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CURVE NUMBER DERIVATION FOR WATERSHEDS DRAINING TWO HEADWATER STREAMS IN LOWER COASTAL PLAIN SOUTH CAROLINA, USA[1]

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ABSTRACT: The objective of this study was to assess curve number (CN) values derived for two forested headwater catchments in the Lower Coastal Plain (LCP) of South Carolina using a three-year period of storm event rainfall and runoff data in comparison with results obtained from CN method calculations. Derived CNs from rainfall/runoff pairs ranged from 46 to 90 for the Upper Debidue Creek (UDC) watershed and from 42 to 89 for the Watershed 80 (WS80). However, runoff generation from storm events was strongly related to water table elevation, where seasonally variable evapotranspirative wet and dry moisture conditions persist. Seasonal water table fluctuation is independent of, but can be compounded by, wet conditions that occur as a result of prior storm events, further complicating flow prediction. Runoff predictions for LCP first-order watersheds do not compare closely to measured flow under the average moisture condition normally associated with the CN method. In this study, however, results show improvement in flow predictions using CNs adjusted for antecedent runoff conditions and based on water table position. These results indicate that adaptations of CN model parameters are required for reliable flow predictions for these LCP catchments with shallow water tables. Low gradient topography and shallow water table characteristics of LCP watersheds allow for unique hydrologic conditions that must be assessed and managed differently than higher gradient watersheds.

(KEY TERMS: surface water/groundwater interactions; runoff; stormwater management; watershed management; curve number method; first-order streams.)

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INTRODUCTION

Land cover conversion from forested areas to residential and commercial use can alter site and watershed hydrology. Adverse downstream impacts have been shown to increase with the degree of impervious cover in developed watersheds (Arnold and Gibbons, 1996; Booth and Jackson, 1997; Booth *et al.*, 2002). The rainfall response of developed watersheds is characterized by higher runoff volumes and peak flows compared with the predevelopment condition

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(Arnold and Gibbons, 1996). In urban watersheds, large rain events typically produce rapid and significant surface runoff, resulting in flashy flow conditions that can have negative instream and downstream consequences — erosion, flooding, and water quality impairment — due to increased peak flow and volume as well as a reduced time of concentration over the landscape. Sustained groundwater flows also decrease due to reduced groundwater replenishment (Tang *et al.*, 2005; Walsh *et al.*, 2005).

In coastal watersheds, stormwater volume reduction is essential for water and ecological resource management and is typically considered a goal of coastal stormwater management programs (Holland *et al.*, 2004; Hitchcock *et al.*, 2010; Epps *et al.*, 2012). Stormwater regulations in South Carolina require on-site management of surface generated runoff when development takes place based on design storm criteria (SCDHEC, 2005). Site runoff is managed by application of stormwater control measures (also often referred to as "best management practices") that are designed to reduce post-development runoff with a target of predevelopment levels.

The most widely accepted method for calculation of pre- and post-development runoff due to rainfall response is the Soil Conservation Service (SCS) curve number (CN) method (SCS, 1972; USDA, 1986; Ponce and Hawkins, 1996). The SCS method is utilized under the critical and often questionable assumption that the ratio of actual runoff to potential runoff equals the ratio of actual retention to potential retention (SCS, 1972; Yu, 2012). The CN method was originally developed to predict outflows for small upland agricultural watersheds in the Midwest United States (U.S.), where conditions are very different from the Lower Coastal Plain (LCP) watersheds in terms of topography, methods of runoff generation, and groundwater influence (SCS, 1972). Since its development, the CN method has been used as a design tool to predict runoff on watersheds that have very different hydrologic conditions than for those watersheds in which the model was originally calibrated and validated (Ponce and Hawkins, 1996; Van Mullem *et al.*, 2002; Zhan and Huang, 2004; Yu, 2012). Beyond these thorough studies, limitations of the CN method have continued to be identified, and efforts have been conducted to explore the nonlinearity of the retention runoff relationship (Jain *et al.*, 2006; Babu and Mishra, 2012), to determine improved CNs to address these limitations (Wang *et al.*, 2008), and to improve empirical CN modeling with runoff predictions coupled with storm duration and antecedent moisture conditions (Sahu *et al.*, 2012).

The LCP of South Carolina has unique hydrologic conditions that differ from higher gradient upland watersheds. The LCP region is characterized by very flat topography and a shallow water table, both of which can influence runoff generation prediction in coastal first-order watersheds. Seasonal groundwater trends have implications related to the antecedent runoff condition (ARC) and CN predictions of direct runoff. High water table conditions that characterize wet ARC are dominant during the winter months. Direct runoff estimates using the average ARC (CN-II), as opposed to using CNs for dry (CN-I) and wet (CN-III) conditions, have the potential to be lower than actual runoff generation for high water table conditions and wet ARC. Conversely, direct runoff estimates using the average ARC will likely be higher than actual runoff generation for low water table elevations and dry conditions. Although the average ARC represents the central tendency for runoff generation for the watersheds of the LCP, runoff generation that is expected by this median CN may be less likely to occur for any given storm event. Wet and dry conditions persist during winter and summer months, respectively, and influence the fluctuation between periods of higher and lower runoff generation related to water table position. The seasonal trend of water table elevation influences ARC on a seasonal basis because of the close relationship observed. This trend in runoff generation should be accounted for CN applications for LCP headwater catchments. The use of the CN-II for average ARC in all design applications will likely result in systematic errors for direct runoff estimates that are related to seasonal trends in water table elevation and ARC. Runoff will likely be underpredicted during the winter months and overpredicted during the summer months when using the CN-II to calculate watershed discharge. For both focal watersheds in this study, groundwater elevations are higher in the winter months, approaching and exceeding the breakpoint water table elevations, that is, the elevations at which observed runoff generation begins to occur. High evapotranspiration (ET) rates during the summer months are accompanied by a decline in groundwater elevation that falls below these breakpoint water table elevations and subsequent dry ARCs persist.

Curve number parameter definition typically involves the use of much longer datasets that cover many watersheds (Hawkins, 1993). La Torre Torres (2008) used 51 storm events from a historic data (1964-1973) for the third-order forested LCP watershed in South Carolina to derive a weighted average CN value. The author reported weighted CN values ranging from 31 to 99 depending upon the seasonality, with an average of 72. Given the numerous hydrological complexities for lower coastal plain watersheds as described previously, and especially those related to highly variable seasonal runoff generation, the effective application of the CN method for runoff prediction has been questioned for these watersheds. The potential lack of accurate runoff predictions with the CN method in coastal watersheds can be attributed to the fact that the model was tested and developed for watersheds with very different characteristics and hydrologic conditions (Ponce and Hawkins, 1996). Furthermore, selection of a CN for a watershed is typically a function of the site-specific hydrologic soil group (HSG) and land cover/land use, and the CN is typically calculated from table values that have been developed from empirical data. Proper model parameter selection is crucial for reliable estimates of direct runoff, but even site-specific parameterization may not produce realistic results for some hydrologic conditions due to the assumptions that the model makes in regard to runoff generation.

Although the empirical Technical Release 55 (TR-55) method and CN model are simple and generally reliable for watershed outflow prediction in many cases, it often lacks true representation of rainfall allocation involved in runoff generation, such as infiltration and ET processes (Boughton, 1989). Representation of different hydrologic conditions can be accomplished by varying the parameters of the model to more accurately reflect watershed characteristics and conditions. Site-specific model adaptation is rarely conducted for the sake of simplicity despite guidance in TR-55 of conditions in site hydrology that could lead to poor model performance compared with typical CN method applications (Ponce and Hawkins, 1996).

Direct runoff estimates are more sensitive to changes in the CN than to rainfall variability. For example, Boughton (1989) has shown that a 15-20% increase in CN almost doubles direct runoff predictions, while a similar magnitude of CN reduction predicts nearly half the flow. CN selection involves the classification of site conditions by discrete categories as defined by TR-55. Natural deviation among these conditions and the potential for misclassification may produce unrealistic runoff estimates due to incorrect CN selection, especially for forested watersheds (Hawkins, 1993). Dual HSG soils further complicate CN selection. The additional site classification between drained and undrained conditions, generally determined by water table elevation, produces a large difference in runoff estimates. Direct measurement of site CN is difficult because the runoff generation is variable between storm events. The CN has been interpreted as a random variable that varies for any given storm based on the ARC (Hjelmfelt, 1991; Van Mullem *et al.*, 2002). The CN method offers very little guidance on accounting for differences in runoff generation between dry and wet conditions. The ARC has been previously referred to as antecedent moisture conditions (AMC) — in this work, ARC reflects TR-55 terminology (USDA, 1986). The TR-55 outlines the use of the SCS CN method for small urban watersheds and is most often used for stormwater practice design for developing watersheds. ARC was initially based on a five-day antecedent precipitation index (API) measured as rainfall totals for five days prior to a storm event (Van Mullem *et al.*, 2002). This index was later revised due to differences in regional definitions for site moisture (Ponce and Hawkins, 1996). No specific CN method guidelines for ARC determination are currently offered in TR-55. CN tables for site determination are listed for the average ARC (CN-II), interpreted as the median CN measured by analysis of rainfall and runoff data. A correction must be applied to the CN-II for the dry ARC (CN-I) and wet ARC (CN-III) (Ponce and Hawkins, 1996). These values are considered probabilistic upper and lower limits for runoff generation for a given site based on frequency analysis of the range of soil moisture conditions (Hjelmfelt, 1991; Ponce and Hawkins, 1996). Accounting for differences in runoff generation according to ARC is based on user discretion and site-specific parameter adjustments. Selection of the CN that is best suited to a given site or land parcel for runoff estimation and stormwater management criteria and design of respective practices can be difficult and may be prone to error.

This study was designed to define those factors that contribute to runoff generation and watershed outflow and to derive CNs based on observed hydrological measurements from two typical LCP watersheds in South Carolina, USA. The specific objectives of this study were to:

1. compare the CN selected using the TR-55 method (USDA, 1986) for two LCP watersheds to derived curve numbers (DCNs) from storm event data.
2. assess seasonal trends in DCNs related to runoff generation trends in LCP headwater catchments.
3. assess the relationship between measures of ARC and DCNs to define the determining factors for variability in runoff generation for LCP headwater streams as they relate to the use of the CN for direct runoff estimates.

MATERIALS AND METHODS

Curve Number Method

The CN method (as described in USDA Technical Release 55, 1986) assigns CNs to land surfaces based on HSG, cover type, treatment, hydrologic condition, and ARC. The CN is a function of maximum potential retention and can be interpreted as the degree of storage for the corresponding land cover conditions. Curve numbers have a range from 0 to 100 representing conditions from infinite infiltration to fully impermeable, respectively. Typical observed values range from 40 to 98; however, they may be lower for forested conditions (Van Mullem *et al.*, 2002). Soil types are assigned to one of four HSGs (A, B, C, or D) based on infiltration and hydraulic conductance properties, with "A" being the most permeable and "D" the most impermeable. Wet soils are typically assigned dual HSGs (A/D, B/D, C/D). These soils are assigned as Group D in the undrained condition and are better modeled as the alternate HSG ("A", "B", or "C") if adequately drained (USDA, 2007). Land cover types are further characterized by method of land management and hydrologic condition (Good, Fair, or Poor; based on runoff potential and typically measured by density of plant cover) where applicable. Critical for this study, ARC is a measure of antecedent moisture and it accounts for the range in runoff response that can be expected from dry (CN-I) to wet (CN-III) conditions. Most CN applications use the average ARC (CN-II) for runoff estimates.

The CN is a transformation of the variable S (mm), which represents the potential maximum retention of rainfall by the land.

$$\mathrm{CN} = \frac{25,400}{S + 254} \tag{1}$$

Where S is the greatest possible difference between rainfall (P, mm) and direct runoff (Q, mm) for any given storm event. Representative CNs for the combination of land cover conditions and soil composition for a site are weighted by respective area percentages to produce a weighed CN. The selected CN is then applied to the CN equation to predict the direct runoff to be expected from any given storm.

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{where } P \geq I_a, \text{ otherwise } Q = 0 \tag{2}$$

The remaining variable in the CN method is I_a (mm), or the initial abstraction. This variable represents the portion of rainfall that does not produce direct runoff. Initial abstraction is a composite of canopy interception, infiltration, surface storage, and other losses deducted from rainfall before direct runoff is produced (USDA, 1986). The quantity ($P - I_a$) is equivalent to the effective precipitation producing runoff for a storm event. The initial abstraction was originally set at 20% of S based on calibrations performed in the development of the model. This simplified the CN method to one independent parameter, P, once the site CN was defined.

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \text{ where } P \geq 0.2S, \text{ otherwise } Q = 0 \tag{3}$$

Once the CN for a site has been selected based on land cover and soils analyses, Equation (3) can be used to predict the runoff depth (Q) for any given rainfall (P) assuming I_a = 0.2.

Site Descriptions

Two LCP first-order watersheds with low gradient topography and relatively shallow groundwater typical of the region were evaluated toward curve number derivation. Upper Debidue Creek (UDC) (33.38° N, 79.17° W), located in coastal Georgetown County, South Carolina, is a 100 ha freshwater nontidal watershed that has been slated for development. Watershed 80 (WS80), a tributary of Huger Creek located in the Francis Marion National Forest (33.15°N 79.8°W) in Berkeley County, South Carolina, is a 160 ha freshwater nontidal watershed that is federally protected and serves as an undeveloped reference watershed. The UDC and WS80 watersheds are 75 km apart (Figure 1). Both watersheds are characterized by low gradient topography and shallow water table conditions. Each watershed is currently comprised of lowlands with mixed pine and hardwoods and upland pine stands typical of LCP watersheds. The primary soils in the UDC watershed are Lynn Haven (HSG B/D) and Leon (HSG A/D). These soils are formed of sandy marine sediment, are associated with very low gradient conditions, are highly permeable, and poorly drained (USDA, 1980). The primary soils on WS80 are Wahee (HSG D), Meggett (HSG D), Craven (HSG C), and Bethera (HSG D). These soils are formed of clayey Coastal Plain sediments and are typical of areas with low gradient topography USDA, 1974). The WS80 soils are poorly drained with high field capacity and have lower permeability than sandy soils.

Rainfall and outflow were monitored during 2008-2011 on these two first-order LCP watersheds. The location and monitoring design for each watershed are given in Figure 1 and with more detail provided elsewhere (Hitchcock *et al.*, 2008, 2009; Rogers *et al.*, 2009; Epps *et al.*, 2012). Monitoring and data collection included those for rainfall, stream stage, and flow by flume and weir, respectively, for UDC and WS80, and water table position at the edge of each

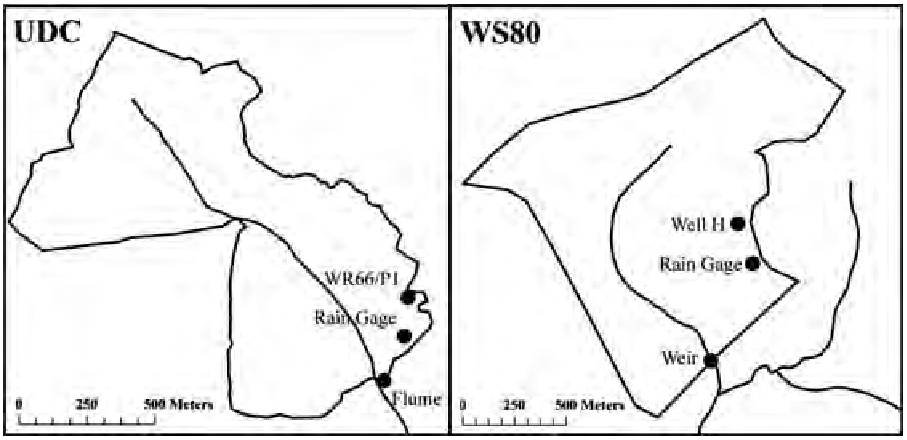

FIGURE 1. (Left) Upper Debidue Creek (UDC) Watershed and (Right) Watershed 80 (WS80) Delineations and Monitoring Networks, Including Outflow and Rainfall Gages, and Water Table Wells (WR66/P1 and Well H, respectively) (Epps *et al.*, 2012).

watershed. These data are used to determine runoff coefficients for these same two watersheds (Epps *et al.*, 2012). In this previous work, direct runoff volumes were determined using an empirical hydrograph separation technique, and these volumes were used for the CN derivation and assessment in this new analysis as described later.

Data Assessment and Derived Curve Numbers

Soil composition and land cover data for both watersheds were obtained from the SC Department of Natural Resources (SC DNR) to perform watershed composite CN-II calculations for average moisture conditions. All areas were classified as "woods in good condition" per the TR-55 guidance (USDA, 1986). *CN-I* and *CN-III* for dry and wet ARC were calculated based on a study of the relationship between these higher and lower CNs and the *CN-II* performed by Hawkins *et al.* (1985) (Equations 4 and 5). These equations are applicable to *CN-II* values in the range of 50-95 (Hawkins *et al.*, 1985).

$$\frac{\mathrm{CN}-I = CN-II}{2.281-0.01281*CN-II} \tag{4}$$

and

$$CN-III = \frac{CN-II}{0.427+0.00573*CN-II} \tag{5}$$

The focus of this study was to derive CNs based on the actual event data, while comparing these results to the typical CNs that would be selected for given watershed scenarios, rather than using event data collected over a given period from two LCP watersheds to define one specific CN for each watershed, thereby evaluating and comparing the prediction capabilities of the model on an event basis. Toward this goal, CN values determined from measured precipitation and flow were evaluated and will be referred to as DCN. Each storm event is represented as rainfall (P, mm) generating a measured runoff (Q, mm) for the given event to be assessed according to SCS CN methodology. Specific storm events greater than 20 mm were selected from measured data from both watersheds during the 2008-2011 period. Direct runoff estimates for storm events were calculated by the hydrograph separation method developed by Williams (2007) and completed by Epps *et al.* (2012) using the stream outflow data from UDC and WS80. For the purpose of deriving CNs from these data, only the surface generated contribution to watershed outflow — direct runoff — was used in this study as based on previous work (Epps *et al.*, 2012).

Curve number derivation was performed by solving the CN equation by the quadratic formula for S (maximum potential retention, mm), and the negative root was taken as the solution to preserve the relationship that $p = Q$ when $S = 0$. Values of S were derived by the following equation, a rearrangement of Equation (2) (Hawkins, 1993):

$$S = 5*[P+2Q-\sqrt{4Q^2+5PQ}] \tag{6}$$

where S was converted to respective CNs (dimensionless) based on Equation (1).

Sample means for dormant and growing season DCNs were compared with seasonal trends, first by an F-test to determine if the variances were equal. Depending on this outcome, the appropriate two-sample t-test for equal or unequal variance was used to determine if there was a significant difference between the dormant season and growing season mean DCN ($\alpha = 0.05$). The five-day API, measured as rainfall that occurred during the 120-h period prior to a given storm event, and antecedent water table elevation, measured during the hour just prior to the start of rainfall, were compiled for each storm as estimates of ARC for comparison to runoff generation. Linear regression was performed to assess the relationship between these estimates of ARC and DCNs at each watershed.

RESULTS AND DISCUSSION

Hydrological Monitoring

Hydrograph separation was performed for 23 storm events at UDC and 20 storm events at WS80 (Epps *et al.*, 2012). Details from each of these storms are given with respect to CN results described later. Water table elevation trends have been observed to be a function of seasonal differences in ET in LCP watersheds (Amatya *et al.*, 2006; Harder *et al.*, 2007; Rogers *et al.*, 2009; Epps *et al.*, 2012). Higher water table elevation and wet conditions dominate during the winter months when ET rates are low. Lower water table elevation and dry conditions dominate during the summer months when ET rates are high. This trend was observed for both watersheds over one year of continuous groundwater elevation measurements. UDC exhibited a water table elevation range of 1.5 m between maximum and minimum, whereas WS80 had a nearly 3 m range between maximum and minimum elevations. The water table rises during the fall months in response to rainfall, although the timing and persistence of higher water table elevations is subject to climatological variability from year to year. These data were used for the assessment of ARC and DCN relationships.

Derived Curve Numbers

Evaluation of the UDC and WS80 soils and land cover composition resulted in an identical CN-II for both watersheds using TR-55 tables for CN determination (Table 1). Based on the TR-55 methodology using CNs based on existing land cover and soils at each site, it was determined that both watersheds have a median CN (or CN-II) of 75 with corresponding value for both sites with CN-I and CN-III of 57 and 88, respectively. The UDC watershed includes several soils that are classified by the dual HSG for drained and undrained conditions, and the CN-II of

TABLE 1. Watershed Curve Numbers (CNs) as Determined by Technical Release 55 and Based on Spatial Assessment of Soils and Land Cover Composition for Upper Debidue Creek (UDC) and Watershed 80 (WS80).

	UDC (undrained)	UDC (drained)	WS80 (undrained)
CN-I	57	20	57
CN-II	75	37	75
CN-III	88	58	88

75 represents conditions for the undrained HSG. In the drained condition, UDC would expect a CN-II of 37. This CN is below the applicable range for CN-I and CN-III calculations by the equations developed by Hawkins *et al.* (1985) and calculated values in Table 1 serve only as estimates. Drained conditions apply to watersheds with dual HSG soils that have been adequately drained so that the seasonal high water table is kept at least 60 cm below the soil surface (USDA, 2007). Some drainage measures have been employed at UDC but saturated conditions with water table elevations above this level do occur.

Storm event rainfall, direct runoff, DCN values, and measures of ARC have been summarized for UDC storm events in Table 2 and WS80 storm events in Table 3. DCN values ranged from 46 to 90 at UDC and from 42 to 89 at WS80, similar to the range obtained by La Torre Torres (2008) for a nearby third-order forested watershed in the Francis Marion National Forest. Storm event CNs were expected to range greatly depending on the ARC at the time of rainfall, and these ranges are comparable to the range from CN-I to CN-III of 57 to 88 that was determined by TR-55. DCNs lower than the CN-I of 57 are representative of very dry ARC conditions on the two watersheds that are likely related to intermittent stream outflows and low antecedent water table elevation. Descriptive statistics for the DCNs have been summarized in Table 4.

The coefficient of variation (COV) was similar for storm events on both watersheds. The COV signifies that the DCNs vary similarly about the mean on both watersheds. The mean and median values for DCN were similar for each watershed with a mean of 70 and median of 72 at UDC and a mean and median of 68 at WS80, about 5% lower than the value obtained by La Torre Torres (2008) using measured storm event data for a large third-order watershed with about 96% forest and remaining 4% on roads and open and agricultural areas. The work by La Torre Torres (2008) also showed a COV value of 0.19, consistent with results from UDC and WS80 study sites. The mean CN for storm events was significantly less than 75 at UDC ($p = 0.047$) and also at WS80 ($p < 0.01$). This evidence suggests that direct runoff

TABLE 2. Summary of Storm Events for Upper Debidue Creek, Derived Curve Numbers, and Antecedent Runoff Condition Measures, Including Water Table Elevation and Five-Day Antecedent Precipitation Index (API). "—" Indicates that no data were available.

Date	Rainfall (mm)	Direct Runoff (mm)	Derived Curve Number	Water Table Elev. (m ASL)	Five-Day API (mm)
2008-07-24	30	1	70	—	11
2008-09-05	87	12	59	—	0
2008-09-11	25	4	86	—	81
2008-09-16	47	12	80	—	0
2008-09-25	42	10	80	—	1
2009-03-01	40	3	72	3.19	1
2009-04-02	60	9	70	3.38	18
2009-08-28	68	0	46	2.34	0
2009-11-10	78	2	49	2.42	5
2010-01-16	22	2	83	3.60	0
2010-01-25	23	5	89	3.73	17
2010-02-02	27	7	87	3.74	20
2010-03-02	24	8	90	3.61	0
2010-05-04	23	0	73	3.25	0
2010-06-20	36	0	60	2.85	0
2010-06-30	35	0	63	2.93	36
2010-07-10	35	0	65	2.95	19
2010-08-01	24	0	72	3.03	6
2010-08-13	40	1	66	2.97	40
2010-08-19	25	0	72	3.29	36
2011-06-29	20	0	76	2.49	0
2011-08-06	81	3	51	2.66	6
2011-08-25	67	5	59	2.76	13
Mean	42	4	70	3.07	13

Note: ASL, Above sea level.

TABLE 3. Summary of Storm Events for Watershed 80, Derived Curve Numbers, and Antecedent Runoff Condition Measures, Including Water Table Elevation and Five-Day Antecedent Precipitation Index (API).

Date	Rainfall (mm)	Direct Runoff (mm)	Derived Curve Number	Water Table Elev. (m ASL)	Five-Day API (mm)
2008-08-21	37	1	66	8.94	31
2008-09-05	98	2	42	8.26	1
2008-09-09	113	31	64	8.97	98
2008-09-25	65	5	61	8.62	1
2008-10-24	154	88	76	8.79	0
2008-11-29	47	4	68	8.64	0
2009-03-01	58	14	75	8.80	4
2009-04-02	67	23	78	9.02	35
2009-07-16	41	1	62	8.69	30
2009-07-22	29	0	68	8.80	0
2009-08-31	57	1	54	7.85	48
2009-11-11	70	0	44	7.53	2
2009-12-18	67	26	80	9.06	12
2009-12-25	31	7	84	9.06	3
2010-01-16	51	9	74	8.97	0
2010-01-25	42	19	89	9.08	25
2010-03-28	31	4	81	8.97	0
2010-05-04	52	0	52	8.07	0
2010-09-29	75	12	64	9.09	147
2011-02-02	66	10	67	8.88	12
Mean	63	13	68	8.70	22

Note: ASL, Above sea level.

estimates for the storm events on these two watersheds were not as high on average as TR-55 CN estimates would have predicted. In previous studies, the influence of smaller storms on CN measurement from event data has been shown to have a positive bias on CN estimates (Hawkins *et al.*, 1985; Hjelmfelt, 1991). This analysis for three years of data included storms that ranged from 20 to 154 mm,

TABLE 4. Select Descriptive Statistics for Storm Event Derived Curve Numbers for Upper Debidue Creek (UDC) and Watershed 80 (WS80).

	UDC	WS80
Count (*n*)	23	20
Mean	70	68
Standard error	2.65	2.88
Median	72	68
Standard deviation	12.72	12.87
Minimum	46	42
Maximum	90	89
COV	0.18	0.19

consistent with the range of 20-175 mm used by La Torre Torres (2008). The selected storm events represent relatively larger rain events over the time period for each watershed, but they do not represent even larger and less frequent storms that are typically used for direct site CN measurement. Despite this method of storm selection and data distribution, along with the potential for positive bias by smaller storms, storm event data indicated that the CNs for these two watersheds may be lower than those determined using the TR-55 method without site-specific hydrological data.

Measured storm event rainfall-runoff (*P*-*Q*) data pairs were plotted along with curves representing TR-55 determined CNs in Figure 2. In the *P*-*Q* plot, CNs decrease toward the bottom right-hand side of the graph. Traversing the plot, increasing rainfall amounts that produced the same amount of runoff are associated with decreasing CN values. The CN-I and CN-III curves are expected to encompass storm event data when ranging from dry ARC to wet ARC. TR-55 values capture the observed range for the most part as shown by (*P*-*Q*) pairs for storm events that fall within the range of these two curves. Several storms fall below the CN-I curve for dry ARC on both watersheds as discussed before, and these are related to very dry ARC conditions on these watersheds that TR-55 does not account for. The vertical distribution of storm events of similar rainfall amounts is evident when compared between both watersheds. This comparable distribution is indicative of the large range in runoff generation that has been observed on these LCP headwater streams for similar rainfall amounts at different locations (Eshleman *et al.*, 1994; Amatya *et al.*, 2000, 2006; Slattery *et al.*, 2006; Harder *et al.*, 2007; La Torre Torres *et al.*, 2011). For UDC, the CN-II that represents the drained condition has been included to demonstrate that it is a poor estimate for the CN at this site (Figure 2). All storm events in the dataset had DCN values above 37, and it is unlikely that the UDC watershed is drained adequately to warrant the drained soil classification for CN-II.

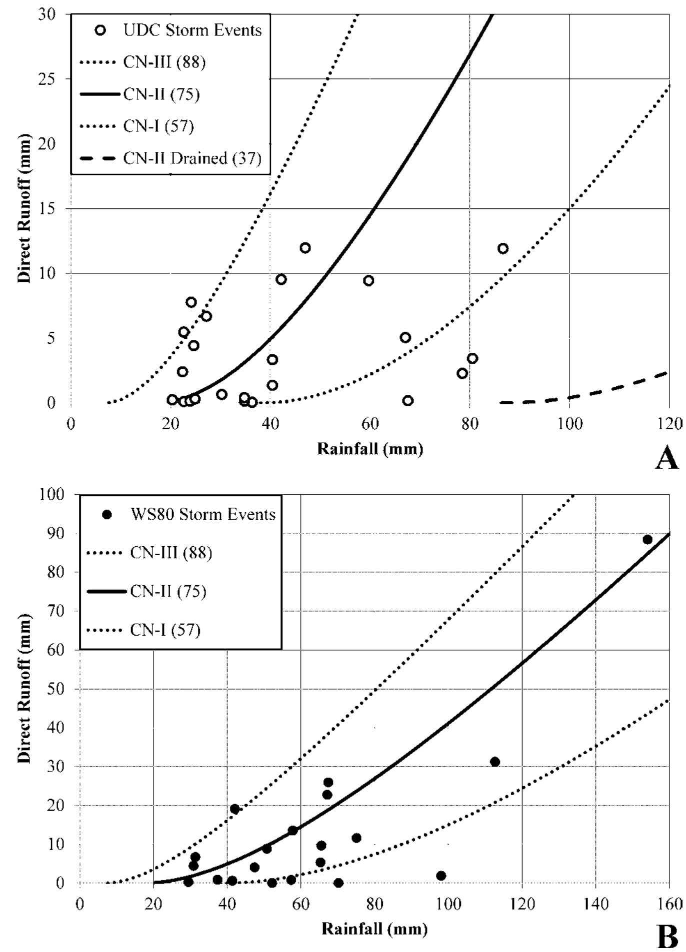

FIGURE 2. Actual Storm Event Rainfall-Runoff (*P*-*Q*) Data Pairs in Comparison with Selected Technical Release 55 Curve Number (CN) Curves for (A) Upper Debidue Creek (UDC) and (B) Watershed 80 (WS80).

Seasonal Trends in Curve Number

Storm events were separated into dormant season and growing season events based on frost dates as described in Epps *et al.* (2012) for each watershed and analysis of the DCNs indicates a seasonal difference (Table 5). The mean CN was significantly higher for dormant season storm events than for growing season storm events at both UDC ($p < 0.01$) and WS80 ($p < 0.01$) using the *t*-test for comparing the means (Table 5). This difference in mean DCN between seasons supports the discussion in Van Mullem *et al.* (2002) concerning seasonal variation in CN that has been observed in humid regions. Descriptive statistics for the seasonally separated storm event CNs are summarized in Table 5. The range in dormant season CNs overlaps the range in growing season CN on both watersheds, but it is mostly higher with less variation than for growing season events. This is evidenced by the lower COV measured for

TABLE 5. Summary for Derived Curve Numbers Separated by Dormant and Growing Seasons for Upper Debidue Creek (UDC) and Watershed 80 (WS80).

	UDC		WS80	
	Dormant	**Growing**	**Dormant**	**Growing**
Count (n)	5	18	7	13
Mean	84	67	77	62
Standard error	3.40	2.62	3.08	3.40
Median	87	68	75	64
Standard deviation	7.59	11.09	8.15	12.27
Minimum	72	46	67	42
Maximum	90	86	89	81
COV	0.09	0.17	0.11	0.20

dormant season storms at both watersheds. The growing season in the LCP of South Carolina is relatively long (mid-March to mid-November) and encompasses a wider range in ARC than the more dominantly wet and shorter dormant season. The seasonal difference in mean DCNs demonstrates seasonal trends in runoff generation that have been linked to trends in ARC.

This seasonal trend is displayed when storm event CNs are plotted by Julian day independent of the year of occurrence in Figure 3. TR-55 CNs have been plotted as straight lines to display seasonal trends as storm event runoff generation ranges between the CN-I and CN-III. Higher CNs are observed above the median CN-II and CN-III on dates during the beginning and end of the year that coincide with the dormant season when wet conditions dominate and runoff generation is higher. CNs below the CN-II and closer to the CN-I fall during the middle of the year and represent the growing season. The lowest CNs are observed between the Julian days of 180-250 representing the summer months. High ET during this period contributes to lower water table elevations and lower runoff generation that Sun *et al.* (2002) attributed to increased soil storage. This seasonal shift in runoff generation is subject to climatological variability from year to year as evidenced by the low CN (49) observed at UDC for the storm event on November 10, 2009. This storm event was associated with very dry conditions into the dormant season associated with low rainfall. Despite this variability, runoff generation and CN are linked to seasonal trends in ARC on LCP headwater streams. Therefore, the use of a single median CN by SCS methodology would not adequately predict runoff totals in the LCP because of this seasonal variability in resulting DCN values.

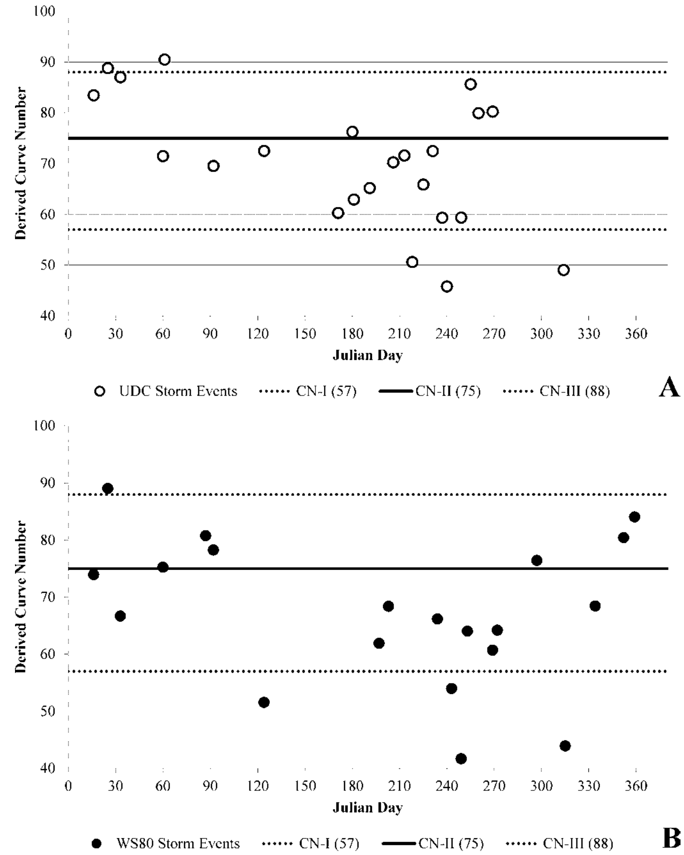

FIGURE 3. Derived Curve Numbers for (A) Upper Debidue Creek (UDC) and (B) Watershed 80 (WS80) Storm Events Plotted by Julian Day to Display Seasonal Trend in Runoff Generation. The horizontal line (CN = 75) is the selected CN for the watershed based on TR-55 criteria.

Runoff Generation and ARC

Previous classifications of CN for dry and wet ARC were applied based on the five-day API. There is a weak relationship between five-day API and DCN for storm events at UDC and WS80 (Figure 4). This result suggests that five-day API is not a good measure of ARC for headwater catchments in the LCP. As it was stated previously, soil moisture conditions on LCP watersheds are not determined by rainfall alone. The balance between rainfall, ET, and watershed outflows determines the water table elevation at any given time, while the water table elevation has the greatest effect on runoff generation. Thus, the range in CNs measured on LCP headwater catchments is more closely related to antecedent water table elevation than the five-day API. This observation was further supported when the relationship between antecedent water table elevation and DCN was observed (Figure 5).

The relationship between antecedent water table elevation and the DCN is strong and indicates that water table elevations determine CN-measured runoff generation in these LCP headwater streams. Results of linear regression illustrate this close relationship at UDC (r^2 = 0.75, p < 0.01) and at WS80 (r^2 = 0.66,

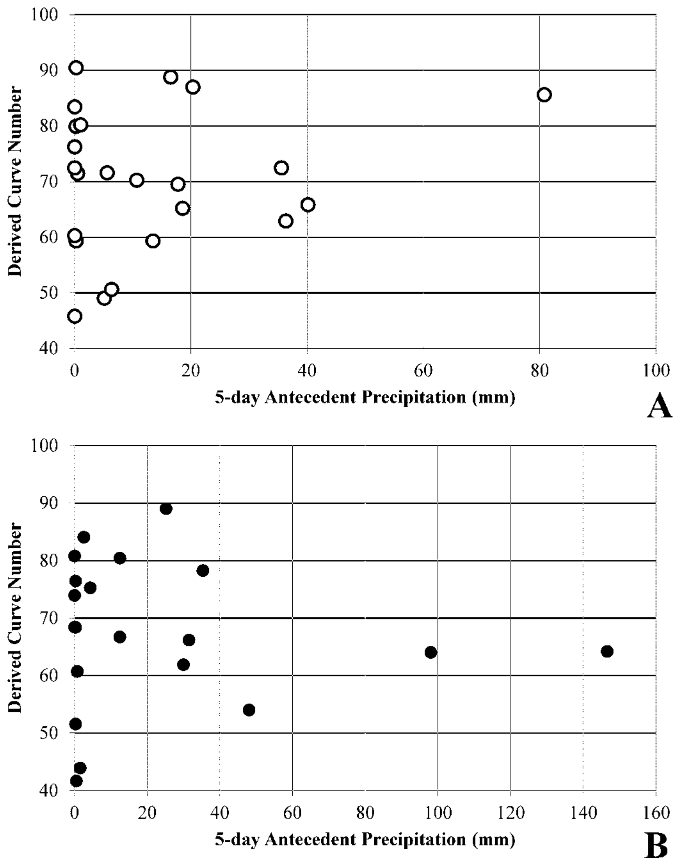

FIGURE 4. Derived Curve Numbers Plotted Against Five-Day Antecedent Precipitation for (A) Upper Debidue Creek (UDC) and (B) Watershed 80 (WS80) Storm Events.

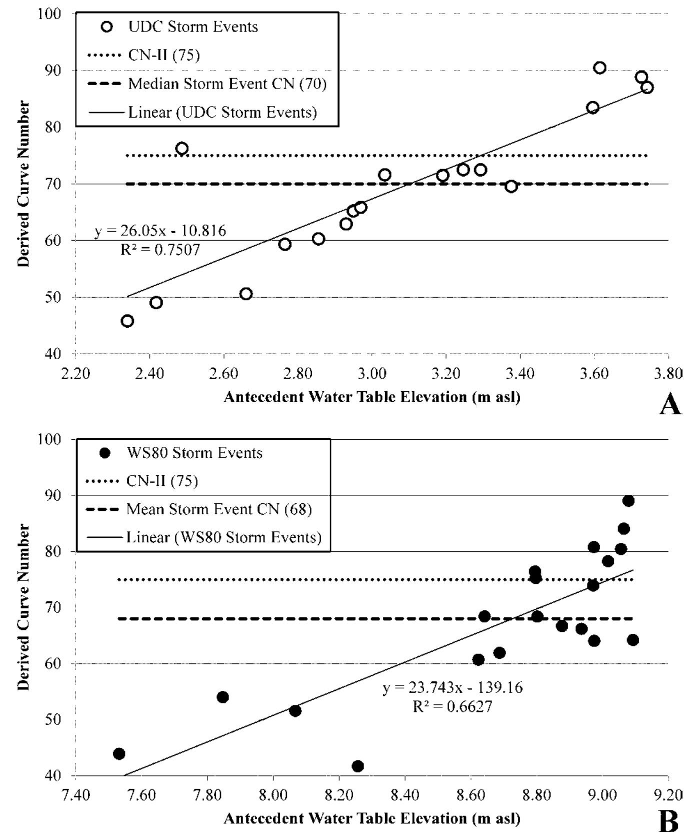

FIGURE 5. Derived Curve Numbers for (A) Upper Debidue Creek (UDC) and (B) Watershed 80 (WS80) Storm Events Showing a Linear Positive Trend with Antecedent Water Table Elevation. The storm event on June 29, 2011 for UDC deviates from this trend due to the positive curve number bias that smaller storms have on back calculation (storm event rainfall was 20 mm, the smallest storm considered).

$p < 0.01$). The linear trend lines are provided in the graphs. UDC DCN relationships demonstrate greater linearity than WS80 DCNs, and the latter may be better modeled by a nonlinear function. Lower water table elevations are associated with lower CNs indicating that runoff generation is lower and that these conditions define dry ARC. DCNs increase along with water table elevation and runoff generation is higher when the water table elevation is closer to the ground surface, indicative of a wet ARC. These results demonstrate that runoff generation varies between storm events based on the position of the water table on these watersheds prior to rainfall. Thus, the ARC for LCP headwater streams is probably best determined using antecedent water table elevation.

The CN-II as determined by TR-55 and the mean storm event CN are included in Figure 5 to illustrate where the trend in CNs intersects them. Storms with CNs that fall below the lines are mostly related to lower water table elevations than storms above the lines and represent drier than average ARC. Conversely, storm events with CNs above the lines are mostly associated with higher water table elevations and wetter than average ARC. These graphical results show a trend between antecedent water table elevation and CN at each watershed that approximates the relationship between water table elevation and runoff generation for the two specific LCP watersheds. Response differences between the watersheds are likely due to differences in site conditions that contribute to runoff generation. Previous work within these study watersheds determined breakpoint water table elevations for measures of outflow and runoff at each of these watersheds above which runoff generation increased sharply. These breakpoints were in the range of 3.25–3.5 m above sea level at UDC and 8.5–8.97 m above sea level at WS80 (Epps *et al.*, 2012). Figure 5 demonstrates that the trend in CNs plotted by antecedent water table elevation approximately intersects the CN-II and mean storm event CN lines within these water table elevation ranges at each of the watersheds. These results further indicate that previously observed breakpoint water table elevations for these two watersheds may provide estimates for site-specific divisions between dry and wet ARC, and this analysis further supports the use of antecedent water table elevation as the determinant for ARC in LCP watersheds. Variable runoff generation is a function of water table elevation on LCP headwater streams. DCNs follow a seasonal trend as shown before, with higher CNs during the dormant season than during the growing season. This pattern follows seasonal trends in groundwater elevation as described earlier in this section.

CONCLUSIONS

The two first-order watersheds characterized in this study on the LCP are hydrologically representative of other undeveloped watersheds that are typically vulnerable to imminent residential and commercial development. Analyses of rainfall and direct runoff estimates for storm events indicated that the application of the CN method may need certain adaptations to best model runoff generation for watersheds in the LCP. In this study, the CNs assigned to these representative watersheds by soil and land cover analyses using TR-55 were determined to be higher than estimates from observed data. Runoff generation and storm event CN are related to seasonal trends in water table position on these watersheds, where a strong relationship between antecedent water table elevation and runoff generation as determined by the use of DCNs was observed. This study suggests that ARC should be defined in relation to variable water table conditions on LCP headwater catchments when using the CN method for storm-flow predictions. Because seasonal trends in ET influence seasonal trends in water table elevation, the use of the average ARC CN-II for design work could result in systematic error in runoff prediction, including the underprediction of runoff during the winter months and an overprediction of runoff during the summer months. The range in runoff generation from dry to wet ARC for these watersheds should be considered in decision making due to seasonal variation within a given year, thus allowing for more accurate runoff predictions and improved water resource management in LCP headwater streams.

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