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Continuous Simulation Model for Hydrologic Forecasting Based on Modified SCS-CN Concept

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ABSTRACT: A new lumped conceptual model based on the modified Soil Conservation Service Curve Number (SCS-CN) concept has been proposed in this paper for long-term hydrologic simulation and it has been tested using the data of three catchments from different climatic and geographic settings of India. The proposed model based on modified SCS-CN concept has been compared with a lumped conceptual model based on Variable Source Area (VSA) theory (Mishra *et al.*, 2005). The comparison revealed the proposed model to perform better in all applications. Both the models however exhibited a better match between the simulated and observed runoff in high runoff producing watersheds than did in low runoff producing catchments. The performance was evaluated in terms of the catchment response and the streamflow generation by producing satisfactory results through model efficiency and relative error. Using the results of the proposed model, dominant/dormant processes involved in watershed's runoff generating mechanism were also identified.

Keywords: Hydrological Forecasting, Long-term Hydrologic Simulation, Streamflow, Rainfall-runoff, Variable Source Area, Curve Number, Antecedent Moisture.

INTRODUCTION

Hydrological modeling provides a prognosis of the future performance of catchment behavior. It is unlikely to have a complete representation of every process existing in the system. However it is possible to identify and understand the response of major processes as accurately as possible, and this, in turn, allows simplification of the system. Simulation of rainfall-generated runoff is important in various activities of water resources development and management such as flood control and its management, irrigation scheduling, design of irrigation and drainage works, design of hydraulic structures, and hydropower generation etc. The process of transformation of rainfall to runoff is highly complex, dynamic, nonlinear, and exhibits temporal and spatial variability, further affected by many and often interrelated physical factors. The basic need of a hydrologic algorithm is to predict various processes involved in the streamflow generation by explaining the flow paths and source areas, and considering the spatial and temporal variation over the catchment. However an understanding of various hydrologic variations (spatial and temporal) over long periods is necessary for identification of these complex and heterogeneous watershed characteristics.

The hydrological response of a watershed to a rainfall event is determined by several interacting forces that control runoff generation. Continuous hydrologic models, unlike event models, account for a watershed's soil moisture balance over a long term period and are suitable for simulating daily, monthly, and seasonal streamflow. The long-term hydrologic simulation plays an important role in watershed management practices. It is also used for augmentation of hydrologic data beneficial for water resources for planning and management (Mishra and Singh, 2004).

In this paper, a lumped conceptual rainfall-runoff model is presented for continuous long-term hydrologic simulation by adopting the modified Soil Conservation Service Curve Number (SCS-CN) concept in order to represent the catchment behavior and a comparison is made with the long-term simulation model based on Variable Source Area (VSA) theory (Mishra *et al.*, 2005). Conceptually these models divide the potential path of rainfall onto a watershed into different moisture zones and constitute three runoff components. Both the models need certain number of parameters to model hydrologic processes such as initial abstraction, infiltration, drainage, deep seepage, percolation, deep percolation, evapotranspiration, surface runoff, throughflow, base flow, etc.

This study was initiated for (i) suggesting an appropriate continuous long-term hydrologic simulation model to transform rainfall into runoff, (ii) understanding and identification of the various hydrologic processes involved in the runoff generation mechanism, and also to investigate the dominancy/dormancy of these processes. This study attempted to compare the rainfall-runoff models developed in two different approaches: (i) by adopting the modified Soil Conservation Service Curve Number (SCS-CN) technique; (ii) by Incorporating Variable Source Area (VSA) theory. These long term hydrologic models are capable of simulating streamflow and its components such as surface runoff, throughflow, and base flow and are also quantifying the various hydrologic components in the runoff generation process. The mathematical formulation for modified SCS-CN-based model for long-term hydrologic forecasting (Figure 1) is detailed below:

FORMULATION OF CONTINUOUS SIMULATION MODEL USING MODIFIED SCS-CN METHOD

The present model formulation incorporates the SCS-CN concept revised for rainfall-dependent initial abstraction and quantification of flows adopting various flow paths in streamflow generation, such as (i) Surface runoff, (ii) Throughflow and (iii) Base flow. It is also conceptualized to have two different moisture stores, i.e. soil moisture store and ground water store. This algorithm operates on daily time basis and, therefore, requires daily data of rainfall and evaporation as input to explain the physical behavior of the catchment. The observed runoff is used for model evaluation. A complete description of individual components of the proposed model as follows:

A Review of Existing SCS-CN Model

The original SCS-CN method was documented in Section 4 of the National Engineering Handbook (NEH) in 1956. The document has since been revised subsequently in 1964, 1965, 1971, 1972, 1985, 1993 (In: Mishra and Singh, 2003), and 2004 (SCS, 2004). The method which is derived to compute the surface runoff from rainfall in small agricultural watersheds is based on water balance equation and the two hypotheses, respectively, as follows (Mishra and Singh, 2003),

$$P = I_a + F + Q\,;\ \frac{Q}{P - I_a} = \frac{F}{S}\,;\ I_a = \lambda S \quad \ldots \text{(1a, b, c)}$$

where P = total precipitation; I_a = initial abstraction; F = cumulative infiltration; Q = direct runoff; S = potential maximum retention or infiltration; λ = initial abstraction coefficient. But λ varies in the range of 0 to $\propto$ and is assumed as a standard value of 0.2 in usual practical applications (Mishra and Singh, 2004). Physically this means that for a given storm, 20% of the potential maximum water retention is the initial abstraction before runoff begins (Singh, 1992).

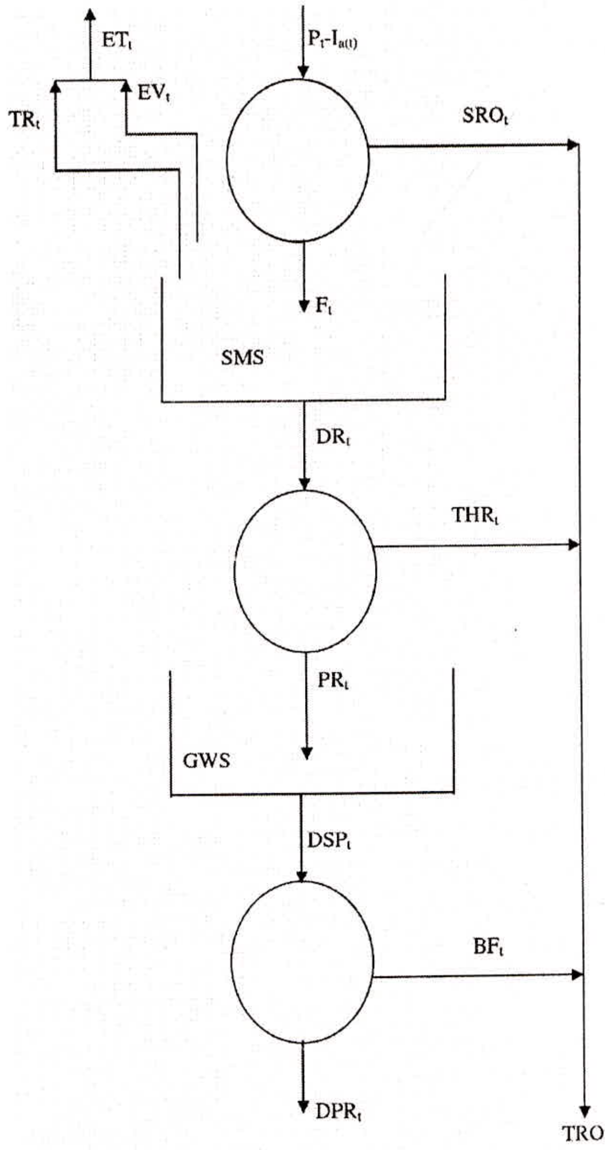

Fig. 1: Schematic diagram of modified SCS-CN-based lumped conceptual rainfall-runoff model

Hydrologic Components of Modified SCS-CN-based Rainfall-runoff Model

Figure 1 presents a schematic diagram of the suggested model which is based on the modified SCS-CN concept. The modifications made over the existing SCS-CN model are: (i) an improvement in the I_a–S relationship by incorporating the effect of rainfall P and maximum potential water retention S, (ii) to improve the space available for water retention S and hence initial abstraction value by taking into account of the input into as well as the losses from the moisture store. The various processes considered in the development of the model are explained in the following sections:

Initial Abstraction

Initial abstraction is considered as a short term loss before ponding such as interception, infiltration, surface storage (Ponce and Hawkins, 1996; Mishra and Singh, 2003). Here it is assumed that this loss is a fraction of the possible retention in the soil and is computed as,

$$I_{a(t)} = \lambda S_t \text{ if } t \leq 5 \text{ days}; \; I_{a(t)} = \lambda S_t \left[\frac{S_t}{P_t + S_t} \right]^{\alpha} \text{ if } t > 5 \text{ days} \qquad \ldots (2a, b)$$

where λ_1 and α are the coefficient and exponent of the initial abstraction which are to be optimised. The present model introduces an implicit relationship between initial abstraction I_a and moisture level in the soil store S by incorporating the effect of daily rainfall P_t if number of days exceeds 5. Here it is considered that I_a is always a part of S though there is no rainfall. It is evident that the higher is the moisture level, the lower will be the initial abstraction, and vice versa, which is close to the reality.

Antecedent Rainfall

In literature, the term antecedent varies from previous 5 to 30 days (SCS, 1971; Singh, 1992; Mishra and Singh, 2003). However no explicit guideline is available to vary the soil moisture with the antecedent rainfall of certain duration. Since the NEH-4 (SCS, 1971) uses 5 days rainfall based on the exhaustive field investigations, this duration of 5 days was retained. In this model, for the first 5 days beginning from the starting day of simulation (June 1 to June 5, in this study), curve number CN is taken as CN_0 and as the day advances beyond 5, CN varies with respect to antecedent moisture amount, AM, based on the antecedent rainfall (ANTRF) as,

$$\text{ANTRF}_t = P_{(t-1)} + P_{(t-2)} + P_{(t-2)} + P_{(t-3)} + P_{(t-4)} + P_{(t-5)} \qquad \ldots (3)$$

where t is the day under consideration and P is the rainfall of the respective day.

Antecedent Moisture

The initial moisture available in the soil prior to storm plays a vital role in the estimation of runoff (Mishra and Singh, 2002) as curve number CN variability is primarily attributed to antecedent moisture amount rather than the antecedent moisture conditions (SCS, 1971; Mishra and Singh, 2003) which may lead to sudden jumps in daily curve number values. This model assumes that the current space available for water retention S_t is constant for first 5 days of simulation and hence $CN_t = CN_0$. Using Eqn. (4) S_t can be computed from curve number CN_0 of the first day which is determined by optimisation,

$$S_t = \frac{25400}{CN_t} - 254 \qquad \ldots (4)$$

When the number of days exceeds 5, the antecedent moisture, representing the initial moisture available in the watershed on the day under consideration (AM_t), can be computed as follows,

$$AM_t = \beta \sqrt{ANTRF_t} \qquad \ldots (5)$$

Here, β is the coefficient of antecedent moisture which is to be determined by optimisation. Then, S_t^* is modified as S_t if $t > 5$ days,

$$S_t = \frac{(S_t)^2}{(AM_t + S_t)} \qquad \ldots (6)$$

Here in this model, it is considered that daily antecedent moisture amount AM_t varies with respect to antecedent rainfall $ANTRF_t$ (Eqn. 3) when number of days exceeds 5 days and hence the daily possible water retention of the soil is computed using Eqn. (6).

Rainfall Excess

The amount of rainfall (P) reaching on the ground after the initial losses (I_a) is termed as effective rainfall (P_e) and this is available for initiating various other processes in the hydrologic cycle. The effective rainfall (P_e) is assumed to be partitioned as surface runoff or rainfall excess (RO) and infiltration (F) as stated in Eqn. (1). Using the daily effective rainfall (P_{et}), the daily rainfall excess RO_t can be computed by using Eqn. (7) for the first 5 days of simulation, only if rainfall P exceeds initial abstraction (I_a), it is zero otherwise,

$$RO_t = \frac{(P_t - I_{at})^2}{P_t - I_{at} + S_t} \qquad \dots (7)$$

Routing of Rainfall Excess

When the number of days exceeds 5, to transform the surface runoff that is produced at the outlet of the basin, the rainfall excess RO_t (Eqn. 7) is routed using a single linear reservoir concept, as follows (Nash, 1957; Mishra and Singh, 2003),

$$SRO_t = C_0 \times RO_t + C1 \times RO_{(t-1)} + C2 \times SRO_{(t-1)} \quad \dots (8)$$

where

$$C_0 = \frac{(1/K)}{2+(1/K)};\ C_1 = C_0;\ C_2 = \frac{2-(1/K)}{2+(1/K)} \quad \dots \text{(9a, b, c)}$$

where K is the storage coefficient.

Infiltration

Here it is assumed that water (effective rainfall) reaches the ground and partitions into two: (i) infiltration and (ii) surface runoff. This amount of water reaching the ground after initial abstraction and not produced as surface runoff is assumed to infiltrate into the upper soil. It is modelled as,

$$F_t = P_t - I_{a(t)} - RO_{(t)} \qquad \dots (10)$$

Evapotranspiration

The amount of water goes back or lost to the atmosphere is in the form of evapotranspiration ET_t and can be obtained by the summation of daily evaporation from the water bodies and transpiration from the soil zone in the watershed.The daily evaporation EV_t is computed as follows,

$$EV_t = PANC \times EVP_t \qquad \dots (11)$$

where EVP_t is the potential evaporation based on the field data and PANC is the Penmann coefficient, assumed as 0.8 for June–September and 0.6 for October–November, and 0.7 for February–May (Project Report, 1978).Transpiration from the soil zone is considered as a function of water content available in the soil store above the wilting point of the soil. The transpiration is computed as,

$$TR_t = K_1 \times (S_{abs} - S_t - \theta_w) \qquad \dots (12)$$

where K_1 = coefficient of transpiration from soil zone, θ_w = wilting point of the soil, S_{abs} = the absolute maximum potential water retention, and S_t = maximum possible water retention on t^{th} day. The total actual evapotranspiration is taken as the sum of evaporation and transpiration as follows,

$$ET_t = EV_t + TR_t \qquad \dots (13)$$

Drainage

The term drainage (DR_t) is used as the outflow from a linear reservoir (Nash, 1957) only when the moisture content in the soil zone increases and exceeds the field capacity θ_f as,

$$DR_t = K_2 \times (S_{abs} - S_t - \theta_f) \qquad \dots (14)$$

where K_2 = subsoil drainage coefficient; θ_f = field capacity of the soil.

Throughflow and Percolation

The outflow from the unsaturated soil store is partitioned into two components: (i) subsurface flow in lateral direction and (ii) vertical percolation into ground water zone. The former component representing the through flow (THR_t) is taken as a fraction of the drainage rate (Mishra *et al.*, 2005; Geetha *et al.*, 2007),

$$THR_t = K_3 \times DR_t \qquad \dots (15)$$

where K_3= unsaturated soil zone runoff coefficient The outflow in the vertical direction from the unsaturated zone meets the ground water store due to the permeability of the soil. This percolated amount of water (PR_t) is considered as a part of drainage, and it is estimated as (Mishra *et al.*, 2005),

$$PR_t = (1 - K_3) DR_t \qquad \dots (16)$$

Deep Seepage

The saturated store is considered as a non-linear reservoir and from this saturated store, outflow occurs at an exponential rate in the form of deep seepage. The formulation for the deep seepage is made as an exponential function of the water content above the field capacity and is modeled as follows,

$$DSP_t = (\Psi_t - \Psi_{fg})^E \qquad \dots (17)$$

where DSP_t = deep seepage at any time 't'; ψ_t is the ground water content at any time 't'; ψ_{fg} is the field capacity of the ground water store; and E = exponent of ground water store. Deep seepage can travel in lateral direction as well as vertical direction through the saturated store. This seepage is again bifurcated into two components: (i) active ground water flow (base flow) and (ii) inactive ground water flow (deep percolation) into the aquifers.

Base Flow and Deep Percolation

The base flow of a watershed is the ground water release from a catchment in a stream. This active ground water flow which is also known as delayed flow can be modeled as outflow from a non-linear storage in the form of base flow (BF_t) as follows,

$$BF_t = BCOEF \times DSP_t \qquad \ldots (18)$$

The inactive ground water flow into aquifers is termed as deep percolation (DPR_t), occurs from the saturated ground water zone in vertical direction, and is considered as a loss from the saturated store which is modeled as (Mishra *et al.*; 2005),

$$DPR_t = (1 - BCOEF) \times DSP_t \qquad \ldots (19)$$

where $BCOEF$ = ground water zone runoff coefficient.

Total Stream Flow

The total stream flow (TRO_t) on a day t, is obtained as the sum of the above three components, surface runoff, throughflow, and base flow,

$$TRO_t = RO_t + THR_t + BF_t \text{ if } t \le 5 \text{ days} \qquad \ldots (20a)$$

$$TRO_t = SRO_t + THR_t + BF_t \text{ if } t > 5 \text{ days} \qquad \ldots (20b)$$

Water Retention Budgeting

The computation of daily water retention storage or soil moisture budgeting is essential in a daily hydrologic simulation. This SCS-CN-based model represents a soil-water balance model. The current space available for retention of water S_t is modified by taking into account the evapotranspiration loss, drainage from the soil moisture zone, and daily infiltration to the unsaturated store as,

$$S_t = S_{(t-1)} - F_{(t-1)} + ET_{(t-1)} + DR_{(t-1)} \qquad \ldots (21)$$

where $S_{(t-1)}$ is the previous day maximum potential retention; $ET_{(t-1)}$ is the previous day evapotranspiration; $DR_{(t-1)}$ is the drainage on the previous day; $F_{(t-1)}$ is the previous day infiltration, computed using water balance equation,

$$F_{(t-1)} = P_{(t-1)} - I_{a(t-1)} - RO_{(t-1)} \qquad \ldots (22)$$

Here, if $P_{e(t)} \ge 0$, $F \ge 0$. All processes are considered in terms of depth and units are in mm. The two moisture storage assumed in the model are soil moisture store and ground water store. The representation of moisture content is a great simplification as it will vary spatially throughout the catchment due to non-uniformity of soil composition, soil structure, soil depth, etc. as well as the non-uniformity of rainfall. The water balance in the soil and ground water store is worked out as follows (Mishra *et al.*, 2005, Geetha *et al.*, 2007),

$$\frac{d\theta}{dt} = F_t - ET_t - DR_t\,;$$

$$\frac{d\psi}{dt} = PR_t - BF_t - DPR_t \qquad \ldots 23(a, b)$$

where $\frac{d\theta}{dt}$ and $\frac{d\psi}{dt}$ are change in water content in soil moisture store and ground water store respectively.This developed rainfall-runoff model consist of fifteen parameters: CN_0, λ, α, β, K, S_{abs}, θ_f, θ_w, K_1, K_2, K_3, ψ_{fg}, $\psi_{t(1)}$, $BCOEF$ and E.

DEVELOPMENT OF CONTINUOUS SIMULATION MODEL

The proposed long-term hydrologic simulation model (Figure 1) is developed for describing watershed hydrology by considering temporal and spatial variations of various processes involved in the runoff generation mechanism and also by incorporating modified soil conservation service curve number (SCS-CN) technique as well as storage concepts to represent the catchment response in a better way. This modified SCS-CN based lumped rainfall-runoff model that captures the relevant catchment features requires fifteen parameters, such as CN_0, λ, α, β, K, S_{abs}, θ_f, θ_w, K_1, K_2, K_3, ψ_{fg}, $\psi_{t(1)}$, $BCOEF$, and E to derive an acceptable model output. Commonly, a close fit between calculated and observed variables is possible for models with a high number of parameters even if the model assumptions are false (Grayson *et al.*, 1992). In contrast to the studies showing less number of parameters is needed to establish rainfall-runoff relationship (Jakeman and Hornberger, 1993), here the number of parameters involved in the model is comparatively large, but it is at the gain of significant higher efficiency and it generates not only streamflow but also its components, a distinctive feature. It is notable that the presented model requires easily available rainfall and evaporation in order to generate streamflow and its components. Here the parameters involved in the model are optimised using non-linear Marquardt algorithm (In: Mishra and Singh 2003), coupled with trial and error, utilising the objective function of minimising errors between the computed and observed data or maximising model efficiency (Nash-Sutcliffe, 1970). Optimisation is carried out to arrive at their best possible value for each of them to generate an acceptable model output. The ranges and initial values are selected appropriately for the optimization. Notably, initial estimates of the parameters fixed by trial-and-error need not be provided.

A comparison has also been made between the present model based on SCS-CN concept and a model based on Variable Source Area (VSA) theory. This 3-component VSA-based model assumes three different stores of moisture as interception store, soil moisture store, and ground water store (Mishra *et al.*, 2005). The model quantifies daily as well as annual streamflow and its components i.e. source area runoff, throughflow and base flow. The main difference between the modified SCS-CN-based model and VSA-based model is that the former is an infiltration-excess model and assumes the surface runoff to be produced from the entire catchment whereas the latter produces it from source areas only, i.e. certain dynamic contributing areas varying with storm intensity. Furthermore, the former assumes the surface runoff to be produced due to infiltration-excess overland flow, similar to Hortonian overland flow whereas the latter produces the surface runoff due to saturation-excess overland flow. The latter model is a modification of the Kentucky watershed model (James, 1972) and SAHYADRI model (Putty and Prasad, 2000), as these models do not account for the deep seepage and deep percolation. The VSA-based developed model is calibrated and validated using rainfall-runoff annual data of the study watersheds. This model also involves fourteen parameters (Mishra *et al.*, 2005). Out of these 14 parameters, seven are related to the characteristics of the soil zone and ground zone. These are the wilting point θ_w; field capacities such as θ_f and Ψ_f in the soil store and ground water store respectively; pore capacities such as θ_p and Ψ_p in the soil store and ground water store respectively; and the initial moisture contents from soil zone θ_t (1) and ground water zone Ψ_t (1). The parameter, source-area exponent C_1 reflects the catchment topography to certain extent. The parameters that depend on vegetation and its characteristics are the interception capacity $I_{\max}$ and the coefficient of transpiration from soil zone C_2. The remaining four parameters, soil zone recession coefficient K_1, soil zone runoff coefficient K_2, ground water zone exponent K_3, and ground water zone exponent E are quasi-physically based parameters relying on ground water storage characteristics. It is noted that the model calibration included both the trial and error and an appropriate search technique for optimization to obtain the optimal estimates of fourteen parameters of the proposed model. The ranges of the parameters values for optimization are chosen appropriately depending on the vegetation and the extent of cover so as to yield minimum deviation between observed and simulated flows.

STUDY SITES AND RELEVANT DATA

The study areas selected are on the catchments of River Cauvery and River Narmada, falling under different geo-climatic conditions of India. The study catchments Hemavati having drainage area of 600.0 sq. km. is a tributary of River Cauvery, Karnataka state (Mishra and Singh, 2003; Mishra *et al.*, 2005) and the catchments Manot and Mohegaon are tributaries of River Narmada (Mishra *et al.*, 2005), with drainage areas 5032.0 and 4661.0 sq. km. respectively. The hydrologic data collected for the study are daily values of rainfall, evaporation, and runoff. A brief description of study sites and the data length used for simulation are presented in Table 1.

Table 1: Details of Catchment for Model Calibration and Validation

Description	*Catchment*		
	Hemavati	*Manot*	*Mohegaon*
River	Cauvery	Narmada	Narmada
State	Karnataka	Madhya Pradesh	Madhya Pradesh
District	Chikmanglur	Shahdol	Mandla
Area (Sq.km)	600.00	5032.00	4661.00
Latitude	12°55'–13°11' N	22°26'–23°18'N	22°32' N
Longitude	75°29'–75°51'E	80°24'–81°47'E	81°22' E
Topography	Low land, semi hilly and hilly	Hilly	Both flat and undulating lands
Land use	Forest 12% Coffee plantation 29% Agriculture land 59%	Forest 35% Cultivation 52% Waste land 13%	Forest 58% Agriculture 42%
Soil	Red loamy soil and red sandy soil	Red, yellow, and medium black soil	Red and yellow silty loam and silty clay loam
Elevation (m) above m.s.l.	1240–890	450–1110	900–509
Average annual rainfall (mm)	2972.00	1596.00	1547.00
Calibration	June 1974–May 1977 (3 yrs)	June 1981–May 1986 (5 yrs)	June 1981–1986 (5 yrs)
Validation	June 1977–May 1979 (2 yrs)	June 1986–May 1990 (4 yrs)	June 1986–May 1990 (4 yrs)

GOODNESS-OF-FIT STATISTICS

Both the models were applied to the data of the study catchments and then their performance evaluated using the Nash and Sutcliffe (1970) model efficiency, error criteria like root mean square error RMSE, standard error SE, coefficient of determination r^2 and also by computing the deviation between observed and simulated flows.For evaluation of model performance, the model efficiency is determined. The efficiency (Nash and Sutcliffe, 1970) of all the models is computed using,

$$\text{Efficiency} = \left(1 - \frac{RV}{IV}\right) \times 100 \qquad \ldots (24)$$

where

$$RV = \sum_{i=1}^{n} (Q_i - \hat{Q}_i)^2;\ IV = \sum_{i=1}^{n} (Q_i - \overline{Q}_i)^2 \qquad \ldots (25a, b)$$

Here, RV is the remaining variance; IV is the initial variance; Q_i is the observed runoff for i^{th} day; $\hat{Q}_i$ is the computed runoff for i^{th} day; n is the total number of observations; and $\overline{Q}$ is the overall mean daily runoff. Efficiency is used for evaluating the model performance. Efficiency varies at the scale of 0 to 100. It can also assume a negative value if RV > IV, implying that the variance in the observed and computed values is greater than the model variance. The efficiency of 100 implies that the computed values are the same as the observed ones, which is the perfect fit (Mishra and Singh, 2003; Benaman *et al.*, 2005). The following error criteria are also considered in evaluation of model performance in the suggested hydrologic model,

$$RMSE = \sqrt{\frac{\sum_{j=1}^{N} (Qo - Qc)2}{N}};\ SE = \sqrt{\frac{\sum_{j=1}^{N} (Q_o - Q_c)^2}{N - M + 1}} \qquad \ldots (26a,b)$$

$$r^2 = 1 - \frac{\sum_{j=1}^{N} (Q_o - Q_c)^2}{\sum_{j=1}^{N} (Q_o - Q_{mean})_2} \qquad \ldots (26c)$$

where RMSE is the root mean square error; SE is the standard error; r^2 is the coefficient of determination; N is the number of days considered for the analysis; j is an integer varying from 1 to N; m is the number of model parameters; Q_o is the observed quantity (field runoff); Qc is the computed quantity (simulated runoff); Q_{mean} is the mean value of observed runoff. The higher the RMSE, the poorer is the performance of the model, and vice versa. RMSE = 0 indicates a perfect fit. The higher the values of SE and lower values of r^2 show a poor fit and the reverse holds in an otherwise situation. $SE = 0$ exhibits a perfect fit. The value of r^2 varies from 0 to 1; 0 indicates a mean model fitting better than the proposed model whereas 1 exhibits a perfect fit. The coefficient of determination r^2 can be negative in which the model prediction is worse than the average of observation. The model efficiency (Nash and Sutcliffe, 1970) and the coefficient of determination r^2 are same in this study. Another error criterion, known as Relative Error (RE), is also used in evaluating the model performance by computing the deviation between field runoff values and simulated values with respect to field runoff values, as given below,

$$\text{Relative error RE (\%)} = \frac{\left(Q_{obs} - Q_{comp}\right)}{Q_{obs}} \times 100 \qquad \ldots (27)$$

Here Q_{obs} is the observed runoff and Q_{comp} is the simulated runoff. The high RE is indicative of greater deviation from the observed and vice versa.

MODEL CALIBRATION AND VALIDATION

Hydrologic models often require calibration prior to application (McCuen *et al.*, 2006). It involves adjusting the parameters until the difference between the observed and simulated flow is minimized or model efficiency is maximized and hence the final parameters are inevitably related to the calibration data. The validation is more stringent evaluation of a model as it assesses the ability of the model to predict the output in periods and areas outside the calibration data. The above described model employs the modified SCS-CN model incorporating antecedent moisture amount, to calculate the space available for daily water retention; and updates the water retention store daily using evapotranspiration, drainage from soil moisture store, and infiltration to soil moisture store. Its application requires daily data of rainfall and evaporation. It has been applied to the daily data of three study catchments such as Hemavati, Manot, and Mohegaon. The details of study watersheds and the record of hydrologic data used in this analysis are presented in Table 1. Here in the modified SCS-CN-based model, the parameters are estimated and the optimal set of parameter values is presented in Table 2. Goodness-of-fit measures are also evaluated to test the models' accuracy. The efficiency of the model based on modified SCS-CN-concept is calculated by Nash and Sutcliffe (1970) and is also presented in Table 2.

Table 2: Estimates of Model Parameters and Efficiency—Modified SCS-CN-based Model

Sl. No.	*Parameter/ Description*	*Catchment*		
		Hemavati	*Manot*	*Mohegaon*
1.	CN_0	45.00	32.00	30.00
2.	λ	0.001	0.002	0.001
3.	α	5.00	6.00	5.00
4.	β	3.193	2.205	1.142
5.	K	0.93	0.094	0.048
6.	K_1	0.03	0.035	0.035
7.	K_2	0.044	0.611	0.026
8.	K_3	0.090	0.171	0.312
9.	BCOEF	0.93	0.504	0.300
10.	E	0.487	0.792	0.614
11.	S_{abs}	835.78	650.00	556.39
12.	θ_w	60.00	60.00	60.00
13.	θ_f	319.41	374.00	114.48
14.	Ψ_{fg}	347.83	220.00	321.13
15.	$\Psi_{t(1)}$	140.0	140.00	140.0
16.	Efficiency-Calibration	87.51%	74.41%	69.11%
17.	Efficiency-Validation	88.71%	64.12%	52.63%
18.	Runoff factor	0.782	0.448	0.350

RESULTS AND DISCUSSION

Using the parameter values estimated in calibration (Table 2), the model was validated using the above-described data of different watersheds. The comparison of model efficiencies reveals that Hemavati catchment shows best matching among others. The model yields a maximum efficiency of 87.51% and 88.71% in calibration and validation, respectively, in Hemavati catchment. The highest efficiency reveals that the model is efficacious to high runoff producing Hemavati catchment. The other catchments like Manot and Mohegaon also produce 74.41% and 69.11%, respectively, in calibration whereas in validation these catchments yield 64.12% and 52.63% respectively. The lower the efficiency, the higher the error between observed and simulated runoff values. The Nash-Sutcliffe efficiency of all catchments, except Hemavati is higher in calibration than in validation, and reverse holds for the catchment Hemavati. Schaake *et al.* (1996) inferred that the catchments producing improved efficiency in validation may be due to discrepancies in hydrologic conditions during the periods of the two data sets.

Comparing the runoff factor as shown in Table 2, the catchments can be classified as dry, wet, and intermediate category of dry and wet. It is seen that Hemavati catchment yields the highest runoff coefficient 0.782 among three catchments and can be categorized as a wet catchment. The runoff coefficients for Manot and Mohegaon catchments are 0.448 and 0.350 respectively, and these low runoff producing catchments can be described them to lie in the intermediate category of wet and dry catchment, as Gan *et al.* (1997) referred the catchments with streamflow/rainfall ratio of 0.2 or less as dry catchments.

Figure 2a presents daily variations of estimated and observed runoff with respect to daily average rainfall for Hemavati catchment with least deviation of estimated runoff from field values The model performs satisfactorily in this catchment, except for few peaks, where the computed runoff is lower than the observed. It is largely because the limitation of the optimized function that is minimized based on a large number of other data points than the peaks. Table 3 presents the annual values of rainfall, observed, and simulated runoff and also computes error in percentage of runoff. Hemavati catchment receives annual average rainfall of 2854.19 mm, falling in humid regions, whereas Manot and Mohegaon receive 1263.59 mm, and 1231.46 mm, respectively. The relative errors between observed and simulated runoff values are computed for each year and also presented in Table 3.

The annual average Relative Error (RE) values for Hemavati catchment ranges from 0.21% to 25.78% with an average error of 10.41% (Figure 2a), and RE value for Manot ranges from 3.42% to 49.42% with an average error of 25.11%. Mohegaon catchment derives RE values ranging from 13.28% to 40.92% and exhibit an average RE value of 27.08%. It is observed that the RE values is the least for catchment of Hemavati exhibiting a good fit and the highest error involved in the estimation of runoff is for catchment Mohegaon. In some cases, the RE values are negative, implying that the model overestimates the runoff values.

This study involves the estimation of annual water yields of various processes considered. This information is usually helpful in planning for utilization of resources and identification of dominant/dormant processes. Percent estimates of these processes with respect to rainfall are presented in Table 4. It is apparent from Table 4 that the maximum initial abstraction losses occur in Manot and Mohegaon catchments as compared to Hemavati catchment implying that high amount of losses occur from Manot and Mohegaon catchments. Maximum infiltration occurs in Manot and

Mohegaon catchments, and minimum in Hemavati catchment among three study catchments, yet significant infiltration is observed in all watersheds. Similarly maximum surface runoff takes place from Hemavati catchment and minimum for Manot catchment whereas throughflow is insignificant in all watersheds. Base flow is seen as a dormant process in Manot and Mohegaon catchments, maximum from Hemavati catchment. The dormancy of the processes (*-marked) are described in Table 4. It is also observed that the hydrologic processes like initial abstraction and throughflow are dormant in all study catchments. The high amount of runoff is generated in the catchment of Hemavati, and the low runoff is produced from Mohegaon catchment which is in order of the losses occurring from the study catchments (Table 4). Also deep percolation into aquifers is dormant in catchment Hemavati whereas it is dominant in other catchments like Manot and Mohegaon. Same inferences can be seen in Figures 3a and b.

Table 3: Annual Rainfall, Observed Runoff, Simulated Runoff and Relative Error—Model Based on Modified SCS-CN-Concept

Sl. No.	*Year*	*Rainfall (mm)*	*Observed Runoff (mm)*	*Simulated Runoff (mm)*	*Relative Error (%)*
Hemavati					
1.	1974–75	2937.50	2552.53	2128.36	19.93
2.	1975–76	2650.89	1717.96	1682.78	2.05
3.	1976–77	2676.33	1894.46	1890.46	0.21
4.	1977–78	2941.87	2936.71	2179.53	25.78
5.	1978–79	3064.35	2061.74	2146.24	–4.10
Average		2854.19	2232.68	2005.47	10.41
Manot					
1.	1981–82	1135.50	387.53	319.53	17.55
2.	1982–83	1023.90	375.33	388.16	–3.42
3.	1983–84	1391.10	573.62	490.54	14.48
4.	1984–85	1303.40	623.57	538.62	13.62
5.	1985–86	1263.60	721.24	465.19	35.50
6.	1986–87	1378.70	716.23	362.28	49.42
7.	1987–88	1347.40	776.23	442.40	43.00
8.	1988–89	1308.70	638.40	523.49	18.00
9.	1989–90	1220.00	279.04	365.49	–30.98
Average		1263.59	565.69	432.86	25.11
Mohegaon					
1.	1981–82	1240.00	333.64	258.64	22.48
2.	1982–83	1112.90	338.66	290.32	14.27
3.	1983–84	1533.10	485.71	421.19	13.28
4.	1984–85	1294.90	518.13	427.72	17.45
5.	1985–86	1329.10	578.58	341.83	40.92
6.	1986–87	1356.10	470.63	299.10	36.45
7.	1987–88	1125.20	377.41	232.84	38.31
8.	1988–89	1165.90	550.32	338.37	38.51
9.	1989–90	925.90	227.10	176.98	22.07
Average		1231.46	431.13	309.67	27.08

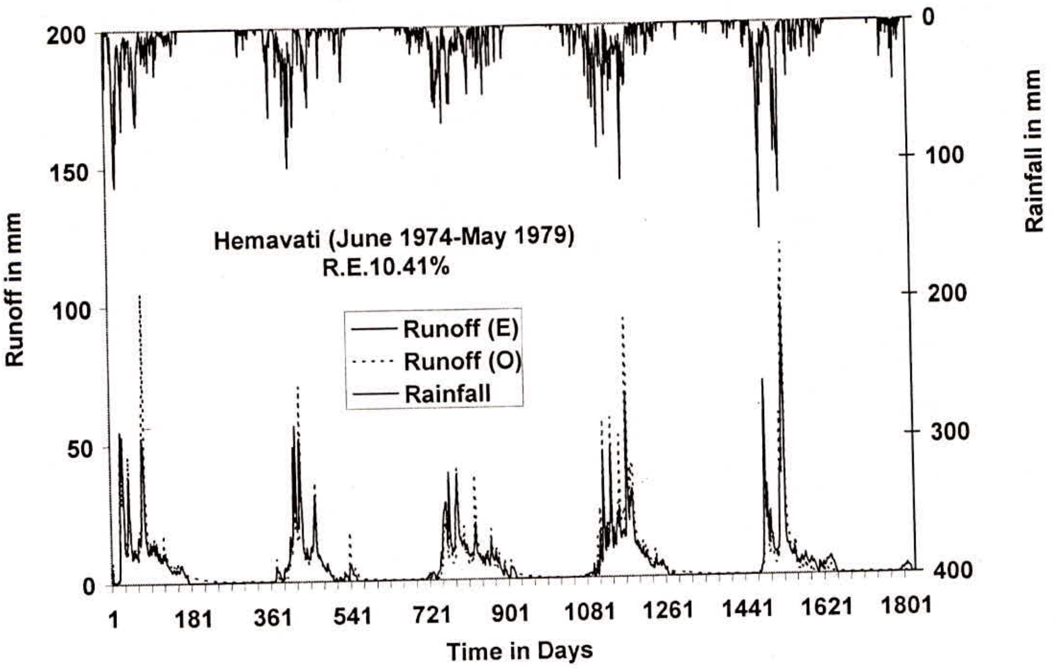

Fig. 2a: Daily variations of rainfall, observed runoff (O), estimated runoff (E) and average relative error (%) of Hemavati catchment—Modified SCS-CN-based model

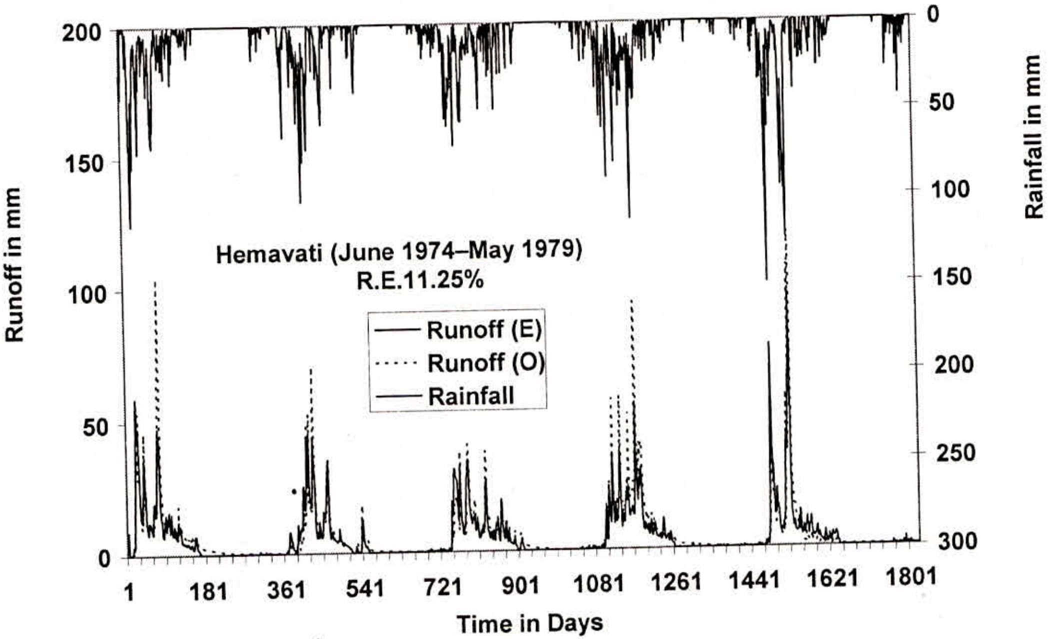

Fig. 2b: Daily variations of rainfall, observed runoff (O), estimated runoff (E) and average relative error (%) of Hemavati catchment—(VSA-based model)

MODEL COMPARISON

This section compares the application of the two models, viz., the proposed SCS-CN-based lumped conceptual model (Figure 1) and the long term hydrologic VSA-based model using storage and source area concepts (Mishra *et al.*, 2005). The optimal estimate of the parameters involved in the hydrologic model based on VSA is presented in Table 5. Both the models show a satisfactory performance (the higher model efficiencies and less relative error) on high runoff producing Hemavati catchment as plotted in Figures (2a and b). The catchments like Manot and Mohegaon, falling under drought prone areas, indicates the lower efficiency in both model applications. The comparison based on model efficiencies indicates the model based on the modified SCS-CN technique performs significantly better than the model based on Variable Source Area (VSA) theory. Model efficiency calculated by Nash-Sutcliffe (1970) as given in Tables (2 and 5) proves that SCS-CN-based model is showing better performance than VSA-based model over the three study watersheds. While comparing these Tables (2 and 5), it is also apparent that SCS-CN-based model is in good agreement with the high runoff producing catchment i.e. Hemavati, with 87.51% in calibration and 88.71% in validation respectively. The other two catchments which are prone to drought affected areas are showing relatively less model efficiencies in calibration and validation. To ascertain the model results, the model performance has been evaluated using error criteria like RMSE, SE, and r^2 and the computed values are tabulated in Table 6.

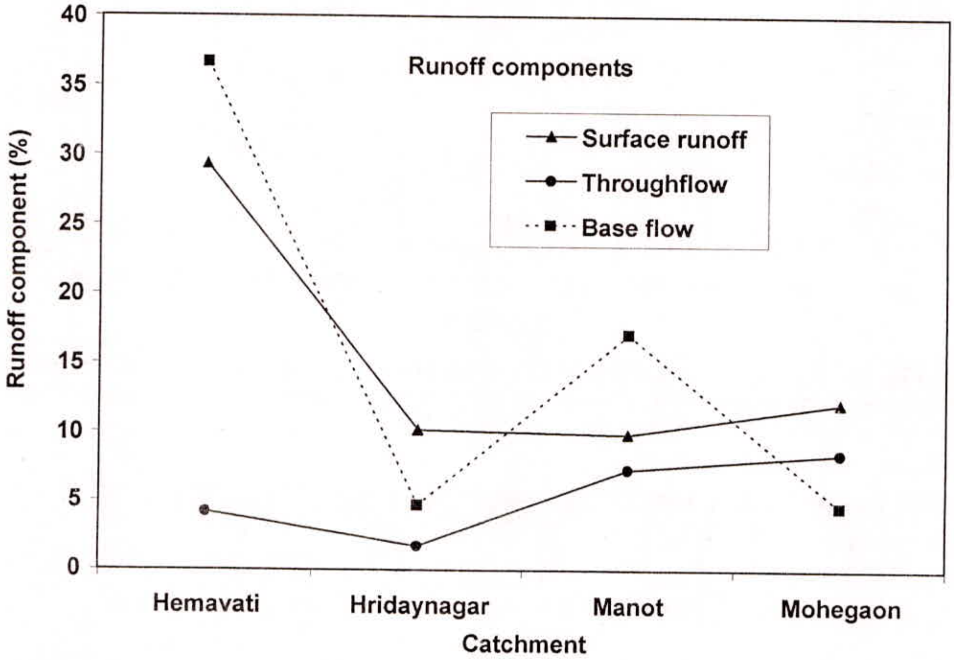

Fig. 3a: Percent estimate of runoff components—Modified SCS-CN-based model

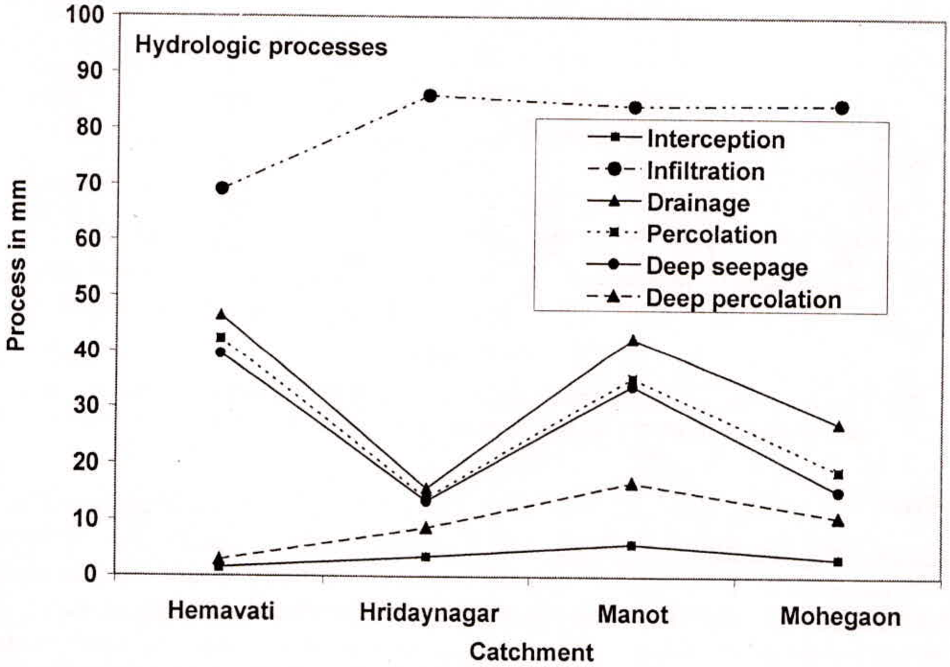

Fig. 3b: Percent estimate of hydrologic components—Modified SCS-CN-based model

Table 4: Percent Estimates of Hydrological Components—Modified SCS-CN-Based Model

Sl. No.	*Components*	*Catchment*		
		Hemavati	*Manot*	*Mohegaon*
1.	Rainfall (P)	100	100	100
2.	Initial abstraction (I_a)	1.54*	5.90*	3.33*
3.	Effective rainfall (P_e)	98.46	94.10	96.67
4.	Infiltration (F_t)	69.09	84.24	84.56
5.	Drainage ((DR_t)	46.56	42.63	27.32
6.	Percolation (PR_t)	42.36	35.33	18.88
7.	Deep seepage (DPr_t)	39.62	33.92	15.34
8.	Deep percolation	2.93*	16.82	10.74
9.	Surface runoff (RO_t)	29.37	9.86*	12.11
10.	Throughflow (THR_t)	4.20*	7.30*	8.44*
11.	Base flow (BF_t)	36.69	17.10	4.60*
12.	Simulated runoff	70.26	34.26	25.15
13.	Observed runoff	78.22	44.77	35.01

*Dormant process

Table 5: Estimates of the Model Parameters for Different Watersheds—VSA-Based Model

Sl. No.	*Parameter/ Description*	*Catchment*		
		Hemavati	*Manot*	*Mohegaon*
1.	I_{max}	1.00	3.00	2.50
2.	C_1	4.90	5.00	4.60
3.	C_2	4.50	1.80	1.70
4.	K_1	0.475	0.505	0.233
5.	K_2	0.525	0.505	0.67
6.	K_3	1.00	0.500	0.900
7.	E	0.33	0.550	0.330
8.	θ_p	550.00	600.00	833.33
9.	θ_f	300.00	450.00	633.33
10.	θ_w	40.00	60.00	40.0
11.	Ψ_p^*	550.00	600.00	833.33
12.	Ψ_f^*	300.00	450.00	633.33
13.	$\theta_t(1)$	240.00	250.00	280.0
14.	$\Psi_t(1)$	150.00	200.00	200.0
16.	Efficiency-Calibration	79.89%	58.11%	43.12%
17.	Efficiency-Validation	77.76%	41.73%	39.01%
18.	Runoff factor	0.782	0.448	0.350

*assumed value

Table 6: Statistics of Goodness-of-Fit

Catchment	*Model Based on Modified SCS-CN Concept (Model I)*			*Model Based on VSA Concept (Model II)*		
	RMSE	*SE*	r^2	*RMSE*	*SE*	r^2
Hemavati	4.08	4.10	0.88	4.94	4.96	0.86
Manot	2.93	2.93	0.68	3.18	3.19	0.63
Mohegaon	2.56	2.57	0.63	2.69	2.70	0.59

While comparing RMSE and SE values of Hemavati catchment, model based on SCS-CN concept shows the least error over VSA-based model; similarly, catchments Manot and Mohegaon also derive the least error in SCS-CN-based model. Table 6 also computes the coefficient of determination and shows the higher coefficients in SCS-CN-based model than VSA-based model in all three study catchments.

CONCLUSION

A modified SCS-CN-based continuous simulation model for hydrologic forecasting has been presented here and applied to the data of watersheds of River Cauvery in Karnataka and River Narmada in Madhya Pradesh, in India. This model can be used in the computation of annual hydrologic components as well as total runoff values. The modeling goal was to describe the hydrologic components and their flow path as well as to identify the dominancy/dormancy of the processes derived from each catchment When compared with the available VSA-based model, the SCS-CN-based model better represented the hydrologic behavior of the catchments with different soil, vegetation, and climate than did the VSA-based model. Both the models however performed satisfactorily on high runoff producing Hemavati watershed. The fact that the SCS-CN-based model is capable of estimating various processes involved in the runoff generation mechanism which is advancement over the existing SCS-CN model. While comparing the model efficiencies and error criteria, the model results due to the SCS-CN-based model are better than the VSA-based model, indicating the better performance of the proposed SCS-CN-based model in long-term hydrologic simulation.

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