Application of Modified SME-CN Method for Predicting Event Runoff and Peak Discharge from a Drained Forest Watershed on the North Carolina Atlantic Coastal Plain

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Highlights

- Proposed new method to assess subsurface and surface runoff from drained forested watershed.
- Factor F_p in the graphical peak discharge method is less in forested wetland watershed than recommended by USDA.
- Modified graphical peak discharge method correctly approximated observed peak discharges.

Abstract. *The NRCS curve number (CN) method is a widely used event-based model for estimating runoff using readily available watershed parameters and rainfall data from upland agricultural catchments. However, there is limited literature on application of the CN method in drained forest systems. This study proposes an application of the modified Sahu-Mishra-Eldho (SME) CN method developed and tested in earlier studies. In this study, the SME method was further modified by redefining the maximum potential retention to assess subsurface drainage and surface runoff, which are parts of total outflow, separately for a pine forest watershed with a high water table soil drained by ditches spaced 100 m apart in coastal North Carolina. Assuming that the measured outflow from the drained watershed was dominated by subsurface drainage, computed event outflow using the modified SME-CN (MSME-CN) model showed good agreement with the observed outflow data (without extreme rainfall events) for the study watershed, yielding a Nash-Sutcliffe coefficient of 0.97, R^2 = 0.97, and RMSE = 3.46 mm. Linking the direct runoff from the MSME model into the SCS graphical peak discharge method (GPDM) also improved event peak flow estimates compared to those from the GPDM using SCS-CN based outflow, with calculated RMSE of 11.93 and 31.35 L s^{-1} and modeling efficiency (EF) of 0.79 and -0.45, respectively. In addition, based on analysis, the wetland factor (F_p) of 0.72 recommended in the GPDM was found to be very large and unsuitable for the study watershed with its high retention capacity. The authors suggest multi-site-year validation of the MSME-CN model, which is sensitive to input parameters such as PET5, P, CN, and a, to gain more confidence in it and the associated GPDM.*

Keywords. *Peak discharge, Pine forest, Poorly drained soil, Potential retention, Subsurface runoff, Surface runoff.*

One of the commonly identified problems in hydrological analysis and design of stormwater management and flood control structures is assessing runoff from ungauged catchments. The USDA Natural Resources Conservation Service (NRCS, originally Soil Conservation Service, SCS) curve number (CN) method is a widely used event-based model for estimating runoff volume using readily available watershed parameters and rainfall data. The method was originally developed for assessing surface runoff from upland agricultural catchments (Ponce and Hawkins, 1996; Soulis and Valiantzas, 2012a). Several different types of rainfall-runoff models are available in the literature. For heterogeneous catchments, Soulis and Valiantzas (2012b) and Wałęga et al. (2015) used a new method to assess empirical CN values. This SCS-CN modeling approach estimated the runoff amount from a catchment characterized by diverse land use, where the CN was defined for dominant homogeneous parts of the catchment. Cho and Engel (2018) presented a continuous SCS-CN method-based hybrid hydrologic model for long-term hydrologic applications in spatially distributed rainfall-runoff generation and routing. Verma et al. (2017) modified the SCS-CN method by introducing the level of soil moisture (V_0) at the beginning of the storm, instead of the initial abstraction, to avoid sudden jumps in CN value. Verma et al. (2018) described a one-parameter SCS-CN model based on the Mishra-Singh model (Mishra and Singh, 2002) and soil moisture accounting (SMA) procedure for surface runoff estimation. Durán-Barroso et al. (2016) solved the lack of in-

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tegration of soil moisture in the NRCS method by adding an SMA procedure. Petroselli et al. (2013) and Grimaldi et al. (2013a, 2013b) modified the SCS-CN model, taking the Green-Ampt infiltration method into account, to get a correct distribution of the direct runoff during a precipitation event. Menberu et al. (2014) found an initial abstraction ratio (λ) that was substantially lower than the recommended value of 0.20 for peat-dominated soils on forested lands in Finland and Norway. Sahu et al. (2007, 2010, 2012) modified the initial abstraction (I_a) in the original SCS-CN method by introducing antecedent moisture (M) and named the proposed method Sahu-Mishra-Eldho (SME). The SME method was further verified by Wałęga and Rutkowska (2015) for a mountainous catchment in the upper Vistula River basin. Bartlett et al. (2016) used a new runoff concept (based on thresholds) within the framework to create an extended SCS-CN method that moved beyond the traditional SCS-CN limitations. Recently, Jiao et al. (2019) revised the NRCS-CN model by modifying the I_a-S relationship consisting of I_d (maximum initial abstraction) = λS and equations describing the effect of antecedent runoff condition. They found improved estimates of runoff with their revised method and methods with varying λ rather than $\lambda = 0.20$.

Depending on the catchment conditions, runoff can be dominated by surface runoff, subsurface drainage, or both. For example, much of the land with poorly drained, high water table soils, including peatlands in the Northern Hemisphere, are artificially drained, and runoff is likely dominated by subsurface drainage (Skaggs et al., 2016), except during extreme rainfall events when surface runoff may also contribute (Amatya et al., 2019). According to Hirt et al. (2011), artificial drainage systems have a short response time to rainfall events, combined with a fast increase to peak discharge rates. This effect is independent of land use and soil texture. Yuan et al. (2001) modified the SCS-CN method to calculate subsurface runoff by defining CN values for drainage flow for five poorly drained sites in east-central Illinois. They reported that the predicted subsurface flows using the modified SCS-CN method were not significantly different from the observed subsurface flows for their calibration and validation. However, there is limited literature on application of the CN method to drained systems, particularly for forested conditions. The limitations of the original SCS-CN method for event runoff estimates also influence the associated peak discharge estimates using the graphical peak discharge method (GPDM), as demonstrated recently by Wałęga et al. (2020), who found substantial overestimates of peak discharge compared to the observed data.

The main aim of this study was to develop a more accurate version of the currently available SME-CN method, expressed as the MSME-CN method, by modifying its parameters for the surface and subsurface components of total event outflow and assessing its performance in calculating total runoff (surface and subsurface) from a drained watershed. Based on previous work (Wałęga et al., 2020), it was evident that the original GPDM, with direct runoff assessed based on the SCS-CN method and an assumed pond and swamp adjustment factor (F_p) of 0.72, as recommended by the USDA (1986), may overestimate peak discharges, leading to oversizing of hydraulic structures. If the runoff values from the modified MSME-CN method are close to the observed runoff and F_p is much smaller than 0.72 (USDA, 1986), this will likely improve the results of the modified original GPDM for assessing design peak discharges. The proposed method was tested in a pine forested watershed drained by open lateral ditches spaced 100 m apart on the North Carolina Coastal Plain.

Materials and Methods

Study Site

The study site is located in a drained pine forest, owned and managed by Weyerhaeuser Company, at approximately 34° 48′ N and 76° 42′ W on the Atlantic Coastal Plain of North Carolina (fig. 1). The study watershed (D1, the control) is adjacent to two other drained treatment watersheds (D2 and D3), each of which is about 25 ha in size on a 14-year-old plantation established in 1988. The average land slope of the site on the shallow water table soils is about 0.1%. The soil is a hydric series: Deloss fine sandy loam (fine-loamy mixed, thermic Typic Umbraquult). Each watershed is drained by four 1.4 to 1.8 m deep parallel lateral ditches spaced 100 m apart that drain to a main roadside ditch through a collector ditch that was built for isolating the three watersheds (fig. 1) (Amatya and Skaggs, 2011). The lateral (east to west) boundary of each watershed was assumed to be the mid-line between the lateral ditches at the edges of the adjacent watersheds. Rows of pine trees planted on 0.4 m high beds parallel to the lateral ditches, acting as surface depression, prevent surface runoff from flowing between the watersheds as well as to the watershed outlet. A restrictive layer that begins at an average depth of about 2.8 m limits vertical seepage (Amatya et al., 1996). The outflow processes on this drained pine plantation consist principally of subsurface flow to the lateral ditches and then channel flow to the watershed outlet.

Hydro-Meteorological Measurements

Rainfall on the study watershed was measured with a tipping-bucket rain gauge backed up by a manual rain gauge on the west side (fig. 1). Rainfall was measured with a Qualimetric tipping-bucket rain gauge with datalogger (Omnidata, Logan, Utah) in an open area of about 70 m × 50 m on the west side of each watershed (Amatya et al., 2000). Although rainfall was recorded continuously, hourly rainfall digitized from the rainfall charts was used to obtain the total rainfall for each event (Amatya et al., 1996).

A 120° V-notched weir with an automatic stage recorder, located in a water level control structure at a depth of about 0.3 m from the bottom of the outlet ditch (fig. 1), was used to continuously measure drainage outflow in each watershed using standard weir equations. A pump, installed in 1990 and downstream from the three watersheds in the roadside collector ditch, helped to minimize weir submergence during larger storm events. An additional recorder was placed downstream from the weirs in May 2005 to determine if weir submergence occurred and to correct flows in that event. A weather station located 800 m away from the study water-

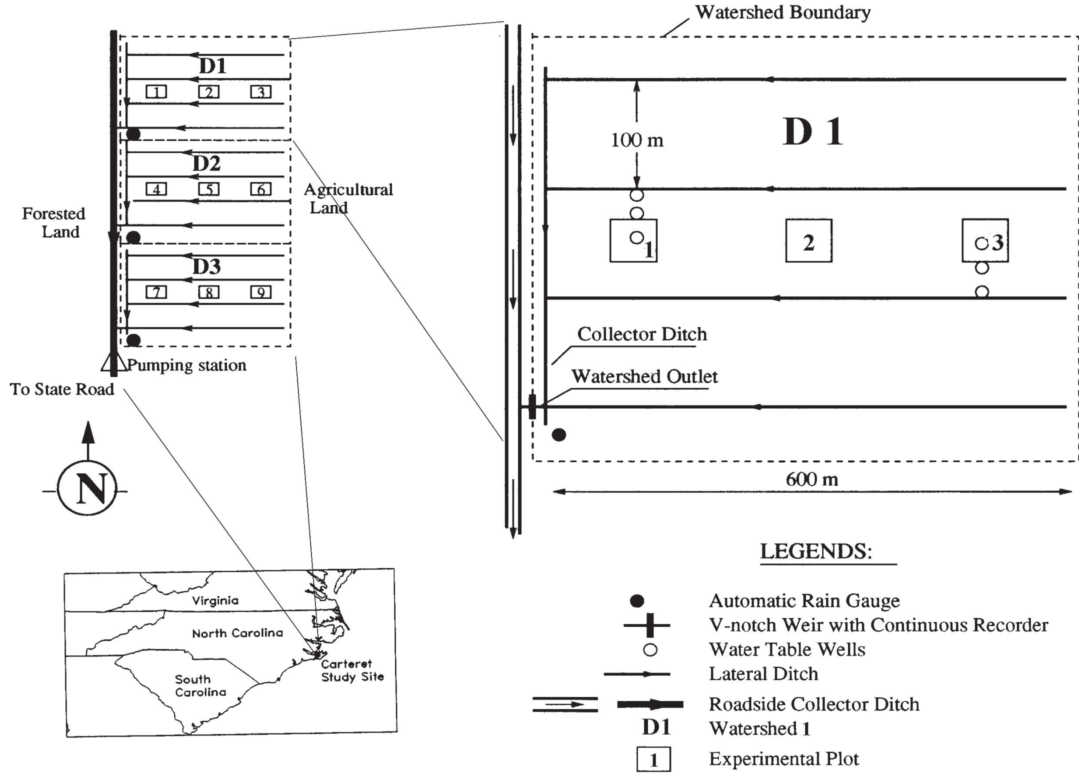


Figure 1. Location of three experimental watersheds and layout of a typical watershed with monitoring stations, Carteret County, North Carolina (after Amatya et al., 2000).

shed measured the temperature, humidity, wind speed, and solar radiation on a continuous basis. Details on the measurements of hydrology, weather, soil, and vegetation parameters on the watersheds are given elsewhere (Amatya et al., 1996, 2000; Amatya and Skaggs, 2011).

Upstream of the weir at the ditch outlet of the watershed, stage (water) levels were recorded at 6 min intervals with a water level recorder (Type F, Leopold and Stevens, Beaverton, Ore.) with datalogger (Omnidata). A Fortran program developed in 1993 by the Weyerhaeuser Company was used to estimate drainage or outflow rates corresponding to the 6 min instantaneous stage elevations. The standard 120° V-notch weir equation was used in the program to compute the flow rates (Amatya et al., 2000), so the peak flow rates for analyzed storm events represent a 6 min basis. Regarding the lag time, a study by Hirt et al. (2011) for several artificially drained sites across Europe and for this site concluded that the response of drainage outflow was visible within the first 6 h after a precipitation event for the study sites with hourly discharge data, including our site.

Data Analysis

We used measured rainfall-runoff data for 29 storm events from the 1991-1993 period for the study site, as described in detail by Amatya et al. (2000), for identifying measurable watershed runoff from corresponding rainfall events. We used data only for the control watershed (D1), which had 18 to 20 year old pine stands that were not disturbed. The amount of rainfall varied from 22 mm for a March 1991 event to as much as 218 mm for an October 1993 event. The event outflow varied from 2.6 mm for a March 1991 event to as much as 110 mm for an April 1993 event. As described above, most of the outflow on this watershed occurs as subsurface drainage and surface runoff rarely occurs, except for extreme rainfall events when the weir outlet can be fully submerged, with uncertainties in flow measurements (Amatya et al., 1998). Daily Penman-Monteith (Monteith, 1965) based potential evapotranspiration (PET), as reported by Amatya et al. (1995) using daily weather data measured at the nearby weather station, was used in the analysis described below.

SCS Curve Number Method and Modified Versions

The concept of the method was taken from the model described by Soulis and Valiantzas (2012b) that allows researchers to determine the empirical CN for heterogeneous watersheds in terms of land use. According to those authors, the catchment was divided into two homogeneous areas characterized by relatively similar land uses. Two CN values (CN_a and CN_b), with $CN_a > CN_b$, were then determined for these areas. If a denotes the area fraction of the catchment with $CN = CN_a$, then $(1 - a)$ is the area fraction of the catchment with $CN = CN_b$. Wałęga et al. (2015) described that "the idea of the catchment division into two homogeneous sub-areas originated from the following research hypothesis: during a rainfall event, surface runoff is first formed in the areas characterized by lower permeability, i.e., smaller storage capacity. With continued rainfall, runoff is also formed in the permeable areas. The maximum runoff is observed when the flow is contributed by the whole catchment area."

In this study, a similar approach was used; however, the runoff was estimated using the Sahu-Mishra-Eldho (SME) model (Sahu et al., 2012) modified by Wałęga and Amatya (2019) (referred to here as the MSME model). In the SME model, the direct runoff is estimated for every rainfall-runoff event using following equations:

$$Q = \frac{\left(P - I_a\right)\cdot\left(P - I_a + M\right)}{P - I_a + S} \text{ if } P > I_a \tag{1}$$

$$Q = 0 \text{ otherwise}$$

$$I_a = \lambda \cdot \left(S - M\right) \tag{2}$$

where S is the maximum retention capacity. In equation 1, the higher the antecedent moisture (M), the lower the initial abstraction (I_a), and vice versa. The antecedent moisture is given as:

$$M = \beta\left[\frac{\left(P5 - \lambda S\right)\lambda S}{\left(P5 - \lambda S\right) + S}\right] \text{ for P5} > \lambda S \tag{3}$$

$$M = 0 \text{ for P5} < \lambda S$$

where β and λ are parameters that are optimized. Parameter β is a part of the 5 d rainfall that is intercepted. In equation 3, parameter β means that M at the beginning of a rainfall event is equal to a fraction (β) of the amount of water infiltrated during the antecedent 5 d period (P5). The assumption is based on the fact that only a fraction, in general, of the water added to the soil profile contributes to M because of evapotranspiration (ET), drainage, and other losses during the 5 d antecedent period (Sahu et al., 2010; Wałęga et al., 2017a). Accordingly, a further modification was made to the SME model to calculate the subsurface runoff (drainage) and surface runoff individually. The combination of both was assumed to be total runoff.

Subsurface runoff was calculated using equations 4 to 9:

$$\text{MSME}_{Qsubs} = \frac{\left(P - I_{a1}\right)\cdot\left(P - I_{a1} + M\right)}{\left(P - I_{a1} + S_a\right)} \text{ if } P > I_{a1} \tag{4}$$

$$I_{a1} = a \cdot \left(\text{PET5} + \left(S_a - M\right)\right) \tag{5}$$

$$\text{MSME}_{Qsubs} = \text{if } P < I_{a1} \tag{6}$$

$$M = \beta \cdot \frac{\left(\text{P5} - \text{PET5}\right)\cdot S_a}{\left(\text{P5} - \text{PET5}\right) + S_a} \text{ if P5} > \text{PET5} \tag{7}$$

$$M = 0 \text{ for P5} < \text{PET5} \tag{8}$$

$$S_a = a \cdot \left(\frac{25400}{\text{CN}} - 254\right) \tag{9}$$

Surface runoff was calculated using equations 10 to 14:

$$\text{MSME}_{Qsurf} = \frac{\left(P - I_{a2}\right)\cdot\left(P - I_{a2}\right)}{\left(P - I_{a2} + S_b\right)} \text{ if } P > I_{a2} \tag{10}$$

$$I_{a2} = \left(1 - a\right)\cdot\left(\text{PET5} + \left(S_b\right)\right) \tag{11}$$

$$\text{MSME}_{Qsurf} = 0 \text{ if } P < I_{a2} \tag{12}$$

$$S_b = \left(1 - a\right)\cdot\left(\frac{25400}{\left(100 - \text{CN}\right)} - 254\right) \tag{13}$$

$$w = \left(1 - a\right)\cdot\left(S_b\right) \tag{14}$$

Total runoff was calculated as the sum of surface and subsurface runoff:

$$\text{MSME}_{tot} = \text{MSME}_{Qsurf} + \text{MSME}_{Qsubs} \tag{15}$$

where P is the sum of the precipitation during the event (mm), I_{a1} is the initial abstraction for subsurface runoff (mm), M is the antecedent moisture (mm), S_a is the maximum potential retention for the area where subsurface runoff occurs (mm), a is the coefficient for the proportion of area with saturated soil (this parameter is calibrated), PET5 is the sum of 5 d PET using the Penman-Monteith method (mm), I_{a2} is the initial abstraction for surface runoff (mm), S_b is the maximum potential retention for the area where surface runoff occurs (mm), CN is the CN parameter, MSME_{Qsubs} is the subsurface runoff (mm), and MSME_{Qsurf} is the surface runoff (mm).

Theoretical Background

In the case of a flat, low-gradient watershed with runoff driven by the shallow water table, which is characteristic of the poorly drained soils of the lower coastal plain, surface runoff occurs either when the water table nears the surface due to very high rainfall events (Amatya and Skaggs, 2011; Amatya et al., 1996) and/or due to the sealed surface layer with low permeability. In most cases, saturated runoff or subsurface drainage occurs. Skaggs et al. (2016) noted that the drained system provides primarily subsurface drainage through parallel ditches about 1 m deep and typically spaced 100 to 200 m apart. The tree seedlings are planted in beds, about 30 cm in height, which provide protection from flooded conditions and good soil-root contact. For example, those authors reported that water ponded between the beds as a result of more than 150 mm of rainfall during a hurricane. The furrows between the beds are not connected to the ditches; thus, the intensity of surface drainage is very low. Although there may be some runoff during extreme events, annual surface runoff is small, and nearly all of the drainage water is removed by relatively slow subsurface flow. Therefore, attempts were made to separate the total runoff into subsurface flow and surface runoff.

In the initial phase of rainfall, when the soil is dry with a large soil water deficit (storage), it was assumed that runoff does not occur (fig. 2). When the first soil saturation threshold (I_{a1}) is exceeded, subsurface flow begins, depending on the drainage intensity (ditch depth and spacing). The factor determining the proportion of saturated area is parameter a. We hypothesized that the watershed is completely saturated with water only in a situation when P5 corresponds to the maximum potential retention S, and surface runoff or saturated overflow is then initiated. If the watershed is only par-

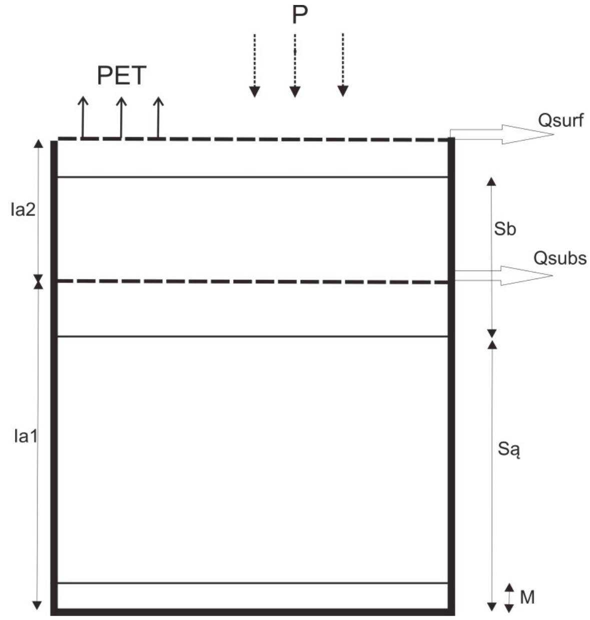


Figure 2. Diagram of soil moisture store in SME model calculations.

tially saturated (a < 1.0), subsurface runoff may occur only from the part of the catchment that is closest to the ditch. However, if the rainfall (P) continues during the event, the soil will continue to be saturated, achieving the second threshold (I_{a2}) and resulting in the occurrence of surface runoff. To perform runoff calculations for these conditions in ungauged catchments, we assumed that the CN parameter can be used to test these hypotheses.

The calculations were carried out using following procedure: in the first case, CN was determined for each of the rainfall-runoff events based on the equations given by Wałęga et al. (2017a), and parameters a, λ, and β were optimized using the Nash and Sutcliffe coefficient as an objective function. In addition, the results were compared with the original SCS-CN method for the average CN value.

The root mean square error (RMSE) and the modeling efficiency (EF) (Nash and Sutcliffe, 1970) were used as goodness-of-fit measures to assess and compare the performance of the models:

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

$$\text{EF} = 1 - \frac{\sum_{i=1}^{N}\left(Q_i - Q_{calc,i}\right)^2}{\sum_{i=1}^{N}\left(Q_i - \bar{Q}_{obs,i}\right)^2} \tag{17}$$

where $Q_{obs,i}$ is the observed direct runoff, $Q_{calc,i}$ is the direct runoff calculated using equation 15, and $\bar{Q}_{obs,i}$ is the mean value of the observed direct runoff values. Equation 17 was used as an objective function during the calibration processes following parameters a, λ, and β. Optimum values of these parameters was achieved when EF was maximum. The calibration processes was performed using the Solver tool in Microsoft Excel.

We used the criteria of Ritter and Muñoz-Carpena (2013) to evaluate the model performance, where EF < 0.65 was deemed the lower threshold for unsatisfactory performance. Other model performance ratings were as follows: acceptable (0.65 ≤ EF < 0.80), good (0.80 ≤ EF < 0.90), and very good (EF > 0.90).

As the final step, an analysis was conducted to assess the sensitivity of the proposed model to changes in the input parameters. The sensitivity is an indicator of the relative change in model output values resulting from a relative change in an input parameter (Wałęga et al., 2014). Theoretically, if $x_1, ..., x_n$ are model input variables, and $y = y(x_1, ..., x_n)$ is the model output series, then the flexibility (relative sensitivity) of y with respect to the ith variable at $(x_1, ..., x_i^0, ..., x_n)$ is:

$$e(y) = \frac{\partial y}{\partial x_i}\left(x_1, \ldots x_i^0, \ldots, x_n\right) \times \frac{x_i^0}{y\left(x_1, \ldots x_i^0, \ldots, x_n\right)} \tag{18}$$

An absolute value of e equal to or greater than 1 is a sign of a substantial change in the output value relative to the change in the input value; otherwise, the model cannot be deemed sensitive (Wałęga et al., 2017a). To assess the ranked sensitivity of the model, the sensitivity index classes described by Feki et al. (2018) were used. If $e(y)$ = 0.00 to 0.05, sensitivity is small to negligible, 0.05 to 0.2 = medium, 0.2 to 1.00 = high, and >1.00 = very high.

Sensitivity analysis was performed to assess the impact of the S, P5, a, PET5, and CN input parameters on the total runoff value, with Q as the model output. When the sensitivity of the modified SME method was assessed for one parameter, the values of the other parameters were assumed to remain constant.

Peak Discharge Rate Calculation

To determine the peak discharge of observed storm events, the simpler USDA TR55 procedure (USDA, 1986), based on the GPDM, was used. The TR55 graphical peak discharge equation for a storm event is:

$$q_p = q_u \cdot A_m \cdot Q \cdot F_p \tag{19}$$

where q_p is the event peak discharge (cfs); q_u is the unit peak discharge (csm in.$^{-1}$), which is a function of time of concentration (t_c) and I_a/P ratio; A_m is the drainage area (mi^2); Q is the runoff (in.); and F_p is the pond and swamp adjustment factor.

Runoff (Q) estimates from the MSME and original SCS-CN methods were used individually in the TR55 procedure (eq. 19) to calculate peak discharge (q_p) for the observed rainfall events. For the SCS-CN method, CN was assumed as the mean value based on 29 observed rainfall-runoff events.

Unit peak discharge (q_u) was determined assuming a type II rainfall distribution for all the three study watersheds and using the corresponding calculated t_c and I_a/P coefficients for each site from the Exhibit 4-II Chart (USDA, 1986). An

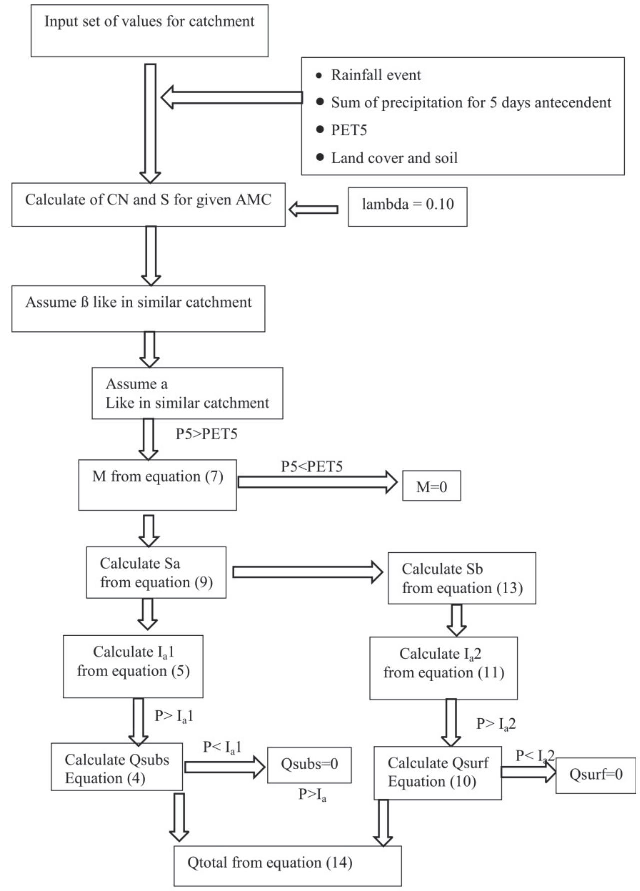


Figure 3. Flowchart for calculating direct outflow according to the proposed model.

F_p value equal to 0.72 for 5% swamp and pond areas is recommended by the USDA, likely for agricultural settings (USDA, 1986). For this study site in a pine forest with high surface storage due to raised beds, we identified the best F_p value by optimizing the modeling efficiency (EF) as an objective function using the Solver tool in Microsoft Excel. This assessment was conducted following a recent study by Wałęga et al. (2020), who demonstrated that F_p of 0.72, as recommended by the NRCS (USDA, 1986), is too high for forested watersheds; consequently, peak discharge is likely overestimated using F_p = 0.72. The nonlinear algorithm option was chosen to find an optimal value for F_p.

Based on comparison of predicted direct runoff values using both models (MSME and SCS-CN) with the observed runoff data as well as the corresponding peak discharge for the D1 watershed, the most accurate method was selected for both the direct runoff and peak discharge calculation methods using the model performance criteria in equations 16 and 17. The flowchart in figure 3 shows the procedure used to calculate runoff from similar watersheds that lack runoff data. In this method, CN is calculated using the USDA method (USDA, 2004), and parameters a, λ, and β should be used from this study site, assuming similar conditions of runoff generation.

Probability of Exceedance of Peak Discharge

Peak discharge values computed by the GPDM using both the MSME and SCS-CN models for outflow as well as those obtained from the observed data were used to derive their probability of exceedance based on the Weibull equation (Maidment, 1993). The probabilities of occurrence estimated by both methods were also compared with the observed values.

Results and Discussion

Table 1 shows that the mean PET5 is 12.10 mm, which is close to the median value. This shows that PET5 has a close to normal distribution. This is confirmed by the low values of kurtosis and skewness. The situation is different for rainfall (*P*). There is a very high variability of rainfall, as expressed by the standard deviation (SD) of 50.90 mm. The high values of kurtosis and skewness and the clear difference between the mean and median show an asymmetrical distribution of *P*. A similar tendency is shown for P5, *Q*, and CN_{emp}, which was calculated based on observed rainfall-runoff events. PET, which is primarily controlled by radiant energy, is small during rainfall events when solar radiation is low. CN_{emp} was relatively high, with a mean of 78.42. Higher CN values are related to high runoff and relatively small and medium rainfall (fig. 4). A probable explanation for this phenomenon is that, during small rainfall events, runoff occurs only when the soil is saturated. As discussed later, in the case of small rainfall events, the MSME-CN model only produced subsurface runoff. When high rainfall occurs, CN is small due higher soil water capacity. CN values have high variability, which can be an effect of rainfall and highly variable soil moisture due to draining of the watershed by ditches.

Rainfall (*P*), runoff (*Q*), and CN_{emp} values for the 29 analyzed events are presented in figure 4. Precipitation showed a consistent pattern, with three extremely high rainfall events occurring in each year. The duration of these extreme events varied from almost 3 d to over 5 d (Amatya et al., 2000). The amount of event rainfall varied from 22 mm for a March 1991 event to as much as 218 mm for an October 1993 event, while the size of the outflow from the D1 watershed was variable and fluctuated from 2.30 mm in 1991 to 110.40 mm in spring 1993, with an average of 23.52 mm (table 1). The watershed responded with the largest outflow of 110 mm in early April 1993, which was 89% of the rainfall of 123.7 mm, and was attributed to wetter antecedent conditions and lower ET rates. According to Amatya et al. (2000), the amount of rainfall needed to generate a drainage event generally depends on the antecedent conditions. For example, in

Table 1. Parameter statistics for 29 selected rainfall-runoff events.

Statistics	PET5 (mm)	*P* (mm)	P5 (mm)	*Q* (mm)	CN_{emp}
Mean	12.10	70.34	18.72	23.52	78.42
Median	12.52	56.90	4.60	17.30	83.37
Minimum	2.20	22.40	0.00	2.30	24.87
Maximum	18.81	218.00	115.90	110.40	97.88
SD	3.88	50.90	29.82	22.24	19.24
Kurtosis	0.13	2.99	4.21	7.50	1.59
Skewness	-0.52	1.86	2.15	2.33	-1.45

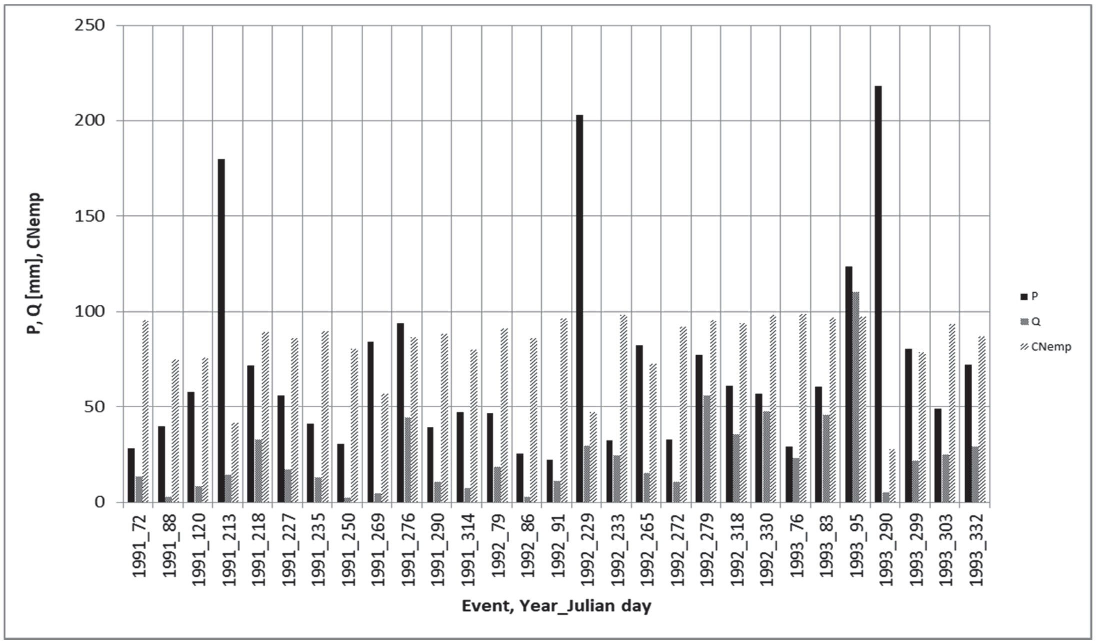


Figure 4. Variability of *P*, *Q*, and CN_{emp} for 29 events from 1991-1993 for the D1 watershed. The data also show the proportion of event runoff to rainfall for each event in the study watershed during the analyzed period.

the case of the large rainfall amount (218.0 mm) for an October 1993 event, very little runoff (5.0 mm) was generated. The deep water table and relatively dry initial soil conditions resulted in a large volume of water-free pore space prior to this event on day 290. Values of CN_{emp} determined based on observed rainfall-runoff events varied from 24.9 for the large rainfall event in October 1993, with runoff of just 2% of rainfall, to 97.9% for the event in March 1993, with runoff of 89% of rainfall (Amatya et al., 2000). The mean value of CN_{emp} was 78, which was relatively stable .

Considering all events combined, there was no clear correlation between *P* and *Q* (fig. 5). The calculated coefficient of determination (R^2) was very low, with the regression equation explaining only about 4.5% of the variation. The main reason for the lack of relationship between *P* and *Q* was the bias caused by the three largest precipitation events (circled in fig. 5), which yielded only small amounts of outflow. As mentioned earlier, despite the high rainfall amounts, the runoff coefficients, i.e., the percentage of rainfall that became runoff, were very low. The initial moisture conditions in the watershed prior to the rainfall events influenced this relationship, consistent with earlier studies of low-gradient

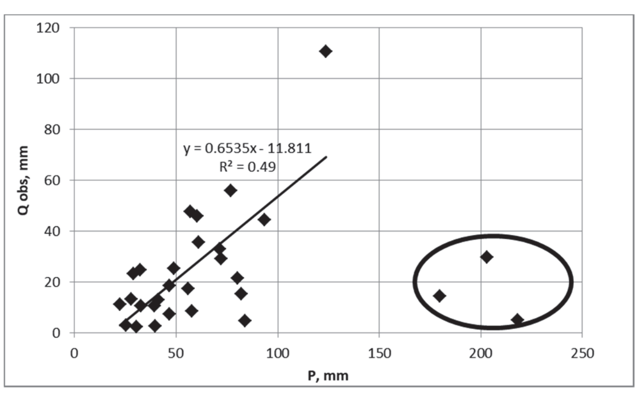


Figure 5. Relationship between *P* and *Q* in catchment D1.

coastal forests (Epps et al., 2013; La Torres Torre et al., 2011; Slattery et al., 2006; Amatya et al., 2000; Amatya and Trettin, 2010). If these values are omitted, the relationship between *P* and *Q* is strong, with R^2 of 0.49, which corresponds to a correlation coefficient (r) of 0.70. This relationship is statistically significant at $\alpha = 0.05$ ($p = 0.000069$).

For all the rainfall events, outflow calculations were made using the proposed MSME method shown in equations 1 and 2. The optimization process yielded the following parameter values: $a = 0.62$, $\lambda = 0.10$, and $\beta = 0.10$. The higher calculated value of *a* indicates that subsurface flow is the dominant form of outflow from this drained forest watershed, which has substantial microtopography due to the raised beds, as stated earlier (Amatya et al., 1996, 2000; Skaggs et al., 2016). This parameter can be interpreted somewhat like the topographic index in TOPMODEL (Beven, 2012), which represents the saturated zone in an area draining to a point on a hillslope. It can also be identified as a variable source area in the catchment. This phenomenon occurs when the soil is so saturated that water cannot permeate into it any further, and the result is called super-saturation surface runoff. The total saturation of the soil, which determines runoff formation, is caused by a rise in the groundwater table or by the occurrence of subsurface runoff. Variable source areas usually occur around riparian areas of watercourses or in areas where the water level and the thickness of the soil layer produce a rapid saturation of the soil due to lateral flow of water in the soil, subsurface runoff, or groundwater outcrop. However, active variable source areas may also occur outside the immediate vicinity of watercourses (Szymczak and Krężałek, 2018; Krężałek, 2018).

Lyon et al. (2004) attempted to combine variable source areas with the classic SCS-CN method as applied to two subwatersheds, one in the Delaware basin in the Catskill Mountains of New York State and the other in southeastern Australia, to produce runoff probability maps. They concluded that the SCS-CN method provides a simple way to predict the fraction of a watershed producing saturation-excess runoff and a manner in which to locate those saturated areas. The initial abstraction coefficient recommended by the USDA (2004) is 0.20. However, many researchers (Baltas et al., 2007; Hawkins et al., 2002; Mishra and Singh, 2004; Woodward et al., 2003; Wałęga et al., 2017b) have claimed values of this parameter that were much lower, typically 0.05, as also supported by Blair et al. (2012) for lower coastal plain watersheds in South Carolina. Those studies demonstrated that the λ value for catchment basins where outflow is significantly influenced by the variable groundwater level should be less than the NRCS recommended value (USDA, 2004). On the other hand, a low value of β (0.10) indicates that infiltrating P5 rainfall does not influence *M* at the beginning of a rainfall event. Other factors, such as water stored in the soil profile from a previous period, can significantly impact the *M* value. A substantial portion of P5 may also evaporate. Jiao et al. (2019) described a concept for modifying the initial abstraction and introduced a potential initial abstraction that is influenced by the processes of seepage and ET before runoff. In comparing our work, as described in this article, to the concept described by Jiao et al. (2019), it is apparent that the MSME model uses a more detailed water balance at the beginning of storm events because we calculated PET based on the Penman-Monteith method and water added from P5 to create soil moisture. Our proposed model assumed that ET is the main process that influences canopy storage (Murakami, 2008). We did not use a canopy storage equation because it was assumed that, in the case of high-intensity rainfall, canopy storage is not limited by total rainfall losses. Potential ET is often used with caution for estimating actual water losses from natural systems (Lu et al., 2005). A study by Amatya et al. (2000), using the same watershed (D1) as this study, showed that the antecedent water table depth, and consequently the soil water content, depend on the ET and drainage rates prior to the event.

The calculations of event outflow for the 29 rainfall-runoff events showed that the proposed SME model had very good performance, according to the criteria of Ritter and Muñoz-Carpena (2013), based on the calculated EF of 0.97, and figure 6 shows the relationship between the observed and calculated runoff using the MSME method. The RMSE was 3.46 mm, and the calculated R^2 was also high (0.97). The strong and significant relationship between the observed runoff and runoff calculated with the MSME method shows that the calculated outflow was in very close agreement with the observed data.

Figure 7 shows the relationship between the rainfall events and the corresponding subsurface (Q_{subs}) and surface (Q_{surf}) runoff as calculated with equations 4 and 10 using the MSME method. In most cases, the model predicted subsurface runoff with zero or negligible surface runoff, except for the three largest events with rainfall >179.9 mm (in July 1991, July 1992, and October 1993) when surface runoff was also predicted by the model. However, the total runoff was not high (<30 mm) due to the small surface runoff of <12 mm. Surface runoff due to heavy rainfall events on this watershed, with its substantial microtopography, is only likely when the subsurface drainage continues to increase as the soil becomes completely saturated with a high water table, sometimes even with surface ponding, and the outlet weir is submerged. This was possibly the case for event 29 (in April 1993). More detailed analysis is required to address this mechanism of surface runoff generation for ponded water conditions in the modified SME model. As shown in figure 6, most of the storm events produced subsurface runoff, as expected for this drained system. For the heaviest rainfall, simulated runoff was slightly overestimated compared to the observed data. This discrepancy may also be due to errors in the measured flow data for large events with weir submergence (Amatya et al., 1998). Other sources of model uncertainty include the need to calibrate the three parameters (*a*, λ and β), the quality of the rainfall-runoff data, and possible errors in PET calculation and rainfall measurement, mainly for high-intensity events.

Figure 8 shows a comparison of the total runoff calculated using the two models and the observed data. All calculations were performed for the same conditions, i.e., the same CN was calculated based on the 29 observed rainfall-runoff events, and λ was 0.2 for both models (as recommended by the USDA, 1986). The results for both models showed some variability, although better results were found with the MSME model, and higher outflow values were found with the SCS-CN model. Based on statistical evaluation of the

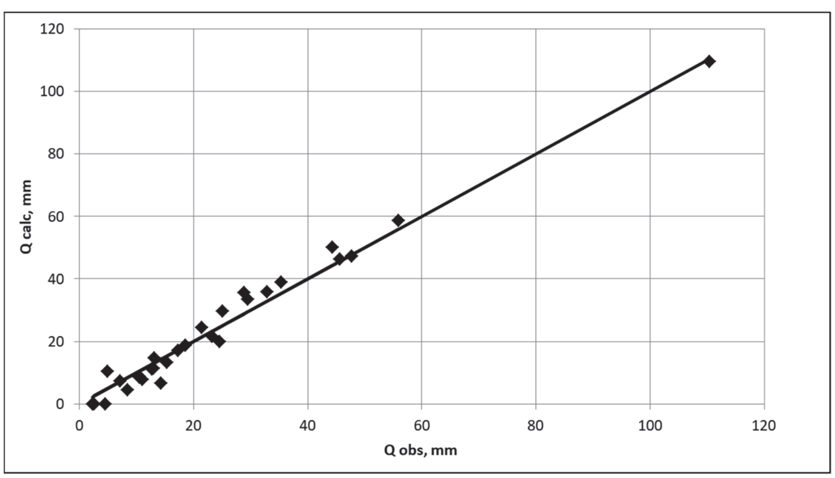


Figure 6. Relationship between Q_{obs} and Q_{calc} for 29 rainfall-runoff events on the study watershed (D1).

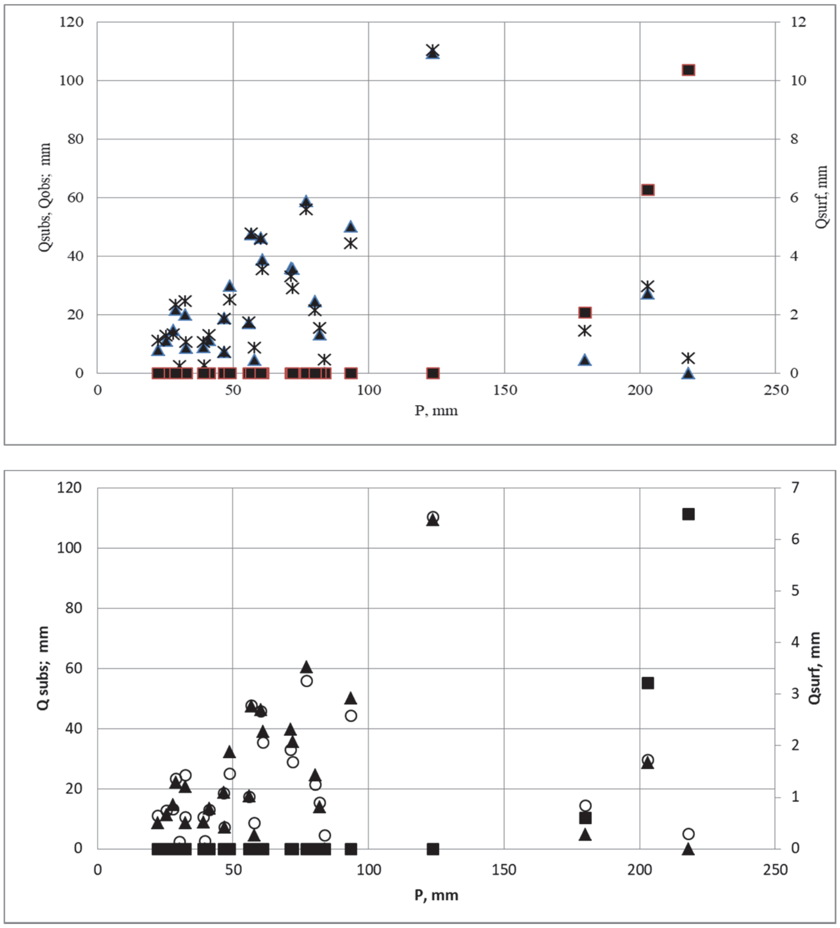


Figure 7. Relationship between *P* and *Q* (Q_{subs} and Q_{surf}) for the D1 watershed. Black squares indicate simulated surface runoff, black triangles indicate simulated subsurface runoff, and black stars indicate observed runoff.

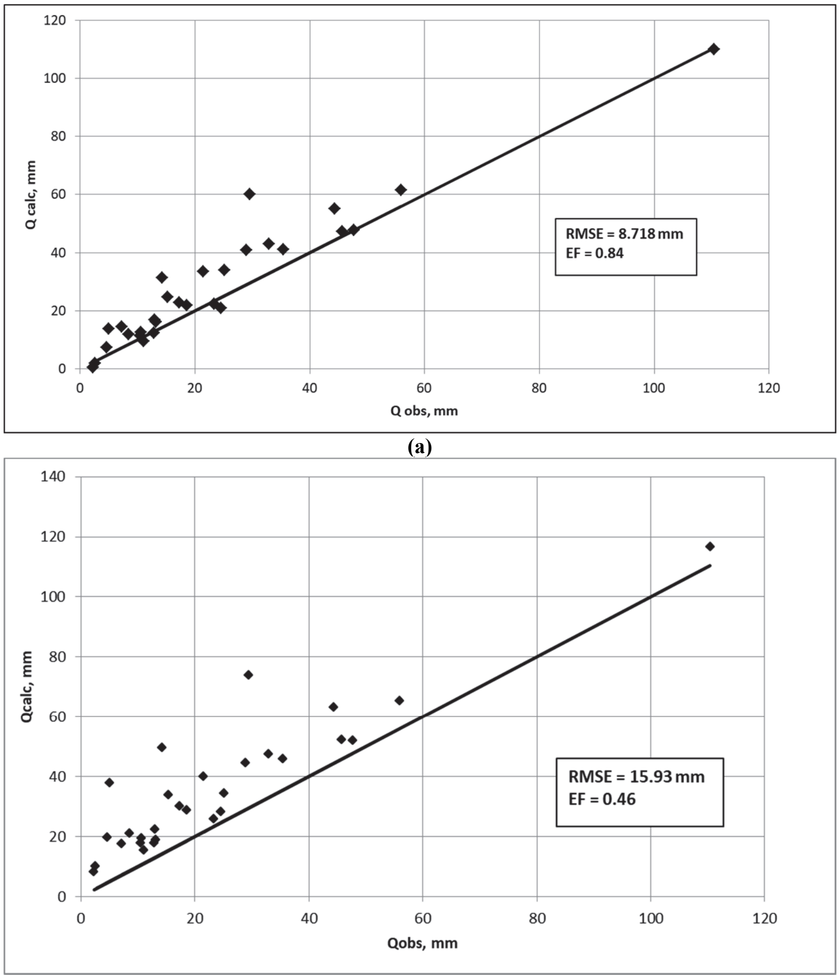
MSME-CN model, the RMSE was 8.72 mm and EF was 0.84. For the SCS-CN model, the RMSE was 15.93 mm and EF was 0.46, The SCS-CN model was found to be unsatisfactory in predicting direct runoff on this watershed.

Results of the model sensitivity analysis for the input parameters, which were varied between -90% to +90% of their base values for the rainfall events, are presented in table 2. High sensitivity of *Q* to PET5 and *P* was evident for the MSME model, as reflected by the high sensitivity coefficients, which were greater than unity for both parameters (table 2). This was due to the fact that precipitation is the main factor controlling surface runoff. Evaporation also influences the increase in soil moisture deficit, potentially causing a decrease in runoff. An increase in P5 together with *Q* may be explained by the fact that high antecedent soil moisture reduces the initial abstraction of precipitation loss, which means that most of the rainfall is converted into runoff. However, the model showed negligible sensitivity to changes in P5. An increase in β caused an increase in *Q*, although the model showed no sensitivity to β. Increasing β was conducive to an increase in *M*, which consequently reduced the initial abstraction (I_a). As mentioned earlier, reduction in the initial abstraction intensifies the formation of direct runoff. In general, the MSME model was very sensitive to changes in precipitation (*P*) causing a flood. This was because *P* is the main cause of surface runoff. The model was also sensitive to changes in CN. Increased CN leads to increased outflow. Increased CN also decreases the maximum potential retention (*S*), resulting in decreased *P* retained in the soil profile and increased runoff. The model was also sensitive to changes in *a*. Increasing the proportion of the saturated area leads to increased subsurface runoff. According to Dahlke et al. (2012a, 2012b), if the water table is 10 cm below the surface, direct runoff is initiated in the form of shallow subsurface flow. They showed that the amount of saturation-excess runoff generated during storm events is controlled, to a great extent, by the available soil water, which changes daily and seasonally with antecedent moisture conditions, consistent with the mechanism presented in this study.

Based on these results, the MSME model was able to predict runoff from this low-gradient watershed under "free" conventional drainage. The results also show that it may be possible to apply the MSME model to runoff calculations for other watersheds that have conditions similar to this study site (i.e., rainfall in the range of 22 to 220 mm, flat topography with an area less than 25 ha, shallow groundwater table, land cover dominated by forest, and fine sandy loam soil).

Peak Discharge Calculation

Figure 9 presents basic statistical distributions in the form of box plots for measured and calculated peak discharges obtained from the GPDM that used the SCS-CN and MSME



(a)

(b)

Figure 8. Relationship between Q_{obs} and Q_{calc} for the (a) MSME model and (b) SCS-CN model.

Table 2. Sensitivity coefficients for MSME model.

Variable	Sensitivity	Result
PET5 → Q	1.083	Highly sensitive
P → Q	1.083	Highly sensitive
P5 → Q	0.015	Negligible
CN → Q	4.416	Highly sensitive
a → Q	1.094	Highly sensitive

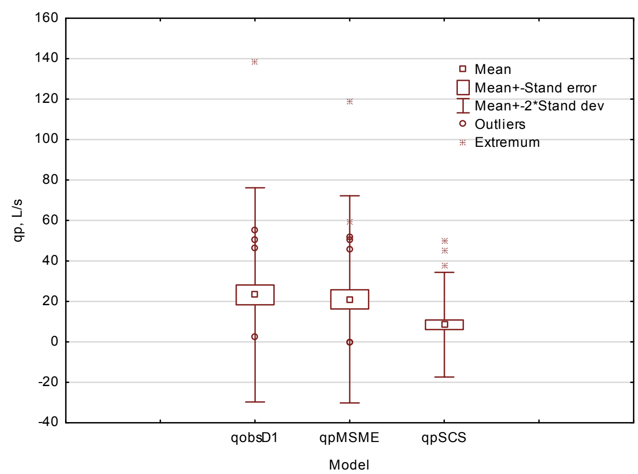


Figure 9. Statistical distribution of peak discharge from both models compared to the observed data in the study watershed.

models individually. The plots show higher variability of peak discharges for the observed events and for the GPDM using the MSME model, in contrast to the GPDM using the SCS-CN model. The mean and range of variability for the GPDM with the MSME model were similar to those for the observed data, suggesting that the proposed modification of the GPDM, where Q is calculated using the MSME model, is suitable for assessing q_p from the drained forested watershed (D1). These good results for q_p were likely caused by optimization of the F_p value, which was found to be only 0.00009 for the GPDM using the MSME model. This value, close to 0, is dramatically lower than the value of 0.72 recommended by the USDA (1986) and other methodologies, i.e., Capece et al. (1986). This result also supports a recent study by Wałęga et al. (2020), who concluded that the default F_p value recommended in TR55 should not be used for these forested watersheds with high retention capacities. For the GPDM using the SCS-CN model, the F_p value was also very low (0.00003). These lower values may likely be the result of the large surface storage caused by the raised surface beds for the trees and the open lateral ditches.

Figure 10 shows that the calculated peak discharge results from the GPDM using the MSME model fit better with the observed data than the original method (GPDM using SCS-

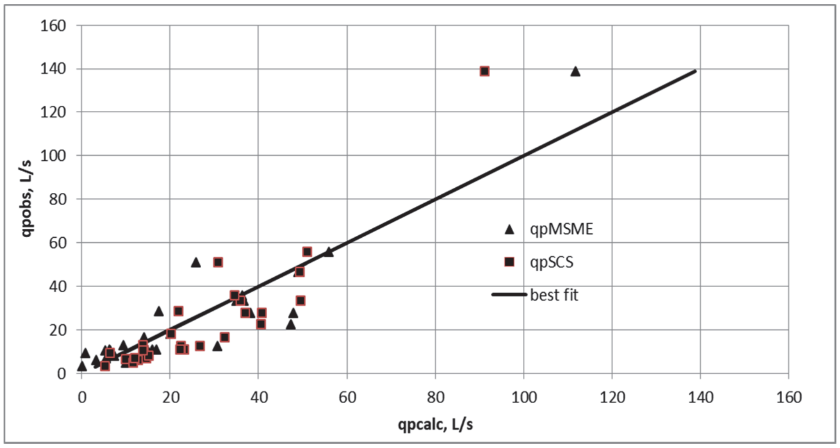


Figure 10. Relationship between q_{pobs} and q_{pcalc} for both methods for the study site.

CN). In the second method, q_p underestimated the peak discharge compared to the observed events. Accordingly, the calculated RMSE values were 10.72 and 13.00 L s^{-1} for the GPDM with the MSME and SCS-CN models, respectively. Similarly, the GPDM with the MSME model yielded a higher positive EF value of 0.83, compared to the negative value of 0.75 for the SCS-CN model, indicating superior performance of the GPDM with the MSME model over the SCS-CN model.

The plots in figure 11 represent empirical exceedance probability curves for q_p calculated using the GPDM with the MSME and SCS models compared to the observed q_p. It is evident that the peak discharges from the GPDM with MSME are in better agreement with the observed peak discharges for all range of empirical quantiles (probabilities of exceedance), including the most extreme range. For the highest quantiles (with the highest probabilities), the observed peak discharge curve is above that from the GPDM using the MSME model. For the lowest quantiles (with the lowest probabilities), which are important for the design of hydraulics structures, the calculated peak discharge from the GPDM with MSME is about 20% lower than the observed peak discharge curve. It is also clear that the curve based on the calculated peak discharge for the GPDM with the SCS method substantially underestimated the observed peak discharges with the lowest probability and slightly overestimated for the probability range of 0.16 to 0.99. The ditches at the study site serve as an artificial path for streamflow and can substantially change the watershed response to rainfall events. Hirt et al. (2011) concluded that artificial drainage systems have a short response time to rainfall events, combined with a fast increase to peak discharge rates. This effect is independent of land use and soil texture. In addition, ditches drain the watershed rapidly during rainfall events due to the sharp hydraulic gradient between the water table position midpoint between the ditches and the ditch water level, producing lateral subsurface drainage as a significant part of the total outflow or runoff.

Nevertheless, although we did not measure surface runoff, field observations showed that subsurface flow dominates the total outflow in most cases, with almost negligible surface runoff, except during heavy rainfall events (fig. 12). For the outflow processes at this site, Amatya et al. (1996) noted that: "Outflow processes on drained pine plantations consist principally of subsurface flow to the lateral ditches and then channel flow to the watershed outlet. The purpose of bedding (20 cm average height) during site preparation is to create well-drained microsites on the bed tops for planting the seedlings. The ridge and valley microtopography created by bedding enhances surface detention storage capacity and

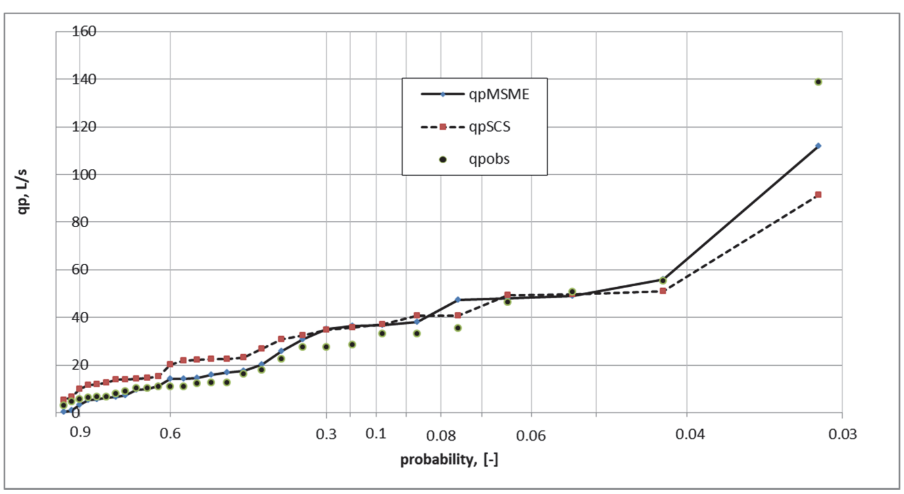


Figure 11. Empirical exceedance probability curve of peak discharges for D1 watershed.

Figure 12. Example of surface runoff from watershed D1 after high rainfall.

precludes surface runoff (overland flow) except for the highest rainfall events. High infiltration capacity in the surface soil layer results in complete infiltration of the net rainfall that reaches the surface. Subsurface drainage to the ditches is coupled with relatively slow channel flow in much of the drainage system."

SUMMARY AND CONCLUSIONS

The aim of this study was to develop a modified version of the SCS curve number (CN) method, called the modified Sahu-Mishra-Eldho (MSME) CN method, for calculating total runoff and surface and subsurface outflows from a drained watershed. The method was tested with data from 29 storm events on a pine forest watershed drained by open lateral ditches spaced 100 m apart in coastal North Carolina.

We introduced boundry conditions (i.e., initial abstraction with two thresholds, CN, and proportion of saturated area) to assess subsurface drainage and surface runoff. The conditions were based on the initial abstraction, which was introduced as the sum of PET estimated by the Penman-Monteith method, potential water retention by the soil, and antecedent soil moisture. Assuming that measured outflow from the wa-tershed was dominated by subsurface drainage, the event outflow results from the modified MSME-CN model were found to be in better agreement than the original SCS-CN method with the observed data for the study site, yielding a Nash-Sutcliffe coefficient of 0.97 and RMSE of 3.46 mm. However, for events with rainfall of <40 mm, runoff was slightly overestimated by the MSME-CN model. Based on R^2 values, using the MSME method for this drained forest watershed showed closer association with the observed data than the previously reported results for a modified CN method on a tile-drained agricultural watershed in the midwest U.S. For higher rainfall, the proposed model slightly overestimated runoff compared to the observed data.

When the direct runoff from the MSME model was introduced into the SCS GPDM, the method clearly improved the results for peak discharge (q_p) estimates compared to the results of the original SCS-CN. This was shown by statistical evaluation: RMSE of 11.93 and 31.35 L s^{-1} and EF of 0.79 and -0.45 for the GPDM with MSME and with SCS-CN, respectively. These results show that the peak discharges calculated using the GPDM with MSME were in better agreement with the observed data than the values from the SCS-CN, indicating the superiority of the former model for application on the study watershed. Although the analysis revealed that the GPDM with MSME yielded better peak discharge values in the whole range of quantiles compared to the measured data, it was in closer agreement with the measured data mainly for the mean and lower probabilities, which is important for the calculation of peak discharge in the design of hydraulic structures.

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