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Assessment of storm direct runoff and peak flow rates using improved SCS-CN models for selected forested watersheds in the Southeastern United States

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ABSTRACT

Study region: Southeastern United States

Study focus: The objective was to evaluate the ability of two modified SCS-CN models to predict direct runoff (DRO) and peak discharge rate (Q_p) for selected storm events in three forested watersheds in the region - one low-gradient system in South Carolina, two high-gradient upland systems in North Carolina, and a mid-gradient upland system in Arkansas.

New hydrological insights for the region: The calculated peak discharge rate Q_p values by all methods were unsatisfactory when using the default pond and swamp adjustment factor (F_p) value of 0.72 recommended in the SCS TR55 guideline, indicating that use of the default F_p value may result in erroneous Q_p estimates for forest watersheds with high retention capacities. These findings, indicating the superiority of the modified Sahu-Mishra-Eldo (SME_m) method to the original SCS method in runoff calculations and substantially lower F_p values in the associated Q_p method, are significant for hydrologists and engineers who frequently apply the methods in design of storm water management structures including road culverts on forested landscapes.

1. Introduction

An accurate method for quantifying the direct runoff volume and peak discharge rate from ungauged catchments is becoming increasingly important to better understand how land-use change affects water balance, stormwater management, and downstream water quality and ecosystem functions and services (Lockaby et al., 2011; O'Driscoll et al., 2010; Walsh et al., 2016). Accordingly, there are many different rainfall-runoff models in the literature available for application in various types of landscapes (Blair et al., 2012; Day and Bremer, 2013; Epps et al., 2013a; Goodrow, 2009; HEC, 2015; Walega and Salata, 2019). The direct runoff, obtained as a balance of precipitation interception, infiltration, surface retention and evapotranspiration (ET), is one of the outputs of some hydrological models (Arnold and Gibbons, 1998; Banasik et al., 2014; Bedient et al., 2013) along with each site's stormwater

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management design practices. The catchment hydrological processes can generally be modeled by using topography, land cover, soil parameters and rainfall characteristics, all potentially affecting direct runoff generation (Vaezi, 2014). The Soil Conservation Service (now Natural Resources Conservation Service (NRCS)) Curve Number (SCS-CN) method (Epps et al., 2013a; USDA, 1986) is a widely accepted method for estimating watershed runoff as a response to rainfall.. The SCS-CN is a storm event-based, lumped, model that uses empirical data to estimate direct runoff volume from a given storm rainfall amount (Ponce, 1989; Ponce and Hawkins, 1996; USDA, 2004). This model has been used since 1970s around the world because it is computationally user friendly with easily available required inputs, that relate runoff to the soil type, land cover/land use, and hydrological conditions.

The SCS-CN method estimates direct event runoff for a rainfall amount of known quantity using a CN value obtained from catchment characteristics and antecedent rainfall 5-days prior to the event. The CN values for an ungauged catchment are derived from lookup tables based on the soil hydrologic group (a function of soil type and land cover and land use), and antecedent moisture condition (AMC) (Cunha et al., 2010; Maidment, 1993; Mishra et al., 2013; USDA, 1986; Woodward et al., 2003). Numerous studies have shown that CN values, either theoretical or those obtained using the SCS-CN guidelines, can be substantially different from empirically calculated values using observed rainfall-runoff events (Banasik and Woodward, 2010; Ebrahimian et al., 2012; Epps et al., 2013a; King and Balogh, 2008; Soulis and Valiantzas, 2013; Walega and Salata, 2019), warranting a need for their improvement (Caviedes-Voullième et al., 2012; Ponce and Hawkins, 1996; Walega et al., 2015; Walega and Rutkowska, 2015) including in the application for events with less than a 24-h duration (Meadows, 2016). One of the greatest weaknesses of the original SCS-CN method for deriving single direct runoff is a missing explicit dependency between the initial abstraction and the AMC (Sahu et al., 2012). Initial abstraction is all losses, including water stored in surface depressions, vegetation canopy interception and evaporation, and infiltration (USDA, 1986), before the runoff begins. Berni et al. (2008) stated "…runoff depth estimates using a distributed CN are as much as 100 % higher than that obtained considering a uniform CN. Underestimation of runoff depth due to CN compositing is most severe for wide CN ranges, low CN values and low precipitation depths." Woodward et al. (2010) and Meadows (2016) stated that the SCS-CN method was not applicable at time resolutions smaller than 24-hr. According to Hawkins (1993) the SCS-CN calculated runoff was much more sensitive to the value of CN chosen than it was to rainfall amounts. In addition, it is also not as easy to accurately select CN values from available literature. One of the large uncertainties results from a consistent decline in storm-event CN values with increasing rainfall amount. This is mainly attributed to the discounting of the temporal variation in rainfall and runoff process (Ponce and Hawkins, 1996).

Bartlett et al. (2016) introduced a revised SCS-CN method by incorporating a spatial description of runoff that includes the source areas of runoff and the probability distribution functions characterizing the runoff variability. Besides variable watershed moisture conditions, the higher abundance of precipitation also affects the CN parameter.. Unfortunately, engineers/designers and land managers still use the original SCS_CN method in their hydrological design and analyses, which can potentially lead to unreliable results of actual flood parameters. Furthermore, calculated direct runoff depths are also often used in empirical formulas estimating the storm event-based or design peak discharge rates that are frequently used in the design of transportation and water management infrastructures. The reliability and appropriate method of such peak discharge formulas, besides other factors, are increasingly becoming a concern in economic and risk analyses of such structures in the face of growing extreme precipitation events in recent years. Thus, first potential discrepancies in direct runoff depths using the classic SCS-CN methods have direct consequences in peak discharge estimates. Therefore, it is becoming critical to validate the the SCS-CN method for range of hydro-climatic conditions before promoting its wide application in engineering practice to reduce the modeling uncertainty and predictions.. Secondly, peak discharge formulas generally use the maximum 24-h design rainfall for a given frequency published in the literature for a given locality within a region (USDA, 1986; Bonnin et al., 2006). Also SCS-CN is simply, empirical model that does not included factors that potentially influence on outflow, like topography and infiltration processes. That means the method is not as appropriate for estimating the incremental rainfall excess during a storm event. (Grimaldi et al., 2013; Grimaldi and Petroselli, 2014).

Literature based CN values are most successfully applied for traditional agricultural watersheds, less successfully for semiarid rangelands, and least successfully for forest watersheds (Epps et al., 2013a). Tedela et al. (2012) also emphasized that the methods are still weak and have large uncertainties for application in forested landscapes with complex soil, land cover, and topographic conditions. Amatya and Jha (2011) used a SWAT model and adjusted CN values to calibrate the stream flow for a large forested watershed. The only other study the authors are aware of that evaluates the SCS-CN method for forested conditions was conducted by Tedela et al. (2012), but that study was limited to upland high gradient watersheds in the northeastern United States and did not include any modifications of the original SCS-CN method.

The main objectives of this study were: a) to evaluate the usefulness of two modified SCS-CN methods and identify the most accurate method for determining the direct runoff for upland and lowland forested watersheds, and b) to modify the SCS TR55-based Graphical Peak Discharge Method by applying calculated event runoff using the modified SCS-CN method for both upland and lowland forested watersheds. The following hypotheses were tested: 1) the original SCS-CN underestimates direct runofffrom small forested watersheds, 2) modified Sahu-Mishra-Eldo (SME) method (SME_m) is expected to provide more accurate results than the original SCS-CN method for direct runofffrom forested watersheds, 3) use of the SME_m method for assessing direct runoffincreases the precision of calculated peak flow rate using the SCS-TR55 method, 4) finally, the pond and swamp adjustment factor (F_p) factor in the Graphical Peak Discharge method has lower values for forested watersheds than were recommended in the original formula, and is a function of the event precipitation. The calibrated peak discharge method was then applied to assess the design peak discharges using the 24-h design rainfall intensity following the (Bonnin et al., 2006) for various return periods for all the study sites. This work was carried out to compliment the study by Tian et al. (2019) who assessed various widely used methods of computing design discharges, except the SCS-CN based methods, using both the on-site long-term rainfall and flow data based and NOAA based precipitation intensity-duration-frequency for application in design of forest road cross-drainage structures at the same study sites.

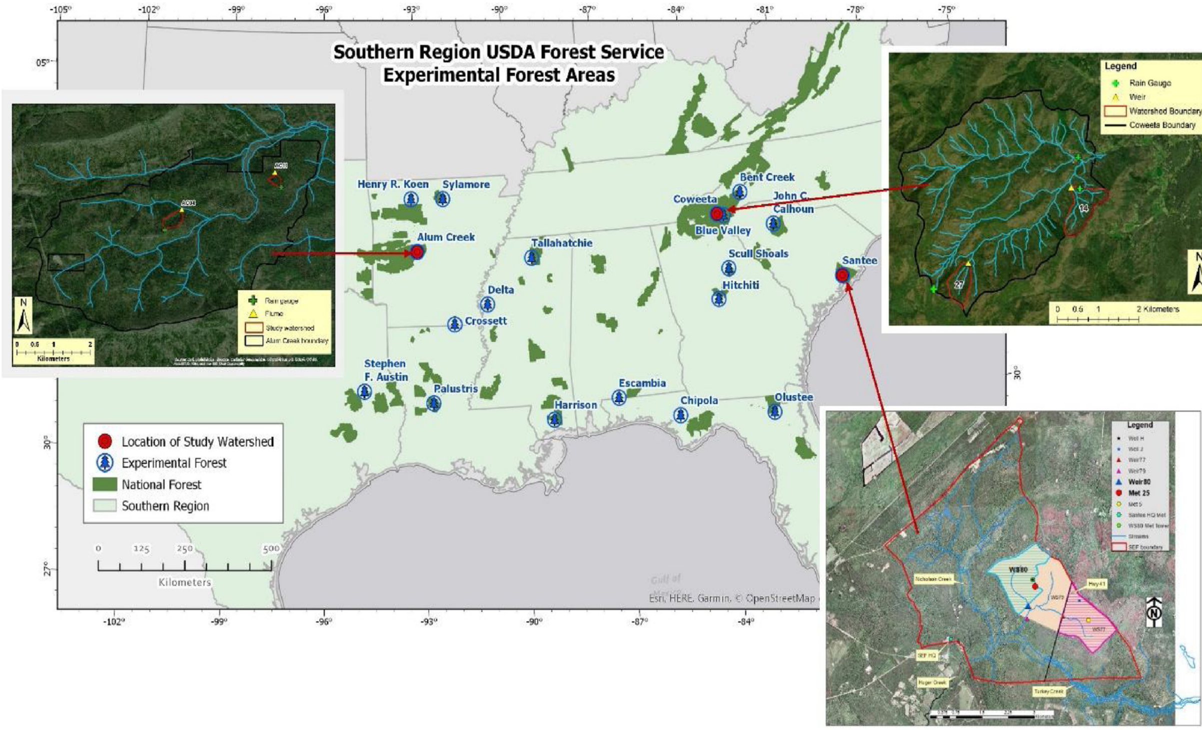

Fig. 1. A map of the Southeastern United States showing National Forest lands along with experimental forests and ranges (EFR). Large red circles within the map indicate the locations of three study watersheds with arrows pointed to WS14 at Coweeta Hydrologic Laboratory, NC (top right), WS80 at Santee Experimental Forest, SC (bottom right), and AC11 at Alum Creek Experimental Forest, AR (top left) (*Source:* Tian et al., 2019) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2. Material and methods

2.1. Study sites

This study was conducted using data from three USDA Forest Service long-term experimental forest sites in distinct physiographic regions of the Southeast, a low-gradient coastal watershed in South Carolina (SC), a high-gradient mountainous watershed in North Carolina (NC), and a lower relief mountain type watershed in Arkansas (AR) (Fig. 1).

2.1.1. Coweeta watershed (WS14), NC

The Coweeta Hydrologic Laboratory (CHL) is located in western North Carolina (35.05 °N, 83.43 °W) and is representative of southern Appalachian mixed deciduous hardwoods. Streamflow records in the 61 ha reference WS14 (Fig. 1) began in 1936, and the watershed has been used as a reference for paired watershed experiments dating back to the 1950s. WS14 was selectively harvested in the early 1920s prior to the establishment of the CHL (Douglass and Hoover, 1988) but has been unmanaged since that time. Elevation in the NW-facing WS14 ranges from 701 to 1007 m (mean 872 m) with mean slopes of 50 %. Sixty-nine percent of the watershed consists of soils of Hydrologic Soil Group B and 22 % Group C, with the balance consisting of rock outcrop. The annual precipitation and temperature average 1847 mm and 12.9 °C, respectively, based on the data from the main climate station at the site. Additional information about the watershed characteristics are given in Table 1.

2.1.2. Santee Watershed (WS80), SC

The second study site, Watershed 80 (WS80), is a 1st order headwater stream that drains to Huger Creek, a tributary of East Branch of Cooper River, and then drains further downstream to Charleston Harbor (Fig. 1). The site is located at the USDA Forest Service Santee Experimental Forest (33.15 °N, 79.8 °W), which is about 60 km from the City of Charleston, SC. This long-term experimental forest watershed, the control in a paired system, had an initial drainage area of 206 ha that was reduced to 160 ha in 2001. The watershed is characterized by low gradient topography (less than three percent slope) and shallow water table conditions (Harder et al., 2007). The watershed is currently comprised of about 70 % mixed pine and hardwood stands and 30 % forested wetland. WS80 has poorly drained soils, dominated by the Wahee type with a high field capacity and lower permeability than sandy soils (Harder et al., 2007). The long-term mean rainfall and temperature of the site are 1370 mm and 18.3 °C, respectively (Dai et al., 2013). Rainfall has been continuously measured using an automatic gauge backed up by a manual gauge in the middle of the watershed. The streamflow rates have been computed using a continuously measured stage height and an equation for a compound v-

Table 1
Features of study watersheds WS14 at Coweeta Hydrologic Laboratory (Coweeta), NC, WS80 at Santee Experimental Forest (Santee), SC, and AC04 at Alum Creek Experimental Forest (Alum Creek), AR study sites.

Study Site	Coweeta, NC	Santee, SC	Alum Creek, AR
10-digit Hydrologic Unit Code	06010202	0305020103	
Latitude	35.05 °N;	33.15 °N;	34.81 °N;
Longitude	83.43°' W	79.8 °W	93.00 °W
Elevation, m	701 – 1007	4.0 - 6.0	330 – 380
Basin Slope, %	49.5	< 2.0	15 – 35 %
Area, ha	61	160	4.9
Channel Slope, %	36.2		16.8
Maximum Channel length, m	1295		241
Time of concentration, min	24.0	123.5	9.4
Weighted average CN	60		70
Dominant soil type	Well drained Trimont series	Poorly drained Wahee series	Well-drained, Pirum, Townley, or Carnasaw series
Hydrologic soil group (HSG) of dominant soil type	B	D	C
Dominant vegetation	Mixed deciduous hardwoods	Pine mixed hardwood	Mixed pine hardwood
% Wetlands	0	30	0
No. of Storm Events	27	36	19
Event Rainfall Range, mm	21.1 – 102.4	46.6 – 157.7	14.3 – 90.5
5-Day Antecedent Range, mm	0 – 77.7	0 – 46.5	0 – 53.9
Event Outflow Range, mm	2.5 – 75.7	3.2 – 57.0	0.47 – 57.9
Peak Flow Rate Range, l/sec	19.2 – 184.3	54.7 – 1546.0	2.41 – 504.0

notch weir installed at the watershed outlet (Fig. 1). The hydrologic water balance, characteristics of storm event hydrology, and long-term flow dynamics of this site have been described by Amatya et al. (2016); Epps et al. (2013b), and Harder et al. (2007).

2.1.3. Alum creek watershed (AC11), AR

The 4.9-ha AC11 watershed is located in the Ouachita Mountains of central Arkansas, and is part of the USDA Forest Service Alum Creek Experimental Forest (Fig. 1). The Ouachita Mountains have a humid subtropical climate with hot summers, relatively mild winters, and year-round precipitation. Mean annual temperatures in the area range from -1° to 34 °C, while mean annual precipitation is 1321 mm and occurs predominantly as rain. The AC11 watershed has a mostly NW aspect with a maximum elevation just over 380 m, slope gradients typically between 15 and 35 %, and an overall relief of 51.8 m. The underlying bedrock is comprised of intermixed Paleozoic sandstone and shale formations, which are highly folded and faulted. The drainage pattern is dendritic. Soils are Hapludults in the Pirum, Townley, or Carnasaw series. These soils are typically well drained, shallow (< 1 m) gravelly to stony silt-loams. The watershed is covered by a mixed pine-hardwood forest with shortleaf pine (*Pinus echinata*), a variety of oaks (*Quercus* spp.*)*, and Sweetgum (*Liquidambar styraciflua*) as the dominant overstory species. Overstory age ranges from 60 to 100+ years. Streamflow is mostly continuous during the winter and spring, but becomes sporadic during the summer and fall. A streamflow gauging station was operated at the AC11 outlet from 1979 through 2016. Streamflow was measured using a 0.9-m H-flume and water elevations were recorded on either charts or digital data recorders. No timber harvesting has occurred since the Alum Creek Experimental Forest was established in 1959, and there is little evidence of harvesting before 1907-08 when the Ouachita National Forest was created. This basin has served as a control in past studies evaluating the effects of timber harvesting on streamflow quantity and quality (Miller et al., 1985, 1988).

2.2. Storm event data

Approximately five medium to large storm events event rainfall amount of 12.5 mm (half-inch) or higher were identified from each of the five years (2011-15) of storm event data recorded at each of the above forested watersheds. The data consisted of rainfall amount and corresponding estimated stormflow volume, peak flow rate, and baseflow volume for each event obtained using hydrograph separation techniques of Hibbert and Cunningham (1966) with a linear recess function for upland Coweeta and Alum Creek watersheds and Epps et al. (2013b) with an exponential recess for the low-gradient Santee watershed. Hourly precipitation data from 2011 to 2015 from a nearby rain gage at each site was used to analyze the flow hydrograph as a response of the storm event and its characteristics. We used 36 observed rainfall-runoff events for W80 watershed, 27 for WS14, and 19 for AC11 watersheds in the analysis. Time resolution for measured flow rates was equal to 10 min for both the WS80 and AC11 and, 5-min for the WS14. Direct outflow was separated from base flow using a straight line where beginning was start of rising limb and end was identified as an inflection point on recession limb of the storm runoff hydrograph.

Time step for rainfall data measured using an automatic tipping bucket rain gauge with instantaneous tips to obtain the total rainfall of each storm event was assumed adequate for small forested watershed with mild slope. The simulation time steps assumed in conceptual hydrological models depend on the dynamics of the output. It is clear that watershed filtering the high frequencies of the input signal (rainfall) and those of the processes related to production of rainfall excess in the watershed is lagged and outflow can be assumed with longer time resolution. Especially in case of forested watersheds generally with high retention, the flow response of watershed to rainfall signal is generally lagged longer and, thus, the process dynamics is not so rapid like in watershed with small retention capacity. Other data describing basin characteristics including area, aspect, basin and channel slopes, elevation (maximum and lowest at the outlet), hydrologic soil group type for the given soil, main stream length, land use, (percent wetland area, if any), and calculated time of concentration for each of the study watersheds were computed in a Geographical Information System (Table 1).

2.3. Computations of SCS (1986) and empirical curve numbers

A general form of the SCS-CN model (USDA, 1986) is expressed by the following equations:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \; if\; P > Ia \tag{1}$$

$$Q = 0 \; otherwise, \tag{2}$$

$$I_a = \lambda S \tag{3}$$

where Q is direct runoff (note that direct runoff is total event direct runoff volume) (mm), P is cumulative precipitation for event (mm), I_a is initial abstraction (mm), S is potential maximum retention (mm) and λ is the initial abstraction coefficient (dimensionless).

The parameter S is expressed as:

$$S = \frac{25400}{CN} - 254 \tag{4}$$

where S is in mm and CN is the curve number, which depends on the soil type, land cover and land use, hydrological conditions, and antecedent moisture condition (AMC) obtained from the SCS (USDA, 1986). According to USDA (2004): "Hydrologic condition is based on combinations of factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good > 20 %), and (e) degree of surface toughness."

In the next step, empirical curve number (CN_{emp}) values were determined for each storm event measured on each investigated watershed, using the recorded rainfall-runoff (P-Q) events based on the formula below, developed by Deshmukh et al. (2013), where P and Q represent the rainfall and runoff amounts for each event.

$$CN_{emp} = \frac{25400}{254 + S_{emp}} \tag{5}$$

The empirical value of potential maximum retention S_{emp} was calculated using the equation provided by Chen (1982):

$$S_{emp} = \frac{P}{\lambda} + \frac{(1 - \lambda)Q - \sqrt{(1 - \lambda)^2 Q^2 + 4\lambda PQ}}{2\lambda^2} \tag{6}$$

The measured P and Q values for each watershed were sorted separately and realigned on a rank order basis to form P-Q pairs of equal return periods (Hawkins, 1993). Next, the measured P-Q data were transformed into the equivalent P-CN_{emp}. The CN parameter was determined as a function of precipitation depth using the standard asymptote model described by Hawkins (1993) and summarized by the formula:

$$CN(P)1 = CN_\infty + (100 - CN_\infty) \bullet \exp(-k \bullet P) \tag{7}$$

where, CN_∞ is constant value approached as $P \to \infty$, k is a constant obtained by fitting asymptotic function to observed P-Q pairs. Then, the arithmetic mean, median, and geometric mean of CN_{emp} was calculated for each watershed. The standard asymptotic model was used in describing the P-Q pair relationship with two individual variants of λ parameter: 0.2 for standard value and 0.05 as recommended elsewhere in the literature (Blair et al., 2012).

Curve number calculated based on observed rainfall-runoff events (eq 5), CN according to USDA (2004), and empirical CN form asymptotic curve (eq 7) were used in further calculation of direct runoff according to the method described in Section 2.4 paragraph.

2.4. Methods for calculation of direct runoff (q)

Estimates of direct runoff (Q) are then calculated using each of the following methods: 1) original SCS-CN method (USDA, 2004), 2) Mishra-Singh model (MS model) (Mishra and Singh, 2002), and 3) the modified SME model (SME_m) (Walega and Salata, 2019).

2.4.1. Mishra-Singh (MS) model

Mishra and Singh (2002) modified the original SCS-CN method in Eq. (1) to include a measure of antecedent moisture (M):

$$Q = \frac{(P - I_a) \bullet (P - I_a + M)}{P - I_a + M + S} \tag{8}$$

where, M is the antecedent moisture (mm):

$$M = 0.5\bullet[-(1+\lambda)S + \sqrt{(1-\lambda)^2\bullet S^2 + 4\bullet P_5\bullet S}] \tag{9}$$

Here, I_a and λ are the same as in Eqs. (1) and (2) and P_5 is the amount of antecedent 5-day rainfall. Eq. (9) represents the amount of moisture added to the dry soil profile by rain P_5 (Walega et al., 2016).

2.4.2. Modified Sahu-Mishra-Eldo (SME) model (SME_m)

The SME model (Sahu et al., 2012) uses a more continuous expression for estimating antecedent moisture and allows for optimization of the absolute maximum retention capacity, and thus uses a constant quantity for a specific watershed. Sahu et al. (2010, 2012) allowed for antecedent moisture in their calculations of the direct runoff. In this model, the authors introduced the S_0 parameter, which is the absolute maximum retention capacity, and M is the antecedent moisture that is assumed to be a fraction (β) of the amount of moisture/water infiltrated during the antecedent period, depending on the 5-day antecedent rainfall amount (P_5). This assumption is based on the fact that only a fractionof the rainfall added to the soil profile will contribute to M because of evapotranspiration, drainage, and other losses during the antecedent 5-day period. According to Sahu et al. (2012) and the SME method, S_0 is the potential maximum retention in completely dry conditions and is independent of the antecedent moisture and fully depends on catchment characteristics. Recently, Walega and Salata (2019) further modified the 3-parameter SME model (SME_m) to calculate direct runoff using just a 2-parameter equation:

$$Q = \frac{(P-I_a)\bullet(P-I_a+M)}{P-I_a+S}\ if\ P > Ia \tag{10}$$

$$Q = 0\ otherwise \tag{11}$$

$$I_a = \lambda\bullet(S-M) \tag{12}$$

where S is the maximum retention capacity, replacing the S_0 of the SME method, obtained in the second stage. In Eq. 12, the higher the antecedent moisture M, the lower the initial abstraction I_a, and vice versa. The antecedent moisture is given as:

$$M = \beta\left[\frac{(P_5-\lambda S)\bullet S}{(P_5-\lambda S)+S}\right] for\ P5 > \lambda S \tag{13}$$

$$M = 0 \text{ for } P_5 < \lambda S \tag{14}$$

where: β is the parameter to be optimized and the parameter λ is equal to 0.20 (as in the first stage). The parameter β is a part of the 5-day rainfall that is intercepted. This parameter was calibrated base on the observed rainfall-runoff events.

The main difference between the original SME and the proposed modified SME_m method is the way the parameter S is calibrated. In the original method, S_0 was assumed to be the parameter functionally related to the catchment characteristics. A different approach is adopted in the SME_m method by Walega and Salata (2019) when the SCS-CN and SME method are combined: S_0 is substituted with the maximum potential retention, S, established from Eq. (4). The SCS-CN method is also widely used in arid and semi-arid regions (Bo et al., 2011; Rawat and Singh, 2017). It was assumed that, in moderate-climate catchments, which are rather rich in moisture, such as those investigated and described in this paper, the absolute maximum retention values higher than S are not typical of catchments in the Southeastern US region. Therefore, the original parameter, S_0, was substituted for with S. Moreover, according to Sahu et al. (2010), the values of S_0 may be equal to or higher than S, therefore, the authors adopted the less desirable variant, $S_0=S$, in this work. The positive difference between S_0 and S (S is equal to or higher than S_0) determined that model generates lower rainfall losses and higher runoff values when compared to the original SME method. Values S_0 and S have a constant quantity for a given watershed.

2.5. Assessment of peak discharge rate

For determining the peak discharge of storm events with different return periods the simpler USDA TR55 procedure (USDA, 1986) based Graphical Peak Discharge method was used instead of the model that uses a unit hydrograph method and was employed by Blair et al. (2012) based on time and discharge ratios developed by the USDA (2007). The TR55 Graphical Peak Discharge equation for a storm event is given by

$$q_p = q_u\bullet A_m\bullet Q\bullet F_p \tag{15}$$

where q_p = peak discharge (cfs), q_u = unit peak discharge (csm/in), which is a function of time of concentration (t_c) and I_a/P ratio, Am = drainage area (mi^2), Q = runoff (in), and F_p = pond and swamp adjustment factor. In the USDA (2007) method, q_u is represented by $(PRF\cdot A\cdot Q)\ /\ T_p$, where PRF is the peak rate factor defined as a ratio of recession and peaking limbs of the hydrograph, and depends upon terrain gradient and catchment imperviousness, A is the watershed area and T_p is time to peak of the hydrograph. Blair et al. (2012) used a lower value of PRF = 200 as a suitable number for the low-gradient Southeastern coastal plain landscape that is characteristic of higher ratio of recession to peak hydrograph instead of the default value of 484 recommended by NRCS for the upland sites potentially with lower recession to peak ratios.

Next Q was calculated using the original SCS-CN method and also the SME_m method. Unit peak discharge (q_u) was determined assuming a type-II rainfall distribution for all the three study sites and using corresponding calculated t_c and Ia/P coefficients for each study site from Exhibit4-II Chart USDA (1986). In case of the observed rainfall events, the P value is the cumulative rainfall for the event and 24-hr maximum rainfall from NOAA-Atlas 14 (Bonnin et al., 2006) for design rainfall events. In the final step design peak discharge for each return period was calculated from Eq. (15). An F_p value equal to 0.72 for five percent of swamp and pond areas was recommended by the USDA, likely for agricultural settings (1986). But for these forest watershed study sites, the authors examined the land cover using available high-resolution spatial data to estimate the percentage of wetlands and accurately estimate the value of F_p by using it as a calibration factor. The rest of the parameters were held constant and were not calibrated. For example, for each rainfall event and Q assessed based on the method described above, Q_p was calculated for different F_p values. Then, the values of F_p were optimized using the *Solver tools* available in Excel (MS-EXCEL 2013). The nonlinear algorithm option was chosen to find an optimal value of F_p for each event.

Based on the comparisons of predicted direct runoff values using each of the three CN models with the observed runoff data for each of the three forested watershed study sites, the most accurate method for each watershed was selected using the model performance criteria stated below.

2.6. Model performance assessment

The root mean square error (*RMSE*) and modeling efficiency *EF* (Nash and Sutcliffe, 1970) were used as goodness of fit measures to assess performance of the three above models SCS-CN, MS, and modified SME (SME_m) for three scenarios (*CN* based on observed events, *CN* according to USDA (2004) and CN_{emp} based on Hawkins (1993):

$$RMSE = \sqrt{\frac{1}{N}\cdot\sum_{i=1}^{N}(Q_{obs,i} - Q_{calc,i})^2} \tag{16}$$

$$EF = 1 - \frac{\sum_{i=1}^{N}(Q_i - Q_{calc,i})^2}{\sum_{i=1}^{N}(Q_i - Q_{obs,i})^2} \tag{17}$$

where Q_i is the observed direct runoff, $Q_{calc,i}$ is the direct runoff calculated, and $\bar{Q}_{obs,i}$ QUOTEis the mean value of the observed direct runoff values, i – i-th number of events for total N events. In judging *EF* values, the Ritter and Muñoz-Carpena (2013) criteria is used where an $EF < 0.65$ is deemed unsatisfactory. Other model performance ratings were as follows: acceptable ($0.65 \le EF < 0.80$), good ($0.80 \le EF < 0.90$), and very good ($EF > 0.90$).

2.7. Design discharge calculations

The final step was to make calculations for the design discharge values for each of the three watersheds for the 2-, 5-, 10-, 25-, 50-, and 100-yr return periods. Design precipitation intensity duration frequency (*PIDF*) values from the NOAA Atlas maps (Bonnin et al., 2006) for durations of 24 h were obtained for each of the three watershed sites. The Atlas 14 PIDF also provides estimates of upper and lower bounds at 90 % confidence interval of the mean and made the data available in raster format for efficient modeling and analysis in GIS framework. As per the Atlas 14 metadata (hdsc.nws.noaa.gov/hdsc/pfds/meta/na14_vol9_se_grid_metadata.xml), PIDF estimates are used as basic design criteria for a wide variety of hydraulic structures such as culverts, roadway drainages, bridges and small dams. In U.S., with the advent of satellite remote sensing and geospatial technology, long-term weather stations based latest PIDF gridded data is now available in 800 m resolution at NOAA site (hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html). This new PIDF data developed by NOAA- HDSC uses the partial series based design storm events data instead of just 24-hr maximum, with a precipitation raster development process employed by the PRISM mean annual precipitation (Daly et al., 2008).

Peak discharge rates for each design frequency were assessed according to the TR55 (Eq. 15), and direct runoff was calculated according to the modified SME model. F_p values were obtained from the equation shown in Fig. 6, because the peak discharges calculated using the TR55 method with the direct runoff obtained from the modified SME model were found to be more accurate (Fig. 5). Then, these peak discharges were compared to the values that were calculated using the TR55 and direct runoff based on the original SCS-CN for AMCII and $F_p = 0.72$. All calculations were performed for rainfall distribution type II and with a CN for medium antecedent conditions.

3. Results and discussion

3.1. The CN_{emp} values versus CN according to USDA (2004)

Based on 27 observed rainfall-runoff event data for the high-gradient mountainous Coweeta watershed WS14 (Table 1), the empirical method using Eq. 5 yielded the mean, median, and geometric mean CN_{emp} of 64.6, 66.3, and 65.9, respectively. These small differences in calculated mean and median CN values suggest that this CN parameter is stable and can probably be described by a normal distribution for this mountain watershed. In other words, stable conditions seem to exist for formation of direct outflow at this site that was potentially attributed to homogenous land cover and soil types.

These estimated values were slightly (7–10 %) higher than the CN value of 60 recommended by the original USDA (2004) method for AMCII given the site's land cover and soil characteristics. It is possible that using the same default lower CN value from the USDA (2004) is the reason Tedela et al. (2012) found only a marginal correlation between predicted flow and the observed data for mountainous WS36 and WS37 at Coweeta (not shown), although a somewhat modest correlation ($EF = 0.56$) was found for Coweeta WS28. Similarly, using the measured event rainfall-runoff data for the low-gradient coastal watershed (WS80), the CN_{emp} values were 66.3, 60.1 and 65.8 respectively, which were much lower than the CN value of 75 recommended by the USDA (2004) for AMCII and land cover and soil characteristics of the watershed. Based on their analysis of 23 storm events recorded from 2008 to 2011, Epps et al. (2013a) found a mean value of 70, also lower than that from the USDA (2004). In their simulation study, using a SWAT model for a 52 km^2 forest watershed nearby the WS80 watershed, Amatya and Jha (2011) reduced the CNII values for all the Hydrologic Response Units (HRU) obtained by using the USDA (2004) method based on given land cover and soil type by 10 % as a part of calibration of the predicted daily streamflow with the measured data. On the other hand, for the observed rainfall-runoff events on the AC11 watershed in Arkansas, the computed mean, median, and geometric mean of the CN_{emp} values were 79.1, 80.7, and 81.9, respectively, higher than the *CN* value of 70 recommended by the USDA (2004) for AMCII and the site's land cover and soil characteristics. The results showed that, compared to the measured data-based empirical values, the NRCS-based method seems to underestimate the CN value and runoff for upland sites like Coweeta and Alum Creek, and overestimate CN and runoff for lowland sites like the WS80 watershed.

Tedela et al. (2012) noted that when a tabulated NRCS curve number consistently underestimates runoff from an undeveloped forest, the effect of urbanization will be consistently overestimated, causing drainage to be overdesigned, potentially wasting resources unnecessarily. The authors also noted that the causes of inaccurate runoff estimates established by using tabulated curve numbers in 10 forested watersheds in the northeastern United States are unclear. The original information used to estimate the tabulated curve numbers for forested areas is no longer available (Hawkins et al., 2009). The authors ruled out errors in selection of the soil hydrologic group and hydrologic conditions as potential contributors to the discrepancies they observed between the observed and tabulated CN values in their study. This demonstrates a need for further studies into the calculation of direct runoff using other forms of the modified SCS-CN method.

Assessment of CN for storm events resulting from increased magnitude of intense precipitation was also investigated using P-CN_{emp} relationship to address uncertainties in predictions. Analysis for 27 rainfall-runoff episodes at the Coweeta watershed were performed with an initial abstraction coefficient of $\lambda = 0.20$. From Fig. 2 it is evident that empirical plot of *P*-CN_{emp} data are closely located to the theoretical curve according to standard behavior, so the model correctly approximated the empirical data for $\lambda = 0.20$. It can also be observed from the relationship that an increasing *P* is accompanied by a reduction in CN_{emp}. However, clear stabilization of CN with an asymptotic behavior at higher rainfalls as described by other authors (Banasik et al., 2014; Banasik and Woodward, 2010; King and Balogh, 2008) was not observed. CN would possibly have been stabilized for event rainfall amount exceeding maximum observed equal to 102.3 mm, which was not observed during the study period. Similar relationships were found in the watersheds of southern Poland that measured between 25 and almost 55 ha (Kowalik and Walega, 2015).

It has been suggested that the decrease in CN_{emp} with increasing P might be a result of different runoff triggering mechanisms, such as rapid subsurface flow due to macropores in the matured forest stands as was noted recently by Skaggs et al. (2019) for matured managed pine stands in coastal NC. In addition, even small precipitation falling directly on the streams and shallow subsurface flow from near-stream riparian areas also contribute to rapid flow response, similar to variable source area concept (Szymczak and Krężałek, 2018), resulting in higher curve numbers for small events. Larger events would have these mechanisms as well, but these would be overshadowed by the larger and delayed contribution from areas outside the riparian zone resulting in a lower curve number for larger events. As a result, small precipitation events are associated with high CN_{emp} values, although seasonal

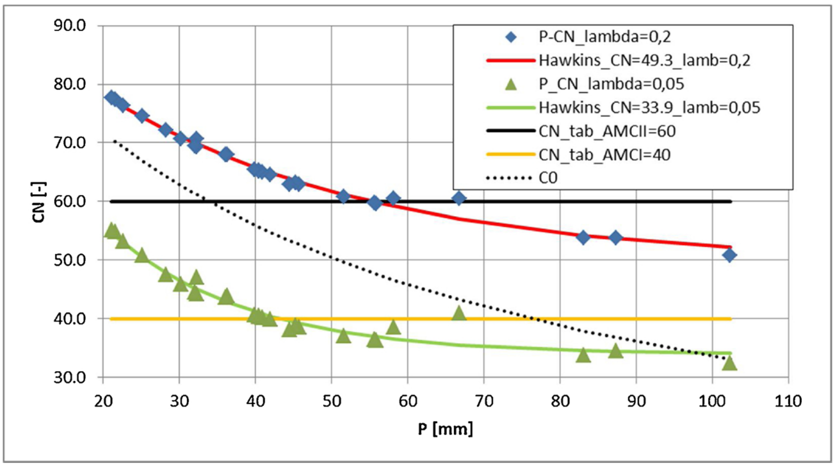

Fig. 2. CN-P relationships yielded by the standard model in the Coweeta watershed: *C0* represents a threshold value at which point runoff might be initiated for each *P*.

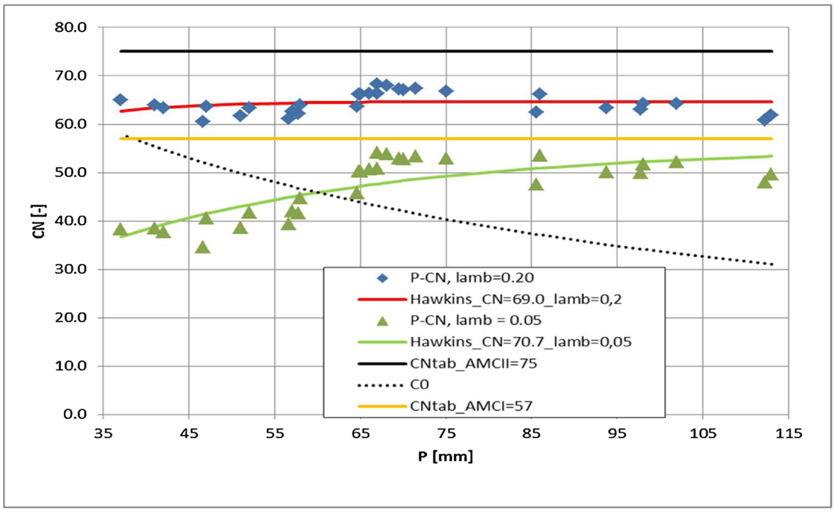

Fig. 3. CN-P relationship yielded by the standard CN model for the W80 watershed, where *C0* represents a threshold value at which point runoff might be initiated for each *P*.

antecedent conditions, generally during wet winters with low *ET* demands prior to the precipitation event may also cause this.

Using Eq. (7) and the observed data, the $P\text{-}CN_{obs}$ relationship resulted in the following:

$$CN(P) = 49.3 + (100 - 49.3)\exp\left(\frac{-P}{435.6}\right) \tag{18}$$

The analysis revealed improved model accuracy for $\lambda = 0.20$ with an *RMSE* equal to 0.84 mm and $EF = 0.99$ when compared to results from the standard CN method. In the Coweeta watershed, the value of $CN_\infty = 49.3$ was lower than the CN_{theor} determined for AMCII. These results clearly indicate that measures should be taken to accurately determine the actual soil moisture when using the original SCS-CN method, as this parameter is crucial for calculating the amount of the direct runoff. In practice, CN for AMCII generally assumes soil moisture for normal conditions, which often leads to underestimation of the catchment runoff. Similar results were observed by Tedela et al. (2012) for small, forested watersheds in the mountains of the eastern United States. For Coweeta watersheds 2, 28, 36 and 37, tabulated CN was 55 (for AMCII) but mean, median, geometric mean, and CN_∞ varied between 58 and 75.3. For $\lambda = 0.05$, a stable $P\text{-}CN_{emp}$ relationship was found for precipitation above 70 mm. The CN_{emp} for higher precipitation was 49.3.

In contrast to the Coweeta watershed, the standard asymptote model fairly approximated the empirical data for the WS80 watershed and $\lambda = 0.20$ (Fig. 3). The CN_{emp} is almost a flat straight line indicating absolutely no influence of *P* on the *CN* value. This is likely due to higher soil-water retention capacity and ET rates of WS80 when compared to the high-gradient Coweeta watershed, which could potentially store a higher amount of precipitation in the soil profile. This observation is consistent with Tedela et al. (2012) who found substantially smaller curve numbers for the low-to-mid elevation watersheds (2 and 28) at their Coweeta site compared to the two higher elevation watersheds (36 and 37). The authors attributed these large differences in hydrologic responses to the physical differences between the watersheds, i.e., soil depth and annual ET that were much larger on the lower elevation watersheds (Swift et al., 1988; Sun et al., 2002), and increased the potential for soil moisture storage and controlling subsurface flow during storm events (Hibbert and Troendle, 1988; Hewlett and Hibbert, 1966).

A better approximation of the P-CN relationship was achieved for the initial abstraction $\lambda = 0.05$ (Fig. 3), which is consistent with Blair et al. (2012), who based on a recent reevaluation of the ratio by NRCS found that 0.05 fits better than 0.2 as a default value, requiring a change in conversion of *S* and CN values (Woodward et al., 2010). This relationship with $\lambda = 0.05$ shows a “violent behavior” which is opposite of that noted by Hawkins (1993), who showed a decreasing *CN* for increasing *P* values as was observed for the Coweeta site in Fig. 2 above. The violent behavior in this case shows increasing *CN* value with increasing P, likely due to decreasing soil capacity. This result showed that in watershed WS80, which has a lower permeability due to a restrictive clayey layer than sandy soils, the runoff process is possibly influenced by other processes (e.g. antecedent moisture condition, shallow water tables) as the key parameters controlling the storage available in these shallow poorly drained soils (Williams and Amatya, 2016) than in watersheds with better soil retention capacity. These results are also consistent with earlier studies on event rainfall-runoff relationships and their association with curve number at WS80. For example, La Torre Torres et al. (2011) also found a poor relationship, with large seasonal variability, between event runoff and rainfall, potentially due to the differences in forest ET that might have affected seasonal soil moisture conditions and a slightly better relationship for wet winter periods with relatively lower soil-water storage and ET demands. The authors suggested that soil water status, i.e. antecedent soil moisture and groundwater table level, is important to consider in addition to the rainfall and seasonal runoff generation in the coastal plain region with shallow soil

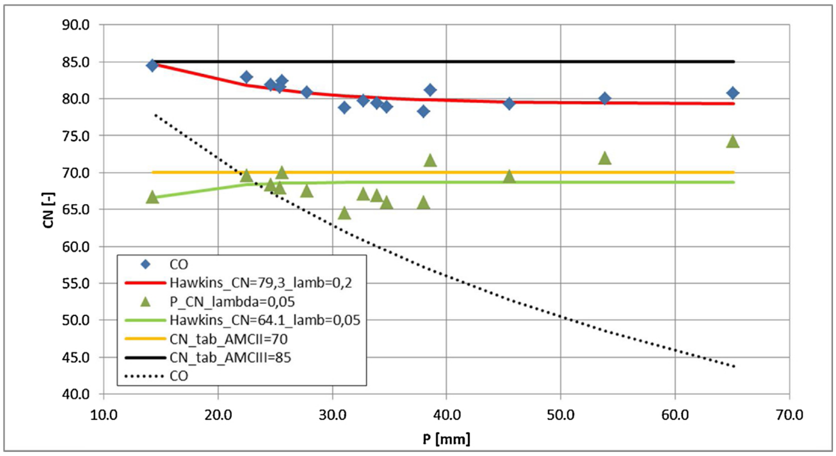

Fig. 4. CN-P relationship yielded by the standard model in the AC11 watershed, where *C0* represents a threshold value at which point runoff might be initiated for each *P*.

argillic horizons. Accordingly, Epps et al. (2013a) noted that runoff generation from storm events on this watershed (WS80) were strongly related to water table elevation, where seasonally variable ET-based wet and dry moisture conditions persist. Their results show improvement in flow predictions using CNs adjusted for antecedent runoff conditions and based on water table position (Epps et al., 2013b).

These analyses then resulted in the following $P\text{-}CN_{obs}$ relationship as the violent model described by Hawkins (1993):

$$CN(P) = 55.4 * (1 - exp(-0{,}029 * P)) \tag{19}$$

The $CN = 55.4$ value from the violent behavior is similar to the values obtained by Tedela et al. (2012) for the same conditions. Based on the computed *RMSE* value of 3.40 mm and $EF = 0.63$ for $\lambda = 0.05$, this model was deemed unsatisfactory. The model performance was even worse for $\lambda = 0.20$ based on the calculated *EF* value of only 0.03, although the *RMSE* value of 2.03 mm was slightly lower.

Interestingly, the Hawkins model was able to successfully approximate the CN_{emp} and *P* relationship for the AC11 watershed in Arkansas for $\lambda = 0.20$ (Fig. 4). The relationship shows that as *P* increases, the calculated CN value decreases asymptotically, likely due to reasons similar to those suggested previously for the upland Coweeta watershed. Fig. 4 also shows that the CN value has a tendency to stabilize at $P > 35$ mm. The stable CN of 79.3 for this *P* value and $\lambda = 0.20$ is similar to the mean value (79.1) from all events, and is close to the CN value of 85 for AMCIII (USDA, 2004). In case of $\lambda = 0.05$ with lower initial abstraction, this tendency is clearly visible with increasing CN with *P* due to higher soil moisture.

The analyses were then used to develop a $P\text{-}CN_{emp}$ relationship for $\lambda = 0.20$ using the standard model described as follows:

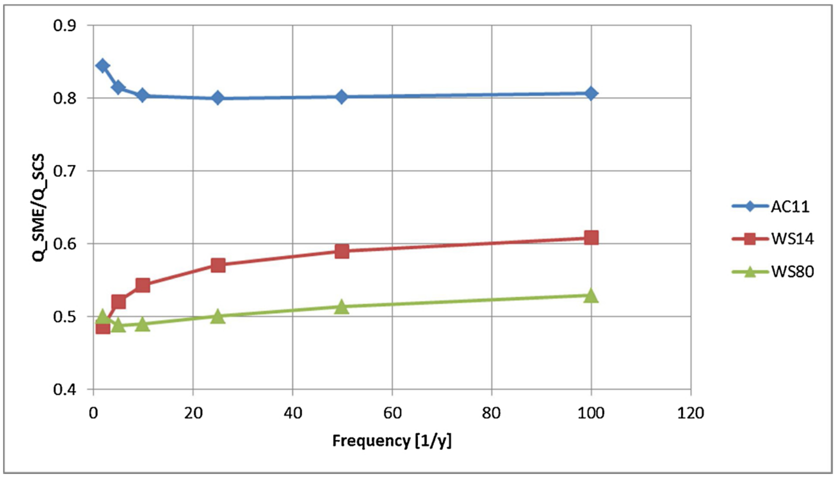

Fig. 5. Comparison of differences shown as ratios between direct runoff calculated from the modified SME and SCS-CN methods for different storm frequencies in three study watersheds.

Table 2
Comparison of direct runoff from three methods for three study watersheds.

Methods	Observed events		CN according to USDA (2004)			CN_{emp} according to Hawkins (1993)		
	MS	SME_m	SCS	MS	SME_m	SCS	MS	SME_m
	Coweeta watershed							
RMSE (mm)	0.97	0.93	1.99	2.00	1.92	2.03	1.72	1.68
EF (-)	0.81	0.83	0.22	0.21	0.27	0.19	0.41	0.44
	WS80 watershed							
RMSE (mm)	13.27	13.30	8.29	7.21	8.39	-*	–	–
EF (-)	0.30	0.30	0.73	0.79	0.72	–	–	–
	AC 11 watershed							
RMSE (mm)	5.01	5.25	3.50	3.28	3.85	6.51	5.31	5.46
EF (-)	0.79	0.77	0.93	0.91	0.91	0.75	0.77	0.75

* CN method based on the Hawkins method was not assessed for the WS80 watershed.

$$CN(P) = 79.3 + (100 - 79.3)\exp\left(\frac{-P}{10.748}\right) \tag{20}$$

The corresponding calculated *RMSE* was equal to 0.98 mm and $EF = 0.65$. The worst approximation of P-CN was obtained for $\lambda = 0.05$ with the calculated *RMSE* and *EF* values of 2.41 mm and 0.04, respectively, indicating that $\lambda = 0.20$ is perhaps a better parameter than 0.05 for this mild-gradient upland watershed.

3.2. Comparison of direct event outflow by three methods

Computed values of statistics for evaluation of the models are presented in Table 2. In the table, direct runoff from the SCS-CN method was not calculated for observed events because all parameters like CN and S were estimated empirically (e.g. CN was calculated based on soil hydrologic group and land cover) whereas in the MS and original SME models parameters like S, lambda and beta were calibrated.

Accordingly, the MS and SME_m models were shown to perform almost the same like the original, following Ritter and Muñoz-Carpena (2013) criteria, if parameters were calibrated based on observed rainfall-runoff events for the Coweeta and AC11 high gradient watersheds. In the case of the Coweeta watershed, if the CN was assessed based on the Hawkins standard model instead of the USDA model (2004), results of direct runoff were better but still unsatisfactory because the modified SME_m model yielded the *EF* of 0.44 and *RMSE* of 1.68 mm, followed by the MS model, which performed more poorly, with an $EF = 0.41$ and $RMSE = 1.72$ mm. When the CN assessment was done using the USDA tables (USDA, 2004) and the AMC was estimated based on the observed rainfall-runoff events, all models for Coweeta watershed were rated as unsatisfactory (Table 2). For example, the SME_m model yielded an $EF = 0.27$ and an $RMSE = 1.91$ mm, although it was slightly better when compared to the results from the MS and SCS method, both of which performed similarly. Based on this analysis, CN_{emp} based on observed events is recommended for the assessment of direct runoff on Coweeta watershed in NC.

In the case of WS80 in SC, the MS and SME_m model results were deemed unsatisfactory, with the lowest quality performance following Ritter and Muñoz-Carpena (2013) quality criteria although parameters were calibrated based on the observed rainfall-runoff events. This was likely because the S parameter for MS and SME_m was calibrated as independent parameter from the SCS method. In other words, S was not linked with the SCS method following the procedure described by Sahu et al. (2012). However, when the AMC was estimated based on observed rainfall-runoff events, results from all models were found to be satisfactory, with the highest quality performance based on the same criteria. Prediction of the direct runoff from the MS model yielded the highest quality performance ($EF = 0.79$, $RMSE = 7.21$ mm), followed by the modified SME (SME_m) and SCS method, both of which provided similar results. Based on the calibration process, the parameters of the MS method were obtained as $S = 458.8$ mm and $\lambda = 0.01$ and that for the SME model as $S_o = 482.2$ mm and $\beta = 0.96$. In case of WS80 direct runoff calculation using the SCS, MS, and SME_m method was not performed for the scenario with CN assessment by Hawkins asymptotic curve because the curve was not approximated well by the P-CN_{emp} relationships (Fig. 3).

Direct runoff estimated by all the models based on the observed rainfall-runoff events for the AC11 watershed in Arkansas were in good agreement with the measured data and acceptable based on the Ritter and Muñoz-Carpena (2013) quality criteria, with the MS model yielding the highest quality ($EF = 0.79$, $RMSE = 5.01$ mm). On the basis of the calibration process, the parameters of the MS method were obtained as $S = 40.0$ mm and $\lambda = 0.35$, and the SME model yielded the parameters $S_o = 36.8$ mm and $\beta = 0.25$. When the CN assessment was done based on the USDA tables (USDA, 2004) and the AMC estimated based on the observed rainfall-runoff events, the MS and SME models were found to be very good, although the best results were achieved using the original SCS-CN method with an *EF* equal to 0.93 and the $RMSE = 3.50$ mm. Also, when the CN_{emp} was used for calculation, all models yielded similar results when compared to the observed events. Generally, for the moderate upland AC11 watershed in Arkansas, acceptable results of direct runoff calculations were achieved when the CN was assessed using the standard CN obtained from the USDA table (USDA, 2004), consistent with results obtained by Walega and Salata (2019) for a mountain catchment located in the southern part of Poland. The results demonstrated that in general, the use of the modified SME-CN instead of the original SCS-CN method provides a more

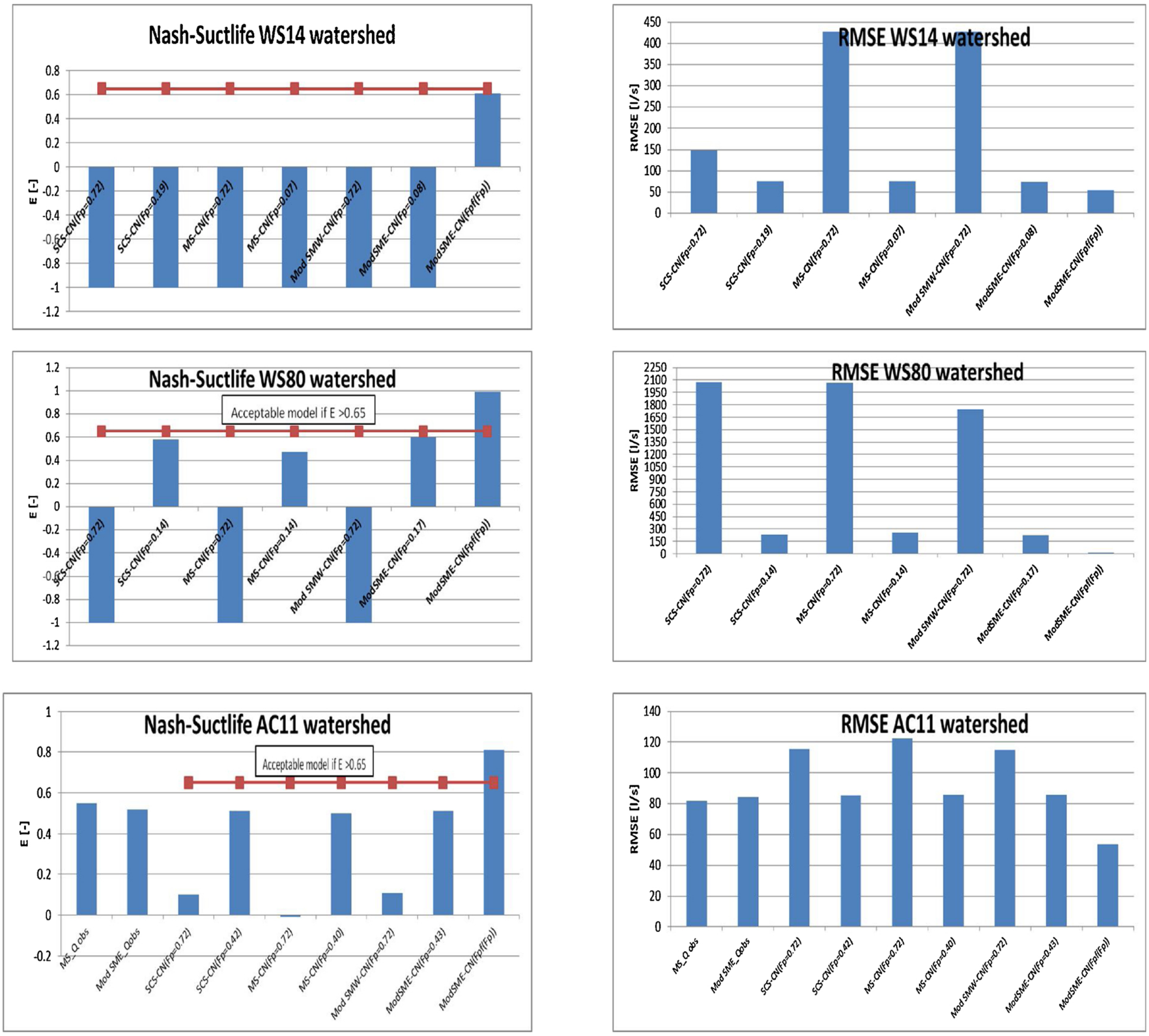

Fig. 6. Nash-Sutcliffe coefficient and *RMSE* for analyzed methods in three watersheds.

accurate prediction of direct runoff in the study watersheds based on the computed model evaluation criteria (Table 2).

The effects of the modified SME_m method are compared to the original SCS method on direct runoff calculation and presented in Fig. 5 as ratios versus the frequencies of design storms. For the WS80 watershed, direct runoff from the SME_m model was smaller about 50 % when compared to the SCS-CN method, and the differences increased with increasing design storm frequency. In the case of the AC11 watershed, runoff from the SCS method was slighty higher than the SME_m method about 20 %, and the differences decreased for lower storm frequency. For the WS14 watershed, results of direct runoff were similar from W of the methods but differences between both method was higher than for W80 watershed.

3.3. Assessment of peak discharges using the TR55 method

Fig. 6 shows the computed values of Nash-Sutcliffe EF and root mean square error (*RMSE*) of peak discharges calculated according to the USDA (1986) TR55 method shown in Eq. 15 using the observed event data. All calculations were performed first using F_p = 0.72 (the default maximum retention value given in the TR55 method) in Fig. 6 and then using the F_p values obtained by calibration with observed events (not shown).

The results showed that the calculated peak discharge (Q_p) for all methods was unsatisfactory when using the F_p value of 0.72 recommended in TR55 (USDA, 1986), with the large *RMSE* values above 115 l/s. The highest *RMSE* was obtained for the WS80 watershed (> 2000 l/s). The Nash-Sutcliffe EF coefficients were below zero in most cases, indicating that the use of a mean value is better than using the predicted values for this site with the largest drainage area (160 ha) of all the sites, as expected, potentially due to more heterogeneity of soils and land cover than the two other smaller watersheds. Our results show the default F_p value

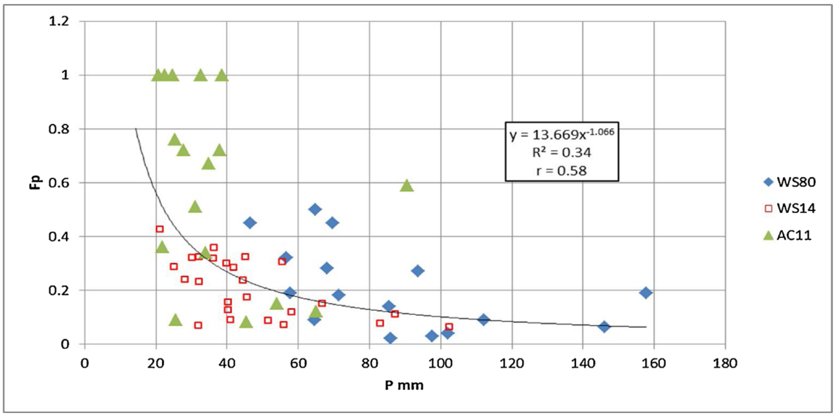

Fig. 7. The relationship between F_p and precipitation (P) for each event for all watersheds.

recommended in TR55 should not be used for these forested watersheds with high retention capacities. Somewhat enhanced results, with an *EF* higher than 0.4, were obtained for calibrated F_p values (not shown). It is interesting to note that the computed *EF* coefficients were found to be similar for both the SCS-CN and SME_m models, although slightly better results were obtained by using the SME_m method. For these forest watersheds with high retention capacity, calibrated F_p values were found to be lower than 0.40 when using all methods.

Relationships between F_p and P for each of the measured events on each study watershed are presented in Fig. 7. Results show that the calibrated F_p values vary from 0.41 to 0.062 for the Coweeta watershed, from 0.50 to 0.02 for WS80, and from 1.00 to 0.08 for AC11 (Fig. 7), respectively. In general, the data showed a decreasing trend in F_p when precipitation increased. As a result, the fitted relationship yielded a correlation coefficient of $r = 0.58$, which is not too high but is statistically significant at $\alpha = 0.05$ and 0.01. However, the large variability of observed data also shows that the F_p perhaps is also influenced by other factors including antecedent soil moisture, soil properties, etc. besides the event rainfall. For example, low rainfall amounts with high antecedent wet conditions may yield larger F_p values, perhaps due to reduced soil water storage in contrast to high rainfall amounts with high antecedent dry conditions, which may yield smaller F_p values due to large soil water storage, as is shown by the fitted relationship. This may indicate that the observed data in Fig. 7 might have been biased for those conditions. This leads to another speculation that the F_p may also be related to soil permeability, as shown by watersheds AC11 (HSG of C) and WS80 (HSG of D) with low soil permeability tending to yield higher ranges of F_p when compared to the low F_p range values yielded by WS14 which had a dominant soil category, B, with higher permeability (infiltration rates) than either of the AC11 or WS80. Thirdly, a close examination of the data also tends to indicate that the F_p factor may be related to watershed drainage area. For example, the smallest watershed AC11 yielded higher F_p values than those for the WS80 and WS14. This seems plausible, as the time of concentration of the smallest watershed, AC11, would be the shortest, potentially reducing residence time and for that matter, retention of runoff, and increasing peak flow rates.

Last but not least, it also seems that F_p values could have been influenced by the duration of each rainfall event, as shown in Fig. 8. Although the correlation coefficient is rather low ($r = 0.46$) it is statistically significant for $\alpha = 0.05$ and 0.01. Short duration rainfall events generally have high intensity, potentially resulting in both reduced loss of precipitation to infiltration and retention of runoff

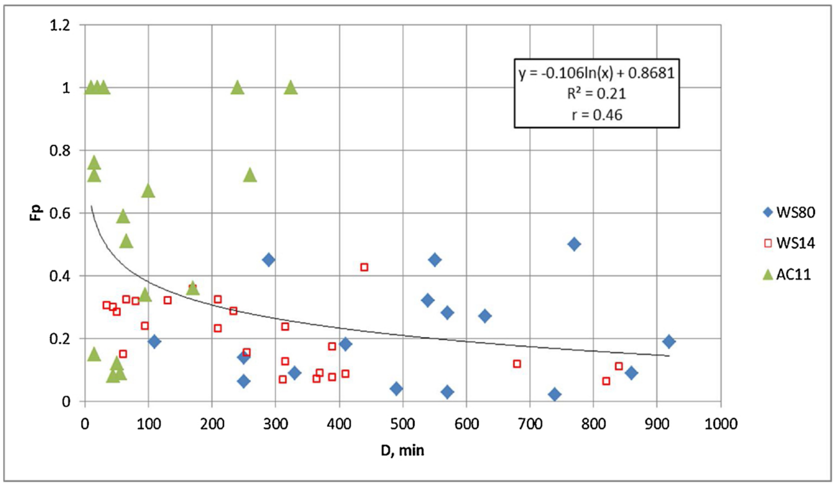

Fig. 8. The relationship between F_p and duration of precipitation (D) for each event for all watersheds.

than would have been observed for longer durations of rainfall. The low intensity long duration rainfall influences soil saturation, potentially recharging/elevating ground water, resulting in saturation excess flow with reduced runoff retention, and thus yielding a higher F_p value and peak flow rate. In that context, use of 24-hr duration rainfall (much higher than the time of concentration) for computing runoff for design storms may have also somewhat biased the peak discharge rates on these small watersheds.

When a variable F_p for each event as a function of P (Fig. 6) was used, the estimates of peak discharges using the modified SME_m model were in better agreement with the observed data. In the case of the WS80 and AC11 watersheds, the results were more satisfactory than those from Coweeta, which provided unacceptable results. The rest of the methods (USDA and MS) yielded poor results. This study's results showed that for watersheds with the highest forest cover and a high soil capacity, the F_p value should be lower than is recommended in TR55, and should be changed for different precipitation levels. Lowering this F_p value is consistent with Blair et al. (2012), who suggested that a peak rate factor of 200 is more representative than the default value of 484 recommended in the peak discharge method they used (USDA, 2007) for the flat terrain of the Southeast coastal plain (often called the low country). The peak rate factor is a constant, intended to reflect the slope of the watershed, and ranges from 600 in steep areas to 100 in flat swampy areas (Sheridan et al., 2002; USDA, 2007).

3.4. Design discharge calculations

Design peak discharges, calculated with TR55 method using the original (SCS-CN) and modified (SME_m) based runoff volumes obtained from 24-h design storms for Type-II design rainfall distribution as described above, are presented in Table 3. The results show that the design peak discharges obtained from the original TR55 procedure, where the direct runoff was calculated using the SCS-CN method and a default F_p parameter equal to 0.72, are higher than the modified SME_m method for design storms by as much as eight or nine times for the WS80 and WS14 watershed. Generally, higher differences were found for large design storms with lower frequencies like those occurring once in 50 or 100-yr frequencies. One of the main reasons for this discrepancy is likely caused by the F_p values, which should be substantially less for flat watersheds with large soil water storage, as noted above and also by Blair et al. (2012). For example, smaller F_p values were obtained for high intensity rainfall amounts for the low-gradient WS80 watershed, where such events generally occur during summer seasons when the soil water storage is generally high due to high evaporative demands of these forests (Fig. 7).

Comparison of the results from Fig. 9 for peak discharges and Fig. 5 for volume of runoff clearly shows that peak discharge is mainly influenced by the F_p parameter as the peak discharges obtained using the modified TR55 release are much less than that from the original TR55. The peak discharges are, however, independent of calculated differences observed in direct runoff volumes by the two methods. For example, even though there was only a 50 % difference in runoff, the SME method yielded as much as nine times smaller peak discharge levels than the SCS for small size high frequency storms to 12 times smaller levels for the large-size low-frequency storms on the WS14 watershed.

These results clearly show that the empirical methods are sensitive to changes in their parameters and, thus, calibration processes is necessary. Such a calibration is possible in gauged watersheds with sufficient hydrometeorological data. But in case of ungauged watersheds, it is impossible or problematic calibrating these parameters. In such circumstances, rainfall-runoff models based on unit hydrographs theory can be used. The examples of these models are synthetic unit hydrograph as SCS-UH or Snyder UH (Cupak and Wałęga, 2018; Egiazarova et al., 2017; Gądek et al., 2017). Also geomorphologic instantaneous unit hydrograph is commonly used to assess the direct hydrograph (Rodríguez-Iturbe and Valdez, 1979). In addition, to address problems with application of the empirical models in ungauged watersheds, the need arises to develop methods that are more objective for practical application, reducing the subjectivity in design hydrograph estimation and in the consequent flood mapping. Event-Based Approach for Small and Ungauged Basins (EBA4SUB) rainfall runoff model is a framework that has been fully adapted for determining runoff in ungauged catchments. EBA4SUB is based on geographic information systems and on the optimization of the topographic information contained in the Digital Elevation Model (DEM), and uses the same input data necessary to apply the well-known Rational formula (Petroselli and Grimaldi, 2018; Piscopia et al., 2015).

Alternate method of PIDF calculation using the PDFS based method:

Above analysis was conducted based on the PIDF from the NOAA Atlas-14 that uses the 24-h maximum only rainfall intensity series. However, if the NOAA's alternate partial frequency duration series based maximum intensity data stated earlier were used, the range of the new PIDF would have been somewhat larger (Table 4) than the 24-h design PIDF values shown in Table 3 in this study. For example, 24-h 100-yr P value of 219.2 mm is at the lower end of the range obtained below in Table 4 for Coweeta, NC. The 100-yr value of 231.6 mm for WS80 is even smaller than the lower range based on the new PIDF (Table 4). Same is true for Alum Creek. We believe further analysis with these new PIDF data is beyond our scope.

4. Summary and conclusions

This study was conducted at three USDA Forest Service long-term experimental forest sites in distinct physiographic regions of the Southeastern United States, the low-gradient coastal watershed in South Carolina, the high-gradient mountainous watershed in North Carolina, and a lower relief mountain type watershed in Arkansas. The objectives of this work were divided into three parts. First objective was to evaluate the performance of some of the modified SCS-CN methods, and identify the most accurate method in determining the direct runoff. The 2nd objective was to modify the SCS TR55-based Graphical Peak Discharge Method first by applying calculated direct runoff using the most reliable modified SCS-CN method followed by evaluating the currently recommended default F_p factor, for both the upland and lowland forested watersheds. The models, including the SCS-CN model, the

Table 3
Comparison of design peak discharges and runoff volume obtained from the original SCS TR55 and the modified SME models. The 24-h (P) design rainfall intensities were obtained from NOAA Atlas-14 (Bonnin et al., 2006).

Frequency [1/y]	WS14					WS80					AC11				
	P [mm]	Q [mm]		q_p [L/s]		P [mm]	Q [mm]		q_p [L/s]		P [mm]	Q [mm]		q_p [L/s]	
		SCS-CN	SME modified	Modified TR55	Original TR55		SCS-CN	SME modified	Modified TR55	Original TR55		SCS-CN	SME modified	Modified TR55	Original TR55
100	219.2	97	59	871.5	10135.0	231.6	154	81	2153.1	17552.2	239.0	145	117	1451.0	1988.9
50	196.3	80	47	693.2	8295.3	200.4	125	64	1703.1	14309.2	210.8	120	96	1188.8	1648.7
25	174.8	64	36	530.6	6391.3	171.9	100	50	1326.3	11428.3	184.2	97	78	957.3	1333.0
10	147.8	46	25	356.0	4535.7	139.2	72	35	934.3	7875.4	151.9	71	57	655.7	919.6
5	128.5	34	18	238.3	3325.3	117.1	54	26	699.4	5514.3	130.0	54	44	422.5	697.5
2	104.4	21	10	122.4	1872.4	91.2	35	17	458.6	3576.2	105.4	36	31	210.6	455.0

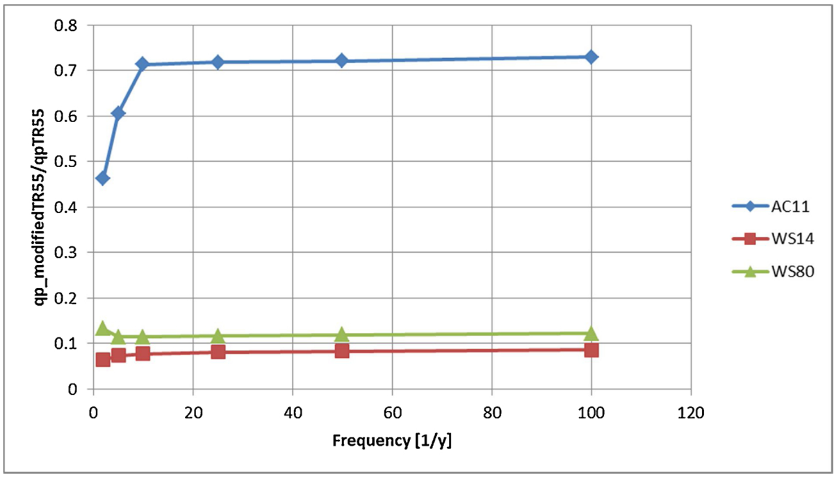

Fig. 9. Comparison of differences shown as ratios between peak discharges calculated from the modified and original TR55 methods for different storm frequencies in three study watersheds.

Table 4
Ranges of 24-h maximum precipitation data from the NOAA's Precipitation Frequency Data Server (PFDS) site that uses the partial duration series rainfall data.

Site Name	2yr 24 h P (mm)		5yr 24 h P (mm)		10yr 24 h P (mm)		25yr 24 h P (mm)		50yr 24 h P (mm)		100yr 24 h P (mm)	
	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
Santee WS80	104.1-106.7	106.2	136.1-137.9	137.2	160.0-162.6	162.3	195.6-198.1	197.6	226.1-228.6	227.6	265.5-261.6	258.8
Coweeta WS14	106.7-139.7	125.2	132.1-172.7	154.2	152.4-200.7	177.5	180.3-236.2	209.6	203.2-266.7	235.7	226.1-292.7	263.4
Alum Creek AC11	114.3-116.8	115.6	142.2-144.8	144.0	167.6-170.2	168.4	203.2-205.7	203.7	231.1-233.7	231.9	259.1-264.2	264.1

Mishra-Singh (MS) model, and the Sahu-Mishra-Eldho (SME) model modified earlier by Walega and Salata (2019) (SME_m model), all modifications of the widely used SCS-CN method, were evaluated using multi-year (2011–2015) storm events (29) data from those study sites.

The results showed that, compared to the empirical values, the USDA (or SCS) based method underestimated the CNII value for the upland sites like Coweeta and Alum Creek and overestimated the same value for the lowland WS80 watershed. For upland watersheds, however, it was shown that the $P\text{-}CN_{emp}$ relationship may be approximated by the model with a standard behavior as described by Hawkins (1993). For the lowland WS80 watershed, $P\text{-}CN_{emp}$ did not show any visible trend for initial abstraction equal 0.20. However, the initial abstraction = 0.05 yielded a good relationship with a Nash-Sutcliffe efficiency (EF) coefficient of 0.63, but was still deemed unsatisfactory, warranting a need for further enhancement in parameters to accurately determine the actual soil moisture when using the original SCS-CN method. Direct runoff calculated using the modified SME_m method was slightly in better agreement with the observed data than that from the MS and original SCS-CN methods for Coweeta watershed, but similar or slightly poorer than the MS or SCS methods for WS80 and AC11. If CN was calculated based on USDA (2004) or Hawkins curve (1993), difference between the SCS-CN, MS, and SME_m methods would not have been visible, but slightly better results were achieved for the MS and SME_m methods. The modified SME_m method included more complex information about soil conditions, mainly the antecedent soil moisture, than the original SCS-CN method and, thus, was expected to more precisely describe the runoff. The SME_m method has a low sensitivity to input parameters apart from rainfall (Walega and Salata, 2019). In case of peak discharges (Q_p), the results showed that the calculated Q_p for all methods was unsatisfactory when using the default F_p value of 0.72 recommended by the TR55 guideline, indicating that use of the default F_p value may mislead the Q_p estimates for these forest watersheds with higher retention capacities. Better results, with an EF higher than 0.4, were obtained for calibrated F_p values. The results of this study also showed that the F_p is likely influenced by soil permeability in watersheds, event rainfall, and duration of rainfall. Furthermore, the results also showed that the peak discharges obtained from the original TR55 procedure, with the standard SCS-CN method and the default F_p parameter value of 0.72, were higher than those obtained using the modified method, with the SME_m method-based direct runoff and the F_p value calibrated for individual events, by 5 to almost 24 times for all study watersheds. In addition, some discrepancies of application of the TR55 peak discharge method on the large WS80 watershed may also have been due to its large size with more heterogeneous soils and land cover than two other smaller watersheds. Generally higher differences in design peak discharge estimates between the two methods were found for design rainfall events with lower frequencies (e.g. 100-yr or 50-yr) that are generally used in design of road culverts, although some discrepancies might have also been due to potential errors in NOAA design rainfall values derived by the interpolation methods. Only on the AC11 watershed, difference between peak discharges was smallest for 2-year frequency. This study indicates a need for further testing of the methods with additional forest watersheds with various catchment characteristics. It also provides an opportunity to assess limitations and uncertainty among the widely used design discharge computation tools including the Rational method that uses the design rainfall intensity and USGS regional flood frequency-based regressions (Tian et al., 2019) for the design of road cross-drainage and other water management structures on these forested watersheds in the humid Southeast US. Furthermore, peak discharge analyses using the NOAA's partial duration frequency series (PDFS) based PIDF would provide a context in comparison with other widely used methods.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2019.100645.

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