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An advanced soil moisture accounting procedure for SCS curve number method

R. K. Sahu,[1] S. K. Mishra,[2] T. I. Eldho[1]* and M. K. Jain[3]

[1] *Department of Civil Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai-400 076, Maharashtra, India*
[2] *Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee-247 667, Uttaranchal, India*
[3] *National Institute of Hydrology, Roorkee, Uttaranchal, India*

Abstract:

The Soil Conservation Service Curve Number (SCS-CN) method has been a topic of much discussion, especially in the last three decades. Recently, Michel *et al.* (2005) pointed out several inconsistencies in the soil moisture accounting (SMA) procedure used in the SCS-CN method and developed a procedure that is more consistent from the SMA viewpoint. However, the model proposed by them does not have any expression for initial soil moisture store level (V_0) and hence there is a scope for further improvement. Like the original method, there is sudden jump in V_0 and therefore a quantum jump in computed runoff is possible. In the present study, an attempt is made to develop an expression for V_0 to make the model a continuous watershed model. Then, the performance of the new model is compared with the model proposed by Michel *et al.* and the original SCS-CN model by applying them in a large number of small watersheds in the United States. The present model was found to perform significantly better than both the original SCS-CN model and the model proposed by Michel *et al.* Copyright © 2007 John Wiley & Sons, Ltd.

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INTRODUCTION

Modelling of the event-based rainfall-runoff process has significant importance in Hydrology. It has been recognized to be fundamental to a range of applications in hydrological practices since the first documentation of hydrology by P. Perreault in 1674 (Linsley, 1982). One of the most commonly used methods to estimate the volume of surface runoff for a given rainfall event is the Soil Conservation Service Curve Number (SCS-CN) method (SCS, 1956, 1964, 1971, 1993), which has been now renamed as Natural Resource Conservation Service Curve Number (NRCS-CN) method. The method is simple, easy to understand, and useful for ungauged watersheds. It accounts for the major runoff producing watershed characteristics, viz., soil type, land use/treatment, surface condition, and antecedent moisture conditions (AMCs) (Ponce and Hawkins, 1996; Mishra and Singh, 2003a; Mishra *et al.*, 2004, 2005). The SCS-CN method has been a topic of much discussion in hydrologic literature, especially in the last three decades (see, McCuen, 1982; Hjelmfelt, 1991; Hawkins, 1993; Steenhuis *et al.*, 1995; Ponce and Hawkins, 1996; Bonta, 1997; Yu, 1998; Mishra and Singh, 1999, 2002a,b,c, 2003a,b; Choi *et al.*, 2002; De Michele and Salvadori, 2002; Muzik, 2002; Mishra *et al.*, 1999, 2004, 2006; Michel *et al.*, 2005; Schneider and McCuen, 2005).

Owing to spatial and temporal variability of rainfall, quality of measured rainfall-runoff data, and the variability of antecedent rainfall and the associated soil moisture amount, the SCS-CN method exhibits variability in runoff computation (Ponce and Hawkins, 1996). The last source of variability is commonly recognized as the AMC. Though the term antecedent is taken to vary from previous 5 days to 30 days (SCS, 1971), there exists no explicit guideline for varying the soil moisture with the antecedent rainfall of certain duration. NEH-4 (SCS, 1971) uses the antecedent 5-days rainfall (P_5) for AMC, and it is the usual practice. AMC is categorized into three levels, AMC I (dry), AMC II (normal), and AMC III (wet), which statistically correspond, respectively, to 90, 10, and 50% cumulative probability of exceedance of runoff depth for a given rainfall (Hjelmfelt *et al.*, 1982). The three AMC levels permit unreasonable sudden jumps in curve numbers (CN), which result in corresponding jumps in estimated runoff. Besides this, the constant initial abstraction coefficient (λ) in the SCS-CN methodology, which largely depends on climatic conditions (Ponce and Hawkins, 1996), is perhaps the most ambiguous assumption and requires considerable refinement. These are perhaps the reasons that the past research endeavors suggested a need for further improvement, overhauling, or replacement of the method (Ponce and Hawkins, 1996; Mishra and Singh, 2002a).

Recently, Michel *et al.* (2005) pointed out several inconsistencies in the soil moisture accounting (SMA) procedure that lies behind the SCS-CN method and

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* Correspondence to: T. I. Eldho, Department of Civil Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai-400 076, Maharashtra, India. E-mail: eldho@civil.iitb.ac.in

proposed a procedure more consistent from the SMA viewpoint. Despite this improvement, the proposed model, however, does not contain any expression for initial soil moisture store level (V_0). This V_0 is taken as AMC-dependent in the simplified version of the model. It leads to a quantum jump in V_0 and, in turn, runoff computations. In the present study, an expression is suggested for V_0 for continuous simulation. Then, the performance of the new model is compared with the model proposed by Michel *et al.* (2005) by applying them to the data of a large number of small U.S. watersheds. The last part of the paper deals with the development of one-parameter model based on the proposed SMA procedure and then compares it with the simplified one-parameter model proposed by Michel *et al.* and the original SCS-CN method.

ORIGINAL SCS-CN METHOD

The SCS-CN method consists of the water balance equation and two fundamental hypotheses (Mishra and Singh, 2003a), which can be expressed, respectively, as follows:

$$P = I_a + F + Q; \quad \frac{\mathrm{Q}}{\mathrm{P} - \mathrm{I_a}} = \frac{\mathrm{F}}{\mathrm{S}}; \quad \mathrm{I_a} = \lambda \mathrm{S} \qquad (1, 2, 3)$$

where $P =$ total precipitation, $I_a =$ initial abstraction, $F =$ cumulative infiltration, $Q =$ direct runoff, $S =$ potential maximum retention, and $\lambda =$ initial abstraction coefficient. Here, all the variables, except λ, which is non-dimensional, are dimensional [L] quantities. A combination of Equations (1) and (2) leads to the popular form of the existing SCS-CN method:

$$Q = \frac{(P - I_a)^2}{P - I_a + S}, \text{ if } P > I_a \qquad (4)$$
$$= 0, \text{ otherwise}$$

In the application to both gauged and ungauged watersheds, $\lambda = 0{\cdot}2$, and the parameter S is expressed as

$$S = \frac{25\,400}{\mathrm{CN}} - 254 \qquad (5)$$

where S is in mm and CN is the curve number, which depends on land use, hydrologic soil group, hydrologic condition, and AMC (SCS, 1971).

MICHEL *ET AL.* MODEL

Michel *et al.* (2005) hypothesized that the SCS-CN model is valid not only at the end of a storm but also at any instant along a storm. They considered an SMA store which would absorb that part of the rainfall that is not transformed into runoff by the SCS-CN equation (this amount is noted as $F + I_a$ in the original SCS-CN method). Their SMA procedure is based on the notion that higher the moisture store level, higher the fraction of rainfall that is converted into runoff. If the moisture store level is full, all the rainfall will become runoff. The following SMA equation was given:

$$\mathrm{V} = \mathrm{V_0} + \mathrm{P} - \mathrm{Q} \qquad (6)$$

where $V_0 =$ soil moisture store level at the beginning of the rainfall event (mm), $P =$ accumulated rainfall at time t along a storm (mm), $Q =$ accumulated runoff at time t along a storm (mm), and $V =$ soil moisture store level at time t, i.e. when the accumulated rainfall is equal to P (mm). On the basis of the above hypothesis and Equation (6), Michel *et al.* pointed out severe structural inconsistencies in the original SCS-CN method, arising partly from the confusion between intrinsic parameter and the initial condition, and partly from an incorrect use of the underlying SMA procedure. Then, with a change of parameter, by incorporating a new parameter 'S_a' and eliminating the initial abstraction term I_a, and a sounder perception of the underlying SMA procedure, they presented the following equations to compute the runoff:

$$\text{If } V_0 \le S_a - P, \text{ then } Q = 0 \qquad (7)$$

If $S_a - P < V_0 < S_a$, then

$$Q = \frac{(P + V_0 - S_a)^2}{P + V_0 - S_a + S} \qquad (8)$$

If $S_a \le V_0 \le S_a + S$, then

$$Q = P\left[1 - \frac{(S + S_a - V_0)^2}{S^2 + (S + S_a - V_0)P}\right] \qquad (9)$$

Simplified version

Michel *et al.* simplified the above formulation, including Equations (7–9), by letting S_a be a set fraction of S. Thus, S_a can be expressed as

$$S_a = \alpha S \qquad (10)$$

where $\alpha =$ a parameter (fraction). On the basis of the results of model application to a large number of French watersheds, they recommended $S_a = S/3$, and then replacing V_0 by a fraction of S, they finally suggested a one-parameter model to compute the surface runoff for the three AMCs:

$$\text{For AMC I } (V_0 = 0{\cdot}33\mathrm{S}), \quad Q = P\left[\frac{P}{S + P}\right] \qquad (11)$$

$$\text{For AMC II } (V_0 = 0{\cdot}61\mathrm{S}), \quad Q = P\left[\frac{0{\cdot}48S + 0{\cdot}72P}{S + 0{\cdot}72P}\right] \qquad (12)$$

$$\text{For AMC III } (V_0 = 0{\cdot}87S), \quad Q = P\left[\frac{0{\cdot}79S + 0{\cdot}46P}{S + 0{\cdot}46P}\right] \qquad (13)$$

In the present study, the above models (Equations 7–9 and 11–13) are referred as MICHEL model and MICHEL-SIMP model, respectively, in the subsequent text.

ADVANCEMENT IN SMA PROCEDURE

Scope for improvement in MICHEL model

Despite improvement from the SMA viewpoint, the MICHEL model has scope for further improvement by incorporating an expression for the initial soil moisture store level (V_0). This V_0 is optimized in the generalized version (Equations 7–9) while it depends on the AMC in the simplified version (Equations (11–13) of the model. Thus, because of a sudden jump in V_0, a quantum jump in runoff computation would be experienced. Hence, an expression for V_0 is necessary to make the model a continuous one, which forms the main theme of this paper.

Derivation of expression for initial soil moisture store level (V_0)

Since the three AMC levels used with the original SCS-CN method and the MICHEL-SIMP model permit unreasonable sudden jumps in CN and V_0, respectively, a continuous equation is needed to estimate the antecedent moisture. Mishra and Singh (2002a) proposed such an equation based on some assumptions and proved dependency of antecedent moisture on P_5 as well as S. They assumed that the watershed is completely dry 5 days before the onset of rainfall, which may not be true, in general. They also assumed that their SCS-CN-based model, which includes I_a, was valid for $P = P_5$. Since the use of I_a is being discouraged (Michel *et al.*, 2005), refinement in the expression of antecedent/initial moisture is desirable.

The antecedent or initial soil moisture (V_0) depends not only on P_5 but also on S. The dependency on S is based on the fact that the watershed with larger retention capacity S must retain higher moisture compared to the watershed with lesser S for a given P_5. In the derivation of an expression for V_0, the following assumptions are made:

1. The pre-antecedent moisture level (V_{00}) 5 days before the onset of rainfall is zero or a fraction of S.
2. The initial soil moisture store level (V_0) at the time of the beginning of rainfall storm is equal to the sum of pre-antecedent moisture level (V_{00}) and a fraction (β) of the part of rainfall that is not transformed into runoff ($P_5 - Q_5$) owing to rainfall of P_5 at the time, where Q_5 is the corresponding runoff. This assumption is based on the fact that only a fraction, in general, of moisture/water added to the soil will contribute to V_0 due to evapotranspiration losses in the previous 5 days.
3. MICHEL model is valid for $P = P_5$.

The derivation of expression for V_0 is explained below: From assumption (1),

$$V_{00} = \gamma \mathrm{S} \tag{14}$$

where γ ranges from 0·0 to 1·0. From assumption (2),

$$V_0 = V_{00} + \beta(P_5 - Q_5) \tag{15}$$

Considering Equations (7–9) to be valid for $P = P_5$ (assumption-3), one obtains the following expressions under different conditions:

1. If $V_{00} \le S_a - P_5$, then $Q_5 = 0$; which, when combined with Equation (15), gives

$$V_0 = V_{00} + \beta P_5 \tag{16}$$

2. If $S_a - P_5 < V_{00} < S_a$, then

$$Q_5 = \frac{(P_5 + V_{00} - S_a)^2}{P_5 + V_{00} - S_a + S}$$

which, when combined with Equation (15), gives

$$V_0 = V_{00} + \beta\left[P_5 - \frac{(P_5 + V_{00} - S_a)^2}{P_5 + V_{00} - S_a + S}\right] \tag{17}$$

3. If $S_a \le V_{00} \le S_a + S$, then

$$Q_5 = P_5\left[1 - \frac{(S + S_a - V_{00})^2}{S^2 + (S + S_a - V_{00})P_5}\right]$$

which, when combined with Equation (15), gives

$$V_0 = V_{00} + \beta P_5\left[\frac{(S + S_a - V_{00})^2}{S^2 + (S + S_a - V_{00})P_5}\right] \tag{18}$$

Equations (14), (16), (17), and (18) represent a hydrologically more advanced SMA procedure. These equations coupled with MICHEL model (Equations (7–9)) are referred as the PROPOSED (advanced) model in the forthcoming text. Here, it is worth emphasizing that the parameters S, S_a, and β are catchment-based, whereas V_0 and gamma are mainly dependant on previous days' rainfall events.

APPLICATION

Watersheds and data

For evaluating the model performance, rainfall-runoff events were derived from the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) Water Database, which is a collection of rainfall and stream flow data from small agricultural watersheds of the United States. A total of 82 watersheds having areas varying from 0·17 to 71·99 ha were selected for the present study. Data for a total of 22 052 storm events from all the selected watersheds were used.

Performance criteria

For evaluating the comparative performance of models having unequal number of parameters, standard error (SE) as well as model efficiency (E) criterion was used. The model efficiency is generally recognized by Nash-Sutcliffe (NS) efficiency (Nash and Sutcliffe, 1970) and the same is used in this study. On the other hand, root mean square error (RMSE) and E criteria were used for comparative performance evaluation of models with equal number of parameters. These criteria are explained below:

$$SE = \sqrt{\frac{1}{N-m+1}\sum_{i=1}^{N}(Q_{\text{obs}} - Q_{\text{comp}})_i^2} \quad (19)$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{\text{i}=1}^{\text{N}}(Q_{\text{obs}} - Q_{\text{comp}})_{\text{i}}^2} \quad (20)$$

$$E = \left[1 - \frac{\sum_{\text{i}=1}^{\text{N}}\left(Q_{\text{obs}} - Q_{\text{comp}}\right)_{\text{i}}^2}{\sum_{\text{i}=1}^{\text{N}}\left(Q_{\text{obs}} - \overline{Q_{\text{obs}}}\right)_{\text{i}}^2}\right] \times 100 \quad (21)$$

where Q_{obs} is the observed storm runoff (mm), Q_{comp} is the computed runoff (mm), $\overline{\text{Q}_{\text{obs}}}$ is the average of observed runoff values in a watershed, N is the total number of rainfall-runoff events, m is the number of model parameters, and i is an integer varying from 1 to N. The higher the SE or RMSE, the poorer is the performance of the model, and vice versa. SE = 0 or RMSE = 0 exhibits a perfect fit. The former has the advantages of having the same units (dimensions) as the variable, properly accounting for the degrees of freedom, and being valid for non-linear models as well as linear models (McCuen, 2003). Obviously, the unit of SE or RMSE here is mm. The works of Madsen *et al.* (2002), Mishra *et al.* (2003, 2004), and Itenfisu *et al.* (2003) are but a few examples among many others to cite the wide usage of RMSE. It may be noted that SE and RMSE are equivalent for one-parameter models, for the right-hand side of Equation (19) converts to that of Equation (20) for $m = 1$.

E = 100% indicates perfect agreement between observed and computed values of runoff, and decreasing values indicate less agreement. The value of model efficiency can be negative, which indicates that the average observed value is a better estimate than the model prediction, i.e. model prediction is worse than the average observation. EI-Sadek *et al.* (2001), Fentie *et al.* (2002), Michel *et al.* (2005), and many other researchers used this criterion to compare the model performance.

Parameter estimation

The model parameters were computed using the Marquardt (1963) algorithm of constrained least squares. Marquardt provided an elegant and improved version of the non-linear optimization method originally proposed by Levenberg (1944). The method primarily provides a smooth variation between the two extremes of the inverse-Hessian method and the steepest descent method. The latter is used when the trial solution is far from the minimum and it tends continuously towards the former as the minimum is approached. This Levenberg–Marquardt method is also known as Marquardt method, which works well in practice and has become the standard of non-linear least squares routines.

In applying MICHEL model and the PROPOSED model, the initial estimate of parameter α was taken as 0·33 (Michel *et al.*, 2005) and was assumed to vary in the range 0 to 1. In MICHEL model, V_0 was allowed to vary in the range 0 to 500 mm with its initial estimate of 100 mm. In the PROPOSED version, β was initially taken as 0·5 and was allowed to vary from 0 to 1. Similarly, γ was allowed to vary from 0·0 to 1·0 with its initial estimate as 0·1. In all the applications, the initial estimate of S was taken as 125 mm and it was allowed to vary in the range 0·1 to 2500 mm. In the application of the original SCS-CN model, the initial estimate of CN was taken equal to 50, and its variation was allowed from 1 to 100. The ranges of parameters resulting from applications of all models under study in all the 82 watersheds are presented in Table I.

Table I. Range of parameters resulting from applications of models under study in 82 watersheds

Model	Parameter	Value				90% confidence interval	
		Mean	Median	Min.	Max.	Lower	Upper
MICHEL model	S_a (mm)	113·90	100·22	31·69	497·87	103·10	124·70
	V_0 (mm)	116·59	103·70	39·56	463·84	106·79	126·39
	S (mm)	184·07	100·57	23·83	2500·00	128·73	239·41
PROPOSED (advanced) model	α	0·61	0·57	0·00	1·00	0·57	0·66
	β	0·40	0·41	0·00	1·00	0·37	0·44
	γ	0·52	0·52	0·00	0·99	0·48	0·56
	S (mm)	178·36	101·58	30·13	2500·00	122·39	234·34
PROPOSED-SIMP-3P model	α	0·10	0·08	0·00	1·00	0·08	0·13
	β	0·40	0·41	0·01	0·80	0·38	0·43
	S (mm)	137·42	101·39	30·11	765·15	112·93	161·90
MICHEL-SIMP model	S (mm)	257·26	123·76	39·19	2500·00	173·41	341·11
PROPOSED-SIMP-1P model	S (mm)	100·52	89·31	34·95	265·32	92·12	108·92
Original SCS-CN model	S (mm) (for AMC II)	32·69	28·54	10·03	73·74	29·97	35·41

Note: α, β, and γ are dimensionless.

SIMPLIFICATION OF THE PROPOSED MODEL

In order to simplify the PROPOSED model, several values of V_{00} were tested considering it to be equal to either zero or a fraction of S, as given earlier. The statistic of model efficiencies is presented in Table II. It is evident from this table that the value of V_{00} equal to 0·0 resulted in almost the same efficiency as compared to that when it was either optimized or taken as some fraction of S. Hence, the value of V_{00} could be advantageously taken as zero for the set of watersheds under study, resulting in the lessening of one parameter. This simplification (with $V_{00} = 0$) in the PROPOSED model gives a three-parameter model, which is referred to as PROPOSED-SIMP-3P model in the subsequent text.

For further simplification, the median values of all the optimized values of α and β resulting from the PROPOSED-SIMP-3P model application on 82 watersheds were taken which are 0·1 and 0·4, respectively (Table I). Interestingly, mean and median values for each of these two parameters are almost the same (Table I) and these simplifications yield a one-parameter model, which is referred to as PROPOSED-SIMP-1P model in the subsequent text and is described by the following set of equations:

$$\text{If } P_5 \leq 0{\cdot}1S \text{ then, } V_0 = 0{\cdot}4\ P_5 \tag{22}$$

$$\text{If } P_5 > 0{\cdot}1S \text{ then, } V_0 = S\left[\frac{0{\cdot}44P_5 - 0{\cdot}004S}{P_5 + 0{\cdot}9S}\right] \tag{23}$$

After determining V_0, the runoff Q for any P can be computed by the following equations:

$$\text{If } V_0 + P \leq 0{\cdot}1\text{S, then } Q = 0 \tag{24}$$

If $0{\cdot}1S < V_0 + P < 0{\cdot}1S + P$, then

$$Q = \frac{(P + V_0 - 0{\cdot}1S)^2}{P + V_0 + 0{\cdot}9S} \tag{25}$$

If $0{\cdot}1\text{S} \leq V_0 \leq 1{\cdot}1\text{S}$, then

$$Q = P\left[1 - \frac{(1{\cdot}1S - V_0)^2}{S^2 + (1{\cdot}1S - V_0)P}\right] \tag{26}$$

PERFORMANCE EVALUATION

The values of SE and model efficiency (E) resulting from applications of each of the models to each data set of 82 watersheds were taken for comparative performance evaluation of the models, and these are presented in Table III. Here, it is worth emphasizing that the lesser the SE or the higher the E, the better the model performance, and vice versa. Figure 1 shows efficiency of the PROPOSED-SIMP-3P model, and MICHEL model over each of the 82 watersheds while Figure 2 depicts RMSE derived from application of one-parameter models to the data of each watershed. Here, it is noted that SE = RMSE for one-parameter model. It is evident from Figure 1 that the PROPOSED-SIMP-3P model yields higher efficiency and hence performs better than MICHEL model in most of the watersheds. For example, the former model yields more than 80% efficiency in 19 watersheds while the latter does so in only 6 watersheds. On the other hand, the former yields less than 50% efficiency in only 9 watersheds but the latter does so in 13 watersheds. Hence, the performance of the PROPOSED-SIMP-3P model is better and more consistent than MICHEL model. Similarly, it is obvious from Figure 2 that the PROPOSED-SIMP-1P model performs better than both the MICHEL-SIMP model and the original SCS-CN model in most of the watersheds.

Figures 3 and 4 show observed runoff *versus* computed runoff by PROPOSED-SIMP-3P and MICHEL models and by corresponding one-parameter models in watershed-9004, respectively. For values of observed runoff greater than 5 mm, the PROPOSED-SIMP-3P model yields five data points lying inside ±20% error bands while the MICHEL model yields only three such points (Figure 3). Similarly, it is visible from Figure 4 that these data points in the former model application are closer to the line of perfect fit in most cases than those by the other two one-parameter models.

Furthermore, the mean of the 82 SE-values or E-values resulting from a model application was taken as an overall yardstick for judging the quality of the model and hence for its overall comparative evaluation. The statistics of SE and E, namely, mean, median, and the 90% confidence interval (CI), for MICHEL model, the PROPOSED (advanced) model, and PROPOSED-SIMP-3P model over the 82 watersheds are presented in Table IV. It is evident from this table that the proposed model performed better than the MICHEL model, for the former yielded the lower value of mean SE (= 4·74 mm) and the higher value of mean E (= 68·17%) than the latter, which yielded these values as 5·09 mm and 64·04%, respectively. Such performance is also supported by median values and the 90% confidence interval values of SE as well as E. However, the PROPOSED (advanced) model and the PROPOSED-SIMP-3P model performed almost equally well for the set of watersheds under the present study. Statistical paired comparison t-test showed that the difference between the mean values of SE as well as between those of E produced by the MICHEL model, and the PROPOSED model is significant. Hence, the PROPOSED model performed significantly better than the MICHEL model. These results explain the rationale

Table II. Evaluation of V_{00} based on NS efficiency for the advanced model

S. No.	V_{00}/S	Model efficiency, %	
		Mean	Median
1	0·0	67·92	72·16
2	0·05	68·06	72·16
3	0·1	68·19	72·16
4	0·15	68·17	72·16
5	0·2	68·17	72·16
6	0·25	68·16	72·16
7	V_{00} optimized	68·17	72·16

Table III. Standard error and efficiency resulted by applications of models in 82 watersheds

Sl. No.	Watershed ID	Area (ha)	No. of events	MICHEL model		PROPOSED-SIMP-3P model		Original SCS-CN model		MICHEL-SIMP model		PROPOSED-SIMP-1P model	
				SE (mm)	E (%)	SE (mm)	E (%)	RMSE/SE (mm)	E (%)	RMSE/SE (mm)	E (%)	RMSE/SE (mm)	E (%)
1	9004	23·96	94	2·80	53·71	1·83	80·33	4·59	Negative	9·90	Negative	1·98	76·47
2	16 010	40·47	325	2·50	38·89	2·47	40·37	3·40	Negative	4·76	Negative	2·59	34·05
3	17 001	11·02	586	6·16	75·88	5·80	78·60	5·86	75·24	6·41	73·85	5·80	78·53
4	17 002	20·21	546	6·21	76·61	5·93	78·72	5·91	74·44	6·74	72·36	5·92	78·68
5	17 003	5·08	137	6·10	65·97	5·34	73·93	5·57	67·55	6·72	58·01	5·54	71·44
6	26 010	0·55	879	4·21	61·41	4·10	63·30	4·22	52·80	5·17	41·45	4·19	61·66
7	26 013	0·68	572	3·68	34·68	3·68	34·60	4·25	Negative	6·82	Negative	3·87	27·78
8	26 014	0·26	695	4·42	63·17	4·27	65·62	3·87	62·11	4·98	52·98	4·29	65·16
9	26 016	0·59	358	3·41	53·47	3·31	56·00	3·83	32·44	4·86	4·85	3·37	54·31
10	26 018	0·48	106	4·27	76·85	3·93	80·41	4·92	65·07	4·34	75·68	4·25	76·65
11	26 031	49·37	77	2·99	33·99	3·03	32·17	3·89	Negative	6·06	Negative	3·38	13·26
12	26 791	32·05	1475	4·18	55·79	3·99	59·63	4·16	53·53	4·21	55·02	3·99	59·53
13	26 863	0·17	197	3·02	88·31	3·16	87·20	3·54	83·44	3·35	85·41	3·08	87·67
14	34 001	0·9	258	5·80	62·28	5·61	64·76	5·76	56·37	7·00	44·73	5·64	64·04
15	34 002	1·95	247	6·53	62·47	6·20	66·15	6·02	61·68	6·81	58·85	6·25	65·36
16	34 006	0·71	275	6·39	57·68	6·15	60·75	5·53	50·16	7·48	41·58	6·19	60·01
17	34 007	0·81	262	6·47	62·19	6·04	67·00	5·48	61·43	7·05	54·79	6·04	66·76
18	34 008	1·91	231	6·41	51·19	6·17	54·84	5·67	44·81	8·02	23·10	6·17	54·42
19	35 001	13·52	158	6·66	79·82	6·33	81·79	7·11	71·98	8·04	70·27	6·32	81·61
20	35 002	1·3	151	4·35	74·45	4·34	74·56	5·09	40·81	8·79	Negative	4·76	69·07
21	35 003	1·27	107	6·95	80·16	6·36	83·37	7·71	70·32	8·17	72·07	6·41	82·78
22	35 005	2·14	128	4·79	63·10	4·68	64·84	5·98	20·85	9·01	Negative	4·82	62·06
23	35 008	3·68	129	4·55	73·45	3·88	80·67	3·85	61·30	6·86	38·58	3·91	80·09
24	35 009	5·42	120	4·44	77·09	4·07	80·74	5·19	58·20	7·70	30·04	4·08	80·30
25	35 010	6·35	113	4·75	72·87	3·98	80·94	3·99	64·79	7·15	37·42	4·00	80·43
26	35 011	38·36	99	3·40	40·72	3·21	47·19	4·32	Negative	10·10	Negative	3·53	34·63
27	37 001	6·76	195	10·66	58·84	10·46	60·38	9·87	58·59	10·46	59·97	10·41	60·37
28	37 002	37·23	388	9·21	57·70	8·64	62·76	8·58	58·41	9·18	57·77	8·69	62·15
29	42 006	70·42	819	8·28	67·30	7·36	74·15	7·47	69·89	8·71	63·69	7·46	73·34
30	42 008	17·12	162	11·46	57·13	10·84	61·63	11·51	51·52	12·62	47·28	10·79	61·48
31	42 010	7·97	224	8·66	74·38	8·75	73·85	9·70	65·50	9·66	67·88	8·68	74·06
32	42 012	53·42	277	7·84	71·71	7·64	73·17	8·30	63·41	9·36	59·46	7·66	72·85
33	42 013	32·33	36	5·56	80·61	5·16	83·31	7·23	58·74	7·22	65·36	5·02	83·25
34	42 014	6·6	273	6·62	68·33	6·47	69·76	7·23	57·23	8·82	43·40	6·54	68·91
35	42 015	16·19	128	8·39	68·70	7·92	72·07	9·09	59·71	9·73	57·20	7·87	72·03
36	42 016	8·42	293	6·62	69·07	6·15	73·32	6·58	63·35	8·38	50·06	6·14	73·15
37	42 017	7·53	237	8·83	71·35	8·10	75·88	9·26	63·05	9·55	66·18	8·11	75·61
38	42 037	4·57	181	7·52	72·82	7·04	76·23	6·80	71·40	9·07	60·09	7·06	75·80
39	42 038	2·27	158	10·93	63·29	9·97	69·45	9·80	63·02	11·36	59·89	10·00	68·86
40	42 039	4·01	237	8·57	63·61	7·98	68·44	8·15	55·21	10·89	40·69	8·00	68·03
41	42 040	4·57	226	9·43	59·38	8·95	63·40	9·53	46·32	12·25	30·81	9·04	62·36
42	44 005	1·46	135	4·15	55·58	3·74	63·83	4·30	52·03	8·18	Negative	3·92	59·74
43	44 006	1·38	149	6·32	45·90	5·40	60·47	5·64	52·48	8·65	Negative	5·84	53·12
44	44 007	1·53	524	5·05	72·94	4·52	78·33	4·50	75·09	5·08	72·54	4·56	77·87
45	44 008	1·47	515	5·02	78·11	4·76	80·28	4·25	76·52	5·49	73·65	4·76	80·19
46	44 009	1·63	537	4·18	77·55	3·80	81·45	3·76	76·36	4·93	68·64	3·82	81·25
47	44 013	1·53	248	3·87	69·31	3·68	72·25	3·90	58·96	5·32	41·72	3·73	71·25
48	44 014	1·61	262	4·60	57·66	4·42	60·95	3·71	40·44	5·74	33·59	4·53	58·59
49	44 015	1·56	295	4·65	72·33	4·29	76·46	3·96	69·15	5·08	66·81	4·28	76·44
50	44 016	1·48	309	5·19	65·28	4·98	67·95	4·61	55·57	5·75	56·98	5·04	66·95
51	44 017	1·38	276	4·08	78·45	3·69	82·32	3·41	75·66	5·12	65·74	3·69	82·26
52	44 018	1·36	274	4·50	76·55	3·99	81·57	3·78	75·72	5·08	69·94	3·99	81·44
53	44 019	1·46	303	4·34	72·75	4·13	75·30	3·67	67·53	5·02	63·33	4·20	74·35
54	44 020	1·44	281	4·39	77·07	4·00	80·98	4·05	77·65	4·83	72·03	3·99	80·89
55	44 021	1·6	321	4·38	75·73	3·99	79·83	4·06	75·17	4·96	68·66	3·98	79·80
56	44 022	1·51	320	4·04	70·29	3·96	71·41	4·90	49·28	6·21	29·32	4·10	69·28
57	44 023	1·66	258	4·47	77·53	4·08	81·26	3·41	77·64	4·82	73·60	4·08	81·12
58	44 024	1·64	264	4·74	56·94	4·43	62·49	4·34	37·63	5·22	47·48	4·74	56·72
59	44 025	1·59	238	5·23	65·96	4·82	71·11	4·34	64·16	5·57	61·04	4·81	70·97
60	44 026	1·55	241	4·61	75·58	4·32	78·55	3·74	73·29	5·96	58·89	4·34	78·20
61	44 027	1·64	277	4·80	72·50	4·42	76·74	3·91	69·49	5·45	64·40	4·44	76·33

Table III. (*Continued*)

Sl. No.	Watershed ID	Area (ha)	No. of events	MICHEL model		PROPOSED-SIMP-3P model		Original SCS-CN model		MICHEL-SIMP model		PROPOSED-SIMP-1P model	
				SE (mm)	E (%)	SE (mm)	E (%)	RMSE/SE (mm)	E (%)	RMSE/SE (mm)	E (%)	RMSE/SE (mm)	E (%)
62	44 028	1·7	269	4·82	75·65	4·36	80·06	3·85	75·81	5·79	64·66	4·39	79·63
63	56 001	59·41	229	0·68	36·83	0·70	32·49	1·88	Negative	2·30	Negative	0·82	7·28
64	56 002	71·99	123	0·70	47·17	0·72	45·08	1·82	Negative	1·46	Negative	0·79	32·02
65	61 002	18·41	386	4·31	54·63	4·21	56·68	4·12	42·47	7·35	Negative	4·22	56·19
66	61 004	25·5	342	3·57	38·92	3·37	45·41	4·08	5·55	5·66	Negative	3·58	37·92
67	62 014	0·59	134	7·68	70·88	6·63	78·35	6·89	71·72	6·99	75·54	6·75	77·20
68	63 102	1·46	132	2·26	77·97	2·22	78·84	2·58	69·00	2·53	72·00	2·25	77·78
69	63 103	3·68	94	1·60	92·57	1·60	92·61	3·14	70·48	2·55	80·73	1·92	89·05
70	63 104	4·53	83	2·16	80·77	2·14	81·11	2·79	65·29	2·58	71·92	2·25	78·71
71	66 004	2·56	389	1·38	38·17	1·33	42·98	2·49	Negative	2·74	Negative	1·42	34·40
72	66 005	3·86	244	2·23	59·04	2·12	63·15	2·52	54·20	3·04	23·53	2·11	62·98
73	68 013	40·47	201	0·73	24·21	0·74	23·09	1·91	Negative	0·91	Negative	0·79	11·73
74	68 014	13·35	40	1·49	11·70	1·54	5·03	1·99	Negative	4·97	Negative	1·64	Negative
75	69 032	17·91	198	4·62	67·24	4·11	74·18	4·09	63·92	5·30	56·61	4·15	73·37
76	69 033	12·11	156	5·35	61·34	4·76	69·35	4·45	59·66	6·11	48·95	4·83	68·10
77	69 034	5·16	94	5·71	43·28	5·31	50·90	4·53	47·98	7·67	Negative	5·29	50·12
78	69 036	10·73	113	4·99	53·45	4·60	60·55	5·52	31·32	7·53	Negative	4·57	60·38
79	69 037	11·04	123	3·69	43·24	3·46	49·99	3·97	31·06	7·95	Negative	3·46	49·27
80	69 044	7·77	225	4·09	77·62	3·59	82·80	3·99	74·96	4·69	70·32	3·66	81·93
81	69 045	11·15	250	3·54	73·27	3·01	80·73	2·94	76·20	4·50	56·42	3·01	80·54
82	70 011	2·91	41	5·39	89·18	3·30	95·95	5·05	87·52	7·55	77·63	3·96	93·86

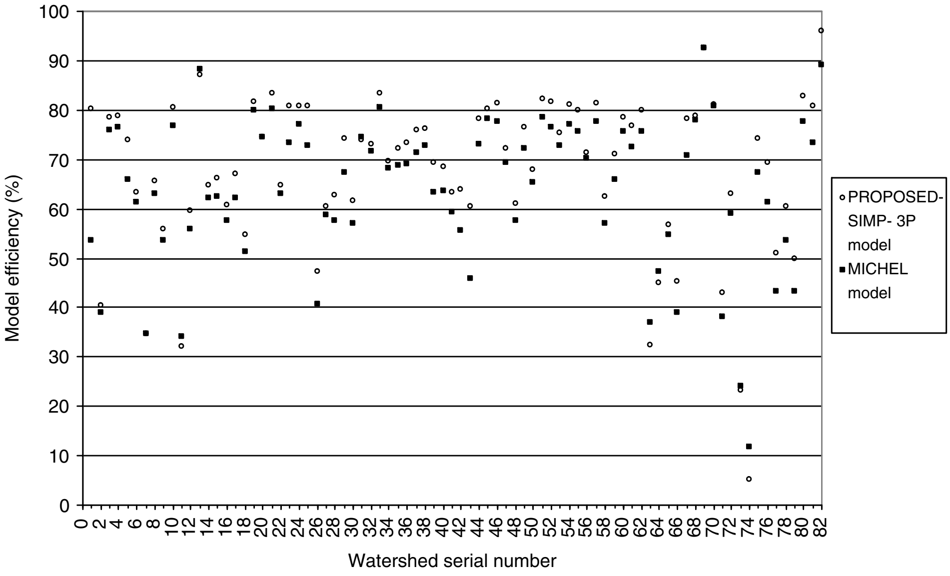

Figure 1. Efficiency of PROPOSED-SIMP-3P model and MICHEL model over the 82 watersheds

of incorporating the expression of V_0 in SMA procedure of the proposed model.

Among all the one-parameter models, namely, PROPOSED-SIMP-1P model, MICHEL-SIMP model, and the original SCS-CN model, the first model performed the best, as the mean RMSE (= 4·81 mm) yielded by this model is the minimum among the three models (Table V). Statistical paired comparison *t*-test showed that this value is significantly lower than the other two values, which are 6·54 mm and 5·07 mm, respectively, for MICHEL-SIMP model and the original SCS-CN model. It is also supported by the median value and the 90% confidence interval values of RMSE. Here, the overall performance cannot be judged by mean model efficiency because this efficiency is negative in some watersheds in case of these three one-parameter models, as evident from Table III. However, it is obvious that efficiency is negative in 1, 19, and 10 watersheds, respectively, by PROPOSED-SIMP-1P, MICHEL-SIMP, and the original SCS-CN models, indicating the performance of the first model is better than the other two. Interestingly, on the basis of SE, the first model was found to perform significantly better than MICHEL model. The overall mean SE-based performance of all the models is shown in Figure 5.

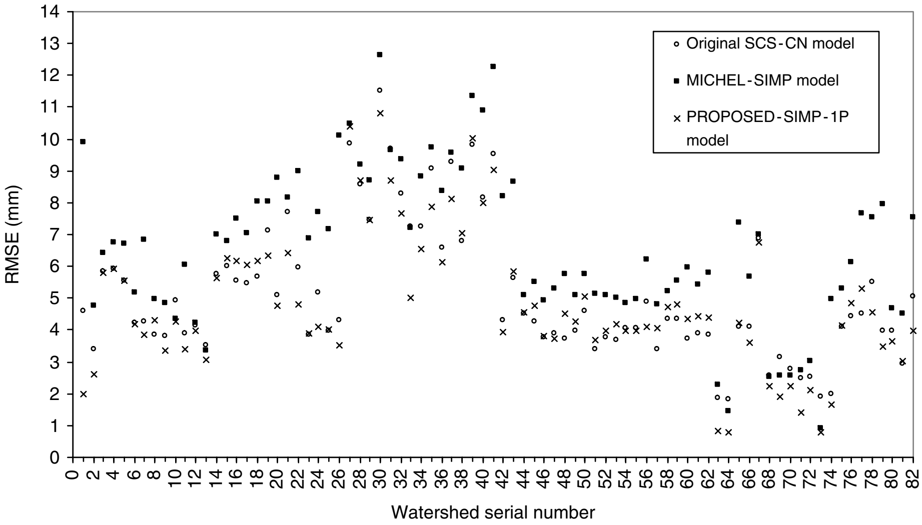

Figure 2. RMSE obtained by application of one-parameter models over the 82 watersheds

Table IV. Comparative overall performances of MICHEL model, PROPOSED (advanced) model, and PROPOSED-SIMP-3P model over the 82 watersheds

Model	No. of parameters	Standard error (mm)				Model efficiency (%)			
		Mean	Median	90% confidence interval		Mean	Median	90% confidence interval	
				Lower	Upper			Lower	Upper
MICHEL model	3	5·09	4·64	4·68	5·51	64·04	67·27	61·29	66·80
PROPOSED (advanced) model	4	4·74	4·32	4·35	5·13	68·17	72·16	65·37	70·97
PROPOSED-SIMP-3P model	3	4·74	4·31	4·35	5·13	67·92	72·16	65·02	70·81

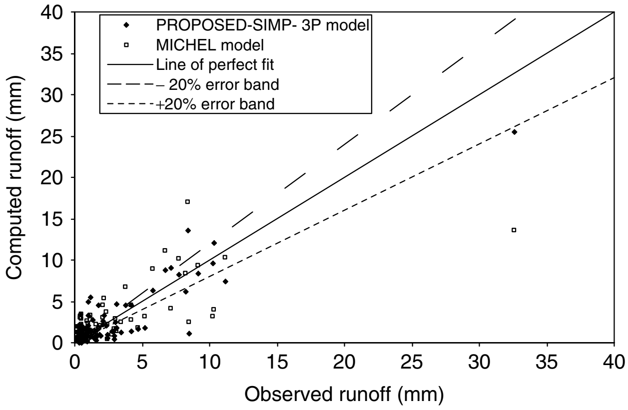

Figure 3. Plot of observed runoff *versus* computed runoff by PROPOSED-SIMP-3P model and MICHEL model in the watershed-9004

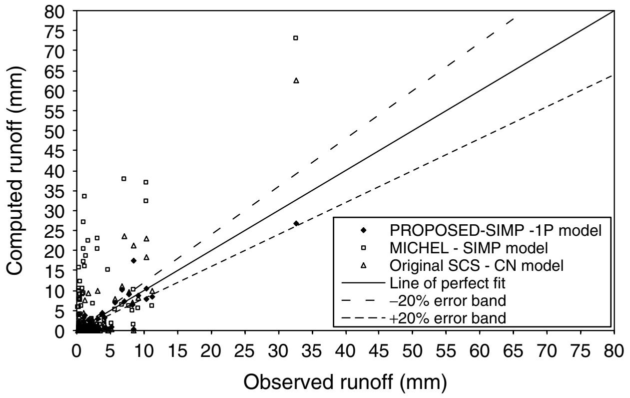

Figure 4. Plot of observed runoff *versus* computed runoff by one-parameter models in the watershed-9004

It is obvious from Table V and Figure 5 that the MICHEL-SIMP model performed the poorest of all the models, and significantly poorer than the original SCS-CN model. This might be due to the fact that it was developed on the basis of parameter values derived from MICHEL model in its application to the data of French watersheds, which is geomorphologically and climatically different from those of the U.S. watersheds used in the present study.

Since the values of α and β in the PROPOSED-SIMP-1P model, which is the simplified version of the proposed (advanced) model, are fixed, their field estimation is obviated. As discussed earlier, this model performs significantly better than the other two one-parameter models. Furthermore, this model obviates sudden jumps in V_0, a major drawback of both the MICHEL-SIMP model and the original SCS-CN model due to three AMC levels. Therefore, the PROPOSED-SIMP-1P model can be a more viable alternative to the original SCS-CN model and the MICHEL-SIMP model for field applications.

Table V. Comparative overall performances of the one-parameter models over the 82 watersheds

Model	SE/RMSE[a] (mm)				No. of watersheds for which E is negative	Mean E (%) over rest of the watersheds
	Mean	Median	90% confidence interval			
			Lower	Upper		
MICHEL-SIMP model	6·54	6·31	6·10	6·98	19	57·26
PROPOSED-SIMP-1P model	4·81	4·31	4·43	5·20	1	66·40
Original SCS-CN model	5·07	4·33	4·69	5·45	10	60·58

[a] SE and RMSE are same for one-parameter model.

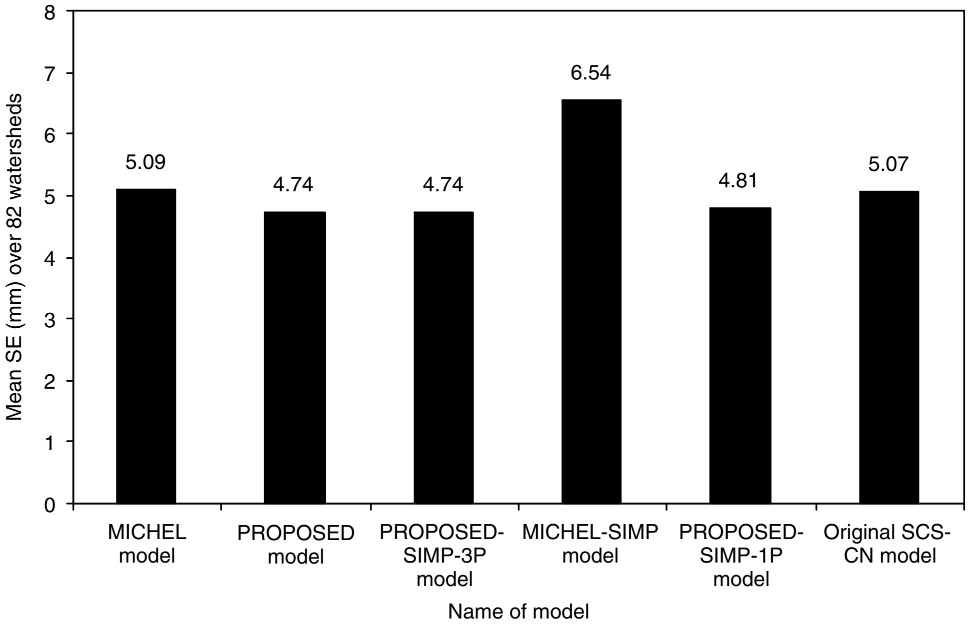

Figure 5. Mean SE resulted by all the models under the present study

CONCLUSIONS

The SMA (or MICHEL) model proposed by Michel *et al.* (2005) was revised for initial soil moisture store level (V_0) incorporating an expression for it. On the basis of SE and model efficiency criteria, both the PROPOSED and PROPOSED-SIMP-3P models performed significantly better than the MICHEL model when applied to a large set of data from a number of small U.S. watersheds, supporting the rationale of V_0-expression. Among simplified one-parameter models, the PROPOSED-SIMP-1P model performed significantly better than the MICHEL-SIMP and original SCS-CN models, and better than the MICHEL model. Therefore, the PROPOSED-SIMP-1P model can be a more viable alternative to both the original SCS-CN and the MICHEL-SIMP models.

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