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APPLICATION OF
A MODIFIED SCS-CN MODEL

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Rainfall-runoff modelling provides an useful input to the water resources planning and management. The Soil Conservation Service Curve Number (SCS-CN) method (SCS, 1956) is the most widely used method world over. Mishra and Singh (1998a) presented a modified version of the SCS-CN method. In this report, the modified version is applied to the storm rainfall-runoff data of 14 watersheds from an arid region and 2 from sub-humid regions of India, and the results are compared with those of the existing version. The modified version is found to perform better than the existing SCS-CN method in all applications to the data of 16 watersheds.

1. INTRODUCTION

The Soil Conservation Service-Curve Number (SCS-CN) method [Soil Conservation Service, 1956; 1964; 1985] is one of the most popular methods for computing the volume of surface runoff for a given rainfall event from small agricultural watersheds. The method has been the focus of much discussion in recent hydrologic literature. For example, McCuen [1982] provided guide-lines for using SCS methods for hydrologic analyses and Ponce and Hawkins [1996] critically reviewed and examined this method; clarified its conceptual and empirical basis; delineated its capabilities, limitations, and uses; and described future scope of research in the SCS-CN methodology. Hjelmfelt [1991], Hawkins [1993], and Bonta [1997] suggested procedures for determining curve numbers for a watershed using field data. Hjelmfelt [1991] discussed the heritage of the method and provided an interpretation of antecedent moisture conditions (AMC), Mishra [1998] defined S as the available storage space in the soil for a given AMC, and Steenhuis et al. [1995] found the SCS method to be based on the principles used in partial area hydrology for predicting the contributing area [Hewlett and Hibbert, 1967; Dunne and Black, 1970]. Using CN concept, Svoboda [1991] calculated soil-water content for estimating rainfall contribution to direct runoff and groundwater. The application study of Ritter and Gardner [1991] employed SCS-CN method to watersheds located on reclaimed surface coal mines in Central Pennsylvania. Mishra and Singh [1998a] connected the SCS-CN hypothesis with the Mockus [1949] method analytically and derived the modified and general forms of the method and found the modified method to be an improvement over the existing one in some field applications. Thus, the objective of this report is to apply the modified version of the SCS-CN method to arid and sub-humid regions of India and compare the results with those of the existing SCS-CN method.

2. METHODOLOGY

2.1 SCS-CN Method

The SCS-CN method is based on the water balance equation and two fundamental hypotheses (Mishra and Singh, 1998a). These are, respectively, expressed mathematically as

$$P = I_a + F + Q \quad (1)$$

$$\frac{Q}{P-I_a} = \frac{F}{S} \quad (2)$$

$$I_a = \lambda S \quad (3)$$

where P= total precipitation; I_a= initial abstraction; F= cumulative infiltration; Q= direct runoff; and S= potential maximum retention, and λ = initial abstraction coefficient. Combination of Eqs. 1 and 2 leads to the popular form of the SCS-CN method:

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

which is used in conjunction with the S-CN relation expressed as

$$S = \frac{1000}{CN} - 10 \quad (5)$$

In Eq. 3, initial abstraction, I_a includes short-term losses, viz., evaporation, interception, surface detention, and infiltration [Ponce and Hawkins, 1996] and its ratio to S describes λ. Since S depends on AMC, and thus, is a variable quantity, λ varies with S for a given I_a. Therefore, I_a can not be a descriptor of S, as defined by McCuen [1982]. In a recent study, Mishra and Singh [1998b] described the functional behaviour of SCS-CN method in λ-I_a^*-C spectrum, where $I_a^*=I_a/P$ and $C = Q/P$= runoff factor. The current version of the SCS-CN method assumes λ equal to 0.2 in routine applications, whereas Mishra and Singh [1998a; 1998b] described its range $(0,\infty)$. Mishra and Singh (1998b) found S for the existing SCS-CN method to be limited to $S<5(P-Q)$. The condition that S is limited by the maximum amount of P minus Q (Mockus, 1964) holds for $\lambda=0$, and thus, is a specific case of immediate ponding situation, for which $I_a=0$.

2.1 Modified SCS-CN Method

Mishra and Singh (1998a) found the basis of the SCS-CN hypothesis to lie in the empirical rainfall-runoff relation expressed by Mockus(1949) as

$$Q = P[1-(10)^{-bP}] \tag{6}$$

where P excludes I_a; b is an index which depends on antecedent moisture condition, vegetative cover, land use, time of the year, storm duration, and soil type. The parameter b can be construed as a reasonable variation of CN with the difference that the latter is a non-dimensional quantity, and the former a dimensional one. Expressing Eq. 6 in an exponential form using a constant B=b.ln(10) and neglecting the third and higher order terms of the expanded exponential lead to deriving an expression:

$$\frac{Q}{P} = \frac{P}{S + \frac{1}{2}P} \tag{7}$$

which is the modified form of the SCS-CN method. The functional behaviour of Eq. 7 can be described from the following relation derived coupling Eq. 7 with Eqs. 1 and 3:

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

From Eq. 8, it can be shown that S/P always assumes a real value. As $\lambda \rightarrow 0$, $S/P \rightarrow 0/0$; and as $C \rightarrow 0$, $S/P \rightarrow 1/\lambda$ (λS or $I_a \rightarrow P$). Since Q is 0 for $P < I_a$, therefore, $\lambda S \rightarrow P$ leads to two concepts: (i) Given S, λ varies such that $\lambda S \rightarrow P$; in such a case, λ is dependent on P. (ii) Given λ, S varies such that the aforementioned inference holds; in this case, S becomes a function of P. The normal practice however is to follow the second concept. For C=0, the maximum S, $S_{max} = P/\lambda$; as an example, for $\lambda = 0.2$, $S_{max} = 5P$. As $C \rightarrow 1$, $S/P \rightarrow 0.3893$ for $\lambda = 0.2$. It can be shown that S will approach P if either $I_a \rightarrow 0$ or $C \rightarrow 0.4143$ if $\lambda = 0.2$ or $\lambda \rightarrow 0.586$ if $C \rightarrow 0$.

3. STUDY WATERSHEDS

The storm rainfall-runoff data utilized in this study belong to arid and sub-humid regions of India, as shown in Table 1. The catchments at Sl. nos. 1 through 14 in Table 1 are the sub-watersheds of Luni river basin in Rajasthan State, the catchment of Narmada up to Manot at Sl. no. 15 in the table falls in the sub-humid region of Madhya Pradesh, and the Ramganga up to Kalagarh catchment at Sl. no. 16 lies in the sub-humid region of Uttar Pradesh. These watersheds vary significantly in size, ranging from 83.1 to 4980 sq. km, and character. A brief description of these river systems follows.

3.1 Luni River System

River Luni (Fig. 1) originates in the Aravalli hill ranges near Ajmer at an elevation of 550 m and flows south-westward to the Great Rann of Kutch, where it disappears, for about 482 kms. Enroute, it is joined by numerous tributaries like the Lilri, the Guhiya, the Bandi, the Mithri, the Sukri, the Jawai, etc. All these streams are ephemeral and have wide sandy beds. Tributaries from the isolated hills and rocky uplands in the plains also contribute to the flow in the Luni. The major tributaries originating in this zone, and joining the Luni, are two Jojris near Jodhpur and Pipar, the Luniwala near Siwana, and the Sagi further south near Bhinmal. All these streams register some good amount of flow during good monsoon rains and flash floods during spells of very high rainfall.

TABLE 1. DATA AVAILABILITY

Sl. No.	River	Gauging site	State	Catch-ment area (sq. km)	No. of storm rainfall-runoff events
Arid Region					
1	Sukri	Sojat Road	Rajasthan	358.6	39
2	Sukri	Sojat	Rajasthan	626.0	37
3	Sukri	Sarangwan	Rajasthan	316.9	37
4	Sukri	Sheopura	Rajasthan	1285.0	36
5	Guhia	Jhupelav	Rajasthan	349.2	32
6	Modiya	Hariamali	Rajasthan	177.5	38
7	Lilri	Dhaneri	Rajasthan	463.3	42
8	Phupheria	Dataredan	Rajasthan	373.3	35
9	Radia	Rohat	Rajasthan	251.0	37
10	Guriya	Sandiya	Rajasthan	264.0	40
11	Guhia Bala	Artiya	Rajasthan	209.0	36
12	Guhiya	Karniyali	Rajasthan	3050.0	37
13	Guhiya	Singari	Rajasthan	2837.6	37
14	Guria	Sabalpura	Rajasthan	83.1	41
Sub-humid Region					
15	Narmada	Manot	M.P.	5117.0	46
16	Ramganga	Kalagarh	U.P.	3134.0	35

All the above major streams are responsible for the formation of vast alluvial plains through which they flow. The dominant land forms are the younger alluvial plains along the major streams, where cultivation is more assured because of ground water, the older alluvial plains, the occasional isolated hills with fringing pediments, and some sand dunes with interdunal plains. Sandu undulating plains usually occur along the margins of the dune-covered areas in the west and north. The ranns of Pachpadra, Sanwarla, and Kaparda are important saline depressions. Salt affected alluvial plains are more numerous near the confluence of the Luni with the Great Rann.

The soils in the Rajasthan State are complex and highly variable, reflecting a variety of differing parent materials, physiographic land features, range of distribution of rainfall and its effects, etc. However, the soils can be broadly classified into five major categories depending on the basic fabric of soils, viz., soil texture which governs its many other properties. These are (a) sandy soils or light soils, (b) sandy loam or light medium soils, (c) loam or medium soils, (d) clay loam to clay or heavy soils, and (e) skeletal soils or shallow rocky and hilly soils.

3.2 Narmada up to Manot

The Narmada basin up to Manot (Fig. 2) lies between east longitudes 80°18' to 81°47' and north latitudes 22°26' to 23°18', most of the part lying in Mandla district and some part in Shahdol district of Madya Pradesh. The basin comprises of 4980 sq. km head water catchment of the Narmada defined by the Central Water Commission gauging site at Manot, to which the river length is 269 km. The river rises in the Maikala range near Amarkantak in the Shahdol district of Madhya Pradesh at an elevation of 1057 m at north longitude 22°40' and east longitude 81°45'. It flows in a generally north-west direction but turns in a loop to the south upstream of Manot.

In the cold weather, the mean annual temperature varies from 17.5 °C to 20 °C and in the hot weather from 30 °C to 32.5 °C. In the sou-west monsoon, the temperature ranges from 27.5 °C to 30 °C. In the post-monsoon season, temperatures vary between 25 °C and 27.5 °C. The maximum and minimum temperatures are experienced ranging from 40.2 °C during April-June and 6.8 °C during October-December, respectively. The normal annual rainfall of the basin is 1570 mm.

3.3 Ramganga up to Kalagarh

The Ramganga river is a major tributary of River Ganga and drains a catchment area of 3134 sq. km. above the Ramganga dam at Kalagarh (Fig. 3). Its catchment lies in the Sivalik ranges of Himalayas and the valley is known as Patlei Dun. Ramganga river originates at Diwali Khal. The catchment lies between elevations 262 m and 2926 m and is considerably below the perpetual snow-line of the Himalayas. Nearly 50% of the catchment area is covered with forest and 30% is under cultivation on terraced fields. The total length of the river up to the Kalagarh dam site is approximately 158 km. The river continues its journey in the plains for another 370 km before joining Ganga at Farrukhabad. During its travel up to Kalagarh, Ramganga river is joined by the following main tributaries: (i) Gangas; (ii) Binao; (iii) Khatraun; (iv) Nair; (v) Badangad; (vi) Mandal; (vii) Helgad; and (viii) Sona Nadi.

Ramganga valley experiences an annual precipitation of 1552 mm based on the available rainfall record from 1955 to 1974. The annual precipitation varies from 654 mm to 2436 mm. The annual evaporation losses are estimated using Rowher's formula and are of the order of 83.3 million cubic meter (MCM).

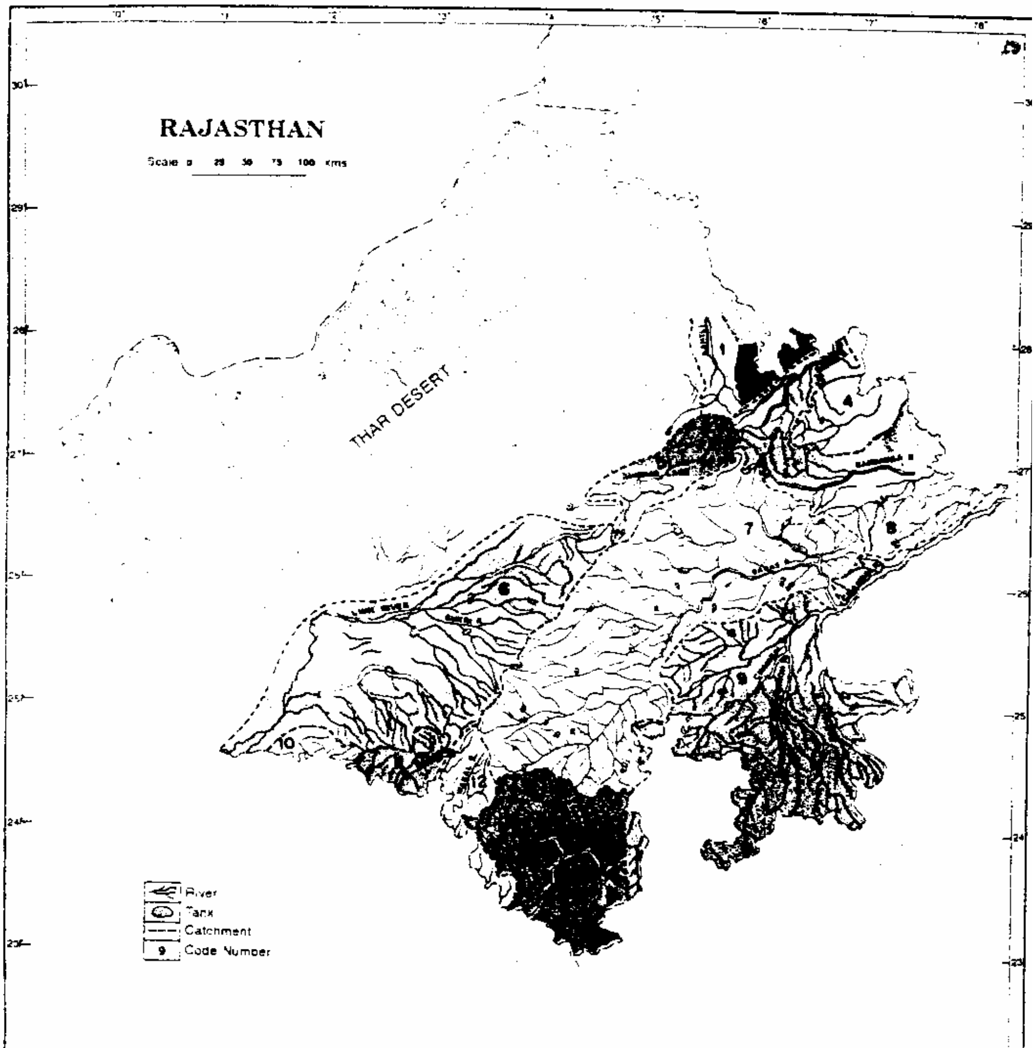

Fig. 1 : Luni River System in Rajasthan.

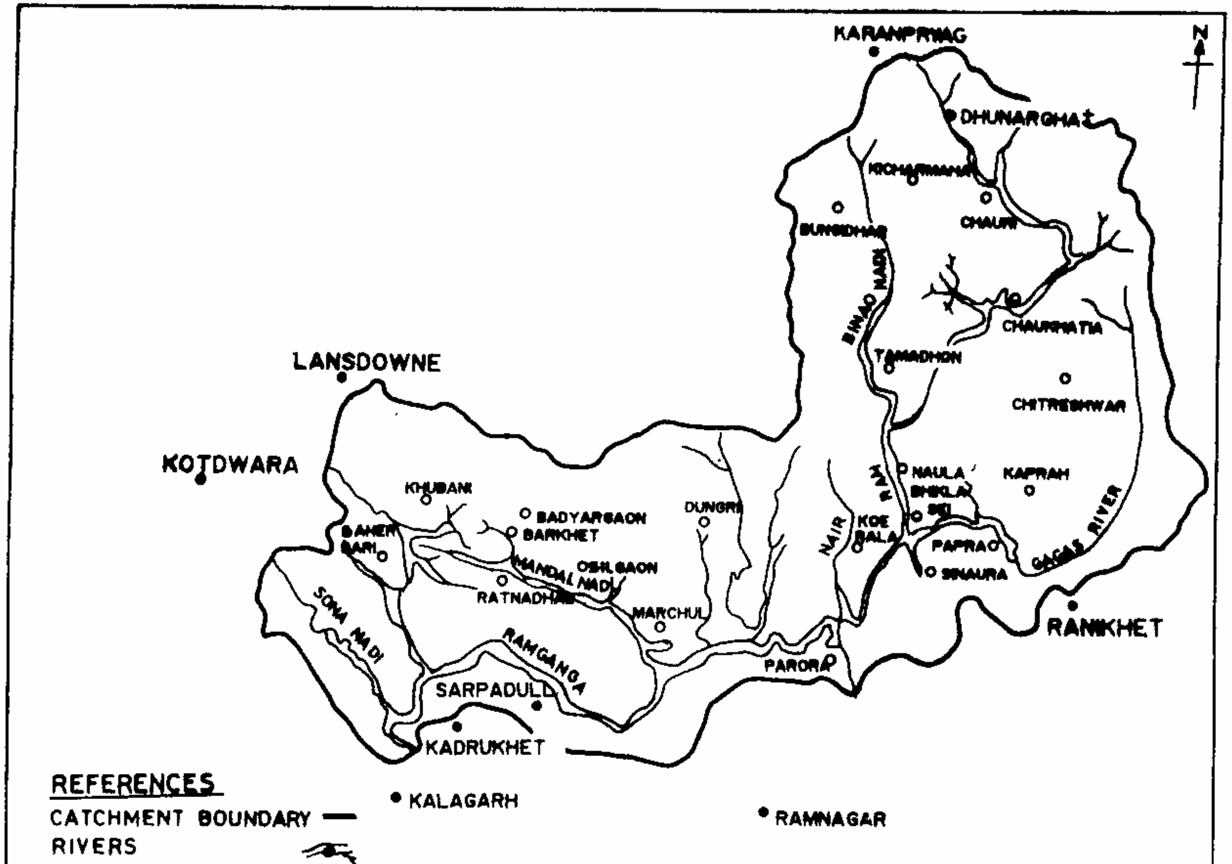

FIG. 2 RAMGANGA CATCHMENT

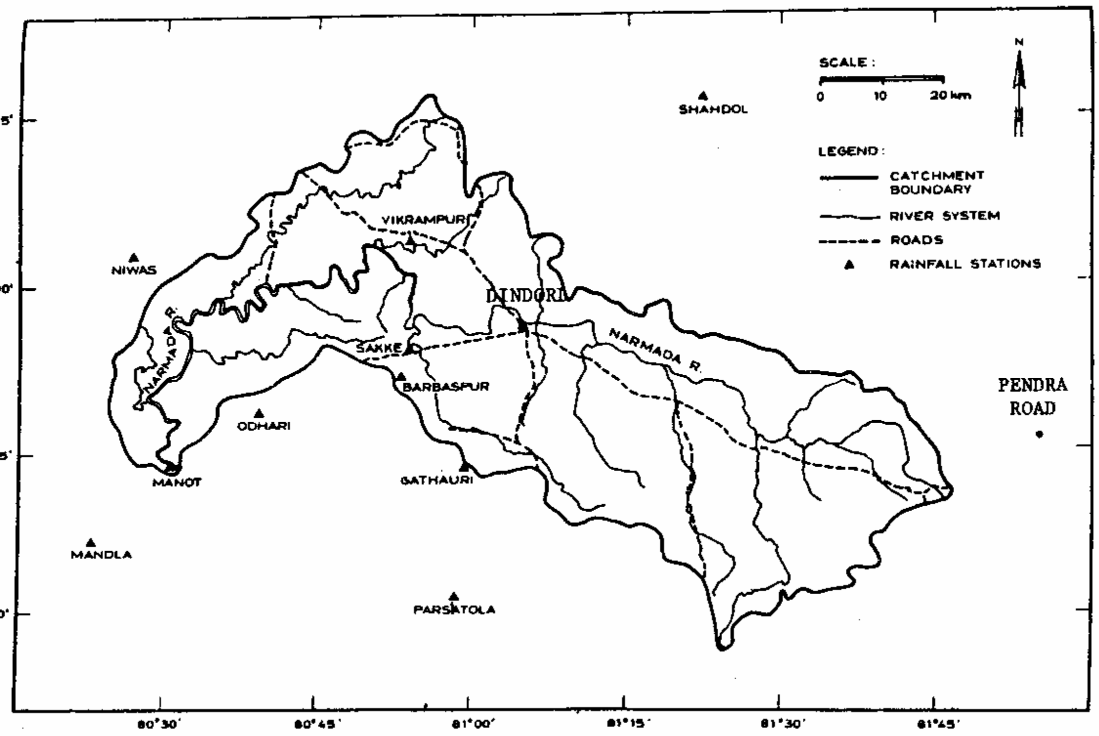

FIGURE 3 - THE NARMADA BASIN UPSTREAM OF THE MANOT GAUGING SITE

4. ANALYSIS

The data of the watersheds described in the previous chapter are utilized for estimating the parameters and evaluating the performance of the modified and existing SCS-CN methods using a goodness-of-fit criterion.

4.1 Goodness-of-Fit

For performance evaluation of the models used in this study, the root mean square (RMS) error is taken as an index of the variance between the computed and observed runoff. Expressed mathematically,

$$RMS = \frac{1}{N}\sum_{i=1}^{N}\sqrt{(Q_{obs} - Q_{comp})_i^2} \qquad (9)$$

where Q_{obs} is the observed storm runoff (mm), the Q_{comp} is the computed runoff (mm), N is the total no. of rainfall-runoff events, and i is an integer varying from 1 to N. The higher the RMS value, the poorer is the performance of the model and the lower RMS value shows a better performance of the model. The RMS value equal to zero indicates a perfect fit.

4.2 Parameter Estimation

Using Eq. 9, the models' parameters are computed utilizing Marquardt algorithm of constrained least squares. It has the advantage that the final parameter estimate does not depend on its initial estimate. In all applications, the initial estimate of parameter CN of both the models was taken equal to 70 and the additional parameter of the modified SCS-CN model, λ, was taken equal to 0.2, a standard value. CN ranged between 0 and 100 and λ was assumed to vary in the range (0,1). The computed values of the models parameters are shown in Table 2.

From Table 2 it is apparent that the CN of the existing SCS-CN method varies from 36.21 to 47.27 in applications to the watersheds of arid region. It is 41.14 for the Manot catchment, and 47.49 for the Ramganga catchment. It is to note that the computed curve numbers that largely depend on antecedent moisture condition are the fitting values to the above events. Since the basic hypothesis of the modified SCS-CN model differs from the existing SCS-CN method for which λ=0.2, the computed CN values of both the models in an application will be different from each other. The modified model yields CN values ranging from 7.58 to 19.37 in applications to the watersheds of arid region. It yields CN value of 19.92 for the Manot watershed, and 24.71 in the Ramganga catchment. Except for two watersheds, the value of modified model parameter λ is equal to zero. It is equal to 0.0021 and 0.0007 respectively for the watersheds at Sl. no. 2

TABLE 2. COMPUTATION OF PARAMETERS AND ROOT MEAN SQUARE ERRORS FOR THE PERFORMANCE OF EXISTING AND MODIFIED SCS-CN METHODS

Sl. No.	Catch-ment area (sq. km)	No. of rainfall-runoff events	Parameter Estimation			Root Mean Square Error	
			Existing SCS-CN method	Modified SCS-CN method		Existing SCS-CN method	Modified SCS-CN method
			CN	λ	CN		
Arid Region							
1	358.6	39	42.23	0.0000	17.86	53.678	42.199
2	626.0	37	40.01	0.0021	16.33	24.527	14.339
3	316.9	37	43.25	0.0000	17.09	63.714	49.030
4	1285.0	36	36.21	0.0000	12.08	22.581	12.788
5	349.2	32	47.27	0.0000	20.56	67.405	59.523
6	177.5	38	43.69	0.0000	15.58	67.325	56.862
7	463.3	42	38.96	0.0000	16.10	36.151	23.646
8	373.3	35	39.73	0.0000	15.88	26.713	11.420
9	251.0	37	37.92	0.0000	13.42	29.100	14.388
10	264.0	40	43.87	0.0000	19.37	34.796	26.692
11	209.0	36	39.92	0.0000	14.12	23.177	12.452
12	3050.0	37	33.96	0.0000	7.58	34.883	24.568
13	2837.6	37	41.04	0.0007	16.69	19.455	8.417
14	83.1	41	42.67	0.0000	13.87	44.006	34.725
Sub-humid Region							
15	4980.0	46	41.14	0.0000	19.92	121.879	98.687
16	3134.0	35	47.49	0.0000	24.71	100.185	94.380

and 13 in Table 2. In general, the value of λ is equal to zero, inferring that the modified SCS-CN model does not, in general, account for initial abstractions, and thus, becomes one parameter model. In systems frame-work, the S of the modified SCS-CN method also accounts for initial losses whereas the S of the existing version excludes and accounts for them separately. It leads to yielding higher S (or lower CN) values by the former model than those by the latter.

4.3 Performance Evaluation

Table 2 shows the RMS values computed from the above two models' applications to the data of various watersheds. In applications to all 16 watersheds, the modified SCS-CN model shows significantly lower RMS values than the corresponding ones from the existing SCS-CN method. For the arid region watersheds, the former model yields RMS values in the range (8.417,59.523), and the latter in the range (19.455,67.405);for the Manot catchment, the former model yields RMS value 98.687, and the latter 121.879; and for the Ramganga catchment, the former yields 94.380, and the latter 100.185. The lower RMS values by the modified model signify its better performance than the existing SCS-CN method. The fittings of the existing and modified models to all the watersheds are shown graphically in Figs. 4 through 19. The better fitting of the modified version of the model to all the watersheds than the existing one underscores the former's applicability to these watersheds.

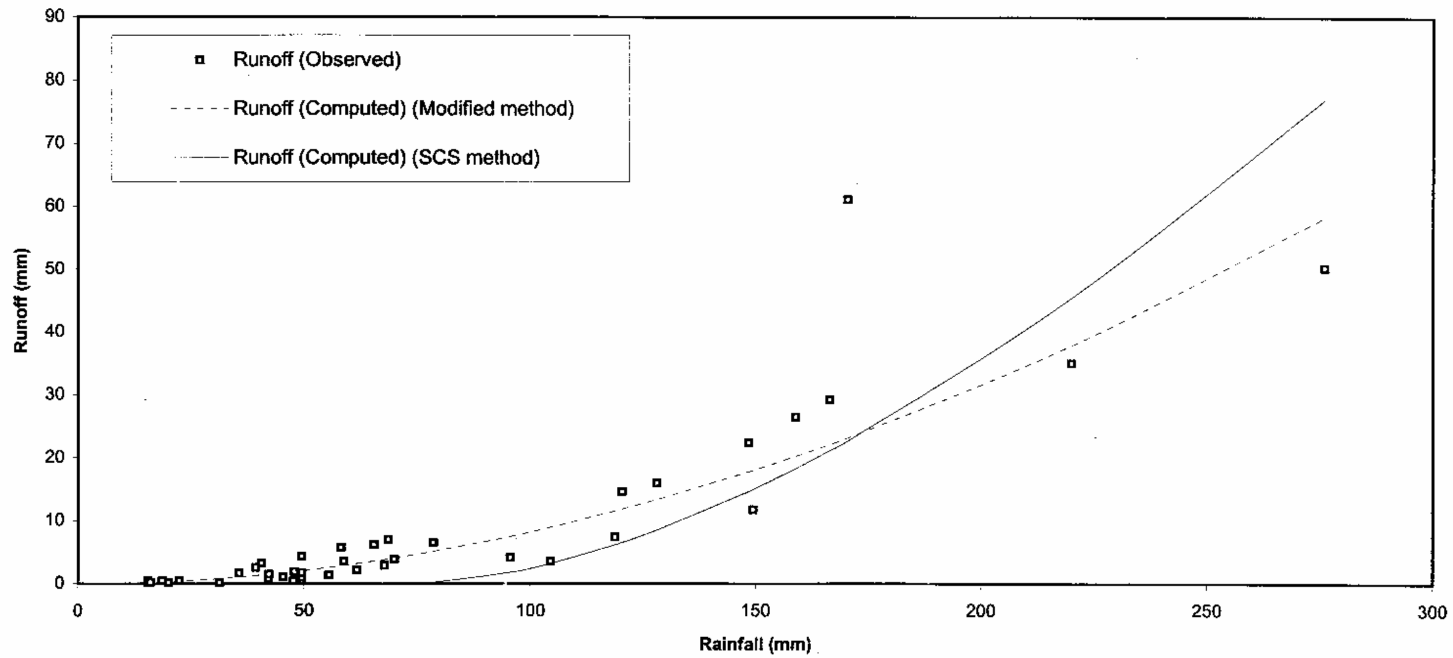

Fig. 4. Fitting of existing and modified SCS-CN methods to the data of watershed 1.

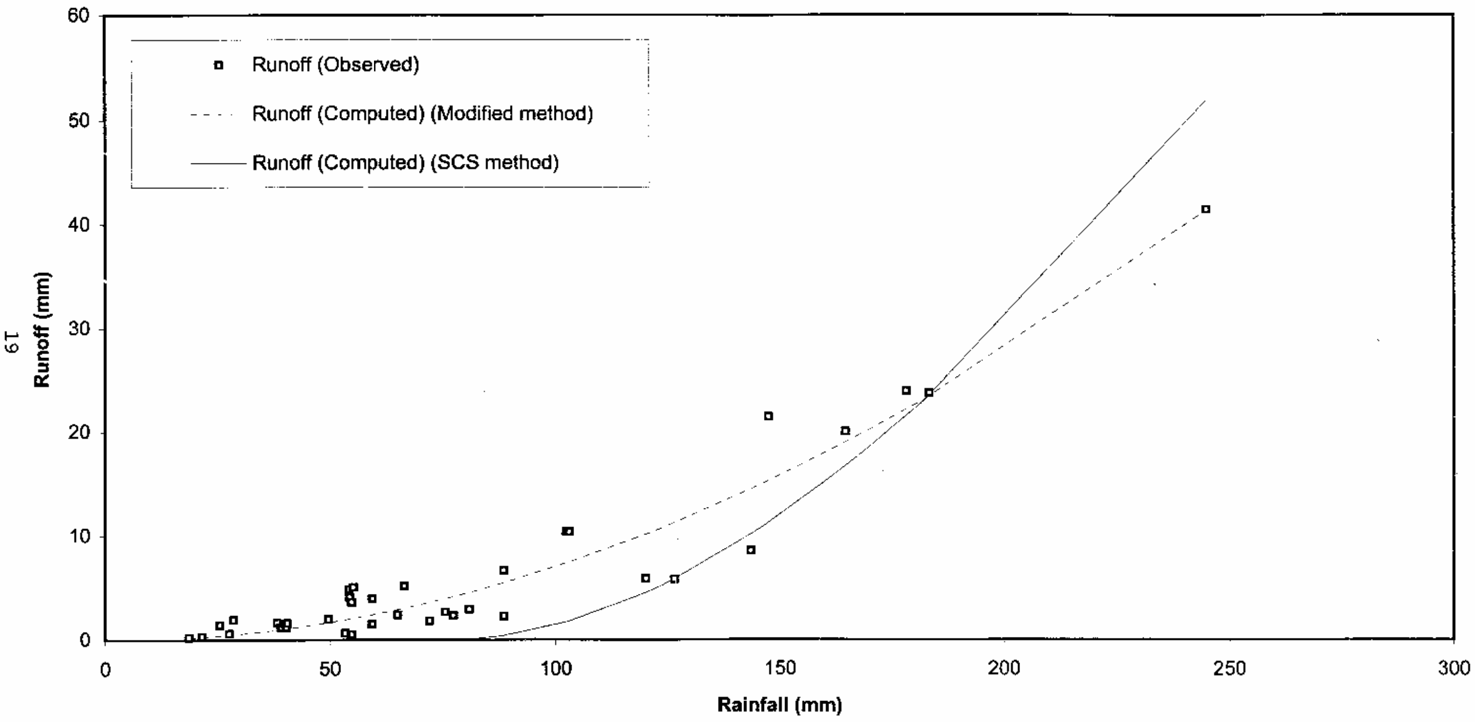

Fig. 5. Fitting of existing and modified SCS-CN methods to the data of watershed 2.

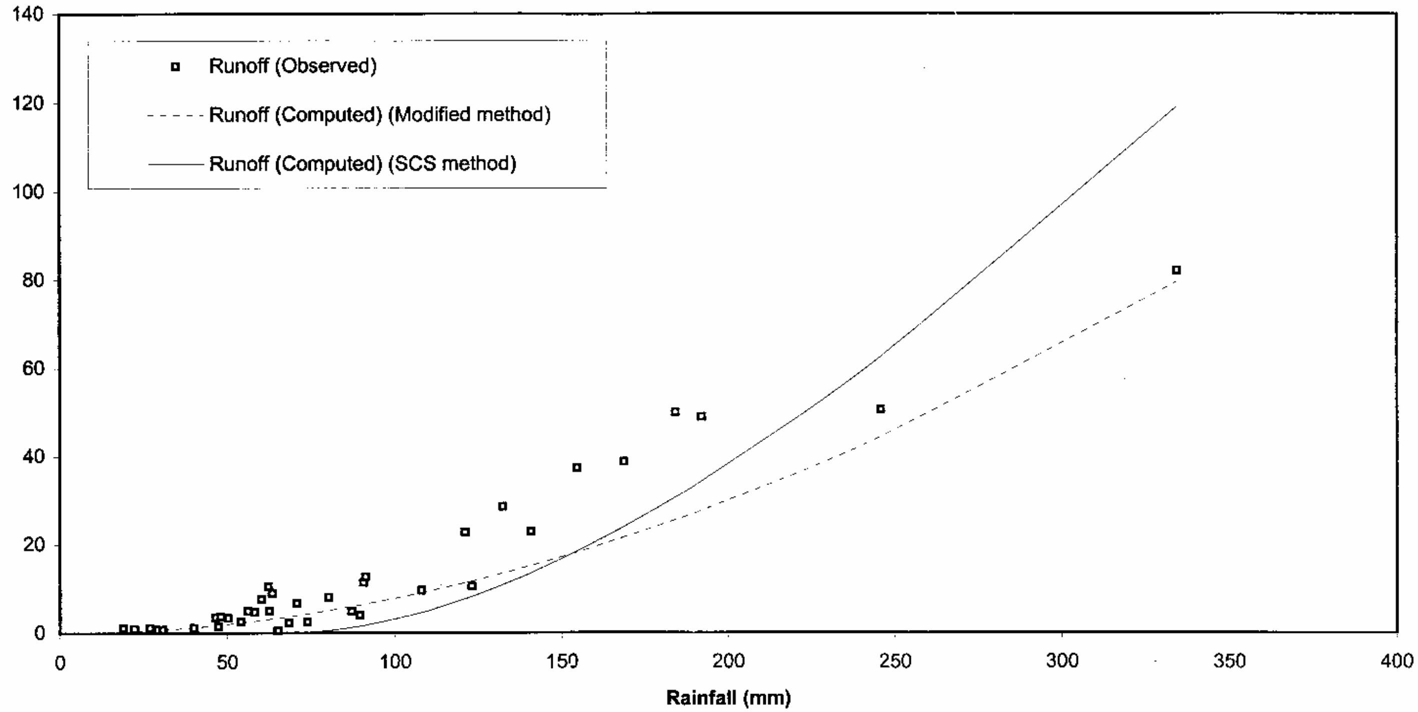

Fig. 6. Fitting of existing and modified SCS-CN methods to the data of watershed 3.

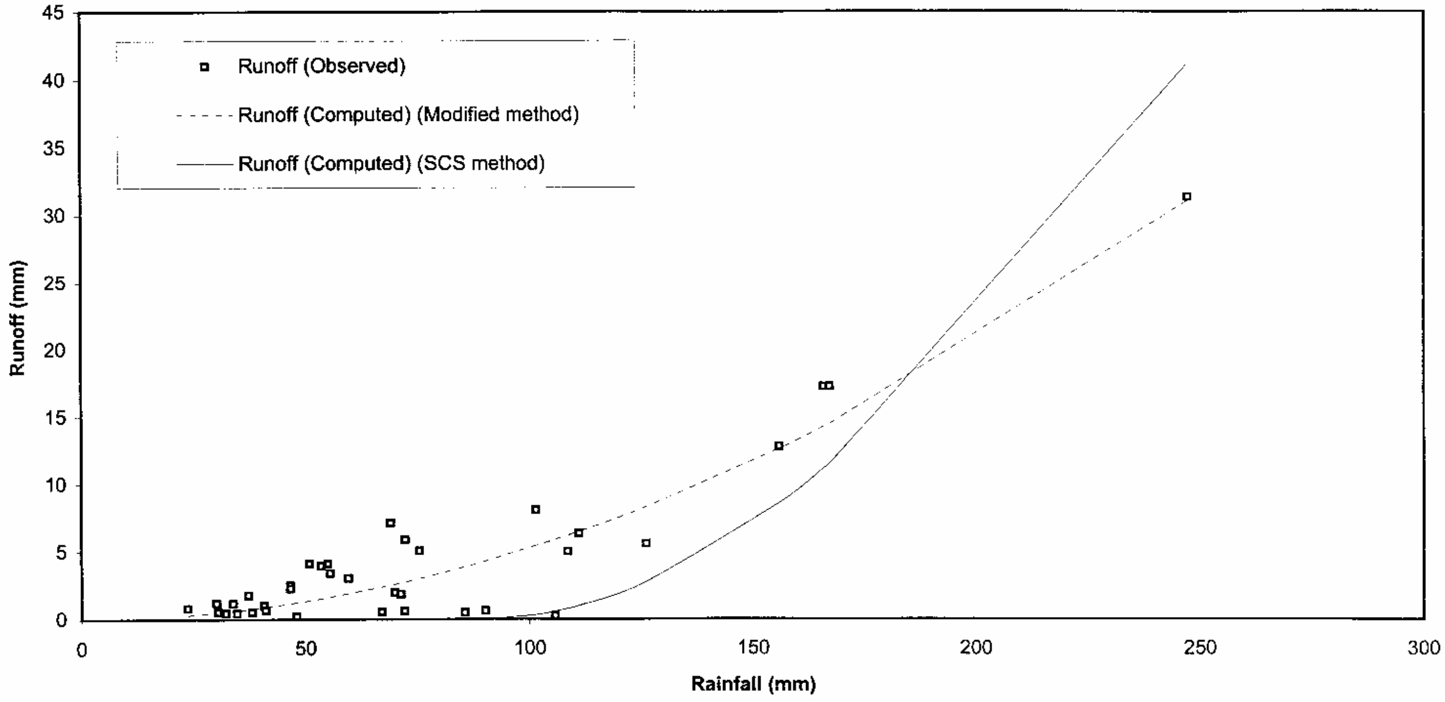

Fig. 7. Fitting of existing and modified SCS-CN methods to the data of watershed 4.

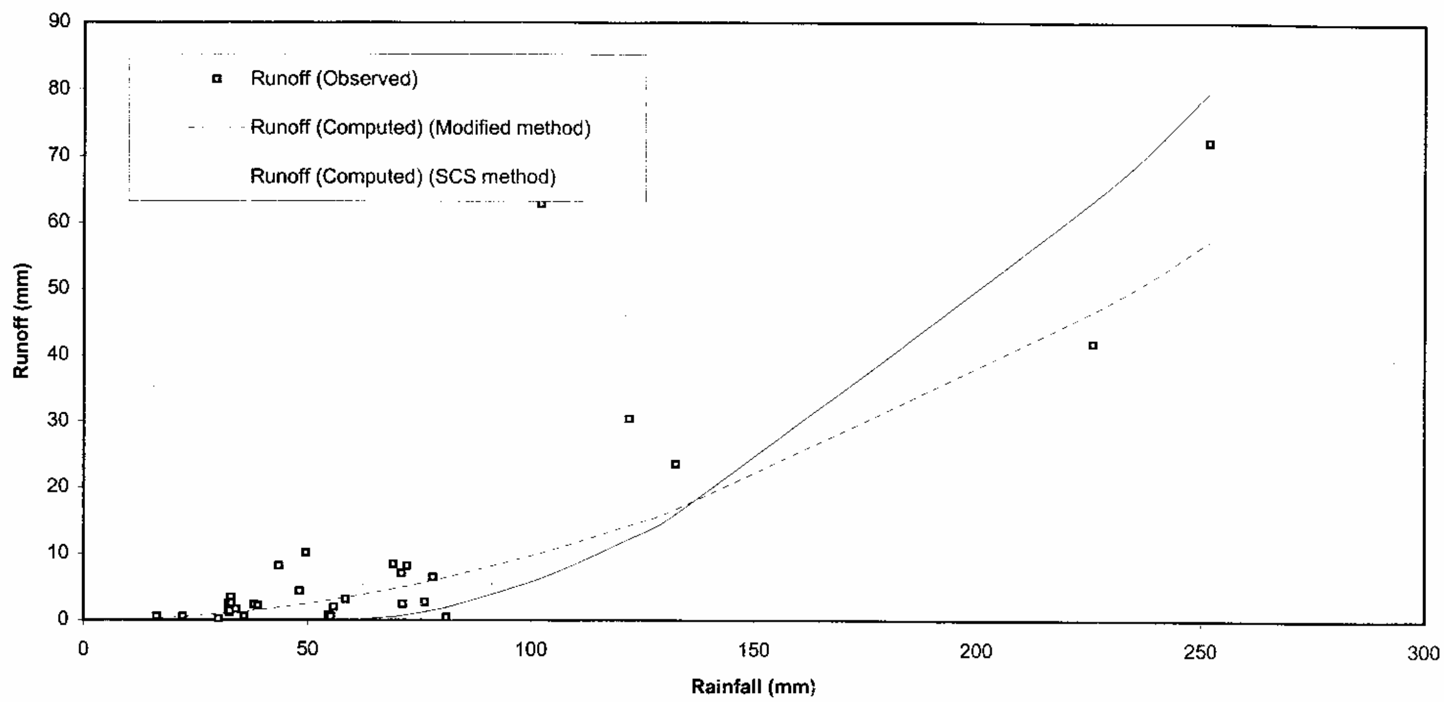

Fig. 8. Fitting of existing and modified SCS-CN methods to the data of watershed 5.

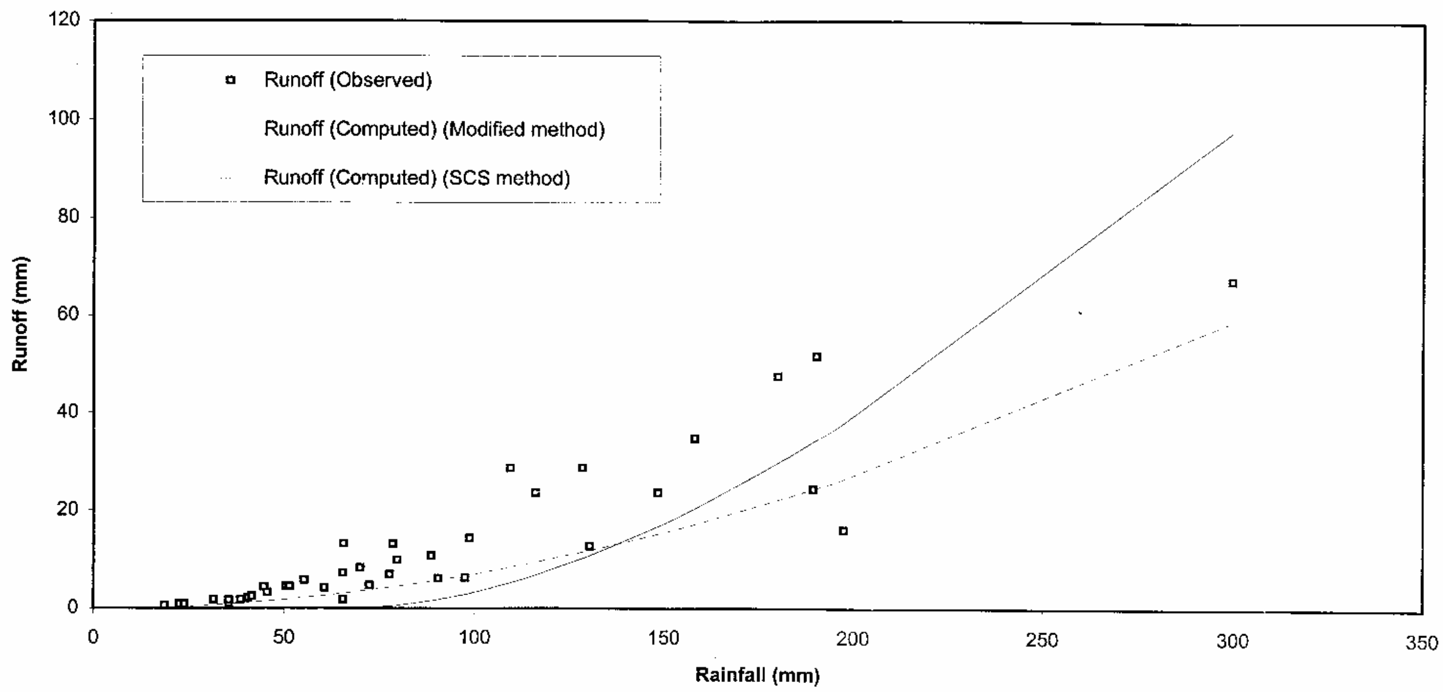

Fig. 9. Fitting of existing and modified SCS-CN methods to the data of watershed 6.

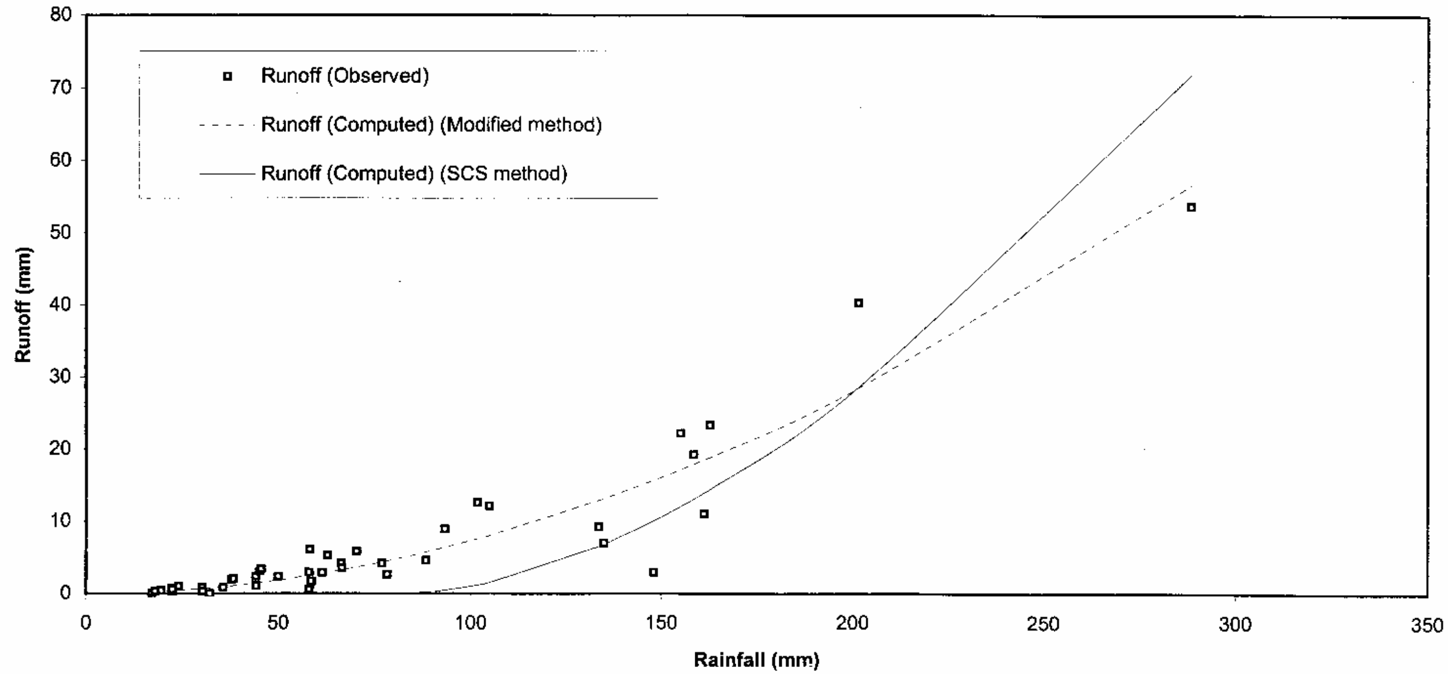

Fig. 10. Fitting of existing and modified SCS-CN methods to the data of watershed 7.

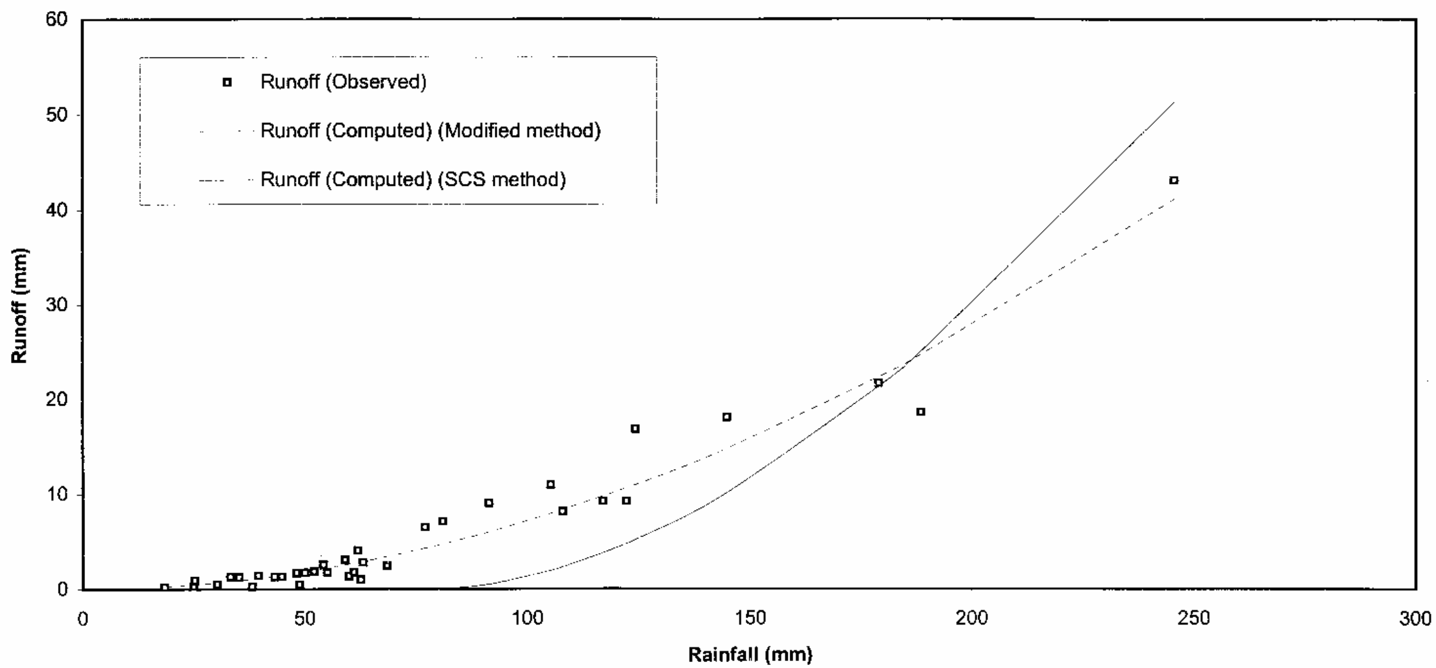

Fig. 11. Fitting of existing and modified SCS-CN methods to the data of watershed 8.

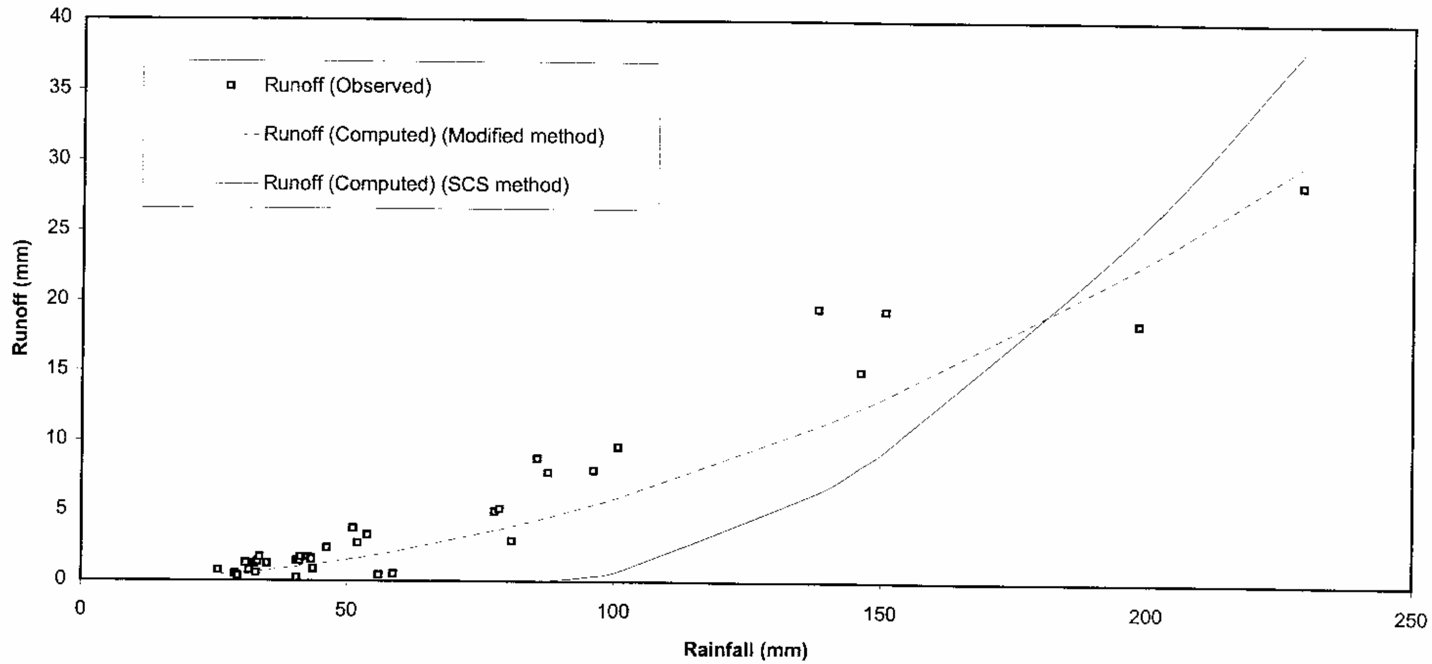

Fig. 12. Fitting of existing and modified SCS-CN methods to the data of watershed 9.

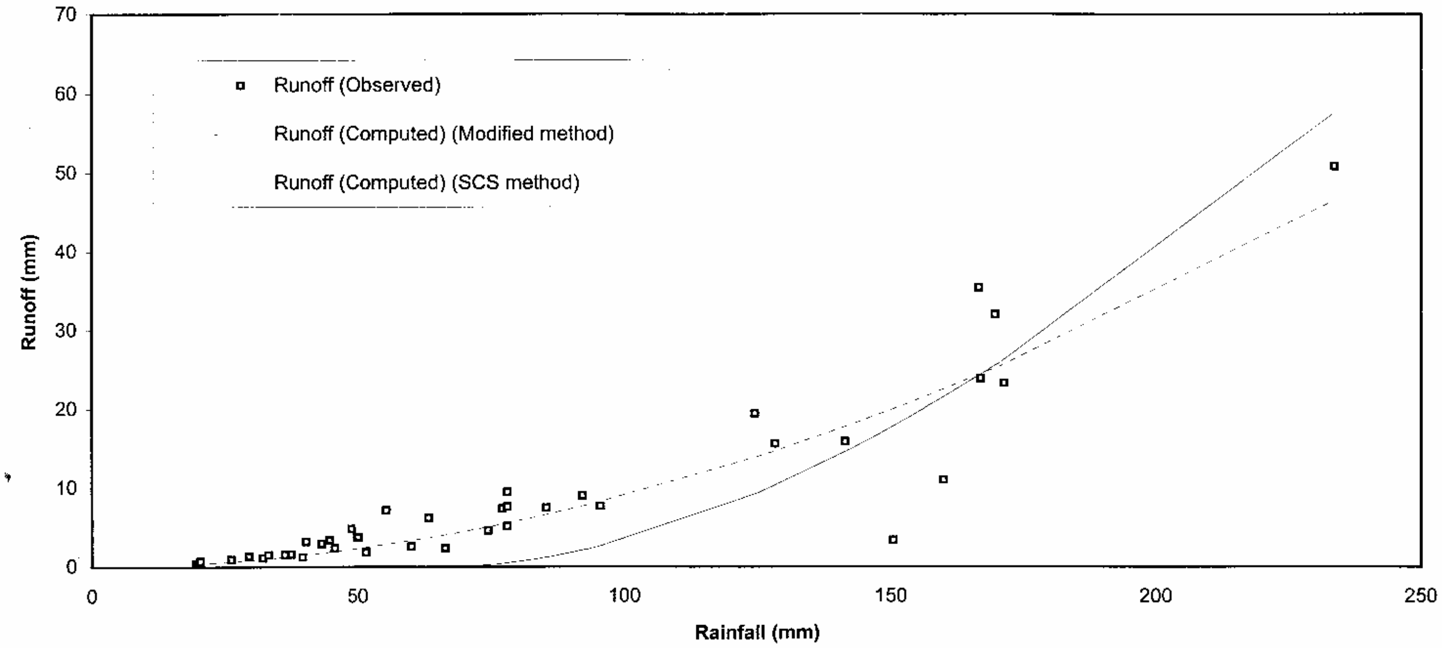

Fig. 13. Fitting of existing and modified SCS-CN methods to the data of watershed 10.

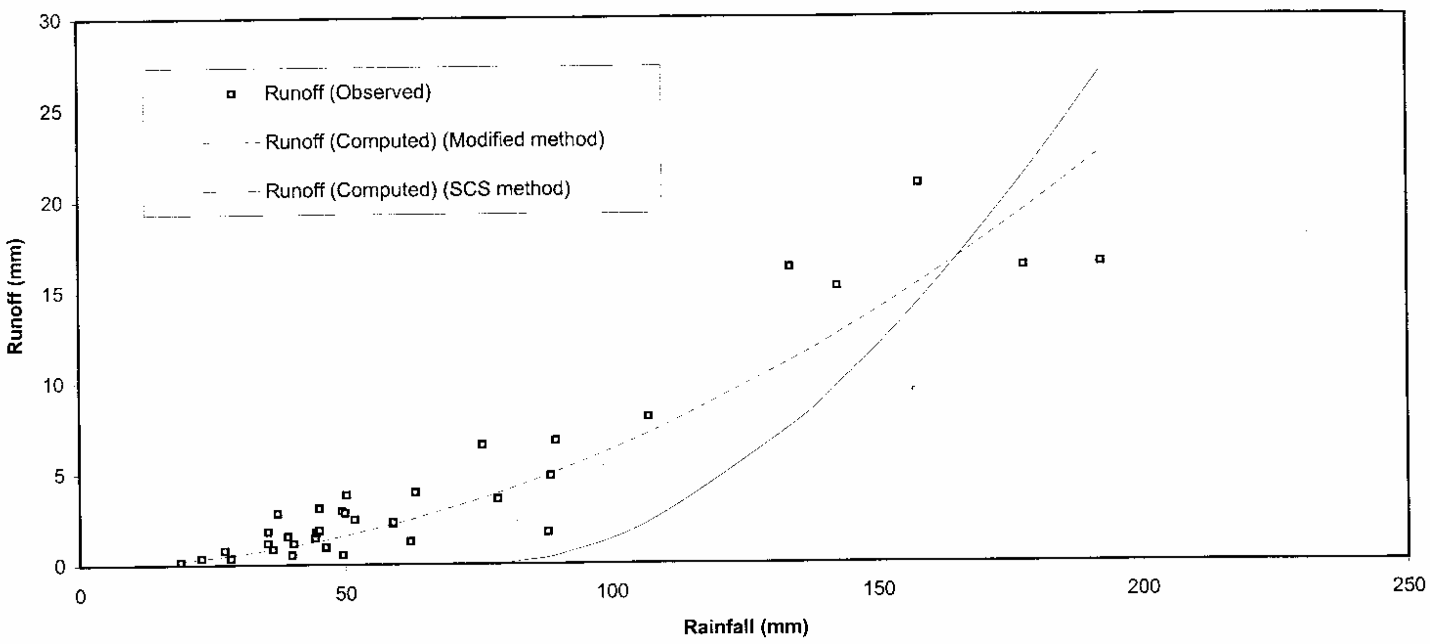

Fig..14. Fitting of existing and modified SCS-CN methods to the data of watershed 11.

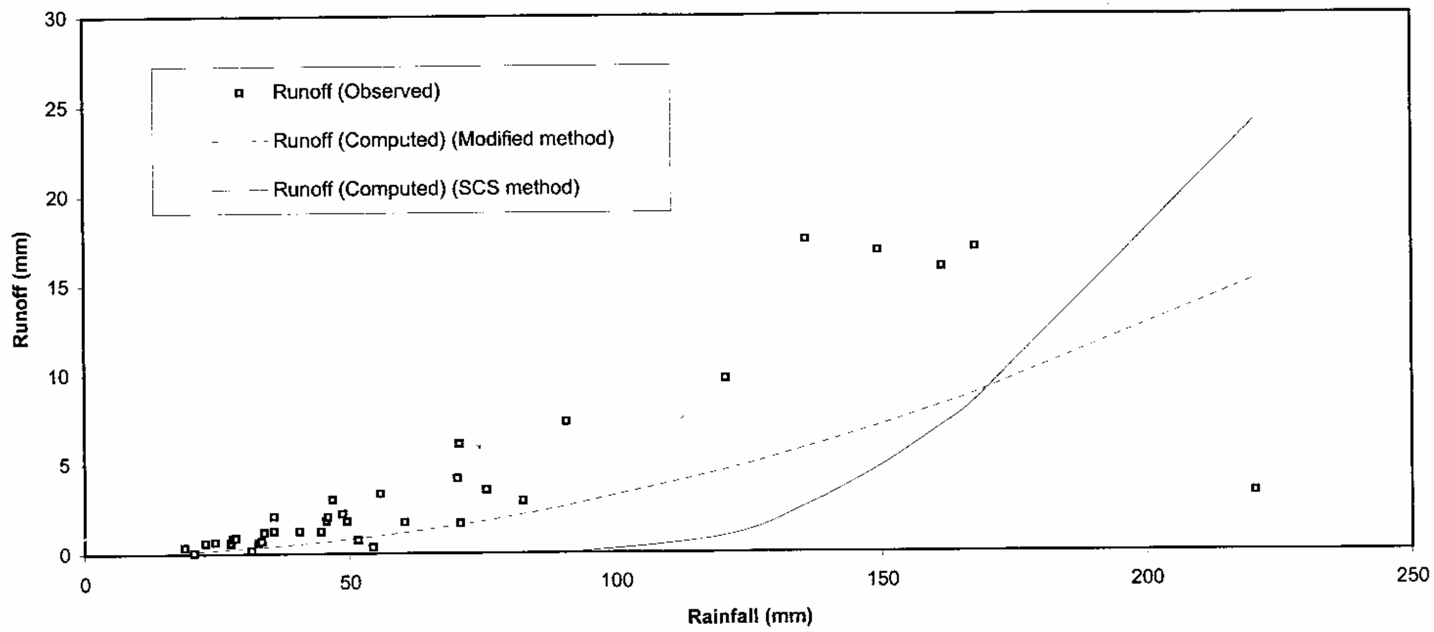

Fig. 15. Fitting of existing and modified SCS-CN methods to the data of watershed 12.

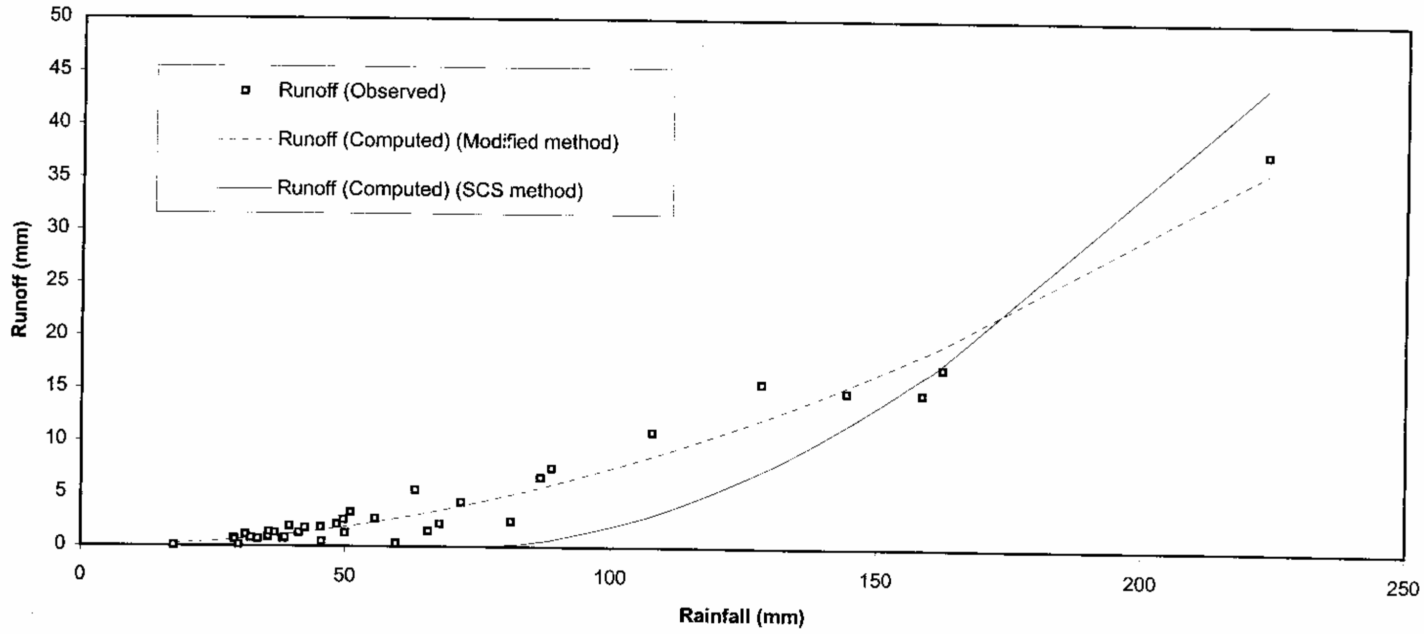

Fig. 16. Fitting of existing and modified SCS-CN methods to the data of watershed 13.

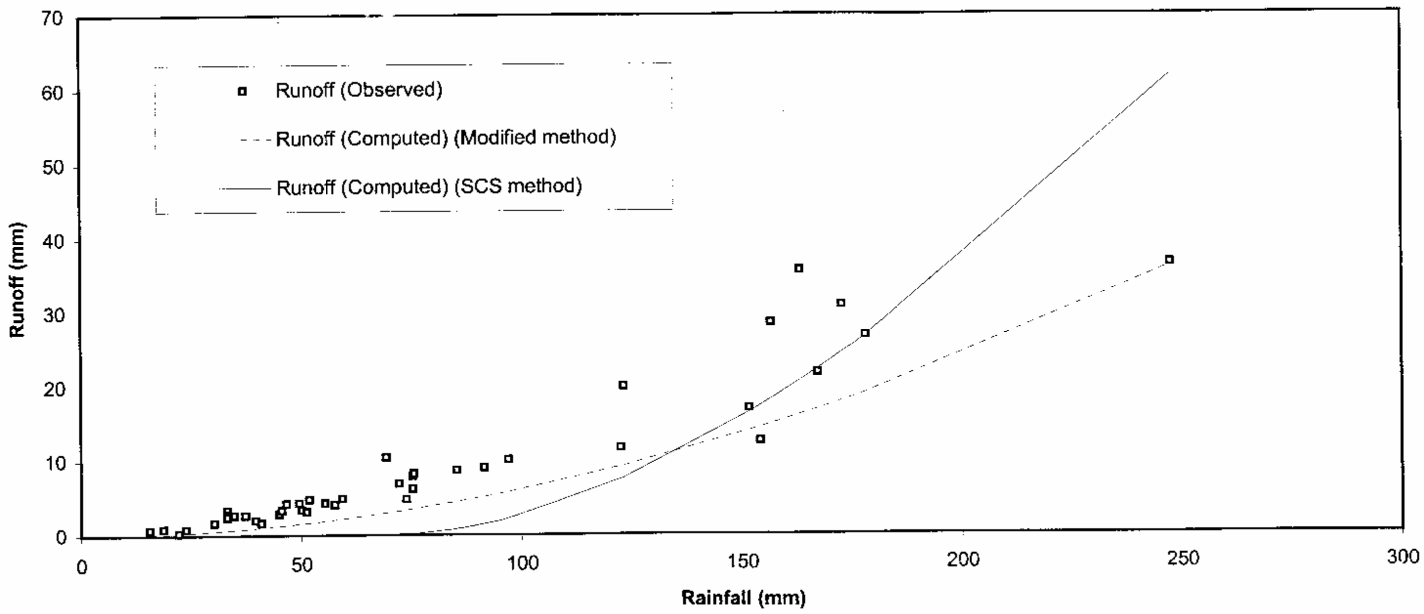

Fig. 17. Fitting of existing and modified SCS-CN methods to the data of watershed 14.

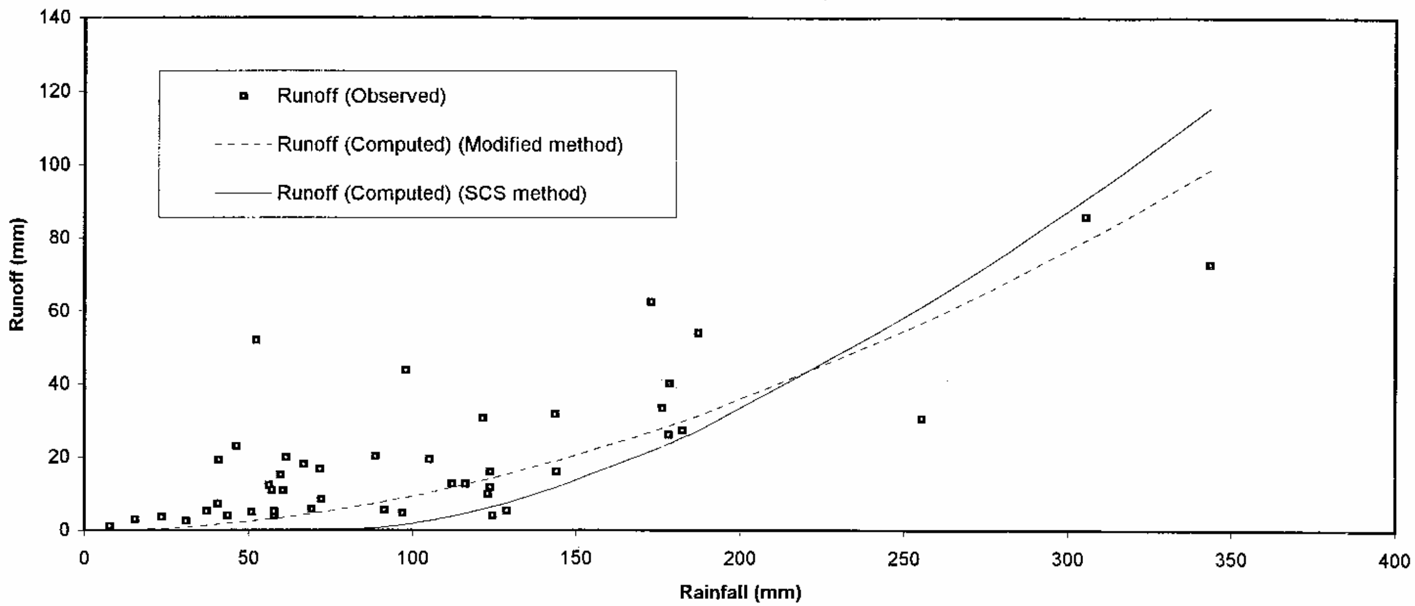

Fig. 18. Fitting of existing and modified SCS-CN methods the data of watershed 15.

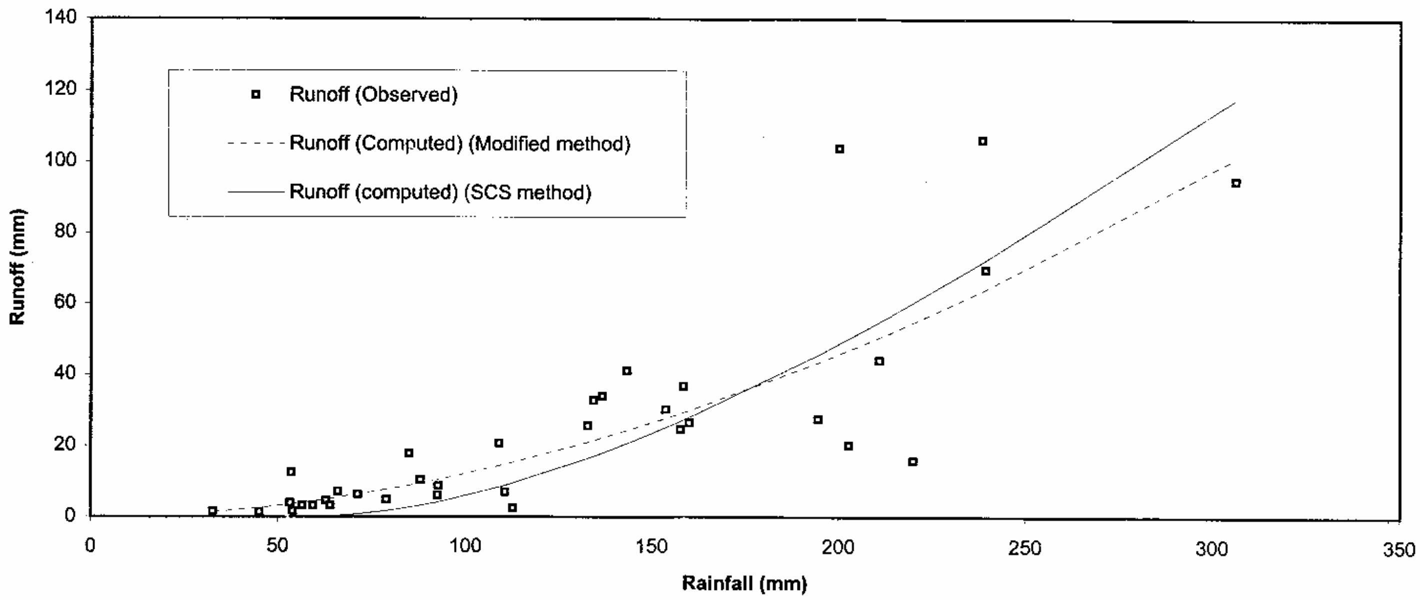

Fig. 19. Fitting of existing and modified SCS-CN methods to the data of watershed 16.

5. SUMMARY

Rainfall-runoff modelling is of paramount importance in watershed hydrology. In this report, the modified version of the SCS-CN method (Mishra and Singh, 1998a) was employed to the data of 16 watersheds falling in arid and sub-humid regions of India and the results were compared with those of the existing SCS-CN method using RMS as a measure of model performance. The former model yielded RMS values in the range (8.417,59.523), and the latter in the range(19.455,67.405) for the watersheds of the arid region; and sequentially, the RMS values by the former and the latter models were 98.687 and 121.879 and 94.380 and 100.185 for the Manot and Ramganga watersheds falling in sub-humid regions, respectively. The lower RMS values by the modified version of the SCS-CN method in all the applications underscores its better performance than the existing method.

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