) in the duration of runoff increases (hydrologic effects) following cutting (Table 1). Curve numbers computed for the precutting period were smaller than for the hydrologic-effect period for all three watersheds, and the differences were statistically significant for Coweeta 37 and Fernow 3 (only following the diameter limit cuts in 1958, 1963, and 1967; Tables 1 and 3).

Greater curve numbers observed after forest cutting indicate that runoff estimates would also be greater for a particular watershed compared to the runoff estimates before forest cutting. The differences between curve numbers computed for precutting and hydrologic effect periods are 8.4 and 16.6 for Coweeta 37 and Hubbard Brook 5, respectively. For Fernow 3, the precutting curve number differed from the curve number computed for the hydrologic effect period caused by the diameter-limit harvests of 1958, 1963, and 1967 by 8.1. The precutting curve number differed by 3.6 from the mean for the hydrologic effect period that included clear-cutting of parts of the watershed in 1969 and 1972 (Table 3). Hubbard Brook 5 and Fernow 3 had the largest and smallest differences in curve numbers between the hydrologic effect and precutting periods, respectively.

The one-way ANOVA (Table 3) showed that the curve number for Coweeta 37 before cutting and the curve number for the hydrologic effect period (1963 to 1973) were significantly different. The precutting curve number for Fernow 3 and the curve number

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Table 3. Curve Numbers for the Precutting and Hydrologic Effect Periods

Watershed	CN_t (SE)	CN_{pt} (SE)	CN_{he} (SE)	$\lvert CN_{pt} - CN_{he} \rvert$	**F**	$p > \mathbf{F}$
Coweeta 37	73.1 (1.6)	68.2 (2.3)	76.6 (2.2)	8.4	8.45	0.008
Fernow 3[a]	82.9 (5.6)	81.7 (1.1)	89.9 (1.3)	8.1	4.55	0.049
Fernow 3[b]	82.9 (5.6)	81.7 (1.1)	85.4 (1.2)	3.6	0.04	0.839
Hubbard Brook 5	81.7 (0.4)	80.6 (1.2)	97.2 (2.6)	16.6	—	—

Note: CN_t = curve number for the entire period; CN_{pt} = precutting curve number; CN_{he} = hydrologic effect curve number; SE = standard error; **F** = statistic calculated in the **F** test; and p = probability. Differences between CN_{pt} and CN_{he} may differ from $CN_{pt} - CN_{he}$ due to rounding.
[a]Period of effects from diameter-limit cuts in 1958, 1963, and 1967.
[b]Partial cutting.

determined during the effects from forest harvesting of 13%, 8%, and 6% of the basal area in water years (May to April) 1958, 1963, and 1968, respectively (Kochenderfer 2006), were also significantly different. However, the Fernow 3 curve number estimated from measurements during the hydrologic effects of clear-cutting parts of the watershed in water years 1969 to 1970 and in 1972 was not significantly different from the precutting curve number (Table 3).

The effect of the Hubbard Brook 5 whole-tree harvest on annual water yield was evident only for water year 1984 immediately after the cut (Hornbeck et al. 1997). The 1984 maximum runoff was clearly exceptional compared to the maximum rainfall that caused the runoff. This marked increase in water yield during 1984 produced the largest curve number (97) calculated for any annual maximum event for the 48-year record. Engineers and hydrologists rarely use curve numbers of this magnitude except for estimation of runoff from urban areas dominated by impervious surfaces (NRCS 2001, Chapter 9). The fewer years of record that are available to calculate curve numbers, the more that imprecision increases and the greater the chance that these short periods have curve numbers that are not statistically different from values for uncut forests.

Conclusions

The paired forested Appalachian watersheds used in this analysis span a wide range of hydrologic responses between watersheds, and some watershed records are among the longest available. The statistical tests for curve numbers derived for seasonal and forest-cutting effects captured this variability. Despite the large variability for all watersheds investigated, curve numbers for the dormant season were greater than for the growing season. This study established that the calculation of seasonal curve numbers is not sensitive to the exact definition of growing and dormancy seasons.

Likewise, this investigation showed higher curve numbers for the hydrologic effect period following forest cutting compared to the precutting period for all three watersheds evaluated. However, the capability to detect significant curve number changes associated with forest cutting will be strongly dependent upon the magnitude and duration of evapotranspiration decreases and runoff increases following cutting, which are highly variable for mixed hardwood forests. Because the hydrologic effect periods are temporary, any curve number estimate for forest-cutting practices will be even more imprecise due to the short duration of changes in runoff.

Taken collectively, curve number analysis does not consider major processes that regulate forest hydrologic responses; thus, the method is not reliable in the development of policies and standards for managing eastern hardwood forest runoff. Better management of forested watersheds and the effects on runoff seem to require a new simplified rainfall–runoff relationship consistent with curve number procedure.

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