

EXAMINATION OF CURVE NUMBERS FROM A SMALL PIEDMONT CATCHMENT UNDER 33 YEARS OF NO-TILL CROP MANAGEMENT

Dinku M. Endale*, Harry H. Schomberg, Dwight S. Fisher and Michael B. Jenkins

USDA-ARS J. Phil Campbell Sr. Natural Resource Conservation Center,
1420 Experiment Station Road, Watkinsville, GA 30677

*Corresponding Author. Phone 706-769-5631. Email Dinku.Endale@ars.usda.gov

Abstract: The Curve Number (CN) method for estimating direct runoff from storm rainfall developed in the 1950's by the then USDA Soil Conservation Service has been adopted by large groups of users across the world. This has helped to gradually highlight its strengths and weaknesses. Recently users have identified the need for locally defined CN values to address concerns with regional and seasonal variations. We determined CN values from rainfall-runoff data gathered from 126 storms between 1976 - 2009 on a 2.7 ha instrumented catchment (P1), managed under no-till at the USDA-ARS research station in Watkinsville, GA. Summer crops included soybean, sorghum, millet, cotton and corn, with barley, wheat, crimson clover and rye as cover crops. Mean and median CN values were 36 and 31, respectively. In contrast, CN values from standard Tables for the conditions at P1 are approximately 60 to 70, indicating an expectation of greater runoff than was measured. On average, 6.5% of the rainfall was partitioned to runoff. Half of the events partitioned <1% to runoff. Hence, CN estimates for a historically eroded watershed under long-term no-till management proved similar to those of a pasture or meadow in good hydrologic condition. A proposed change to improve the CN method is to replace the current initial abstraction ratio (λ) value of 0.2 with 0.05. The median λ value in our study was 0.04 which is in close agreement with the proposed value. Future work will examine the variability of the CN values with season, crops, prior rainfall, and weather conditions and across time.

INTRODUCTION

In the 1950s, hydrologists at the then USDA Soil Conservation Service (SCS), after empirical analysis of large amounts of rainfall and runoff data from small catchments and hill-slope plots, developed the SCS Curve Number methodology for estimating event runoff from event rainfall with a minimal data set (Hawkins et al., 2009). The SI unit equivalent of the derived equation is:

$$Q = (P - I_a)^2 / (P - I_a + S) \quad \text{for } P > I_a; Q=0 \text{ for } P \leq I_a; \quad (1)$$

$$CN = 25400 / [254 + S] \quad (2)$$

Where Q is runoff (mm), P is rainfall (mm), I_a is the initial abstraction (mm) and equals to λS , with the ratio λ set at 0.2, and S is the potential maximum retention (mm).

Land use, conservation practice, hydrologic condition of soil cover, hydrologic soil group, and antecedent moisture conditions (AMC- now called antecedent rainfall

condition ARC) were used to estimate CN values from tables. Graphical charts were then used to enter P and CN to obtain Q. To develop CN from measured data one would solve Eq. 1 for S knowing P and Q (Hjelmfelt et al., 1982), or knowing P, Q and Ia, which equals the amount of rainfall at the start of runoff. With S determined, Eq. 2 can be used to solve for CN. This simple empirical model continues to be used today across the world and is a vital component of many popular hydrologic models in current use. Hawkins et al. (2009) have summarized the origin, development, role, application and current status of the CN method, and cite studies by several researchers and task forces working to improve the method by incorporating knowledge developed since the original formulation. Some inconsistencies, limitations and problems have been identified.

The CN method has had its fair share of critiques, notably related to the rather rigid use of the value 0.2 for the initial abstraction ratio λ . Research data across regions indicates a much smaller 0.05 value as more appropriate. The soil hydrologic classes can be expanded to include data bases that have been developed since the original formulation. In addition, there might have been bias in the original development from working with larger storms since the model appears not to work well for small storm events, which most storms are. The method shows variance with infiltration-based analysis and the role of prior rain is not clear. Sometimes, additional data have shown the CN equation to be at variance with patterns of observed rainfall-runoff. The model is also more sensitive to CN than rainfall depth. While measurement and analysis of rainfall and its characteristics abound (for example locally, regionally), ground truth data for CN are lacking. Concerns with regional and seasonal variation in CN have raised calls for the development of locally defined CN.

Our objective in this study was to derive and analyze CN values from rainfall-runoff data gathered from 1976 to 2009 on a 2.7 ha catchment (P1) at the USDA-ARS research station in Watkinsville, GA, in the Georgia Piedmont. During this period P1 has continuously been under no-till management. A summary of the cropping history is given in Table 1, and Figure 1 shows the soil and topographic layout. We hypothesize that even with such a small single catchment with unchanging topography, and perhaps soil textural characteristics, curve numbers will show much variability due to the variation in storm characteristics, seasonal weather and management patterns, cover as well as soil water conditions.

MATERIALS AND METHODS

Catchment: The research catchment P1 was established during the spring and summer of 1972 on 2.7 ha at the USDA-ARS J. Phil Campbell Senior, Natural Resource Conservation Center, Watkinsville, GA (83° 24' W longitude and 33° 54' N latitude). Slopes range from 2 to 7 percent. The catchment consists of three soil types: a gravelly Cecil sandy loam (clayey, kaolinitic thermic Typic Kanhapludults) with 2 to 6 percent slopes is dominant; a similar soil but with thinner solum, a gravelly Pacolet sandy loam, occurs on a smaller area on the 5 to 7 percent slopes; and a Starr sandy loam occupies the lower portion of the catchment on 2 to 4 percent slopes.

Table 1 Summary of cropping history at P1.

Year	Tillage	Spring-Summer		Fall-Winter	
		Crop	Years	Crop	Years
1972-1974	Conventional	Soybean	3	Fallow	2
				Barley	1
1975-2009	No-till	Soybean	12	Barley	6
		Grain Sorghum	12	Wheat	8
		Forage sorghum	3	Clover	11
		Cotton	5	Rye	9
		Corn	2		
		Pearl millet	1		
Total years	Conventional		3		3
	No-till		35		34

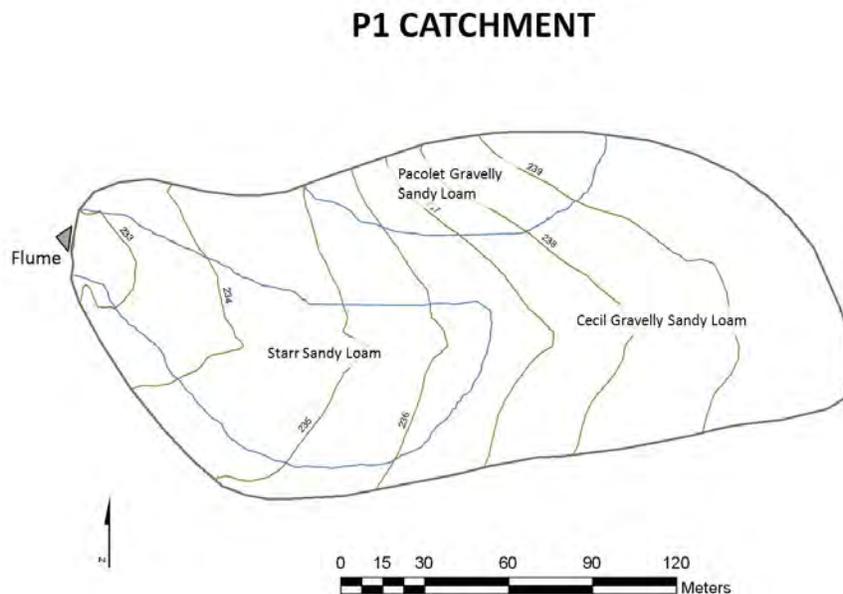


Figure 1 P1 Catchment showing soil distribution and elevation contours.

Research started at P1 in 1972 to evaluate sediment and herbicide transport in runoff from a Piedmont watershed. The study was conducted cooperatively between the USDA-Agricultural Research Service and Environmental Protection Agency (Smith et al., 1978). As shown in Table 1, after 3 conventionally-tilled soybean crops, management converted to conservation cropping systems consisting of double-crop conservation tillage (no-till) rotations which have been maintained ever since (Langdale and Leonard, 1983; Endale et al., 2000). A gully formed during the conventional tillage phase on the lower part of the catchment which was renovated by establishing an 11-m wide (0.32 ha) fescue (*Festuca arundinacea* Schreb.) grassed waterway in October 1974 (Langdale et al., 1979). The

grassed waterway was converted back to the crop rotation during the summer of 1997 because of negligible soil losses from the catchment arising over the long conservation tillage history.

Hydrology: Until 1998, rainfall was gauged with a chart-based Fergusson-type weighing and recording rain gauge while flow was measured with a 0.762 m (2.5 ft) stainless steel H-flume of USDA specification (Brakensiek et al., 1979) located at the outlet and fitted with a chart-based Friez-type Fw-1 water-level recorder. Charts were manually processed to quantify and archive rainfall and runoff amounts. Beginning in 1998 the rainfall-runoff monitoring system was upgraded and automated. Rainfall was measured with a Texas Electronics Inc. (Dallas, Texas) TR525M tipping bucket rain gauge. Flow depth was measured with a Druck (New Fairfield, CT) submersible pressure transducer suspended in the stilling well of the flume. The rain gauge and transducer were connected to a Campbell Scientific Inc. (Logan, UT) CR10X data logger to process and save 5-min cumulative rainfall (mm) and runoff amounts (liters) in the data logger memory for downloading to a computer through a phone line or manually on to a storage module. The data logger was programmed to convert the transducer flow depth values into runoff rates using the standard flume calibration curve (Bos, 1978). In March 2006 the transducer-based water flow sensing was changed to one based on a Shaft Encoder (Campbell Scientific Inc.) because of occasional instability of the transducer.

Endale et al. (2000) have summarized 26-years (1972-1998) of runoff and sediment data from P1 that show impacts of the contrasting cropping systems on long-term runoff and sediment losses and residue production. The major conclusions after 26 years were:

- Double cropped conservation cropping system following conventional tillage cropping immediately reduced runoff and soil erosion.
- Conservation cropping system was essential to successfully combat accelerated erosive effects of high-energy storms following conventional tillage.
- Residue of $9.9 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ was produced over 20 years under conservation cropping systems. The residue modified surface soil properties that allowed more infiltration and therefore less runoff. Residue production did not exceed $2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ under conventional tillage system.

Curve Number Investigations: Rainfall and runoff data were compiled for CN analysis beginning in 1976, one year into conservation tillage management. The 1976-1990 data were already available in a spreadsheet after staff had digitized the charts. The 1991-1998 data came from current staff digitizing the charts which had been kept intact. From 1999 on the data were obtained from the data logger of the automated system. By going through rainfall-runoff graphs, 126 events were identified for analysis. Runoff varied from as little as 0.071 to as large as 1410 cubic meters. All runoff data except those that could not be quantified or could not be matched with the corresponding rainfall due to instrument, recording, processing, or some other error were included in the analysis. A common criticism of past CN evaluations has been that there was bias toward selecting larger storm events. The initial step was to chronologically tabulate by columns the selected events and enter details such as rainfall amount, start and end of rain times, the runoff start, peak and end times, and runoff amount in liters. Runoff expressed as depth

was tabulated next by dividing volumetric runoff by the catchment area. For each event the rainfall amount up to the start of runoff was determined next representing the initial abstraction (I_a ; Eq. 1). At this point, Q , P and I_a of Eq. 1 are known leaving S as the only unknown. The equation is solved for S and the results tabulated. Curve Numbers are then calculated using Eq. 2. Descriptive statistics were determined and graphs developed next.

RESULTS AND DISCUSSIONS

Descriptive statistics for considered parameters are given in Table 2. As expected, the standard deviations for all parameters were high indicating large variability. Values in Table 2 indicate a highly skewed distribution for runoff, percent runoff, peak flow, the retention parameter S and the initial abstraction ratio λ . As previously reported (Endale et al., 2000), no-till management of P1 continues to significantly limit runoff compared to when the catchment was managed under conventional tillage.

Table 2 Descriptive statistics for parameters in Curve Number analysis.

	Rainfall	Runoff	Peak		Initial	Retention	Initial	Curve
	P	Q	flow	Q/P	abstraction I_a	S	abstraction	Number
Statistics	mm	mm	L/s	%	mm	mm	ratio λ	CN
Mean	55.3	4.8	23.6	6.5	27.7	9604	0.15	36.3
Standard Error	2.7	0.8	4.4	1.0	1.8	2742	0.02	2.8
Median	46.9	0.3	1.9	0.6	24.0	577	0.04	30.6
Standard Deviation	30.8	9.4	49.2	11.0	19.8	30778	0.23	31.0
Minimum	10.4	0.0	0.0	0.0	0.1	15	0.00	0.1
Maximum	166.7	52.2	262.0	46.0	91.0	238436	0.97	94.3
Count	126	126	126	126	126	126	126	126
Confidence Level(95.0%)	5.42	1.65	8.7	1.94	3.50	5427	0.04	5.5

Despite a mean percent runoff of 6.5, partitioning of the rainfall into runoff was <1% in 50% of the events. Few large runoff events have skewed the mean. There was a 5% probability of exceeding a 35% Q/P ratio, and a 20% probability of exceeding a 10% ratio. The runoff partitioning on an annual rainfall basis is much smaller. Piedmont landscapes are prone to serious runoff problems when disturbed by tillage and left without proper cover. In a 1940-1959 study of conventionally tilled continuous cotton on plots close to P1, Hendrickson et al. (1963) found that about 21% of the 1250 mm yr⁻¹ of rainfall was partitioned into runoff. Endale et al. (2000) reported that runoff at P1 during the initial 2.5 years of conventional tillage practice averaged 180.4 mm yr⁻¹ compared to 22.9 mm yr⁻¹ during 24 subsequent years of conservation tillage-based management. Endale et al. (2006) also reported that in an adjacent 10-ha field, the percent annual rainfall partitioned into annual runoff from 1940 to 1984 had a median of 5.1 and mean of 6.7. This field has been in pasture for the latter 40 of the 45 years.

The calculated mean and median CN values at P1 were < 40, which support the observed low runoff generating potential of no-till management at P1. In contrast, the CN values from standard Tables (the NRCS National Engineering Handbook, Section 4, Hydrology) for conditions at P1 would be in the 60 to 70 range at antecedent rainfall condition II.

That is: for hydrologic soil group A (least runoff-prone; sand, loamy sand, sandy loam); row crops on straight row and with good hydrologic condition; and small grains on straight row and good hydrologic condition. The effect of the grass waterway was to reduce the Table-obtained CN values by approximately 3. Using a value of 63 for CN and 0.2 for the initial abstraction ratio in equations 1 and 2, the runoff estimate from the mean rainfall amount of 55 mm (Table 2) becomes 7.5 mm, which is 60% over the recorded mean runoff of 4.8 mm. According to the standard CN Tables, CN values in the 30 to 40 range are assigned to pastures or meadows in good hydrologic condition. Hence P1 is acting as such under the long-term no-till management. Nevertheless, there was a 30% probability of exceeding a CN value of 60 but with no correlation with runoff amount (i.e. for $CN > 60$, Q varied from very small to large). On the other hand a plot of CN versus Q/P (not shown) indicates CN values > 60 for $Q/P \geq 15\%$ approximately. Below a Q/P value of 15% the CN values are scattered in a band that approximately has its upper bound line at $CN = 80$, and its lower bound a line from $CN=0$ to $CN = 60$ at Q/P of 15% with a couple of values showing outside of these bounds either side.

There was agricultural drought in 13 of the 33 years whereby, in addition to reduced rainfall during crop growing season, annual rainfall was 747 to 1169 mm compared to the long-term average of 1250 mm. These years usually occurred in clusters: 1985-1988 (876-1007 mm); 1999-2002 (917-1169 mm); and 2006-2008 (747-1038 mm). Generally the mean number of annual runoff events was somewhat lower during these relatively 'dry' years than during the other 'normal-wet' years. However, the correlation for a regression of the number of the yearly runoff events against the annual rainfall proved low (r^2 0.19), but the slope (0.005) was significant while the intercept (-2.93) was not. As previously indicated, some but not many runoff events had not been considered because we could not accurately quantify the runoff due to errors.

A major thrust in recent times towards improving the CN method is the idea of replacing the initial abstraction ratio (λ) value of 0.2 with 0.05 (Hawkins et al., 2009). It is interesting that the mean λ value found in this study was 0.15. However, the median was 0.04. Hawkins et al. (2009) and others have pointed out that in the original selection of λ , 0.2 was in fact the slope of the median line for a regression of the initial abstraction I_a against the maximum storage potential S . So the data here support the call to changing λ to 0.05.

Hawkins et al. (2009) and others have suggested ordered pairs and asymptotic approach towards a more standardized method to calculating CN with a potential to include many smaller storms than the existing approach. Under this procedure, each of the rainfall and runoff data are sorted on a rank order which pairs the rainfall-runoff data on similar probability index. This means individual runoff events might not necessarily be associated with the rainfall that caused them. Curve Numbers are then calculated from these ordered pairs.

CONCLUSIONS

Long-term (33-yrs) continuous row crop management of a small Georgia Piedmont

catchment under no-till resulted in low mean and median CN values (30-40). Runoff partitioning was <1% of rainfall in 50% of the storms. The CN values from standard Tables for the conditions at the catchment are approximately double those found here. This led to a 60% over prediction of runoff when the standard CN method was used with the 33-yr mean rainfall and CN of 63. Curve Numbers exceeded a value of 60 for $Q/P \geq 15\%$. Below a Q/P value of 15% the CN values are scattered in a band that approximately has its upper bound line at $CN = 80$, and its lower bound a line from $CN=0$ to $CN = 60$ at Q/P of 15% with a couple of values showing outside of these bounds either side. The initial abstraction ratio λ had a median value of 0.04 in contrast to the standard value of 0.2, supporting recent calls for changing this standard value to 0.05. Agricultural drought, where annual rainfall was approximately 80 to 500 mm below long-term average, slightly reduced runoff events but the correlation of annual rainfall with the annual number of runoff events was weak.

In a calibration and verification study such as this, it is extremely important that the data accurately represent field conditions. Vigilance is required to scrutinize all data from digitized charts and more recent automated systems to make sure that volumes and synchronization of rainfall and runoff are accurate. For example, in earlier digitized data, where there was some doubt about the correct synchronization of the rainfall-runoff curves, the choice of the correct initial abstraction I_a proved critical. A small change in I_a produced large swings in CN and λ , including some times $\lambda > 1$, an unacceptable values for this model. Future work will more closely examine the variability of the CN values over the 33 years with respect to runoff amount, seasons, crops and crop stages, weather data, prior rainfall, and temporally. The suggested ordered pairs and asymptotic approach for calculating CN values (Hawkins et al., 2009) will also be investigated.

Acknowledgements: We appreciate the competent technical support of Stephen Norris, Robin Woodroof, Michael Thornton, Jeff Scarbrough, Tony Dillard, Eric Elsner, Clara Parker, Ronald Phillips, Dwight Seman, and all others before us who have contributed to the P1 legacy.

Disclaimer: The use of trade, firm, or corporation names is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

REFERENCES

- Brakensiek D.L., Osborn H.B., and Rawls W.J. (1979). Field Manual for Research in Agricultural Hydrology. Agricultural Handbook. USDA, Washington, D.C.
- Bos, M.G. (1978). Discharge Measurement Structures. Publication #20. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.
- Endale, D.M., Schomberg, H.H., and Steiner, J.L. (2000). "Long term sediment yield and mitigation in a small Southern Piedmont watershed" Intern. J. of Sediment Research 15(1), pp 60-68.

- Endale, D.M., Fisher, D.S., and Steiner, J.L. (2006). "Hydrology of a zero-order Southern Piedmont watershed through 45 years of changing agricultural land use: 1. Monthly and seasonal rainfall-runoff relationships" *Journal of Hydrology*, 316, pp 1-12.
- Hawkins, R.H., Ward T.J., Woodward, D.E., and Van Mullem, J.A. (eds). (2009). *Curve Number Hydrology. State of the Practice*. American Society of Civil Engineers.
- Hendricksen, B.H., Barnett, A.P., and Beale, O.W. (1963). *Conservation Methods for Soils of the Southern Piedmont*. Agriculture Information Bulletin No. 269. USDA, Washington, D.C.
- Hjelmfelt, Jr, A.T., Kramer, L.A., and Burwell, R.E. (1982). "Curve Numbers as random variables," In *Rainfall-Runoff Relationships*, Water Resources Publications, Littleton, CO, pp 365-370.
- Langdale, G.W., Barnett A.P., Leonard, R.A., and Fleming, W.G. (1979). "Reduction of soil erosion by no-till systems in Southern Piedmont" *Transaction of the ASAE*, 22, pp 82-86.
- Langdale, G.W. and Leonard, R.A. (1983). "Nutrient and sediment losses associated with conventional and reduced tillage agricultural practices". In Lowrance, R., Asmussen, T.L., and Leonard, R. (eds.). *Nutrient Cycling in Agricultural Ecosystems*. Univ. of Ga. College of Agric. Exp. Stations, Spec. Pub. 23. Athens, GA, pp. 457-467.
- Smith, C.N., Leonard, R.A., Langdale, G.W. and Bailey, G.W. (1978). *Transport of Agricultural Chemicals from Upland Piedmont Watersheds*. EPA-600/3-78-056. U.S. Environ. Protection Agency, Athens, GA, and U.S. Department of Agriculture, Watkinsville GA.