# A Runoff Model for Small Watersheds in the Semi-Arid Tropics

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ABSTRACT

A modified Soil Conservation Service (SCS) runoff model and a soil moisture accounting procedure were used to simulate runoff for small watersheds. The validity of the model and the moisture accounting procedure were tested using hydrological data collected from small Vertisol watersheds at ICRISAT Center in India. The agreement between measured and simulated daily, monthly, and annual runoff was good. The root mean square error values between the measured and simulated annual, monthly, and daily runoff from a Vertisol watershed were 5.2, 3.1, and 1.6 mm, respectively. The modified model and the moisture accounting procedure simulated quite accurately runoff for high, low as well as normal rainfall years in the semi-arid environment.

## INTRODUCTION

Information on surface runoff volume is needed for several purposes in soil and water management. For example, it is needed in the design of soil conservation structures, for studying the effectiveness of land treatments and for planning supplemental irrigation facilities. In the semi-arid tropics (SAT), there exist few runoff records which cover sufficient duration of the rainy season to enable accurate assessment of runoff characteristics of the watersheds. On the other hand, daily rainfall records that are representative of watersheds are usually available or can be estimated from nearby rain-gauges. Therefore, models that are capable of utilizing these rainfall records to simulate runoff accurately will be of great utility.

The Soil Conservation Service curve number (USDA-SCS, 1972) is one of the most widely used methods for runoff estimation from small watersheds. For example, it has been used in large, more complex models like CREAMS and EPIC to calculate runoff in order to assess nutrient loss and the effect of erosion on soil productivity (Williams et al., 1982, 1983, 1985). The curve number (CN) method is simple and provides reasonably accurate results under certain conditions (Williams and LaSeur, 1976). Its biggest advantage is that it requires few inputs which are generally available.

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Some major drawbacks however are (Williams and LaSeur, 1976; Hawkins, 1978, 1979, 1985)

1. The model does not take into consideration the effects of surface roughness. It provides soil profile water retention on the basis of the soil type only.
2. Because a discrete rather than a continuous relationship between CN and soil moisture content is used in the original model, small changes in water content sometimes result in sudden shifts in CN which then give unrealistic quantum jumps in the calculated runoff. This aspect is discussed further in the section on model development and description.

It was therefore not surprising that when the original SCS curve number model was used to estimate runoff from gauged watersheds at ICRISAT Center, India, the estimated runoff did not agree well with the observed runoff data.

### Objective

The purpose of this article is to present a runoff model based on the modified SCS runoff equation (Hawkins, 1978, 1979) and a soil moisture accounting procedure to simulate daily, monthly and annual runoff for small watersheds (< 50 ha). The hydrological data collected from small watersheds at ICRISAT Center, from 1973/74 to 1982/83, were used to test the model's performance.

## MODEL DEVELOPMENT AND DESCRIPTION

Figure 1 shows the flow chart of the runoff model. The various components and steps in computation are as follows.

### Runoff Simulation

In the original SCS curve number model, runoff is simulated from daily rainfall using the relationship

$$Q = (P-0.2S)^2/(P+0.8S) \quad P > 0.2S \quad \ldots\ldots\ldots [1a]$$

$$Q = 0 \quad P < 0.2S \quad \ldots\ldots\ldots [1b]$$

where
Q = the daily runoff,
P = the daily rainfall in mm.

The parameter describing water retention S (in mm) in the soil is related to CN by the equation

$$S = (25400/CN)-254 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [2]$$

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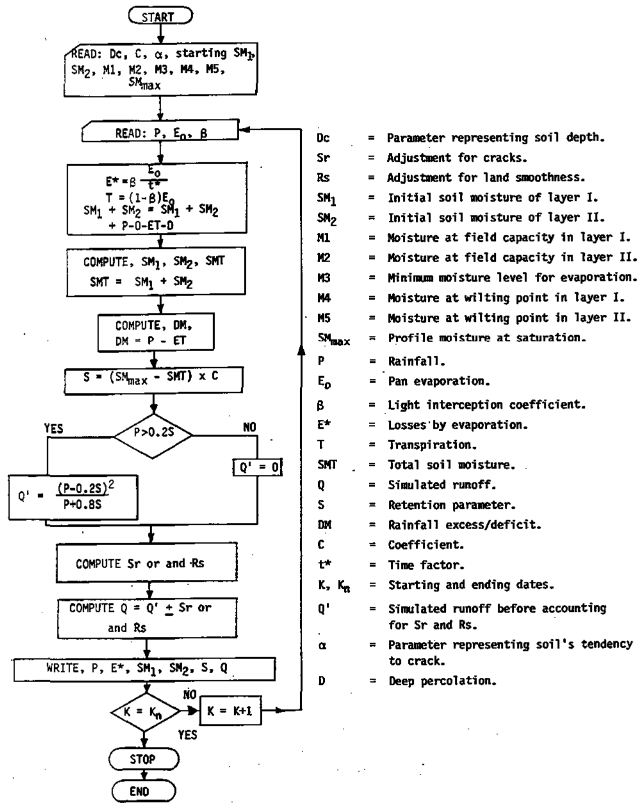


**Fig. 1—Flow chart of runoff model.**

The CN parameter varies between 0 and 100 and is a function of the dominant soil type, infiltration behavior of the soil, vegetative cover, antecedent soil water content and land use. Guidelines for the determination of CN are documented in USDA-SCS, 1972 which also presents criteria for discrete partitioning of soil moisture between wet conditions with high runoff potential AMC-III, average condition with medium runoff potential AMC-II and dry conditions with low runoff potential AMC-I. This partitioning suggests that the rainfall-runoff relationship is discrete, implying sudden shifts in CN with corresponding quantum jumps in calculated runoff. In reality CN varies continuously with soil moisture and thus has many continuous values instead of only three. Therefore, the accuracy of runoff simulation can be improved considerably by using a soil moisture accounting procedure to estimate S for each storm.

Following Hawkins (1978) the relationship between S and total water storage $V_1$ available at time $= t_1$ is.

$$V_1 = 1.2S_1 \quad \text{[3]}$$

since $\lim_{P \to \infty} (P\text{-}Q) = 1.2S$

At time $= t_2$, $(t_2 > t_1)$ any change in $V_1$ will be caused by evapotranspiration losses ET (which adds to $V_1$), and the difference between rainfall P and associated runoff Q plus deep percolation D during the elasped time $t = t_2 - t_1$, which reduces $V_1$. Thus, the total water storage $V_2$ available at $t_2$ is

$$V_2 = V_1 + ET_1 - (P_1 - Q_1 - D_1) = 1.2S_2 \quad \text{[4]}$$

Similarly total water storage $V_n$ available at time $= t_n$ will be given by

$$V_n = V_{n-1} + (ET)_{n-1} - (P_{n-1} - Q_{n-1} - D_{n-1}) = 1.2S_n \quad \text{[5]}$$

In equation [5], $Q_{n-1}$, $D_{n-1}$ and $(ET)_{n-1}$ refer to runoff, deep percolation, and evapotranspiration losses between time $t_{n-1}$ and $t_n$. The storage terms $S_1$, $S_2$..... $S_n$ in equations [3], [4] and [5] are calculated from equation [2] and curve numbers associated wtih $P_1$, $P_2$, .... $P_{n-1}$.

Equation [5] does not define clearly the depths of soil profile under consideration. In our model, runoff calculations are based on the water status for a particular depth of soil. This provides a logical basis for calculating runoff from different soils, land treatments, and topographic conditions.

For a particular soil type and land treatment, the soil depth Dc is fixed and is determined through optimization. Thus, we calculate the retention parameter S using the relationship

$$S = C(SM_{max} - SMT) \quad \text{[6]}$$

where

$SM_{max}$ = soil moisture at saturation in mm,
SMT = actual soil moisture in mm at any particular time,
C = a coefficient whose value is determined through calibration.

For Vertisols at ICRISAT Center, C was 1.2. The daily values of SMT are determined by using a soil moisture accounting procedure.

**Soil Moisture Accounting Procedure**

Soil moisture, evapotranspiration and deep percolation are calculated on a daily basis by a soil moisture accounting procedure developed in our laboratories. This moisture accounting procedure is based on an assumption that whenever there is rainfall or irrigation the upper layer is fully recharged before any moisture is transmitted to the lower layer. The daily soil evaporation and transpiration are calculated separately using equations [7] and [8]:

$$E^* = \beta \frac{E_o}{t^*} \quad \text{[7]}$$

$$T = (1-\beta) E_o \quad \text{[8]}$$

In equations [7] and [8], $E_o$ = daily open pan evaporation, $E^*$ = daily evaporation from soil, $\beta$ = light interception coefficient (range from 0 to 1), T = daily transpiration, and $t^*$ = time factor. The value of $t^*$ depends on the frequency of soil wetting. When soil is wetted either by rainfall or irrigation, $t^*$ for the first non-rainy day is 1, for the second non-rainy day it is 2, for the third non-rainy day it is 3 and so on throughout the subsequent rainfree days. On a rainy day, $t^*$ is taken as 2, except in situations where there was rainfall greater than the open pan evaporation during the previous day in which case $t^*$ starts at 1 again, because we do not know what time during the day the rain occurred. If rainfall is less than open pan evaporation, the value of t* proceeds uninterrupted.

The light interception coefficient, $\beta$, represents only the light intercepted by crop canopy. For most of the important crops, the average weekly values of $\beta$ are generally available. In our model, we stored the average weekly values of $\beta$ for crops such as sorghum, maize, chickpea, wheat, groundnut, and pigeonpea. To use $\beta$ values for these crops, our model needs information on name of the crop and its date of planting (which could be the actual planting date or normal date of planting for that particular crop in that locality). Based on these two pieces of information, the model selects appropriate $\beta$ values. In situations where the light interception coefficient values are not available, information on leaf area index (LAI) could be used since LAI is very closely related to $\beta$.

Daily evaporation loss is assumed to occur uniformly and exclusively from the top 30-cm layer and it is only after the moisture in this layer is depleted that evaporation loss will occur from the lower layers. However, transpiration demand is met by plants extracting water uniformly from the entire root zone. The moisture accounting procedure can simulate the soil moisture of various layers at 5, 10, and 15-cm depth increments. For each layer, daily evaporation, transpiration, deep percolation, and soil moisture are calculated. The soil moisture for the first layer is calculated using the equation

$$(SM_2)_1 = (SM_1)_1 + \left\{ P_1 - Q_1 - E_1 - T_1 - D_1 \right\} \quad \ldots\ldots [9]$$

in which $(SM_1)_1$ = the previous day's soil moisture content and $(SM_2)_1$ = the soil moisture content of the first layer for the day under consideration. In equation [9], $E_1$, $T_1$ and $D_1$ are, respectively, the evaporation, transpiration, and deep percolation losses from the first layer. Soil moisture levels for the layer below the first are calculated using the equation

$$(SM_2)_2 = (SM_1)_2 + \left\{ D_1 - E_2 - T_2 - D_2 \right\} \quad \ldots\ldots [10]$$

where

$(SM_1)_2$ = the previous day's soil moisture content,
$(SM_2)_2$ = the soil moisture content of the second layer for the day under consideration,
$E_2, T_2, D_2$ = the evaporation, transpiration and deep percolation losses from the second layer.

Soil moisture of the other layers are calculated using equations similar to equation [10].

In our earlier version of the soil moisture accounting procedure, deficiencies were observed in the simulated daily soil moisture for clay soils, eg. Vertisols, during periods when frequent rains were received because the model assumed the immediate transfer of excess moisture (that is, difference between actual soil moisture and field capacity) to lower layers. In clay soils, this immediate transfer does not normally occur as the excess moisture is temporarily held in the upper layers because of low saturated hydraulic conductivity. Consequently, the moisture accounting procedure was modified by introducing a time delay factor to account for the reduced transmission. This modification resulted in a good agreement between the measured and simulated daily soil moisture and, therefore, an accurate simulation of runoff volumes on Vertisols (Fig. 2).

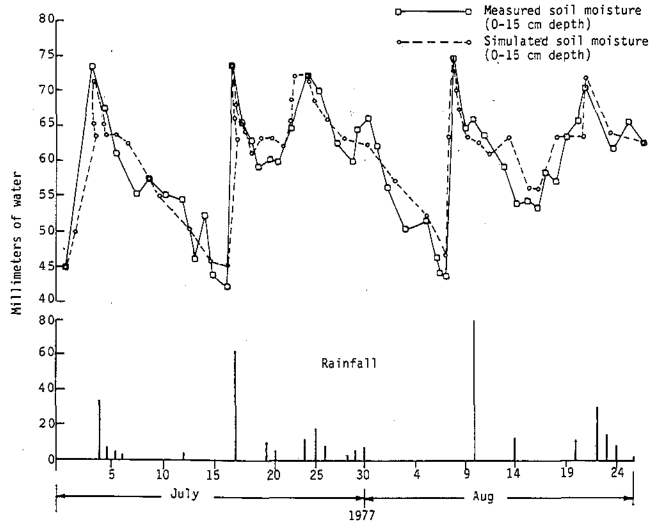


**Fig. 2—Performance of soil moisture model.**

The concept of time delay factor is based on an assumption that the deep percolation rate from any soil layer is directly proportional to the excess moisture temporarily held in that layer, so that

$$D \propto (SMa - SMf) \quad \ldots\ldots [11]$$

which upon the introduction of a constant of proportionality df, becomes

$$D = df(SMa - SMf) \quad \ldots\ldots [12]$$

where

D = deep percolation in mm per day,
df = time delay factor for that soil layer,
SMa = soil moisture content at the beginning of the day in mm,
SMf = field capacity moisture content for that layer in mm.

For any soil layer, the time delay factor can be estimated from observed daily soil moisture values. About 8-10 soil moisture observations were found to be adequate for the estimation of the time delay factor, which is the slope of the plot of the excess moisture vs. deep percolation rate (calculated from the observed daily soil moisture values). Once the value of df is known, the daily deep percolation from that layer is calculated by using the equations

$$D_1 = df(SMa_1 - SMf) \quad \ldots\ldots [13]$$

$$D_2 = df(SMa_2 - SMf) \quad \ldots\ldots [14]$$

where

$SMa_2$ = $[SMa_1 - D_1 - E_1 - T_1 + (p_1 - Q_1)]$,
D1 and D2 = are deep percolation during the first and second day, respectively,
$SMa_1$ and $SMa_2$ = are soil moisture at the beginning of the first and second day, respectively,

For the 3rd, 4th up to the nth day, similar equations are used to determine the deep percolation rates.

**Accounting for the Changes in Soil Surface Conditions**

When the model was tested on some watersheds at ICRISAT Center, it generally simulated the annual and monthly runoff well. However, for some individual storms, the model was not accurate apparently because either infiltration or runoff was enhanced by changes in soil-surface conditions. The smoothness of the soil surface caused by previous runoff events would normally increase runoff while small cracks formed at the soil surface during long dry spells in the rainy season would increase infiltration and therefore reduce runoff. We therefore modified the model to allow for these effects (Pathak et al., 1984).

*Runoff Correction for Small Cracks*

The model estimates the negative contribution of cracks to runoff by the equation

$$Sr = \alpha \sum_{1}^{n} E^* \quad \ldots\ldots\ldots [15]$$

where

$Sr$ = runoff 'cracking' adjustment factor (mm), which is subtracted from the simulated runoff for the next storm,

$\alpha$ = a function of the amount and type of clay in the soil, and represents soil's inherent tendency to crack; it is determined by calibration with measured runoff data,

$\sum_{1}^{n} E^*$ = total evaporative demand on the soil during an extended rainless period,

$n$ = the number of days with no rain or with rainfall less than soil evaporation.

This correction for cracking was applied only when the total evaporative demand $(\sum_{1}^{n} E^*)$ exceeds 20 mm.

*Runoff Corrections for Land Smoothness*

Usually, big runoff events considerably reduce surface depressions due to land smoothing. This is particularly true for most of the SAT soils which generally have poor soil structure and so are structurally very unstable. Due to reduction in surface depression storage, runoff from subsequent storms (after big runoff event) are significantly affected. Land smoothness created by a runoff event is described by

$$Ls = (Q_1)\,0.5 - 0.85 \qquad Q_1 \geqslant 15 \text{ mm} \quad \ldots\ldots [16a]$$

$$Ls = 0 \qquad Q_1 < 15 \text{ mm} \quad \ldots\ldots [16b]$$

where Ls is the smoothness correction (mm) created by a runoff event and $Q_1$ is the previous storm runoff amount (mm).

At ICRISAT, we have observed that only runoff events > 15 mm significantly reduce surface depression storage. The effect of other small storms is negligible.

The extent to which land smoothness from one storm affects runoff from the subsequent storm depends on the relative magnitudes of the two runoff events. The contribution of land smoothness to runoff is given by a factor (Rs) which relates to Ls as follows:

$$Rs = Ls \times Q_2'/Q_1 \quad \ldots\ldots\ldots [17]$$

where $Q_2'$ is the current runoff volume under consideration simulated by model before the land smoothness correction.

The second term on the righthand side of equation [17] is the utilization factor whose maximum value is unity.

These two modifications markedly improved the performance of the model in simulating the daily runoff, as well as monthly and annual runoff volumes.

**Model Calibration**

The input parameters Dc, C, df, and $\alpha$ were determined by using runoff and soil moisture content data collected in 1976 and 1977 from the Vertisol watershed BW1 and equations [6], [12], and [15]. About 10-15 daily soil moisture data and runoff events were adequate for the estimation of the parameters. The calibration resulted in values of 75-cm, 1.2 and 0.12 for the parameters Dc, C and $\alpha$, respectively, while df = 0.38 and df = 0.20 were obtained for 0-30 cm and 30-75 cm soil layers respectively. The best set of parameters were that which minimized the sum of the squares of deviations between observed and simulated daily runoff volumes. The estimated parameters and coefficients were then used to simulate the runoff volumes of 1978-80 for BW1 watershed. The estimated parameters from BW1 watersheds were also used to simulate runoff from two other watersheds BW2, BW3A, which were on similar soils with similar land management systems.

## RESULTS AND DISCUSSION

**Runoff Simulation**

The model was validated by comparing simulated daily, monthly, and annual runoff information with measured data from three Vertisol watersheds at ICRISAT Center. The performance of the model in simulating annual, monthly, and daily runoff from the Vertisol watersheds is shown in Fig. 3 and Tables 1 and 2. The agreement between simulated and measured runoff is very good (Fig. 3). The data points are evenly distributed around the 45° line. The model also simulated quite accurately runoff for high, low as well as normal rainfall years (Tables 1 and 2). In 1978 which was a high rainfall year, the model simulated an annual runoff of 270 mm compared with a measured runoff of 264 mm for watershed BW1. The error is 2.3%. In a normal rainfall year, e.g. 1980, its performance accuracy was also quite high (% error = 3.5). The main feature of the model is its ability to simulate quite accurately daily runoff (Fig. 3). High coefficients of determination ($R^2$) and low root mean square error (RMSE) values were obtained between the measured and simulated runoff from a Vertisol watersheds BW2 (Table 3). Although the model output is daily runoff, the simulated monthly and annual runoff also compared well with the measured monthly and annual runoff.

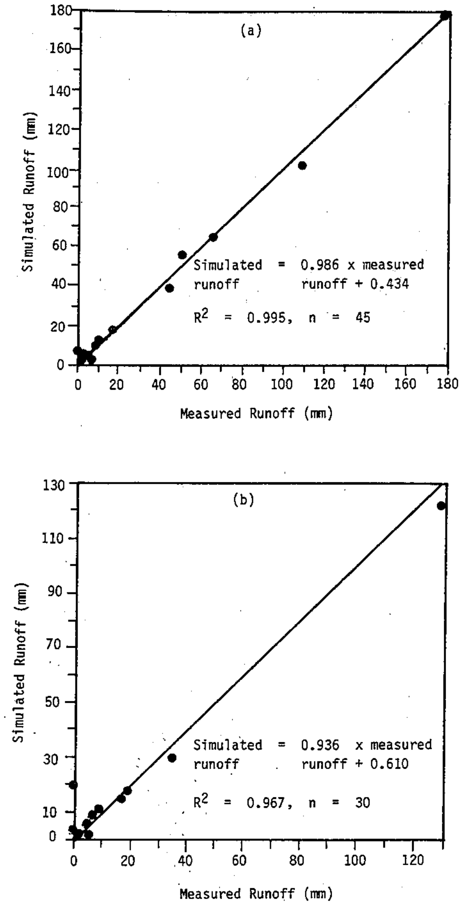


**Fig. 3—Comparison of measured and simulated daily runoff in Vertisol watersheds (a) BW2 watershed (1976-1980), (b) BW3A watershed (1976-1978).**

## SUMMARY AND CONCLUSION

A runoff model based on a modified SCS curve number technique and on a soil-moisture accounting procedure was developed for small watersheds in the semi-arid tropics. In our model, certain soil characteristics which have strong influence on runoff such as cracking and land smoothing are represented. The model uses one-day time intervals and needs simple inputs which are normally available. The main outputs are daily runoff volume and soil moisture. The model has four input parameters which are estimated through calibration using measured runoff and soil moisture content data. Once the parameters are determined for a particular soil and land management system, they can be used to predict runoff and soil moisture from other ungauged watersheds on similar soils with similar land management systems. About 10-15 runoff events and daily soil moisture data are sufficient to estimate the parameters of the model.

Tests with data from three small watersheds at ICRISAT Center in India show that the model is capable of simulating daily, monthly, and annual runoff quite accurately. It is also able to simulate satisfactorily the daily soil moisture. The biggest advantage of this model appears to be its simplicity and accuracy.

TABLE 1. Comparison of measured and simulated annual runoff for Vertisol watersheds at ICRISAT Center, Patancheru, India

| Watershed | Land treatments | Year | Rainfall (mm) | Measured runoff (mm) | Simulated runoff (mm) |
|---|---|---|---|---|---|
| BW1 | BBF* system at 0.6% slope | 1978 | 1091 | 270 | 264 |
| | | 1979 | 616 | 72 | 76 |
| | | 1980 | 728 | 116 | 112 |
| BW2 | BBF system at 0.6% slope with farmers' field bunds | 1977 | 566 | 0 | 0 |
| | | 1978 | 1080 | 186 | 187 |
| | | 1979 | 615 | 38 | 40 |
| | | 1980 | 692 | 66 | 69 |
| BW3A | BBF system at 0.4% slope | 1976 | 644 | 51 | 46 |
| | | 1977 | 562 | 0 | 1 |
| | | 1978 | 1092 | 196 | 202 |

* BBF: Broadbed and furrow.

TABLE 2. Comparison of measured and simulated monthly runoff for Vertisol watersheds at ICRISAT Center, Patancheru, India

| Watershed | Land treatments | Year | Month | Rainfall (mm) | Measured runoff (mm) | Simulated runoff (mm) |
|---|---|---|---|---|---|---|
| BW1 | BBF system at 0.6% slope | 1978 | Jun | 190 | 7 | 7 |
| | | | Jul | 252 | 14 | 22 |
| | | | Aug | 519 | 249 | 235 |
| | | | Sep | 93 | 0 | 0 |
| | | 1979 | Jun | 61 | 0 | 0 |
| | | | Jul | 85 | 0 | 0 |
| | | | Aug | 111 | 0 | 0 |
| | | | Sep | 321 | 72 | 76 |
| BW2 | BBF system at 0.6% slope with farmers' field bunds | 1978 | Jun | 155 | 6 | 5 |
| | | | Jul | 241 | 0 | 0 |
| | | | Aug | 519 | 180 | 182 |
| | | | Sep | 93 | 0 | 0 |
| | | 1979 | Jun | 61 | 0 | 0 |
| | | | Jul | 108 | 0 | 0 |
| | | | Aug | 109 | 0 | 0 |
| | | | Sep | 320 | 38 | 40 |
| BW3A | BBF system at 0.4% slope | 1976 | Jun | 40 | 0 | 0 |
| | | | Jul | 235 | 10 | 12 |
| | | | Aug | 293 | 40 | 35 |
| | | | Sep | 72 | 0 | 0 |
| | | 1977 | Jun | 73 | 0 | 1 |
| | | | Jul | 189 | 0 | 0 |
| | | | Aug | 201 | 0 | 0 |
| | | 1978 | Jun | 162 | 8 | 4 |
| | | | Jul | 241 | 5 | 1 |
| | | | Aug | 524 | 177 | 197 |
| | | | Sep | 86 | 0 | 0 |

TABLE 3. Coefficient of determination ($R^2$) and Root Mean Square Error (RMSE) for Vertisol watershed BW2 (1976-82)

| | $R^2$ | RMSE (mm) |
|---|---|---|
| Annual runoff | 0.992 | 5.2 |
| Monthly runoff | 0.985 | 3.1 |
| Daily runoff | 0.983 | 1.6 |

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