# A comparison of curve number based methods for runoff estimation from small watersheds in a semi-arid region of India

Shakir Ali and V. N. Sharda

## ABSTRACT

The performance of five curve number based methods, generally employed for estimation of runoff, viz. National Engineering Handbook (NEH-4), storm event (SE), rank order (RO), lognormal frequency (LF) and s-probability (SP), was evaluated using runoff data recorded from three small watersheds in a semi-arid region of India. The most effective and reliable curve number method for runoff estimation was selected based upon several tests of goodness of fit including coefficient of determination ($R^2$), index of agreement ($D$), root mean square error (RMSE) and relative bias (RB). The LF method was adjudged as the most promising curve number method for estimating runoff from small watersheds in the semi-arid regions of India. The runoff predicted by the LF method was in close agreement with the observed runoff for all four tests of goodness of fit. Though the performance of the SE, RO and NEH-4 methods was almost comparable to each other, the SP method registered higher deviation from the observed runoff values. From the analysis, it is concluded that the LF method can be successfully employed for estimation of curve number based runoff from small watersheds in the semi-arid regions of India.

**Key words** | curve number, India, runoff, semi-arid region, watershed

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## INTRODUCTION

The scarcity of water in the arid and the semi-arid regions of the world is a major limiting factor in the development of sustainable crop production and ensuring better socio-economic standards. This problem gets further aggravated owing to competing demands for water from agriculture, industrial and municipal sectors and, therefore, conservation and judicious utilization of water has become imperative. Watershed management has been recognized globally as the most effective tool for conservation, development and optimum utilization of land and water resources for sustained biomass production and improvement of socio-economic conditions in a given region. In India, integrated watershed management programmes have been launched on a massive scale as envisaged in the National Water Policy (NWP 2002) for conservation and efficient utilization of water resources. Construction of small water harvesting structures such as dugout and embankment type ponds and check dams, and adoption of *in situ* moisture conservation measures like bunding and terracing in cultivated lands are integral components of such programmes. Efficient design of these water harvesting structures involves reliable estimation of peak rate and volume of runoff from the contributing catchment area. Hence, it is necessary to identify a reliable and accurate method of runoff estimation for the proper design of water harvesting structures in a watershed.

Several methods are in vogue for estimation of surface runoff from micro-watersheds. They include: (i) rational method (Ponce 1989), (ii) SCS curve number method (SCS 1956, 1986), (iii) Cook's method (Schwab *et al.* 1966) and (iv) process-based models such as SWAT (Soil and Water Assessment Tool) (Arnold *et al.* 1993). However, the SCS

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method is one of the most reliable and widely used methods employed for estimation of runoff from small agricultural watersheds (Ponce & Hawkins 1996). This method was developed by the Soil Conservation Service (SCS) of USDA (United States Department of Agriculture) (now the Natural Resources Conservation Service, NRCS) for estimating peak rate and volume of runoff from ungauged watersheds based on rainfall and physiographic characteristics of a watershed. Since its development in 1954, the SCS method has undergone numerous refinements and modifications including extension from agricultural to urban areas (Rallison 1980). Due to its simplicity and ease of application, this method has been used even in complex watershed models such as Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel 1980), Groundwater Loading Effect of Agricultural Management Systems (GLEAMS) (Leonard *et al.* 1986) and Agricultural Non-Point Source (AGNPS) pollution model (Young *et al.* 1985).

The success of the SCS curve number method, however, depends on accurate and reliable estimation of curve number value. A "Curve Number (CN)" value which describes the runoff potential of an area is determined either from: (1) prevailing land use, hydrological condition, hydrologic soil group and Antecedent Moisture Condition (AMC) (SCS 1986) or (2) alternatively from measured rainfall and runoff data (Hjelmfelt 1991; Hawkins 1993; Lewis *et al.* 2000; Hawkins *et al.* 2002; Schneider & McCuen 2005). Many studies have been carried out in India (Mishra & Singh 1999; Mishra *et al.* 2004; Jain *et al.* 2006*a*,*b*) and abroad (Lewis *et al.* 2000; Hawkins *et al.* 2002; Schneider & McCuen 2005) to evaluate the performance of different CN-based runoff estimation methods. Jain *et al.* (2006*a*) evaluated the performance of various CN-based methods for estimating direct runoff from watersheds in the USA by employing the NEH-4 procedure without comparing the CN values with other alternate methods. Lewis *et al.* (2000) used two alternate methods for computing the CN value for the Oak Woodlands watershed in the USA. Schneider & McCuen (2005) compared the accuracy of the CN method as described in the National Engineering Handbook (NEH-4) with three alternate methods for four watersheds in the USA. The development of a criterion for accurate estimation of curve number value for runoff computation and design of structures in small watersheds is an area of major concern in the arid and semi-arid regions of India. The present study was, therefore, undertaken to identify a reliable and accurate method for estimation of curve number value for small watersheds by comparing the performance of commonly employed methods.

## MATERIALS AND METHODS

### Study area

Out of 329 million ha total geographical area of India, 38.8% falls in the semi-arid and 15.1% in the arid region, mainly distributed over the northern, northwestern and southern parts of the country. An arid region is differentiated from a semi-arid region based upon the magnitude of rainfall, temperature and evaporation rate. An arid region generally experiences a dry summer temperature varying from 28–45°C with very low and erratic annual rainfall (100–420 mm) and potential evapotranspiration (PET) varying from 1,500–2,000 mm/yr. In the semi-arid region, dry summer temperature varies between 28–38°C, winter temperature between 20–29°C and annual rainfall between 400–1,000 mm. The semi-arid region of the study area is located in the Kota and Bundi districts of southeastern Rajasthan in India between 25°36′ to 25°51′ N latitude and 75°15′ to 75°38′ E longitude (Figure 1). The area is characterized mainly by a dry semi-arid climate with average annual rainfall of 742 mm, 90% of which is experienced during July to September. The summer (March to June) season is relatively hot with mean daily temperature of 35°C while the winter (November to February) season generally remains cooler and dryer with mean daily temperature of 15°C. The average annual actual and potential evapotranspiration of the study area were recorded as 482 mm and 1,423 mm, respectively. A large number of watershed development programmes have been undertaken in the region which essentially involve estimation of runoff for their successful implementation.

The performance of various CN estimation methods was evaluated using runoff data from three small watersheds in the Kota and Bundi districts in the semi-arid region of India. Table 1 presents salient characteristics of the

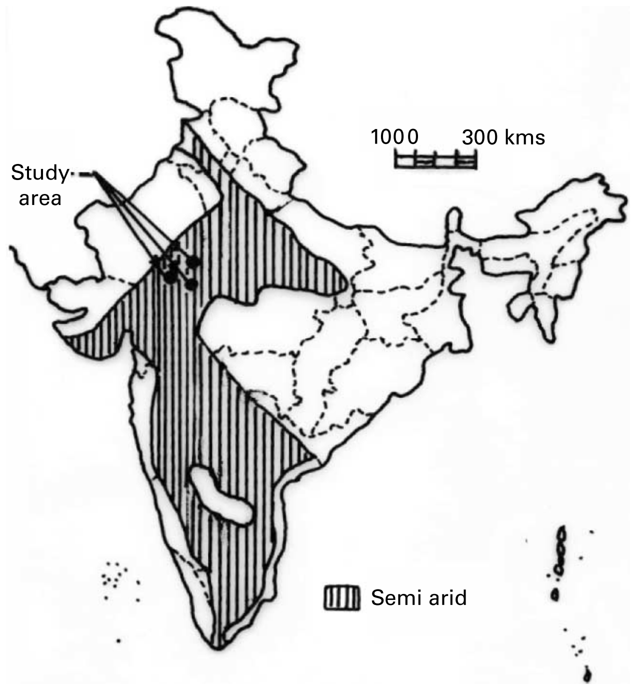


**Figure 1** | Geographical location of the study area in the semi-arid region of India.

selected watersheds which include area, land use cover, hydrologic soil group and hydrologic cover condition. The data on rainfall, runoff and other hydrological characteristics of the watersheds were collected at the Central Soil and Water Conservation Research and Training Institute, Research Centre, Kota (Rajasthan), India. All the low and high rainfall–runoff events were considered rather than yearly extremes as reported in some studies (Lewis *et al.* 2000; Schneider & McCuen 2005). The area of the selected watersheds ranged from 0.4–29.2 ha (Table 1). The Badakhera (BK) and Ravinous (RAV) watersheds have undulating topography with multi-directional slopes varying from 6.5–8.4%, while the agricultural (AG) watershed has a mild slope of 1.1%. The soil texture of the selected watersheds varies from silty clay loam to silty clay. During the study period, the BK watershed had a mixed land use system with agriculture land use comprising of intercropping of cereal (*Sorghum bicolor*) and pulses (*Cajanus cajan* and *Phaseolus mungo L*) and sole crops of cereals (*Sorghum bicolor*, *Zea mays* and *Glycine max*). The wasteland had sparse natural vegetation of *Acacia nilotica* and *Ziziphus zuzuba*. The AG watershed had either pure cereal crops or a mixed crop of cereal and pulses while the RAV watershed was covered with sparse and thorny vegetation of *Ziziphus zuzuba* and *Prosopis juliflora*, and grasses of *Cencharus ciliaris* and *Dicanthium anulatum*. The selected watersheds had no well-defined rural or urban areas.

## Methodology

The Soil Conservation Service-Curve Number (SCS-CN) (USDA) method is an event-based, lumped rainfall–runoff model which is derived from the water balance equation under two assumptions, viz. (i) the ratio of the actual amount of direct runoff ($Q$) to the maximum potential runoff ($P - I_a$) is equal to the ratio of the amount of actual infiltration ($F$) to the amount of maximum potential retention ($S$), and (ii) the amount of initial abstraction ($I_a$) is a fraction of the amount of the maximum potential retention (i.e. $I_a = \lambda S$) which can be expressed as (Mishra & Singh 1999)

$$Q = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S} \quad \text{for } P > I_a \tag{1}$$

Otherwise

$$Q = 0 \quad \text{for } P \le I_a \tag{2}$$

where $Q$ is the direct runoff, $P$ is the precipitation, $S$ is the maximum potential retention, $\lambda$ is the initial abstraction coefficient as a fraction of the maximum potential retention ($S$) and $I_a$ is the initial abstraction ( $= \lambda S$).

**Table 1** | Description of the selected watersheds used to evaluate the performance of different curve number estimation methods

| Water-shed | Location | No. of events | Area (ha) | Average slope (%) | Hydrological soil group | Land use cover | Hydrologic condition | Treatment |
|---|---|---|---|---|---|---|---|---|
| AG | Kota | 75 | 0.4 | 1.1 | D | Small grains | Good | Contour cultivation |
| BK | Bundi | 24 | 29.2 | 8.4 | C | Row/small grains | Poor | Contour cultivation |
| RAV | Kota | 31 | 1.4 | 6.5 | D | Farm woodlots | Poor | – |

The initial abstraction ($I_a$) component accounts for interception, surface storage and infiltration before the beginning of runoff. It can take any value ranging from 0 to $\lambda$, but in the current version of SCS-CN method, $\lambda$ is taken as 0.2 for practical purposes. The maximum potential retention (S) is the potential difference between $Q$ and $P$ (i.e. $S = P - Q$) which depends on the watershed characteristics such as soil type, vegetation and AMC of the soil. The soil parameter $S$ is represented implicitly by another parameter known as the Curve Number (CN) and $S$ and CN are related as

$$S = \frac{25400}{CN} - 254 \quad (3)$$

where $S$ is in mm and $CN$ is dimensionless.

Substitution of $S$ and $\lambda$ values in Equation (1) yield

$$Q = \frac{25.4\left[\frac{P}{25.4} - \frac{200}{\mathrm{CN}} + 2\right]^2}{\left[\frac{P}{25.4} + \frac{800}{\mathrm{CN}} - 8\right]} \quad (4)$$

where $Q$, $P$ and $S$ are in mm.

Equation (4) is valid for

$$P > 0.2\,S \quad \text{or} \quad \frac{5080}{\mathrm{CN}} - 50.80 \quad (5)$$

If the daily precipitation, $P$, is less than the value computed by Equation (5), then $P$ is totally added to the soil moisture content, which gets subsequently evaporated until the maximum value of daily evapotranspiration is reached, i.e. $Q = 0$. In the case the value of daily $P$ is higher than the value computed by Equation (5), the surface runoff, $Q$, is calculated using Equation (4).

The most commonly used curve number methods reported in the literature are: (1) the traditionally used standard method (called the National Engineering Handbook, NEH-4); and (2) alternatively the (i) storm event (SE), (ii) rank order (RO), (iii) log-normal frequency (LF) and (iv) $S$-probability (SP) methods. In the present study, all the methods were considered for evaluating their relative performance.

## NEH-4 method

In this method, the $CN$ value for a given soil series, land use and land treatment is determined using standard tables developed through analysis of watershed data (SCS 1985). The CN values reported in the tables are for the antecedent soil moisture condition-II (AMC-II) which is one of the three conditions established to account for the generation of runoff at the time of occurrence of a storm event. Condition AMC-II is defined by either mean condition or median in the CN tables (SCS 1985). It represents the average runoff producing potential of a given area corresponding to average moisture condition. In general, AMC-I defines the condition prior to a given storm with little or no preceding 5 days rainfall and has the lowest runoff generating potential due to high infiltration rate and dryness of the soil. AMC-III accounts for sufficient rainfall in the preceding 5 days which lowers the infiltration rate, thereby causing the highest runoff generating potential. The CN values for AMC-I and AMC-III are derived from AMC-II as (Lewis *et al.* 2000)

$$\mathrm{CN}(I) = \frac{4.2\,\mathrm{CN}(II)}{10 - 0.058\,\mathrm{CN}(II)} \quad (6)$$

$$\mathrm{CN}(III) = \frac{23\,\mathrm{CN}(II)}{10 + 0.13\,\mathrm{CN}(II)} \quad (7)$$

## Storm event method

In this method, measured values of rainfall ($P$) and runoff ($Q$) depths are required for individual storms for the period under consideration. For each set of measured values of $P$ and $Q$, the maximum potential retention, $S$, is determined following Hawkins (1993) as

$$S = 5\left[P + 2Q - (4Q^2 + 5PQ)^{0.5}\right] \quad (8)$$

The calculated value of $S$ is then substituted in Equation (3) to obtain the $CN$ value for each pair of $P$–$Q$. The best estimate of $CN$ for AMC-II for a watershed is given by the mean of the storm events curve numbers (CNs). The $CN$ values for AMC-I and AMC-III are calculated by employing Equations (6) and (7), respectively.

## Rank-order method

This method does not require matching of the runoff ($Q$) events with the respective rainfall ($P$) events and only the equal frequency of $P$ and $Q$ is matched. Hawkins *et al.* (2002) recommended this method since, in the design of hydraulic structures, the frequency of rainfall is generally assumed to match with the frequency of runoff. The collected data on $P$ and $Q$ in the equal frequency was ranked in order from largest to smallest values of $P$ and $Q$. Thus, largest $P$ corresponds to largest $Q$ by a two data vector $P-Q$. For each rank-order pair of $P$ and $Q$, $S$ and CN were determined following the storm event method. The *CN* value for AMC-II of the watershed is taken as the mean of all the CN values computed with the ranked pairs of $P$ and $Q$. The CN values for AMC-I and AMC-III were calculated as described in the NEH-4 method.

### Log-normal frequency method

In this method, developed by Schneider & McCuen (2005), the data for $P$ and $Q$ were collected as given in the storm event method. The logarithms of each set of $P$ and $Q$ were computed and the mean values of log $P$ and log $Q$ were determined. The value of $S$ was then obtained from Equation (8) using the antilog of the mean log values of $P$ and $Q$ (Schneider & McCuen 2005). The value of CN for AMC-II was computed using Equation (3). The CN values for AMC-I and III were determined following a procedure similar to the storm-event method.

### S-probability method

The $S$-probability method was recommended by Hjelmfelt (1991) in which, for each set of the measured values of $P$ and $Q$, the value of S is determined using Equation (8). The log-normal probability distribution for the calculated values of $S$ is then plotted using Weibull's plotting position. The $S$ values corresponding to 10, 50 and 90% probability levels were used to determine the CN values for AMC-I, II and III, respectively.

## Performance evaluation criteria

Various tests of goodness of fit are in vogue to evaluate the performance of models employed for runoff estimation (Legates & McCabe 1999; Ahmed 2004). They include Nash–Sutcliffe model efficiency (Nash & Sutcliffe 1970), Aitken coefficient of determination (Aitken 1973), James coefficient of performance (James & Burges 1982) and index of agreement (Legates & McCabe 1999). The error analysis for evaluating the performance of CN estimation models was carried out considering absolute error (AE), mean absolute error (MAE), absolute relative error (ARE), mean absolute relative error (MARE), mean square error (MSE), root mean square error (RMSE) and relative bias (RB) (Snyder 1992; Mohan & Arumugam 1995; Raghuwanshi & Wallender 1996) as each technique has unique strengths and weaknesses and no single technique is capable of evaluating the performance of a model in a foolproof manner.

The study employed goodness-of-fit measure encompassing the coefficient of determination ($R^2$) along with one measure of model fit (index of agreement) and two measures of error (root mean square error and relative bias) for evaluating the performance of runoff estimation models. A model is said to be most promising if it has: (i) the highest coefficient of determination ($R^2$) and index of agreement ($D$) and (ii) the least value of the root mean square error (RMSE) and the relative bias (RB).

The coefficient of determination ($R^2$) describes the proportion of the total variance in the dataset and is given by

$$R^2 = \frac{\sum_{i=1}^{N}(X_i - \bar{X})(Y_i - \bar{Y})}{\left[\sum_{i=1}^{N}(X_i - \bar{X})^2\right]^{0.5}\left[\sum_{i=1}^{N}(Y_i - \bar{Y})^2\right]^{0.5}} \quad (9)$$

where $X_i$ are the measured values, $\bar{X}$ is the mean of the measured values, $Y_i$ are the estimated values; $\bar{Y}$ is the mean of estimated values and $N$ is the number of data points.

The value of $R^2$ ranges between 0 to 1, with the highest value indicating best correlation between the datasets and the lowest value signifying no agreement. Normally, an $R^2$ value greater than 0.9 signifies a very good model, between 0.8 and 0.9 a fairly good model and less than 0.8 an unsatisfactory model (Coulibaly *et al.* 2005). Legates & McCabe (1999) opined that the values of correction coefficient ($R$) and the coefficient of determination ($R^2$) are not sufficient statistics for quantitative comparison of performance as they are highly sensitive to outliers.

The index of agreement ($D$) is given by (Legates & McCabe 1999)

$$D = 1.0 - \frac{\sum_{i=1}^{N}(X_i - Y_i)^2}{\sum_{i=1}^{N}\left(|Y_i - \bar{X}| + |X_i - \bar{X}|\right)^2} \quad (10)$$

The value of $D$ indicates the degree of agreement to which one data series approaches another data series. It varies between 0 and 1, with a value 0 signifying no agreement and 1 showing perfect agreement among all the data pairs. This statistical measure indicates the deviation of the dataset from the 1:1 line.

The RMSE and the RB are indices of error measurement and represent average deviation between a pair from a dataset. The *RMSE*, being a measure of nonsystematic variation, defines the accuracy of the model and has been extensively used as a performance indicator. It is computed as

$$\mathrm{RSME} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y_i - X_i)^2} \quad (11)$$

The relative bias ($RB$) is an index of the systematic error, which indicates the amount by which the model underestimates ($RB < 0$) or overestimates ($RB > 0$) the output and is defined as

$$RB = \frac{1}{N}\sum_{i=1}^{N}(Y_i - X_i) \quad (12)$$

## RESULTS AND DISCUSSION

### Curve number estimation

The curve number values were derived using the National Engineering Handbook (NEH-4), the storm event (SE), the rank order (RO), the lognormal frequency (LF) and the $S$-probability (SP) methods and are presented in Table 2. The curve number values for antecedent moisture conditions AMC-I, II and III for the SP method were calculated at 10, 50 and 90% probabilities, respectively. From the analysis, the highest value of curve number was obtained by the SP method for the AMC-II and AMC-III in the AG, RAV the BK watersheds. The lowest value was estimated by the LF method for the AMC-II and III in the AG watershed and for AMC-II in the RAV watershed. The lowest value was also recorded by both the RO and the NEH-4 methods for all the AMCs in BK and the RAV watersheds. The intermediate curve number values were observed for the SE method except for AMC-I in both the BK and RAV watersheds. Lewis *et al.* (2000) also reported a similar trend of computing the highest curve number value (CN) by the SP method from Oak woodland watershed in California, USA.

**Table 2** | Curve number values determined using different curve number estimation methods for selected watersheds in the semi-arid region of India

| | | Curve number estimation methods | | | | |
|---|---|---|---|---|---|---|
| **Water-shed** | **Antecedent moisture condition (AMC)** | **NEH-4** | **SE** | **RO** | **LF** | **SP** |
| AG | AMC-I | 69 | 63 | 63 | 62 | 61 |
| | AMC-II | 84 | 80 | 80 | 79 | 90 |
| | AMC-III | 92 | 90 | 90 | 90 | 98 |
| BK | AMC-I | 72 | 75 | 72 | 73 | 74 |
| | AMC-II | 86 | 88 | 86 | 87 | 89 |
| | AMC-III | 93 | 94 | 93 | 94 | 96 |
| RAV | AMC-I | 67 | 70 | 70 | 69 | 74 |
| | AMC-II | 83 | 84 | 84 | 84 | 85 |
| | AMC-III | 92 | 93 | 93 | 92 | 92 |

NEH-4 = the National Engineering Handbook; SE = the storm event; RO = the rank order; LF = the lognormal frequency; SP = the S-probability methods.

**Table 3** | Statistics of different goodness-of-fit measures for various curve number estimation methods

| | Curve number estimation method | | | | |
|---|---|---|---|---|---|
| **Watershed** | **NEH-4** | **SE** | **RO** | **LF** | **SP** |
| (A) Coefficient of determination ($R^2$) | | | | | |
| AG | 0.7274 | 0.7341 | 0.7333 | 0.7350 | 0.7125 |
| BK | 0.9645 | 0.9684 | 0.9684 | 0.9695 | 0.9695 |
| RAV | 0.8142 | 0.7918 | 0.7918 | 0.7859 | 0.8666 |
| (B) Index of agreement ($D$) | | | | | |
| AG | 0.7887 | 0.8162 | 0.8133 | 0.8200 | 0.7225 |
| BK | 0.9538 | 0.9460 | 0.9460 | 0.9432 | 0.9416 |
| RAV | 0.8042 | 0.8107 | 0.8107 | 0.8114 | 0.8454 |
| (C) Root mean square error ($RMSE$) | | | | | |
| AG | 22.53 | 20.08 | 20.35 | 19.73 | 29.35 |
| BK | 10.75 | 11.99 | 11.99 | 12.43 | 12.66 |
| RAV | 7.42 | 6.98 | 6.99 | 6.88 | 6.49 |
| (D) Relative bias ($RB$) | | | | | |
| AG | 8.44 | 4.99 | 5.38 | 4.49 | 15.03 |
| BK | −0.43 | 0.90 | 0.89 | 1.37 | 1.57 |
| RAV | 1.47 | 0.65 | 0.65 | 0.45 | 1.17 |

**Table 4** | Overall performance evaluation of different curve number estimation methods

| | Performance based on different goodness-of-fit measures | | | | | | | | | | | | | | | | | | | | Performance based on all tests of goodness-of-fit | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $R^2$ | | | | | D | | | | | RMSE | | | | | RB | | | | | | | | | |
| **Water-shed** | **NEH-4** | **SE** | **RO** | **LF** | **SP** | **NEH-4** | **SE** | **RO** | **LF** | **SP** | **NEH-4** | **SE** | **RO** | **LF** | **SP** | **NEH-4** | **SE** | **RO** | **LF** | **SP** | **NEH-4** | **SE** | **RO** | **LF** | **SP** |
| AG | 4 | 8 | 6 | 10 | 2 | 4 | 8 | 6 | 10 | 2 | 4 | 8 | 6 | 10 | 2 | 4 | 8 | 6 | 10 | 2 | 16 | 32 | 24 | 40 | 8 |
| BK | 6 | 8 | 8 | 10 | 10 | 10 | 8 | 8 | 6 | 4 | 10 | 8 | 8 | 6 | 4 | 10 | 6 | 8 | 4 | 2 | 32 | 32 | 32 | 28 | 22 |
| RAV | 8 | 6 | 6 | 4 | 10 | 4 | 6 | 6 | 8 | 10 | 2 | 6 | 4 | 8 | 10 | 4 | 8 | 8 | 10 | 6 | 26 | 26 | 26 | 30 | 36 |
| Total score | 18 | 22 | 20 | 24 | 22 | 18 | 22 | 20 | 24 | 16 | 16 | 22 | 18 | 24 | 16 | 18 | 22 | 22 | 24 | 10 | 70 | 88 | 80 | 96 | 64 |
| Rank | IV | II | III | I | II | IV | II | III | I | V | IV | II | III | I | V | IV | II | II | I | V | IV | II | III | I | V |

The analysis indicated that the BK watershed recorded the highest CN value for AMC-II by all the alternate CN estimation methods followed by the RAV watershed except for the SP method, while the AG watershed registered the lowest CN value. A similar trend was observed for AMC-I and AMC-III. It is attributed to lower infiltration rate in the BK and the RAV watersheds in comparison to rainfall intensity due to higher slope of the watersheds, which is 8–6 times, respectively, higher than the AG watershed. The steeper slope coupled with poor vegetative cover results in poor retention $S$ in the BK and the RAV watersheds. The retention $S$ for a given antecedent moisture condition corresponding to the soil properties, land use and physiographic features of the watershed affects the value of the curve number CN. Using the estimated curve number values by different methods, the runoff values for all the selected watersheds were computed.

## Comparison of runoff estimates

The performance of all the five CN estimation methods was evaluated by comparing their statistical properties. The statistical properties, viz. $R^2$, $D$, RMSE and RB, were determined from two datasets pertaining to estimated and measured runoff values for the selected watersheds and are as presented in Table 3.

The runoff predicted by the LF method was found to be in closest agreement with the measured values using all four tests of goodness of fit for the AG watershed with highest values of $R^2$ ($=0.7350$) and $D$ ($=0.8200$) and lowest values of $RMSE$ ($=19.73$) and $RB$ ($=0.45$) (Table 3). For the BK watershed, the NEH-4 performed best in terms of the $D$, RMSE and RB criteria and the LF was found to be the best if $R^2$ is taken as a measure of goodness of fit. The

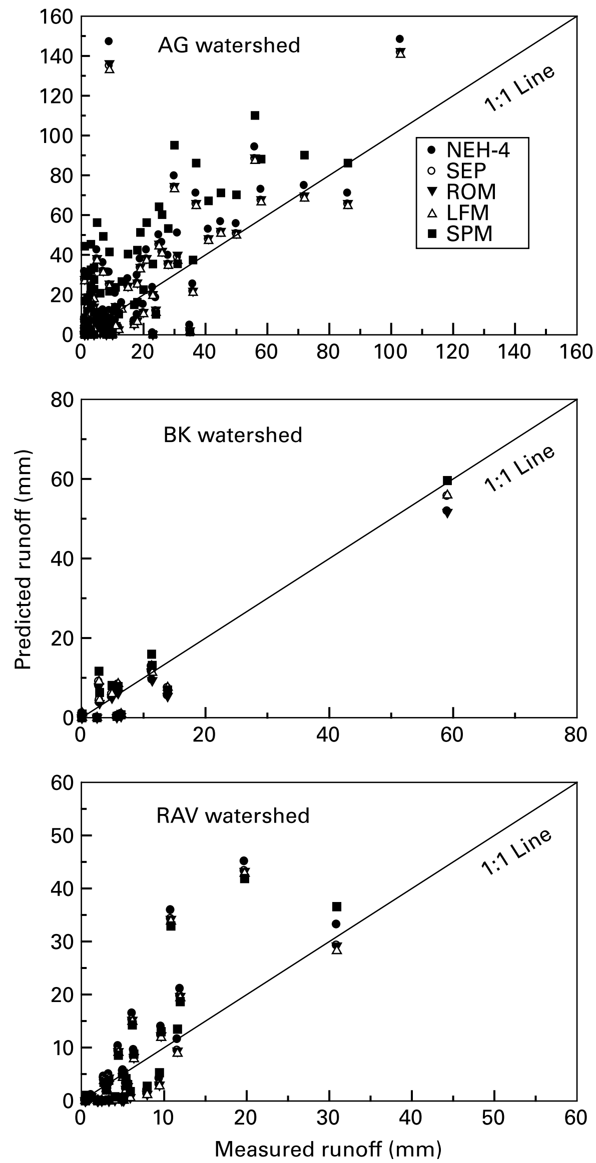


**Figure 2** | Measured versus predicted runoff using different curve number estimation methods for the selected watersheds in the semi-arid region of India.

**Table 5** | Regression coefficient, *F* and Student's *t*-test statistics of the measured and the predicted values of runoff using the different curve number estimation methods

| | | Regression coefficients | | *F* test | | *t*-test | |
|---|---|---|---|---|---|---|---|
| **Watershed** | **CN method** | **Parameters** | **Value** | $F_{calculated}$ | $F_{table}$[a] | $t_{calculated}$ | $t_{table}$[a] |
| AG | NEH-4 | Slope | 1.10 | 82.03 | 3.97 | 0.85 | 2.64 |
| | | Intercept | 6.76 | | | 2.16 | |
| | SE | Slope | 1.05 | 85.29 | 3.97 | 0.45 | 2.64 |
| | | Intercept | 4.16 | | | 1.42 | |
| | RO | Slope | 1.06 | 84.92 | 3.97 | 0.51 | 2.64 |
| | | Intercept | 4.44 | | | 1.51 | |
| | LF | Slope | 1.04 | 85.79 | 3.97 | 0.37 | 2.64 |
| | | Intercept | 3.81 | | | 1.31 | |
| | SP | Slope | 1.26 | 75.26 | 3.97 | 1.76 | 2.64 |
| | | Intercept | 10.89 | | | 2.92 | |
| BK | NEH-4 | Slope | 1.35 | 293.08 | 7.95 | 17.12 | 2.82 |
| | | Intercept | −4.19 | | | 2.26 | |
| | SE | Slope | 1.44 | 331.67 | 7.95 | 18.21 | 2.82 |
| | | Intercept | −3.73 | | | 2.02 | |
| | RO | Slope | 1.44 | 331.67 | 7.95 | 18.21 | 2.82 |
| | | Intercept | −3.37 | | | 2.02 | |
| | LF | Slope | 1.46 | 344.55 | 7.95 | 18.56 | 2.82 |
| | | Intercept | −3.53 | | | 1.91 | |
| | SP | Slope | 1.47 | 344.27 | 7.95 | 18.55 | 2.82 |
| | | Intercept | −3.44 | | | 1.85 | |
| RAV | NEH-4 | Slope | 1.52 | 57.05 | 7.59 | 2.58 | 2.76 |
| | | Intercept | −1.77 | | | 1.01 | |
| | SE | Slope | 1.39 | 48.73 | 7.59 | 1.97 | 2.76 |
| | | Intercept | −1.82 | | | 1.05 | |
| | RO | Slope | 1.39 | 48.73 | 7.59 | 1.97 | 2.76 |
| | | Intercept | −1.82 | | | 1.05 | |
| | LF | Slope | 1.36 | 46.84 | 7.59 | 1.82 | 2.76 |
| | | Intercept | −1.82 | | | 1.05 | |
| | SP | Slope | 1.55 | 87.43 | 7.59 | 3.34 | 2.76 |
| | | Intercept | −2.30 | | | 1.59 | |

[a] 1% significance level.

SP method exhibited the best correlation between the measured and predicted values of runoff for the RAV watershed based on the $R^2$, $D$ and RMSE criteria while LF performed best when the RB error criterion was considered. The second-best CN estimation method for the AG, BK and RAV watersheds was found to be the SE (in all the tests of goodness of fit), the RO (in all criteria) and the LF (in 2 out of 4 criteria), respectively (Table 3). The analysis indicated that no single CN estimating method performed best for all three watersheds in the semi-arid region of India based on all the four tests of goodness of fit, except the LF method, which worked out to be the best at least by one goodness-of-fit measure in all the three watersheds. It is probably attributed to the variations in morphological characteristics:

land uses and soil types of the selected watersheds, which influence the generation of runoff.

The variation in the RMSE values for all the curve number estimation methods was observed to be low (as RMSE = 19.73–29.35; 10.75–12.66 and 6.49–7.42 for the AG, BK and RAV watersheds, respectively). Further, the variation in the RB values of measured and predicted runoff by different methods was also recorded as very low (4.49–15.03; −0.43–1.57 and 0.45–1.17 for the AG, BK and RAV watersheds, respectively). It was observed that all the five methods overestimated runoff in the selected watersheds (as RB > 0) except the NEH-4 method, which underestimated it in the BK watershed (RB < 0). This is expected for the BK watershed due to highly undulating topography and multi-directional slope.

The statistical analysis revealed a close agreement between the data series predicted by all five curve number estimation methods for the selected watersheds (Table 3). If predicted values of runoff by all the methods are statistically close to the measured runoff, then there is no need of recommending one method over the other. Hence, for evaluating the overall performance of the curve number estimation methods, a score of 2–10 (in intervals of 2) was assigned based on their performance in each goodness-of-fit measure. The highest score of 10 was assigned to a method that had: (i) highest correlation coefficient ($R^2$) or index of agreement ($D$) and (ii) least root mean square error (RMSE) or relative bias (RB). The lowest score of 2 was assigned for that method which had the lowest $R^2/D$ or RMSE/RB. The scores of 8, 6 or 4 were assigned for the second, third and fourth higher orders of $R^2/D$ or lower orders of RMSE/RB, respectively. These scores were then summed up to rank the overall performance of the curve number estimation methods. The first rank corresponds to the highest score and the fifth to the lowest score. As is evident from Table 4, the LF method ranked first in each goodness of fit while the SP method ranked fifth in all the goodness-of-fit measures except in the $R^2$ measure for the BK and RAV watersheds. The overall performance evaluation also revealed that the SE, the RO and the NEH-4 methods ranked II, III and IV, respectively in terms of performance (Table 4).

The deviation of one line from another between the measured and predicted runoff values by different curve number estimation methods was also analyzed. The measured and the predicted values of runoff showed good agreement with the 1:1 line for all the watersheds (Figure 2). This correlation is further proved by the statistical value of the $F$-test and Student's $t$-test (Table 5). The high values of the $F$-test calculated at 1% level of significance ($C_{\text{calculated}} > F_{n1,\, n2 \text{ at 1\% significance level}}$) signify a close correlation between the measured and predicted runoff values. The Student's $t$-test (Walpole & Myers 1978) also suggests that neither were the slopes significantly different from unity except in the BK watershed for all the curve number estimates and in the AG watershed for the SP method, nor were the intercepts significantly different from zero at 1% level of significance (Table 5).

## CONCLUSIONS

The data from three small watersheds in the semi-arid region of India have been analyzed to estimate the curve number by five different methods, viz. National Engineering Handbook (NEH-4), the storm event (SE), the rank order (RO), the lognormal frequency (LF) and the $S$-probability (SP). Various statistical measures comprising mainly the coefficient of determination ($R^2$), the index of agreement ($D$), the root mean square error (RMSE) and the relative bias (RB) were used as indicators for selecting the best curve number estimation method used for computation of runoff from small watersheds. The following specific conclusions were drawn from the study:

1. Performance evaluation of the five methods established the superiority and the effectiveness of the lognormal frequency (LF) method over the other four methods for estimation of curve numbers and, in turn, computation of runoff from small watersheds in the semi-arid region of India.
2. The LF method proved to be the best followed by the SE, the RO and the NEH-4 methods as indicated by the performance criteria.
3. The performance of the SE, RO and NEH-4 methods was found to be almost identical except for the SP method, which registered higher deviation from the observed runoff values.
4. The curve number value for the AMC-II derived by the LF method was 79, 87 and 84 for the AG, the BK and the RAV watersheds, respectively.

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