Water Resources Management (2005) 19: 37–62

Field Applicability of the SCS-CN-Based Mishra–Singh General Model and its Variants

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(Received: 21 November 2003; in final form: 12 May 2004)

Abstract. The general soil conservation service curve number (SCS-CN)-based Mishra and Singh (Mishra and Singh, 1999, *J. Hydrologic. Eng.* ASCE, 4(3), 257–264) model and its eight variants were investigated for their field applicability using a large set of rainfall-runoff events, derived from a number of U.S. watersheds varying in size from 0.3 to 30351.5 ha, grouped into five classes based on the rainfall magnitude. The analysis based on the goodness of fit criteria of root mean square error (RMSE) and error in computed and observed mean runoff revealed that the performance of the existing version of the SCS-CN method was significantly poorer than that of all the model variants on all the five data sets with rainfall ≤38.1 mm. The existing version showed a consistently improved performance on the data with increasing rainfall amount, but greater than 38.1 mm. The one-parameter modified SCS-CN method ($a = 0.5$ and $\lambda =$ a median value) performed significantly better than the existing one on all the data sets, but far better on rainfall data less than 2 inches. Finally, the former with $\lambda = 0$ was recommended for routine field applications to any data set.

Key words: agriculture research service, ars water database, curve number, initial abstraction coefficient, soil conservation service, SCS-CN method

Notations

A	parameter of the general model
AMC	antecedent moisture condition
B	Mockus parameter
B	b ln(10)
C	loss coefficient
C	runoff factor
CN	curve number
D	maximum difference of empirical cumulative distribution
D_α	critical D-value for significance level α
F	cumulative infiltration
F_{max}	maximum possible infiltration depth when Q corresponds to $P_{e_{max}}$
F^*_{max}	normalized F_{max}

i	an integer varying from 1 to N
I_a	initial abstraction
L	losses
N	total number of rainfall-runoff events
N_{case}	total number of observed samples
P	total rainfall
P_{max}	maximum rainfall depth
P_e	effective rainfall excluding I_a
$P_{e_{max}}$	maximum effective rainfall depth
P_e^*	normalized P_e
$P_{e_{max}}^*$	maximum effective rainfall depth (nondimensional)
Q	direct runoff
Q_{obs}	observed storm runoff
Q_{comp}	computed runoff
Q^*	normalized Q
RMSE	root mean square error
S	potential maximum retention
S_r	degree of saturation
TTT	two-tailed t-test
α	significance level
λ	initial abstraction coefficient

Superscript * stands for standardization on S

1. Introduction

In watershed hydrology, the soil conservation service-curve number (SCS-CN) method (Soil Conservation Service, 1956, 1964, 1971, 1985, 1993) is one of the most popular methods for computing the volume of surface runoff for a given rainfall event from small agricultural watersheds. In the recent past, significant literature has been published on the SCS-CN method and several recent articles have reviewed the method at length. For example, McCuen (1982) provided guidelines for practical application of the method to hydrologic analyses. Ponce and Hawkins (1996) examined the method critically and delineated its capabilities, limitations, and uses. Hjelmfelt (1991), Hawkins (1993), Bonta (1997), and Bhunya *et al.* (2003) suggested procedures for determining curve numbers for a watershed using field data. Mishra and Singh (2003a) provided the current state of the art of the SCS-CN methodology, its enhanced analytical treatment, and applications to areas other than the originally intended one.

Despite the availability of much work on the SCS-CN methodology, little is known about its applicability to low or high rain events, except for the general notion (Ponce and Hawkins, 1996) that the existing SCS-CN method works well on rainfall-runoff data of high magnitude. Therefore, the use of annual extreme rainfall-runoff events in SCS-CN applications (SCS, 1971; McCuen, 2002) has been quite common. Such experience can largely be attributed to the specific value (= 0.2) (SCS, 1956) of the variable (SCD, 1972; Bosznay, 1989) initial abstraction coefficient in the existing version. The applicability criteria of Mishra and Singh (2003a) also rely on the coefficient range (0.1, 0.3) and high runoff coefficient ($\geq$0.43). Since the SCS-CN concept is applicable to any data set if the observed runoff corresponds to the given rainfall and the initial abstraction coefficient can range (0, ∞) (Mishra and Singh, 1999b, 2003a,b), it is in order to evaluate the rainfall-dependent applicability of the methodology, which forms the major objective of the paper. To this end, the events derived from a variety of U.S. watersheds were grouped into five classes based on rainfall amount and then the performance of the general SCS-CN-based Mishra–Singh model and its eight variants were evaluated for their performance on each set of rainfall-runoff data.

2. SCS-CN Method

The SCS-CN method is based on the water balance equation and two fundamental hypotheses which can be expressed, respectively, as

$$P = I_a + F + Q \tag{1}$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{2}$$

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

where P is total rainfall, I_a is initial abstraction, F is cumulative infiltration, Q is direct runoff, S is potential maximum retention which can range (0, ∞), and λ is initial abstraction coefficient. Mishra and Singh (2003a) described Equation (2) as a proportionality concept, and F as the dynamic portion of infiltration. Mishra and Singh (2003b) derived Equation (2) using the first-order linear hypothesis for the variation of S with rainfall. In Equation (3), the initial abstraction I_a includes short-term losses, viz., evaporation, interception, surface detention, and infiltration and its ratio to S describes λ which depends on climatic conditions and can range (0, ∞). Combination of Eqations (1) and (2) leads to the popular form of the SCS-CN method:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{4}$$

Parameter S in Equation (4) is expressed as

$$S = \frac{25400}{CN} - 254 \tag{5}$$

where S is in mm and CN is a nondimensional quantity varying in the range (0–100).

3. General Mishra–Singh Model

Mishra and Singh (1999a) described the basis of the SCS-CN method to lie in the empirical rainfall-runoff relation expressed by Mockus (1949) as:

$$Q = P_e\left[1 - (10)^{-bP_e}\right] \tag{6a}$$

where

$$P_e = P - I_a \tag{6b}$$

is the effective rainfall excluding I_a and b is an index which depends on the antecedent moisture condition (AMC), vegetative cover, land use, time of the year, storm duration, and soil type. Parameter b can be construed as a reasonable index of CN with the difference that the latter is a non-dimensional quantity, and the former a dimensional one. Expressing Equation (6a) in an exponential form using a constant $B = b\ \ln(10)$ and neglecting the third and higher order terms of the expanded exponential lead to the expression:

$$Q = \frac{(P - I_a)^2}{S + 0.5(P - I_a)} \tag{7}$$

which is the modified form of the SCS-CN method. The functional behaviour of Equation (7) can be described by coupling Equation (7) with Equations (1) and (3):

$$\frac{S}{P} = \frac{[4\lambda + 2C - \lambda C] - \sqrt{C[C(2-\lambda)^2 + 16\lambda]}}{4\,\lambda^2} \tag{8}$$

where $C = Q/P$. From Equation (8), it can be shown that S/P always assumes a real value, which is consistent with its physical significance given by Mishra *et al.* (2003). Mishra and Singh (1999a) generalized Equation (7) by replacing 0.5 by a parameter 'a' as follows:

$$Q = \frac{(P - I_a)^2}{S + a(P - I_a)} \tag{9}$$

which is the general form of the SCS-CN-based Mishra and Singh (1999a) model. Here, I_a and S are described by Equations (3) and (5), respectively. It is evident from Equation (9) that P should be greater than or equal to I_a, $Q = 0$ otherwise. Further analytic is provided as follows:

Equation (9) when standardized on S leads to

$$Q^* = \frac{1}{a}\left[\frac{P_e^{*2}}{P_e^* + 1/a}\right] \quad \text{or} \quad Q = \frac{1}{a}\left[\frac{P_e^2}{P_e + S/a}\right] \tag{10a,b}$$

where $Q^* = Q/S$, $P_e = P - I_a$ = effective rainfall depth, and $P_e^* = P_e/S$. The term inside the bracket [·] represents the traditional SCS-CN equation (Equation (4)), but with S replaced by S/a. Thus, the new equation (Equation 10b) is simply the old equation, but multiplied by 1/a. The ultimate $P{:}Q$ slope as $P \to \infty$ is $1/a$. The limits from the general rainfall-runoff hydrology are as: $0 \leq Q \leq P$, and $0 \leq \partial Q/\partial P \leq 1$. Thus, the upper limit of applicability can be described for $\partial Q/\partial P$ equal to 1. To this end, Equation (9) can be differentiated with respect to P_e as:

$$\frac{\partial Q}{\partial P} = \frac{\partial Q^*}{\partial P^*} = \frac{P_e^*\left[2 + aP_e^*\right]}{\left[1 + aP_e^*\right]^2} \tag{11}$$

Thus, the maximum effective rainfall depth ($P_{e_{max}}^*$) (nondimensional) corresponding to $\partial Q/\partial P$ equal to 1 can be computed as:

$$P_{e_{max}}^* = \frac{1}{a}\left[\frac{1}{\sqrt{1-a}} - 1\right] \quad \text{or} \quad P_{e_{max}} = \frac{S}{a}\left[\frac{1}{\sqrt{1-a}} - 1\right] \tag{12}$$

Equation (12) leads to description of the lower bound of parameter 'a' as:

$$a \geq \frac{1}{2} - \frac{1}{P_{e_{max}}^*} + \sqrt{\frac{1}{4} + \frac{1}{P_{e_{max}}^*}} \tag{13}$$

Furthermore, Equations (12) lead to the following general limits:

a	$P_{e_{max}}^*$	Remark
$-\infty$	0	
0	0.5	Pure quadratic ala Grunsky's equation
0.5	0.8284	
1	Undefined	Traditional SCS-CN structure, for $\partial Q/\partial P \to 1$ as $P_e \to \propto$.

For values of a > 1, the limiting slope $\partial Q/\partial P_e \to 1/a$ and $P_{e_{max}}^*$ does not exist.

In addition, for $P_e > P_{e_{max}}$ and a < 1, it is presumed that the infiltration losses (F) are the maximum possible and will continue at that fixed amount. Thus,

$$F_{max} = P_{e_{max}} - Q \tag{14}$$

where F_{max} is the maximum possible infiltration depth and Q corresponds to $P_{e_{max}}$, given in normalized form (Q^*) as:

$$Q^* = \frac{1}{a^2}\left[\frac{2-a}{\sqrt{1-a}} - 2\right] \tag{15}$$

Similarly, the normalized F_{max} ($= F^*_{max}$) can be given as:

$$F^*_{max} = P^*_{e_{max}} - Q^* = [(2-a) - 2\sqrt{(1-a)}]/a^2 \quad (16)$$

Thus, for $P > P_{max}$, $Q = P_e - F_{max}$, where P_{max} is the maximum rainfall depth. Notably, as parameter $a \to 1$ in Equation (16), $F \to S$, which is consistent with the basic SCS-CN concept for $\partial Q/\partial P = 1$ (Mishra and Singh, 1999a).

In brief, the workability of the general model can be described as follows:

$$\text{(i) For } P^*_e \leq 0 \qquad Q^* = 0 \qquad \partial Q/\partial P = 0 \quad (17a)$$

$$\text{(ii) For } 0 < P^*_e < P^*_{e_{max}} \qquad Q^* = \frac{P^{*2}_e}{aP^*_e + 1} \qquad 0 < \partial Q/\partial P < 1 \quad (17b)$$

$$\text{(iii) For } P^*_e \geq P^*_{e_{max}} \qquad Q^* = P^*_{e_{max}} - F^*_{max} \qquad \partial Q/\partial P = 1 \quad (17c)$$

where superscript * stands for standardization on S, i.e., $P^*_e = P_e/S$; and subscript 'max' stands for maximum. It is noted that both the modified (Equation 7) and general (Equation 9) models do not follow the proportional equality concept (Equation (2)), and therefore the potential maximum retention S of the general model is not the same as of the existing SCS-CN model. Re-writing the water balance equation (Equation 1) as $Q = P - L$, where L = losses, enables both the forms to be valid even for large watersheds, where channel transmission losses are dominant. Furthermore, it is possible to determine the losses L using the modified model, for example, as: $L = cP$, where $c = (1 - 0.5P^*/(1 + 0.5P^*)$ and P^* is the normalized rainfall depth. For a non-zero rainfall and $L \geq 0$, $c \geq 0$ and, therefore, $2S \geq P$. This condition is physically realizable in porous, arid watersheds characterized by large values of the potential maximum retention S and low values of rainfall P.

4. Application

4.1. ARS WATER DATABASE

The data used in this study are taken from the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) Water Database, which is a collection of rainfall and streamflow data from agricultural watersheds of the United States. This archive of variable time-series readings for rainfall and runoff contains sufficient detail to reconstruct storm hydrographs and hyetographs. There are currently about 16 600 station years of data stored in the database. The existing raingauge networks range from one station per watershed to over 200 stations. However, only 1 raingauge for one watershed was so strategically selected that the raingauge reasonably represents its rainfall. The period of record for individual watersheds vary from 1 to 50 yr. Some watersheds have been in continuous operation since the

Table I. Classes for model evaluation

Sl. No.	Class	Rainfall range	No. of watersheds
1	A	Rainfall ≤ 12.7 mm (= 0.5 inch)	220
2	B	12.7 < Rainfall ≤ 25.4 mm (= 1.0 inch)	231
3	C	25.4 < Rainfall ≤ 38.1 mm (= 1.5 inch)	224
4	D	38.1 < Rainfall ≤ 50.8 mm (= 2.0 inch)	184
5	E	Rainfall > 50.8 mm	179

mid-1930s. Various types of ancillary data, such as air temperature, land management practices, topography, and soils information are also maintained along with rainfall and streamflow, and it is easy to extract these data from the ARS web site. In the present study, data for available several thousands of storm events from 231 watersheds vary in size from 0.3 to 30351.5 ha have been used.

4.2. DATA PROCESSING

The available P–Q data were divided into five classes based on rainfall magnitude. These are designated as classes A through E, as shown in Table I. This table shows the number of watersheds whose data were considered in the analysis. Its last column provides ranking of models discussed later. Treating as outliers, very high and low rainfall events and all the events exhibiting $\partial Q/\partial P > 1$ were excluded from the analysis consistent with Equation (17).

4.3. GOODNESS-OF-FIT

For evaluation of model performance, the root mean square error (RMSE) was taken as an index of the variance between computed and observed values of runoff. Expressed mathematically,

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Q_{\mathrm{obs}} - Q_{\mathrm{comp}})_i^2} \tag{18}$$

where Q_{obs} is the observed storm runoff (mm), Q_{comp} is the computed runoff (mm), N is the total number of rainfall-runoff events, and i is an integer varying from 1 to N. The higher the RMSE value, the poorer is the performance of the model, and the lower RMSE value shows a better performance of the model; RMSE = 0 indicates a perfect fit.

4.4. PARAMETER ESTIMATION

Using Equation (18), model parameters were computed using the Marquardt algorithm of constrained least squares for the above five classes A–E (Table I). Here an explanation of the variants of the general model (Equation 9), as shown in Table II,

Table II. Variants of the general model (Equation (9))

Model	Parameter	
	λ	a
1	Varying	1
2	0.2	1
3	Mean value	1
4	Median value	1
5	Varying	0.5
6	0.0	0.5
7	Varying	Varying
8	0.0	Varying
9	0.0	Median value
10	0.0	Mean value

is in order. In Model 1, for example, $a = 1$, and parameter λ is allowed to vary in application to data of each of the five classes (Table I). Thus, the mean and median values of parameters (Tables II and III) correspond to those derived from application of the general form of the model to the data set falling in a class. For example, the mean and median values of parameter λ of respective Models 3 and 4 for a class correspond to those derived from the λ-values resulting from Model 1 application to the data set of that class. Similarly, these values of respective Models 9 and 8 correspond to 'a'-values derived from the application of Model 7 to a particular class data set. The parameter CN in all ten model formulations for all the data sets in different classes is allowed to vary within the prescribed range as follows.

In all the applications, the initial estimate of parameter CN of all the models was taken equal to 50; λ equal to 0.2, a standard value; and parameter 'a' equal to 0.5, which corresponds to Equation (9). CN ranged between 0 and 100, λ was assumed to vary in the range (0–1), and parameter 'a' ranged from 0.01 to 0.999. The computed values of parameters for some models for class E (rainfall $>$50.8 mm) data set are shown in Table IV, and the statistics of all models for both the data sets

Table III. Mean and median parameter values for Models 3, 4, 9, and 10 for different rainfall class data

Model	Parameter	Value	Rainfall class				
			A	B	C	D	E
3	λ	Mean	0.100	0.059	0.175	0.372	0.202
4	λ	Median	0.0	0.001	0.001	0.015	0.001
9	a	Median	0.999	0.999	0.999	0.558	0.979
10	a	Mean	0.765	0.691	0.610	0.499	0.627

Table IV. Computation of parameters of the general model and its variants using data with rainfall >50.8 mm

Sl. No.	Watershed	Area (ha)	No. of events	Average Runoff (mm)	Model-2		Model-9	
					CN	RMSE	CN	RMSE
1	10001	7.8	8	11.69	70.3	9.49	48.5	9.18
2	13007	318.1	9	4.40	45.9	5.34	14.9	4.06
3	13008	361.4	6	8.21	62.1	6.49	32.1	5.23
4	13009	73.7	19	19.01	72.3	16.29	55.5	15.96
5	13010	595.3	28	9.42	61.8	7.13	36.1	7.28
6	13011	224.7	20	10.55	64.7	9.38	41.3	9.91
7	13012	77.7	15	13.88	71.7	9.27	52.3	9.32
8	13013	818.7	10	4.62	50.7	4.31	17.5	2.85
9	13014	157.4	13	12.99	70.9	12.26	48.9	11.81
10	13015	428.3	25	6.63	59.9	5.31	29.8	5.60
11	16006	717.8	24	21.56	76.5	12.91	63	12.81
12	16020	56.7	6	7.01	63	7.17	31.4	6.23
13	17001	11	21	32.33	80.3	20.24	70.6	19.88
14	17002	20.2	24	30.96	79.9	18.49	69.9	18.12
15	17003	5.1	6	39.17	79	22.51	68.7	21.50
16	17004	117.3	24	26.58	75.3	13.91	62.4	13.56
17	19004	1.2	5	11.83	57.6	13.40	29.4	11.46
18	19005	1.1	5	7.10	63.5	4.08	33.4	4.02
19	25001	62.3	42	30.86	84.2	19.26	76.8	19.27
20	26001	0.5	11	18.60	75.8	12.12	60.9	12.17
21	26002	0.5	6	15.16	71.7	11.04	53.8	11.77
22	26003	1.1	15	16.50	70.1	10.35	51.1	10.33
23	26004	1.1	13	11.48	66.7	7.95	43.4	7.99
24	26005	0.7	7	19.06	74.2	6.00	58.8	6.47
25	26007	0.9	6	5.48	54.5	4.02	20.5	3.07
26	26010	0.3	22	29.51	81.9	14.07	72.8	13.98
27	26011	0.7	16	26.37	79.6	14.48	68.3	13.99
28	26012	0.7	14	30.94	83.5	15.67	75.8	15.79
29	26013	0.7	16	13.42	69.9	14.90	48	14.33
30	26014	0.3	13	32.99	84.3	17.94	76.9	17.77
31	26015	0.5	9	24.12	79.2	13.58	67.6	13.44
32	26016	0.6	8	20.76	77.1	15.45	63.6	15.41
33	26017	0.8	16	25.99	76.5	13.79	63.8	13.49
34	26019	0.6	19	12.83	70.9	9.53	49.6	9.09
35	26020	0.6	18	13.70	71.8	9.61	52.1	9.71
36	26021	0.8	12	20.50	74.5	19.45	57.3	18.31
37	26023	3	13	16.17	71.8	8.42	53.5	8.03

(*Continued on next page*)

Table IV. (*Continued*)

Sl. No.	Watershed	Area (ha)	No. of events	Average Runoff (mm)	Model-2		Model-9	
					CN	RMSE	CN	RMSE
38	26024	2.9	18	24.78	77.5	16.95	64.8	16.61
39	26025	3.1	14	22.73	73.3	12.79	58.7	12.68
40	26026	17.6	31	25.50	77.8	10.12	65.9	9.68
41	26027	11.7	22	24.59	77	11.08	64.4	10.62
42	26028	30.6	21	24.00	79.6	12.47	68.5	12.36
43	26029	30	20	25.89	79.8	10.90	69.1	10.74
44	26030	122.6	38	27.09	80.2	11.92	70.4	12.21
45	26032	141.2	21	19.76	76.2	10.54	62.3	10.58
46	26033	372.3	24	27.81	78.4	14.27	67.4	13.96
47	26034	615.1	21	28.81	79.2	15.41	68.7	15.19
48	26035	1040	8	17.64	74.3	5.78	58.8	6.04
49	26036	1853.5	8	23.86	80.3	18.23	69.9	18.43
50	26040	28.2	27	24.81	78.9	10.81	67.3	10.32
51	26041	32.1	14	22.16	73.4	10.83	58.6	10.05
52	26711	118.6	28	28.50	81.3	14.95	71.8	14.81
53	26791	32.1	13	32.61	87.9	15.78	83.1	16.13
54	26828	1.1	11	20.79	73.2	11.22	58.8	11.65
55	26891	0.5	6	17.39	72.9	20.70	54.7	20.30
56	31001	133.6	28	9.89	54.9	7.68	33	7.63
57	31002	9.2	8	7.41	46.6	7.43	19.2	5.96
58	31003	21.3	18	10.38	51.3	6.23	29	6.83
59	31004	69.2	17	14.86	55.8	7.48	35.5	7.61
60	33002	3.8	8	10.53	58.7	8.89	31.3	8.44
61	33003	3.8	6	10.87	53.7	4.55	26.8	4.30
62	33005	5.8	12	38.51	71.7	9.99	59.9	9.19
63	33006	7.9	13	44.88	73.1	23.50	61.7	22.48
64	34001	0.9	20	27.10	82	15.47	72.5	15.27
65	34006	0.7	25	23.06	80.2	15.69	69.5	15.87
66	34007	0.8	22	27.79	82.6	14.64	73.7	14.56
67	34008	1.9	23	21.08	78.3	16.18	65.7	16.16
68	34013	0.8	5	19.20	73.3	6.90	56.5	6.66
69	35001	13.5	20	37.43	85.7	12.76	79.6	12.82
70	35002	1.3	16	24.04	80.2	10.68	69.3	10.36
71	35003	1.3	16	38.64	87.7	13.27	82.6	13.30
72	35004	2.3	7	6.36	62.7	7.72	30.9	7.82
73	35005	2.1	15	19.54	74.9	11.45	59.6	11.25
74	35008	3.7	13	24.96	79.1	11.13	67.5	10.42
75	35009	5.4	12	26.63	81.3	9.98	71.4	9.50

(*Continued on next page*)

Table IV. (*Continued*)

76	35010	6.4	12	23.93	77.4	11.19	65	10.82
77	35011	38.4	12	9.48	62.8	7.07	35.2	5.48
78	37001	6.8	21	36.94	84.1	25.04	77.3	25.08
79	37002	37.2	33	31.71	80.3	24.70	71.5	24.98
80	37003	83.4	7	10.33	67.5	12.91	41.2	12.35
81	42002	234.3	40	37.06	80.4	16.80	70.8	15.88
82	42003	449.2	81	33.27	78.3	21.06	67.6	20.53
83	42004	1772.5	39	33.06	78.9	19.39	68.4	18.84
84	42006	70.4	91	34.69	80.8	21.24	71.7	21.02
85	42007	52.6	30	31.84	80.5	19.88	71.2	19.79
86	42008	17.1	38	32.58	79.8	21.39	69.9	21.12
87	42010	8	37	39.45	83.1	18.27	75.8	18.13
88	42011	125	35	29.88	77.3	16.52	65.6	15.89
89	42012	53.4	39	32.95	81.2	17.74	72.4	17.72
90	42013	32.3	5	35.22	87.7	11.51	82	11.14
91	42014	6.6	34	28.66	76.6	16.59	64.3	15.96
92	42015	16.2	18	38.63	86	18.31	79.7	18.05
93	42016	8.4	37	29.38	77.3	16.67	65.5	15.84
94	42017	7.5	34	39.45	83	19.73	75.2	19.38
95	42023	1.1	24	45.54	86.4	20.87	93.8	28.57
96	42024	1.2	28	41.21	86.4	25.22	80.8	25.24
97	42028	1.2	29	42.97	85.7	23.51	79.6	23.31
98	42035	1.3	28	39.90	81.8	25.59	73.3	25.18
99	42036	1.3	27	36.74	81.7	23.33	72.9	22.89
100	42037	4.6	23	32.76	81.5	15.72	73.3	16.12
101	42038	2.3	30	32.30	79.3	19.70	70.1	19.96
102	42039	4	34	28.94	78.4	18.07	67.9	18.17
103	42040	4.6	36	26.78	78.2	19.17	67.6	19.60
104	44001	194.7	19	30.31	79.5	15.61	69.5	15.34
105	44002	166.3	32	20.94	74.5	10.12	61.5	10.77
106	44003	844.2	30	21.97	73.4	9.54	59.3	9.26
107	44004	1412.4	31	21.40	72.1	10.81	57.2	10.48
108	44005	1.5	12	14.67	71.2	12.03	52.5	12.35
109	44006	1.4	14	18.48	75.5	18.39	60.8	18.64
110	44007	1.5	15	46.14	88.8	18.47	84.3	18.44
111	44008	1.5	16	44.89	86.7	17.77	81.5	17.78
112	44009	1.6	15	36.47	82.5	14.95	75.3	15.46
113	44010	1.6	14	32.18	83.3	16.65	75.7	16.82
114	44011	1.7	15	32.67	82.1	18.20	73.3	17.91
115	44012	1.6	17	25.44	80.4	12.10	70.9	12.86

(*Continued on next page*)

Table IV. (*Continued*)

Sl. No.	Watershed	Area (ha)	No. of events	Average Runoff (mm)	Model-2		Model-9	
					CN	RMSE	CN	RMSE
116	44013	1.5	9	25.99	78.8	9.67	67.9	9.84
117	44014	1.6	9	27.42	77.3	16.07	65.1	15.58
118	44015	1.6	10	36.77	83.4	17.91	75.8	17.74
119	44016	1.5	9	38.73	82.6	22.17	74	21.49
120	44017	1.4	10	36.04	83	10.80	75.6	11.05
121	44018	1.4	11	36.33	84.3	9.67	77.4	9.81
122	44019	1.5	8	37.24	83.1	13.78	75.5	13.61
123	44020	1.4	10	36.27	85.6	12.84	79.5	13.17
124	44021	1.6	10	37.37	85.2	13.80	79.1	14.11
125	44022	1.5	14	25.91	78.8	13.88	67.7	13.83
126	44023	1.7	11	36.36	85.6	10.59	79.5	10.83
127	44024	1.6	9	24.94	75.7	15.33	61.5	14.33
128	44025	1.6	10	33.68	82.5	16.82	74.3	16.74
129	44026	1.5	10	36.49	84.5	12.75	77.8	12.82
130	44027	1.6	10	37.09	84.1	13.99	76.7	13.64
131	44028	1.7	11	39.52	85.4	14.93	79.2	14.92
132	61002	18.4	19	15.70	70.5	9.98	53.7	10.67
133	61003	157.8	13	15.83	75.6	10.64	60.3	11.06
134	61004	25.5	22	11.85	69.4	10.02	46.7	9.75
135	62001	457.5	18	22.57	68.2	12.09	51.7	11.57
136	62002	404.7	24	37.81	83.6	17.93	76.5	18.01
137	62003	2237.9	7	27.69	81.2	14.30	71.2	13.88
138	62004	9226.9	5	20.56	80.5	10.75	69	10.85
139	62005	12990.5	29	23.39	71.3	16.34	55.5	15.29
140	62007	207.2	6	20.08	77.4	6.95	64.1	7.31
141	62008	437.1	7	12.37	71.3	7.14	53	8.73
142	62011	30351.5	23	18.31	61.2	14.79	39.6	12.90
143	62012	3055.4	5	32.64	75	21.31	61.8	19.63
144	62014	0.6	11	41.90	88.6	14.08	84.1	14.21
145	62017	1295	7	20.59	78.9	14.64	67.2	15.11
146	62018	441.1	5	28.29	78.1	17.43	67	17.22
147	67003	836.5	11	13.68	65.1	5.85	43.9	6.23
148	67004	4351.2	9	11.26	63.5	5.83	39.9	5.08
149	67005	11116.4	7	14.85	61.3	13.15	38	12.04
150	67007	2180.9	7	14.50	70.4	4.89	51.4	4.42
151	67008	1564.5	5	7.57	62.8	4.29	32.4	3.67
152	67009	46.9	10	12.88	63.3	6.58	42.4	6.84
153	69030	7.2	6	25.07	74.4	5.77	61.6	6.13

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Table IV. (*Continued*)

154	69032	17.9	11	25.95	80.8	10.57	70.6	10.35
155	69033	12.1	10	27.34	80.9	14.07	70.7	13.68
156	69034	5.2	8	17.38	72.6	12.48	55.1	12.13
157	69035	5.3	9	18.13	74.1	12.66	58	12.45
158	69036	10.7	9	18.85	74.4	10.95	58.5	10.42
159	69037	11	6	10.79	68.8	10.66	46.5	11.09
160	69042	9.6	10	15.67	65.9	13.39	43.7	12.77
161	69043	11	11	14.26	67.6	13.28	46.3	13.42
162	69044	7.8	10	35.28	81.6	11.11	72.8	10.64
163	69045	11.1	11	27.12	77.2	11.67	65.1	11.10
164	69049	3.8	6	43.30	88.6	9.85	84	9.71
165	70004	4365.4	5	9.80	61.8	6.06	35.2	6.26
166	70007	4.1	5	31.76	78.2	14.67	69.8	16.88
167	70009	2.7	6	15.88	70.1	12.49	56.2	15.46
168	71001	30.1	16	10.95	61.1	12.16	33.7	10.34
169	71002	33.5	29	14.56	67.2	13.15	48.7	13.76
170	71003	43.5	26	6.06	54.2	6.90	21.9	6.45
171	71004	60.7	30	7.43	54.6	7.45	23.9	6.44
172	71005	157.5	14	6.96	58	5.43	29.5	6.80
173	74003	1567.6	51	11.60	63.8	10.92	39.7	10.17
174	74006	4993.1	41	20.31	64.6	12.82	44.9	10.50
175	74007	2213.0	45	21.42	66.7	12.87	48.2	11.06
176	74008	1665.6	51	11.38	60.3	8.40	35.9	7.36
177	74009	261.5	50	12.57	59.6	10.97	35.3	9.34
178	77003	2.8	14	14.70	66.3	9.59	47	9.65
179	77006	2.9	5	17.33	52.4	7.45	28.7	5.05

RMSE in mm.

is given in Table V. It is evident from these tables that the CN-values for the existing SCS-CN method ($\lambda = 0.2$ and $a = 1$) (Model 2) in application to class A data set, as an example, varied from 82.0 to 98.1 with an average of 91.05, and RMSE varied from 0.03 to 2.79 mm with an average of 0.98 mm. Similarly, the variation of all parameters of all the models in all applications can be explained. The values of λ equal to 0.10 and 0 for class A data in Models 3 and 4 (Table III) represent, respectively, the mean and median values computed for all the parameters of Model 1 shown in Table IV. Similarly, the values of 'a' equal to 0.999 ($\approx$ 1.00) and 0.765 for class A data in Models 9 and 10 represent, respectively, the median and mean values computed for all the parameters shown for Model 7. The same holds for rainfall data of other classes. Notably, the curve numbers for all the models are distinguished from those for the existing SCS-CN model (Model 2), for which the common definition of the curve number holds. In other words, as described above,

Table V. Range of parameters and resulting errors

Model	CN			λ			'a'			RMSE (mm)		
	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average
Class A- Rainfall ≤12.7 mm (=0.5 in.)												
1	4.70	98.00	70.38	0.00	1.00	0.06	-	-	-	0.03	2.60	0.93
2	82.00	98.10	91.05	0.20	0.20	0.20	-	-	-	0.03	2.79	0.98
3	69.90	97.70	86.91	0.10	0.10	0.10	-	-	-	0.03	2.72	0.96
4	5.40	97.00	68.84	0.00	0.00	0.00	-	-	-	0.03	2.60	0.93
5	4.60	99.30	69.42	0.00	1.00	0.05	0.50	0.50	0.50	0.03	2.66	0.93
6	5.40	99.20	67.81	0.00	0.00	0.00	0.50	0.50	0.50	0.03	2.66	0.94
7	5.30	97.90	70.58	0.00	1.00	0.04	0.00	1.00	0.80	0.03	2.61	0.93
8	5.40	93.40	68.57	0.00	0.00	0.00	0.00	1.00	0.76	0.03	2.61	0.94
9	5.40	97.00	68.84	0.00	0.00	0.00	1.00	1.00	1.00	0.03	2.60	0.93
10	5.40	98.90	68.44	0.00	0.00	0.00	0.76	0.76	0.76	0.03	2.83	0.94
Class B- 12.7 < Rainfall ≤ 25.4 mm (=1.0 in.)												
1	4.80	97.60	64.88	0.00	1.00	0.06	-	-	-	0.06	5.57	2.55
2	69.80	94.60	85.34	0.20	0.20	0.20	-	-	-	0.07	5.74	2.62
3	42.00	92.80	75.36	0.06	0.06	0.06	-	-	-	0.07	5.63	2.58
4	4.80	91.40	62.04	0.00	0.00	0.00	-	-	-	0.06	5.56	2.56
5	2.50	94.60	63.14	0.00	1.00	0.04	0.50	0.50	0.50	0.05	5.57	2.55
6	2.90	97.80	60.05	0.00	0.00	0.00	0.50	0.50	0.50	0.05	5.58	2.57
7	2.90	93.50	64.33	0.00	0.94	0.03	0.00	1.00	0.76	0.05	5.56	2.55
8	2.90	88.60	60.78	0.00	0.00	0.00	0.00	1.00	0.69	0.05	5.56	2.56
9	2.90	91.40	61.57	0.00	0.00	0.00	1.00	1.00	1.00	0.05	5.56	2.56
10	2.90	96.80	60.99	0.00	0.00	0.00	0.69	0.69	0.69	0.05	5.68	2.57

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Table V. (*Continued*)

Class C- 25.4 < Rainfall ≤ 38.1 mm (=1.5 in.)												
1	4.40	96.10	64.58	0.00	1.00	0.17	-	-	-	0.20	10.43	4.62
2	60.20	91.70	80.90	0.20	0.20	0.20	-	-	-	0.25	10.54	4.67
3	56.90	91.30	79.64	0.17	0.17	0.17	-	-	-	0.25	10.53	4.67
4	5.50	87.40	58.29	0.00	0.00	0.00	-	-	-	0.19	10.43	4.63
5	3.00	93.50	62.42	0.00	1.00	0.09	0.50	0.50	0.50	0.20	10.49	4.59
6	4.10	82.90	55.71	0.00	0.00	0.00	0.50	0.50	0.50	0.19	10.49	4.63
7	4.10	94.30	63.38	0.00	1.00	0.06	0.00	1.00	0.73	0.19	10.43	4.59
8	4.10	100.00	56.45	0.00	0.00	0.00	0.00	1.00	0.61	0.19	10.44	4.63
9	4.10	87.40	57.94	0.00	0.00	0.00	1.00	1.00	1.00	0.19	10.43	4.63
10	4.10	95.30	57.03	0.00	0.00	0.00	0.61	0.61	0.61	0.19	10.47	4.64
Class D- 38.1 < Rainfall ≤ 50.8 mm (=2.0 in.)												
1	13.50	95.40	70.02	0.00	1.00	0.37	-	-	-	1.04	15.50	7.17
2	63.00	92.60	78.53	0.20	0.20	0.20	-	-	-	1.08	15.59	7.23
3	73.70	93.90	84.09	0.37	0.37	0.37	-	-	-	1.20	15.64	7.24
4	25.80	90.00	62.14	0.02	0.02	0.02	-	-	-	0.95	15.51	7.23
5	15.10	95.90	66.90	0.00	1.00	0.18	0.50	0.50	0.50	0.94	15.56	7.09
6	16.10	80.90	55.81	0.00	0.00	0.00	0.50	0.50	0.50	0.94	15.56	7.23
7	16.30	99.90	65.71	0.00	1.00	0.14	0.00	1.00	0.59	0.94	15.50	7.13
8	16.40	99.90	56.00	0.00	0.00	0.00	0.00	1.00	0.50	0.94	14.91	7.20
9	16.10	96.30	57.44	0.00	0.00	0.00	0.56	0.56	0.56	0.94	15.08	7.24
10	16.10	96.70	56.89	0.00	0.00	0.00	0.50	0.50	0.50	0.94	14.90	7.22

(*Continued on next page*)

Table V. (*Continued*)

Model	CN			λ			'a'			RMSE (mm)		
	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average
Class E- Rainfall > 50.8 mm (=2.0 in.)												
1	13.40	94.10	65.35	0.00	1.00	0.20	-	-	-	2.87	25.22	12.77
2	45.90	88.80	74.38	0.20	0.20	0.20	-	-	-	4.02	25.59	13.10
3	46.00	88.80	74.46	0.20	0.20	0.20	-	-	-	4.03	25.59	13.11
4	15.40	84.80	59.99	0.00	0.00	0.00	-	-	-	2.87	25.25	12.88
5	8.10	93.80	59.86	0.00	0.85	0.08	0.50	0.50	0.50	3.09	47.67	14.95
6	14.50	90.20	56.02	0.00	0.00	0.00	0.50	0.50	0.50	2.87	45.07	16.61
7	0.00	90.80	58.07	0.00	1.00	0.05	0.00	1.00	0.69	2.85	30.74	13.29
8	15.20	94.70	55.71	0.00	0.00	0.00	0.00	1.00	0.63	2.87	44.80	13.55
9	14.90	93.80	59.65	0.00	0.00	0.00	0.98	0.98	0.98	2.85	28.57	12.92
10	14.60	93.60	55.70	0.00	0.00	0.00	0.63	0.63	0.63	2.87	44.82	13.47

since the basic hypothesis of the general SCS-CN model differs from the existing SCS-CN method for which $\lambda = 0.2$, the computed CN values of both the models in an application would be different from each other. The same term for all the models has, however, been retained because of the S-values mapped on to corresponding CNs using Equation (5) to vary them from 0 to 100. It is also emphasized that the estimates of curve numbers that largely depend on the antecedent moisture condition represent only the fitting values to the above events. It is also apparent from the table that λ, when allowed to vary in application of Models 1, 5, and 7 to class A data, for example, ranged from 0 to 1 with an average of 0.06, 0.05, and 0.04, respectively. As seen, model applications to other data sets also yielded λ-values of the same order. These low λ-values prompted an investigation of the general model for $\lambda = 0$ in some cases, as shown in Tables II–V.

4.5. PERFORMANCE EVALUATION

The evaluation of model performance is based on (i) mean RMSE values (Table VI) coupled with paired comparison t-test and (ii) two-tailed t-test and Kolmogorov–Smirnov (K–S) test for mean runoff.

Consistent with the work of Schramm *et al.* (1974), the paired comparison t-test (Table VII) is performed to evaluate the significance of differing mean RMSE values. If the t-value of a pair was positive, the former model in the pair performed poorer than did the latter, and vice versa. If the absolute value of the t-statistic was larger than t_{crit} (= 1.97), the difference in mean RMSE values of the two models in the pair was significant, otherwise it was insignificant implying that both the models performed almost equally well on a particular data set at the 5% significance level. In total, 44 combinations for each data set were compared. As shown in Table II, Model 1 allows λ to vary in Equation (4), and thus, pairs 1–5 and 1–7 evaluate the impact of change in 'a' from 1 to 0.5 and from 1 to any other value, respectively, on the model performance. Pairs 2–1, 2–3, . . . , 2–10 compare the existing SCS-CN model ($a = 1$ and $\lambda = 0.2$) with all other models. Similarly, the significance of all other pairs can be explained.

The two-tailed t (TTT)- test relies on acceptance or rejection of the null hypothesis that the computed average runoff and the observed one are the same or not. Similarly, the K–S test compares the cumulative distribution functions (Benjamin and Cornell, 1970; Yevjevich, 1972) of the computed mean runoff with the observed ones in terms of $D \leq D_\alpha(N_{case})$, where D is the maximum difference of empirical cumulative distribution, D_α is the critical D-value for significance level α, and N_{case} is the total number of observed samples (= 100).

4.5.1. *Model Ranking*

(a) Based on RMSE. On the basis of the above RMSE values, the models were ranked as shown in Table VI. In the table, the model on the left of any > sign shows an improved performance over the model on the right of this sign. Thus,

Table VI. Model ranking based on three tests

Sl. No.	Class	Paired t-test based on mean RMSE	Tow-tailed t-test based on mean runoff	K–S test based on mean runoff
1	A	7 > 1 > 5 > 4 > 9 > 8 > 6 > 10 > 3 > 2	7 > 8 > 9 > 4 > 10 > 6 > 5 > 3 > 1 > 2	7 > 3 > 1 > 4 > 5 > 8 > 9 > 10 > 6 > 2
2	B	7 > 5 > 1 > 8 > 9 > 4 > 6 > 10 > 3 > 2	7 > 9 > 4 > 10 > 6 > 3 > 8 > 5 > 2 > 1	3 > 5 > 1 > 7 > 4 > 6 > 9 > 10 > 8 > 2
3	C	7 > 5 > 1 > 8 > 9 > 4 > 6 > 10 > 3 > 2	9 > 4 > 10 > 6 > 7 > 3 > 5 > 8 > 1 > 2	1 > 7 > 3 > 5 > 4 > 6 > 9 > 10 > 8 > 2
4	D	5 > 7 > 1 > 8 > 10 > 6 > 4 > 2 > 9 > 3	9 > 6 > 10 > 7 > 3 > 5 > 4 > 2 > 8 > 1	1 > 3 > 7 > 2 > 5 > 8 > 4 > 6 > 9 > 10
5	E	1 > 4 > 9 > 2 > 3 > 7 > 10 > 8 > 5 > 6	4 > 9 > 8 > 2 > 3 > 1 > 10 > 7 > 5 > 6	1 > 7 > 3 > 5 > 2 > 6 > 4 > 8 > 9 > 10

Table VII. Results of paired comparison *t*-test for various classes

Sl. No.	Pair	Class A	Class B	Class C	Class D	Class F
1	1–2	−17.62	−16.71	−7.52	−6.33	−8.82
2	1–3	−16.55	−8.76	−6.74	−7.98	−8.88
3	1–4	−1.97	−0.85	−0.91	−4.06	−1.78
4	1–5	−2.63	1.30	4.06	4.85	−5.76
5	1–6	−3.43	−1.70	−1.05	−3.97	−7.97
6	1–7	1.28	3.08	3.58	1.24	−3.56
7	1–8	−2.27	−0.64	−0.33	−2.21	−3.32
8	1–9	−1.98	−0.71	−0.88	−3.01	−2.05
8	1–10	−2.42	−2.61	−1.63	−3.34	−3.17
9	2–3	14.47	15.30	9.01	−2.20	−7.18
10	2–4	14.19	12.79	5.99	0.27	4.43
11	2–5	17.20	16.63	12.32	7.93	−4.93
12	2–6	14.22	5.88	6.72	0.84	−7.23
13	2–7	15.76	16.65	10.43	3.74	−1.23
14	2–8	12.57	13.05	7.16	2.56	−1.91
15	2–9	14.18	12.73	5.96	−0.31	2.74
16	2–10	8.23	7.74	4.15	1.62	−1.68
17	3–4	13.54	9.07	5.71	0.93	4.45
18	3–5	14.39	9.37	11.56	9.35	−4.92
19	3–6	13.10	1.21	6.44	1.36	−7.22
20	3–7	13.37	10.72	9.91	4.14	−1.21
21	3–8	10.74	8.45	6.89	2.71	−1.90
22	3–9	13.53	9.01	5.67	0.13	2.76
23	3–10	5.13	1.68	3.67	1.94	−1.66
24	4–5	0.20	1.82	4.22	6.05	−5.74
25	4–6	−3.63	−1.54	−0.27	1.01	−7.81
26	4–7	2.14	3.60	4.31	3.35	−2.88
27	4–8	−1.04	0.43	1.89	2.84	−2.90
28	4–9	−1.00	4.65	1.63	−0.43	−0.98
29	4–10	−1.78	−2.49	−1.25	1.87	−2.70
30	5–6	−1.57	−2.15	−4.77	−6.35	−3.80
31	5–7	4.00	2.47	0.40	−1.79	4.70
32	5–8	−0.90	−1.70	−4.06	−4.90	3.52
33	5–9	−0.20	−1.68	−4.18	−5.11	5.58
34	5–10	−1.81	−3.27	−4.85	−5.80	3.63
35	6–7	3.55	3.16	4.59	3.20	8.38
36	6–8	1.11	1.76	2.63	2.36	6.42
37	6–9	3.64	1.60	0.36	−0.67	7.86
38	6–10	−1.23	−0.07	−1.31	1.37	6.51
39	7–8	−3.18	−3.54	−4.05	−2.41	−0.96
40	7–9	−2.15	−3.45	−4.28	−2.99	2.68
41	7–10	−2.67	−4.20	−4.64	−2.85	−0.70
42	8–9	1.04	−0.17	−1.82	−1.78	2.66
43	8–10	−1.41	−2.52	−2.12	−1.88	0.53
44	9–10	−1.78	−2.58	−1.27	1.12	−2.48

$t_{crit} = 1.97$.

the performance improves from right to left. Apparently, Model 2 is ranked as poorest when applied to the data sets of classes A-C. Its performance, however, improves with the increasing rainfall magnitude as seen from the results of its application to class D and E data. It leads to infer that the existing SCS-CN model (Model 2) is more suitable for high rainfall-runoff data than low rainfall data. On the other hand, Model 7 exhibits the lowest RMSE value on classes A–C data and it is the second lowest on class D data. It indicates Model 7 (Mishra–Singh general model) to perform better than any other model on class A–C data, except Model 5 on class D data. Since the parameter 'a' was allowed to vary to a maximum value of 0.999, Model 1 with parameter $a = 1$ exhibited the best performance on class E data. It implies that the existing formulation of the SCS-CN model (Model 1) is best suited to high rainfall (>50.8 mm) data. On the other hand, the formulation of Model 7 is more suitable for rainfall values less than or equal to 50.8 mm.

(b) *Based on mean runoff*. As described above, since both the TTT and K-S tests compare the computed mean runoff with observed, the resulting t-values can be used for model ranking. The greater the t-value, the larger the difference between the computed and observed mean runoff values and vice versa. If it is greater than t_{cri}, the difference is significant, it is insignificant otherwise. The former condition leads to rejection of the null hypothesis, and the latter does to acceptance. Thus, the lowest t-value indicates that the computed mean runoff values are closest to the observed ones, implying the best model performance. The inference will reverse in the otherwise situation. Similarly, the above models can be ranked based on D-values of K-S test. The larger the D-value, the greater the difference between the cumulative distributions of the computed and observed runoff values, indicating a poor model performance, and vice versa.

On the basis of the results of both the TTT and K-S tests (Tables VIII and IX), Table VI ranks the models for performance. Here, it is however not possible to ascertain whether one model performs significantly or insignificantly better than others. It is apparent from Tables VIII and IX that, in computation of mean runoff, Model 2 (existing SCS-CN model) generally performed the poorest of all others for data with rainfall $\leq$38.1 mm. Its performance, however, consistently improved on the data sets with increasing rainfall magnitude, consistent with the results of the above paired t-test. Similarly, the performance of Model 7 (general Mishra–Singh model) generally exhibited a consistent deterioration with the increasing rainfall data. Models 4, 6, and 9 showed a significant improvement over the existing SCS-CN method on data sets with rainfall $\leq$38.1 mm. However, when $\lambda = 0$ in Model 4, impairs the basic structure of the SCS-CN method by excluding the essential initial abstraction component of the rainfall-runoff process. The general deviation in performance results of other models from those due to the paired t-test can largely be attributed to the above differing goodness of fit criteria, and K-S test relying on $N_{case} = 100$. These results, however, affirmed that the parameter 'a' of the general model was apt to variation only for low magnitude rainfall (preferably

Table VIII. Results of two-tailed t-test from the observed t-statistics for different rainfall class

Model	Class A	Class B	Class C	Class D	Class F
Model-1	21.5 (R)	9.9 (R)	3.9 (R)	1.7 (A)	2.8 (R)
Model-2	22.9 (R)	16.8 (R)	3.6 (A)	1.24 (A)	1.7 (A)
Model-3	18.0 (R)	3.4 (R)	1.5 (A)	0.4 (A)	1.7 (A)
Model-4	6.7 (R)	0.9 (A)	0.4 (A)	1.02 (A)	0.4 (A)
Model-5	12.0 (R)	3.9 (R)	1.9 (A)	0.6 (A)	6.5 (R)
Model-6	7.5 (R)	1.58 (A)	0.6 (A)	0.02 (A)	9.3 (R)
Model-7	3.4 (R)	0.6 (A)	0.9 (A)	0.1 (A)	4.13 (A)
Model-8	3.8 (R)	3.5 (R)	3.4 (R)	1.4 (A)	1.7 (A)
Model-9	6.7 (R)	0.9 (A)	0.4 (A)	0.006 (A)	0.5 (A)
Model-10	7.0 (R)	1.3 (A)	0.6 (A)	0.02 (A)	3.7 (R)

A and R in the bracket infer the test statistic to be accepted and rejected, respectively, at 5% significance level. Critical t (t_{cr}) = 1.96 at 5% significance level.

$\leq$50.8 mm) data, it was otherwise 1. On the basis of the paired t-test, the following text compares the models for equal number of model parameters, for reasons of equal competence.

4.5.2. *One-Parameter Models*

Models 2, 3, 4, 6, 9, and 10 form the one-parameter models (Table I). Among these, as seen from Table VI, the existing one-parameter SCS-CN model (Model 2) performed significantly poorer than the other one-parameter Models 3, 4, 6, 9, and

Table IX. Results of two-sample K-S test from the observed t-statistics for different rainfall class

Model	Class A	Class B	Class C	Class D	Class F
Model-1	0.13 (A)	0.26 (R)	0.21 (R)	0.24 (R)	0.13 (A)
Model-2	0.56 (R)	0.314 (R)	0.42 (R)	0.29 (R)	0.163 (A)
Model-3	0.13 (A)	0.21 (R)	0.22 (R)	0.27 (R)	0.15 (R)
Model-4	0.14 (R)	0.29 (R)	0.29 (R)	0.33 (R)	0.21 (R)
Model-5	0.14 (R)	0.25 (R)	0.27 (R)	0.29 (R)	0.15 (R)
Model-6	0.14 (R)	0.29 (R)	0.29 (R)	0.33 (R)	0.17 (R)
Model-7	0.13 (A)	0.26 (R)	0.21 (R)	0.28 (R)	0.13 (A)
Model-8	0.14 (R)	0.30 (R)	0.36 (R)	0.31 (R)	0.21 (R)
Model-9	0.14 (R)	0.29 (R)	0.29 (R)	0.33 (R)	0.21 (R)
Model-10	0.14 (R)	0.29 (R)	0.29 (R)	0.33 (R)	0.21 (R)

A and R in the bracket infer the test statistic to be accepted and rejected, respectively, at 5% significance level and for $N \geq 100$. For $N_{cases} = 100$, $D_\alpha = 0.136$ at 5% significance level.

10 on classes A-C data. It, however, performed significantly better than Model 3, but insignificantly better or poorer than all other one-parameter models on class D data. Similarly, on class E data, it performed significantly better than Models 3 and 6, insignificantly better than Model 10, and significantly poorer than Models 4 and 9. Thus, the existing version is completely unsuitable for low rainfall ($\leq$38.1 mm) data and it has viable alternatives for high rainfall ($>$38.1 mm) data.

4.5.3. *Two-Parameter Models*

Models 1, 5, and 8 fall in the category of two-parameter models (Table II). Among these models, the two-parameter (λ and CN) Model 1 performed significantly better than both the other models on class A data; insignificantly poorer and better than Models 5 and 8, respectively, on class B data; significantly poorer and insignificantly better than Models 5 and 8, respectively, on class C data; significantly poorer and better than Models 5 and 8, respectively, on class D data; and significantly better than both the Models 5 and 8 on class E data. Thus, the formulation of Model 1 is suitable for high rainfall ($>$50.8 mm) data, and Model 5 is, in general, appropriate for rainfall ($\leq$50.8 mm) data. The former model is, in general, is superior to Model 8.

4.5.4. *Three-Parameter Model*

As shown in Table VI, the only three-parameter (a, λ, and CN) Model 7 excelled almost all other models when applied to classes A–D data. Its performance is however quite poorer than others when applied to class E data, because of maximum $a = 0.999$ instead of 1. For significant difference in the resulting mean RMSE values at 5% level, Model 7 can be primarily compared with Models 1 and 5 for classes A–D data. From Table VII, Model 7 performed insignificantly better than Model 1 on classes A and D data and significantly better on classes B and C data. The former, however, performed significantly better than Model 5 on classes A and B data, and insignificantly better and poorer on classes C and D data, respectively. On class E data, Model 7 performed significantly poorer than Models 1, 4, and 9; equivalently with Models 2, 3, 8, and 10; and significantly better than Models 5 and 6. The mixed results suggest the adoption of a simplified version with less number of parameters. However, it can, in general, be inferred that the variation of parameter 'a' is desirable only under low rainfall conditions. It is equal to 1 otherwise, as above.

It follows that the existing SCS-CN method with parameter $\lambda = 0.2$ is not appropriate for its application to widely varying rainfall magnitude and watershed characteristics, such as soil type, land use, and hydrologic conditions besides the antecedent moisture. Among the possible improvements, one can be to replace $\lambda = 0.2$ (generally taken as a standard value) by its median values (Table III) as in Model 4 on different data sets. The low values of λ are consistent with the work of Hawkins *et al*. (2001) who found λ to be of the order of 0.05. Alternatively, Model 9 for which $\lambda = 0$ and 'a' = median values (Table III) for different data sets can be an appropriate choice. Similarly, among the two-parameter models, based on the above evaluation, Model 5 can be the obvious alternative to Model 1 for rainfall (<50.8 mm) data, and the three-parameter Model 7 generally performing better than others for rainfall (<50.8 mm) data infers incorporation of the third parameter '*a*' for low rainfall data, and it is otherwise 1.

Despite the excelling performance of Model 1 for almost all the data sets as above, the one-parameter Model 4 or Model 9 can be of potential use in practical applications. However, it is worth emphasizing that the replacement of $\lambda = 0.2$ by $\lambda = 0.0$ in Equation (4) for Model 4, as seen in Table III, may severely impair the basic structure of the existing SCS-CN model (Model 2), because of the exclusion of losses due to initial abstraction in runoff computations. The initial abstraction forms an essential and unavoidable component of the event-based rainfall-runoff modelling. On the other hand, the modified version (Model 9) incorporates it by taking parameter '*a*' = a median value instead of 1. Thus, Model 9 can be recommended for all rainfall data sets. Typical fits of Models 1, 2, 4, and 9 on the class E data of two watersheds are shown in Figures 1–4. The observed data in all these figures exhibit a large scatter and, therefore, are not amenable to fitting by any simple model. However, Models 4 and 9 appear to fit the data reasonably well compared with the results of Model 1, which requires an apriori knowledge of parameter λ, whereas the former models obviate this restriction.

5. Conclusions

On the basis of the three significance tests, the investigation of the general SCS-CN-based Mishra–Singh model and its eight variants reveals the following:

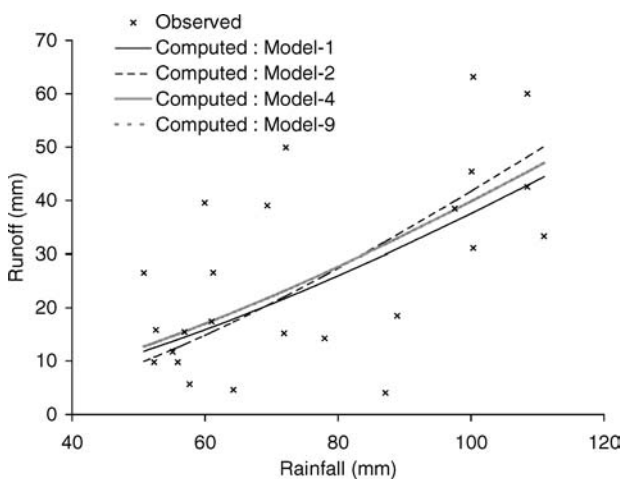

Figure 1. Fitting of models 1, 2, 4 and 9 with the observed rainfall-runoff data of watershed 17004 (Rainfall class: E; Landuse: Cultivated; Soil: Silt loam).

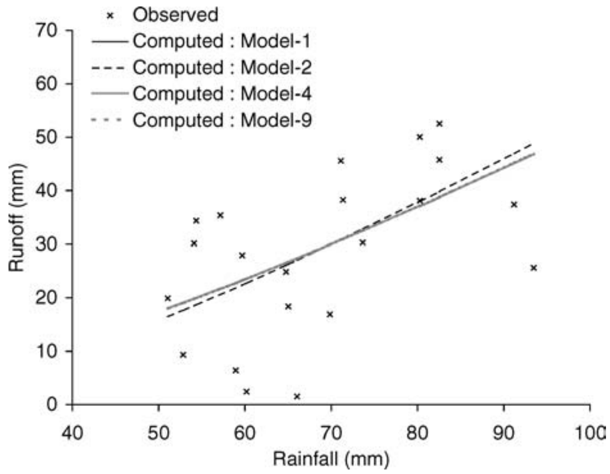

Figure 2. Fitting of models 1, 2, 4 and 9 with the observed rainfall-runoff data of watershed 26010 (Rainfall class: E; Landuse: Cultivated; Soil: Silt loam).

1. The parameter 'a' of the general Mishra–Singh model is apt to variation for low ($\leq$50.8 mm) rainfall data, it is otherwise 1.
2. The existing SCS-CN method with $\lambda = 0.2$ and $a = 1$ (Model 2) generally performs significantly poorer than all the general model variants on all data sets with rainfall $\leq$50.8 mm, and therefore, it is appropriate for high rainfall ($>$50.8 mm) rainfall data.
3. Model 4 with $\lambda =$ median value and $a = 1$ exhibits a significant improvement over the existing SCS-CN method on data sets with rainfall $\leq$38.1 mm, but,

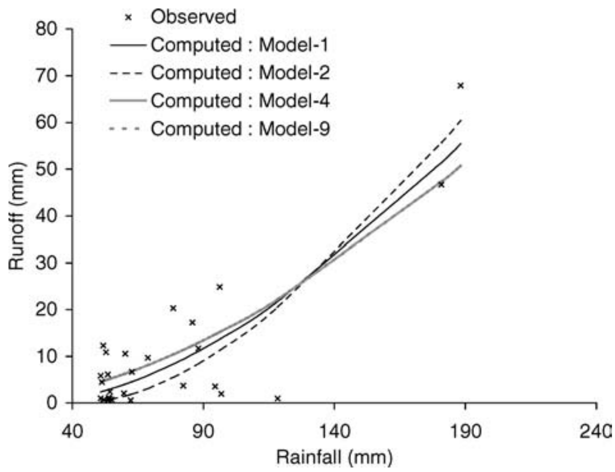

Figure 3. Fitting of models 1, 2, 4 and 9 with the observed rainfall-runoff data of watershed 31001 (Rainfall class: E; Landuse: Mixed (crops); Soil: Silt loam).

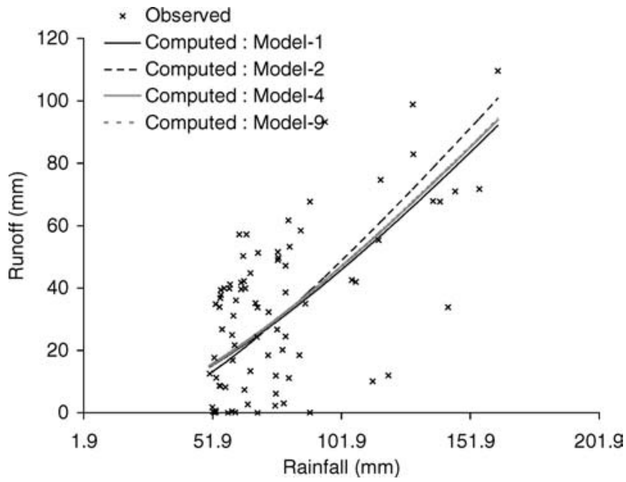

Figure 4. Fitting of models 1, 2, 4 and 9 with the observed rainfall-runoff data of watershed 42003 (Rainfall class: E; Landuse: Mixed (grasses); Soil: Clay loam).

when $\lambda = 0$, impairs the basic structure of the SCS-CN method by excluding the essential initial abstraction component of the rainfall-runoff process.

4. The one-parameter modified SCS-CN method ($a = 0.5$ and $\lambda =$ a median value) (Model 6) performs significantly better than the existing one on all the data sets, but far better on low ($\leq$50.8 mm) rainfall data.
5. The one-parameter modified SCS-CN Model 9 with $\lambda = 0$ can be of potential use in field applications respectively for both high and low rainfall data, for they account for all the losses in terms of the differing value of parameter 'a' from 1.

For field applications of the proposed model, it is necessary that the large scatter seen in the rainfall-runoff plots (Figures 1–4) be accounted for in runoff computations in terms of say, antecedent moisture condition considered in the existing SCS-CN calculations. Since rain and catchment characteristics affect CN, future research can be directed to CN determination using physically measurable attributes, such as storm duration, rainfall intensity, watershed area and slope among others.

Acknowledgement

The authors gratefully acknowledge the anonymous reviewers for providing valuable comments for enhancing the quality of the manuscript. Authors also owe to R.H. Hawkins for his time-to-time suggestions, and providing data and analytical details of the Mishra–Singh (1999a) model.

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