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Soil management and production of Alfisols in the semi-arid tropics. II.* Deriving USDA curve numbers from rainfall simulator data

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Abstract

A comparison of USDA-SCS runoff curve numbers from model calibration using experimental runoff data and rainfall simulation is presented. A rainfall simulator was used to derive curve numbers for a range of antecedent soil water contents and surface cover conditions for an Alfisol soil in the semi-arid tropics of India. These relationships between cover and curve number are compared with relationships that were obtained using model calibration in Part I of this paper.

The results showed that rainfall simulation on dry soils was most useful for deriving curve numbers. Derived curve numbers under dry antecedent conditions (CN_1) can be easily adjusted to curve numbers for average antecedent conditions (CN_2) which is an input parameter for many agricultural simulation models. Further analysis of the effects of cover on curve number showed that a linear function explained up to 86% of the variability between curve number and surface cover.

Curve numbers derived from rainfall simulators were similar to those obtained from model calibration. This has improved confidence in using rainfall simulation to measure a runoff curve number.

Keywords: runoff, curve number, residue, cover.

Introduction

The curve number method was developed by the United States Department of Agriculture, Soil Conservation Service (USDA-SCS), and is frequently used to estimate daily runoff volumes from agricultural areas. Initial development commenced in the 1950*s* (Rallison and Miller 1982) and, in 1972, the USDA-SCS published formal guidelines on the use of the method (Soil Conservation Service 1972). These formal guidelines included tabulated values of curve numbers for a range of soils and surface conditions.

The application of the curve number technique for runoff prediction is often limited due to the difficulty in obtaining an accurate estimate of curve number.

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Curve numbers can be derived by model calibration using daily rainfall and runoff data from small experimental watersheds (e.g. Freebairn and Boughton 1981; Littleboy *et al.* 1992; Silburn and Freebairn 1992; Dilshad and Peel 1994; Littleboy *et al.* 1996). However, such experimental rainfall and runoff data are rarely available. In the past, many applications of the USDA-SCS curve number method have been limited to soils and environments where experimental data are available.

The potential of the curve number method would be enhanced if curve numbers could be derived by a rainfall simulator. In comparison with experimental runoff plots, a rainfall simulator would offer a relatively quick and inexpensive technique to determine curve numbers for different soils and environments. An attempt to derive curve numbers from rainfall simulator data for sites in the United States was reported by Hawkins (1979). He concluded that attempts to wrest curve numbers from simulator data is an assumption-laden exercise, studded with 'potential disappointments, frustration and inconsistencies'. However, he made no attempt to account for the effects of either antecedent moisture conditions or surface cover on the derived curve numbers. Therefore, variations in these factors may be among the reasons for the 'disappointments, frustration and inconsistencies' in determining curve numbers from rainfall simulator data.

A study that highlighted the potential of a rainfall simulator to derive curve numbers was reported by Glanville *et al.* (1984). Curve numbers derived from a 1 m^2 rainfall simulator were similar to curve numbers obtained by calibrating the CREAMS model using 8 years of rainfall and runoff data from 1 ha contour bay catchments. The curve numbers derived from rainfall simulation explained more than 75% of the variation in measured runoff when used in the CREAMS model.

In Part I of this series of papers (Littleboy *et al.* 1996), curve numbers were derived by model calibration for a range of surface treatments on an Alfisol soil in the semi-arid tropics of India. The aim of the present paper is to determine runoff curve numbers from rainfall simulator data and establish the relationship between curve number and surface cover. Predicted runoff using the calibrated and calculated curve numbers will be compared.

Description of USDA-SCS curve number method

The USDA-SCS curve number method is based on the equation

$$Q = (P - 0{\cdot}2S)^2/(P + 0{\cdot}8S) \qquad (P > 0{\cdot}2S)\,, \tag{1}$$

where Q is runoff volume (mm), P is rainfall (mm) and S is the retention parameter. The retention parameter is limited by either soil water deficit or maximum rate of infiltration (Rallison and Miller 1982). It can be inferred that, under dry conditions, S is limited by the maximum infiltration rate while, under wet conditions, S is limited by the soil water content. S is calculated from the input value of the curve number (CN):

$$S = 25{\cdot}4(1000/\mathrm{CN} - 10)\,. \tag{2}$$

In the original USDA-SCS procedure, total rainfall in the previous 5 days was used to adjust the curve number to account for variability in antecedent soil water conditions. Different curve numbers are selected based on wet, average or dry antecedent conditions. Silburn and Freebairn (1992) reviewed a number of different studies in Australia and reported limited success with the antecedent rainfall version of the curve number method and concluded that the use of antecedent rainfall is a major limitation in the use of this method. Relationships between antecedent moisture and rainfall are represented as discrete classes instead of a continuous function. This implies sudden changes in curve number with corresponding changes in estimated runoff (Hawkins 1979). However, the poor performance of this method is not a good guide to the potential of the curve number technique (Silburn and Freebairn 1992). Williams and La Seur (1976) replaced the antecedent rainfall approach with a continuous function of soil water content. This model was further improved and included in the CREAMS model described by Knisel (1980). In the CREAMS model, S is adjusted by the ratio of actual soil water content (SW) to saturated water content (SAT) using the equation

$$S = S_{mx}(1 - \mathrm{SW/SAT})\,. \tag{3}$$

The S_{mx} term is the maximum value of S and is determined by substituting the curve number for dry antecedent conditions (CN_1) into equation (2):

$$S_{mx} = 25{\cdot}4(1000/\mathrm{CN}_1 - 10)\,. \tag{4}$$

This USDA-SCS curve number model with S related to a continuous function of soil water has become an integral component of many simulation models including CREAMS (Knisel 1980), EPIC (Williams 1983), CERES (e.g. Jones and Kiniry 1986), SWRRB (Williams and Nicks 1985), SPAW (Saxton *et al.* 1984), AGNPS (Young *et al.* 1989) and PERFECT (Littleboy *et al.* 1992).

The original version of PERFECT (Littleboy *et al.* 1992) contained a relationship between curve number and surface cover to adjust the curve number on a daily basis according to the amount of surface cover. Both Littleboy *et al.* (1992) and Silburn and Freebairn (1992) reported that the inclusion of this relationship into the curve number model improved runoff prediction. A similar relationship between surface cover and curve number for a duplex soil under pasture was reported by Yet *et al.* (1994). In Part I of this study (Littleboy *et al.* 1996), the following relationship between surface cover (COVER) and curve number was defined for the Alfisol soil in this study:

$$\mathrm{CN} = \mathrm{CN}_{\mathrm{bare}} - (0{\cdot}35 \times \mathrm{COVER})\,. \tag{5}$$

The curve number under bare conditions ($\mathrm{CN}_{\mathrm{bare}}$) is reduced by 0·35 units for every 1% of cover, with a maximum reduction in curve number of 35 units. The combined effects of surface cover (equation 5) and antecedent soil water (equations 2 and 3) on curve number are illustrated in Fig. 1. For a wet soil, the effects of surface cover on curve number are negligible. The effects of surface cover on curve number increase for drier antecedent conditions.

Methods

Rainfall simulation was carried out during October and November 1988 at the ICRISAT Centre, Patancheru, India. Details on the construction and calibration of the rainfall simulator are given by Thomas and El Swaify (1989). Rainfall was simulated on 100 plots that included four levels of surface cover (bare, 45%, 80% and 100%) and two antecedent soil water conditions (dry and wet). Rainfall simulation was undertaken on the same site as the experimental runoff plots described in Part I of this study (Littleboy *et al.* 1996). Simulated rainfall occurred for approximately 60 min at a rate of 70–80 mm/h.

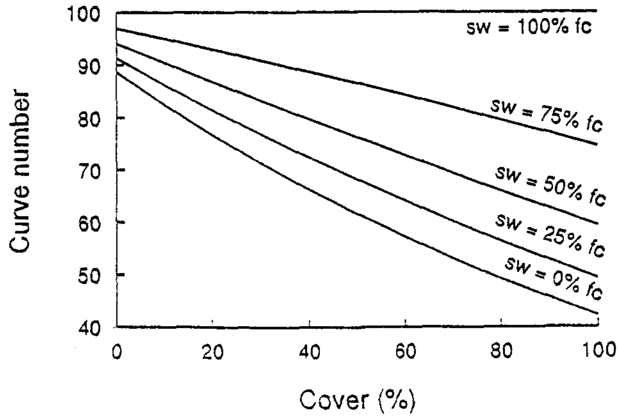

Fig. 1. Theoretical relationships between curve number and crop residue cover for antecedent soil water (SW) ranging from 0% to 100% of saturated water content (SAT). An input curve number of 83 and a maximum reduction in curve number of 25 units at 100% cover under dry conditions were used.

Calculated curve numbers (CN-CALC) were derived from the rainfall simulator data. Total rainfall and runoff volumes were substituted into the equation

$$S = 5\{P + 2Q \pm (4Q^2 + 5PQ)^{\frac{1}{2}}\}, \tag{6}$$

which is the solution of equation (1) for S. The negative root of the equation is used so that $P = Q$ when $S = 0$ (Hawkins 1993). Regression analyses were used to determine the relationship between CN-CALC and surface cover for dry and wet antecedent conditions.

Calibrated curve numbers (CN-CALIB) were obtained by model calibration in Part I of this study (Littleboy *et al.* 1996). The calibrated curve numbers were 94 for bare conditions and 59 at 100% cover.

The value of CN-CALC for bare conditions and the relationship between CN-CALC and surface cover were input into the version of PERFECT modified for this study. A comparison between predicted runoff from CN-CALC and CN-CALIB for the nine tillage and amendment treatments in Part I of this study was undertaken.

Results

Cover v. curve number responses

The CN-CALC values derived from the runoff data collected off 100 rainfall simulator plots are presented in Fig. 2. Relationships between cover and CN-CALC are clearly separated into two distinct groups on the basis of differences in antecedent soil water content. For wet antecedent conditions, there is little effect of cover on CN-CALC. An effect of cover on CN-CALC is only evident under dry antecedent conditions. The linear regression equations for the wet and dry responses are:

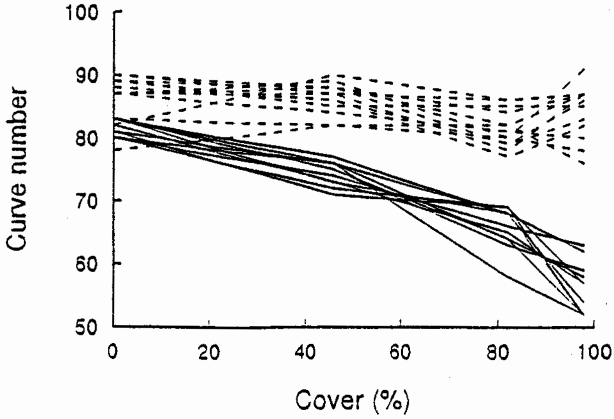

Fig. 2. Relationships between curve number and crop residue cover for wet antecedent conditions (---) and dry antecedent conditions (—).

for wet antecedent conditions:

$$\text{CN-CALC} = 87(\pm 0{\cdot}85) - 0{\cdot}04(\pm 0{\cdot}00016)\text{COVER} \qquad (R^2 = 0{\cdot}16), \tag{7}$$

for dry antecedent conditions:

$$\text{CN-CALC} = 83(\pm 1{\cdot}02) - 0{\cdot}25(\pm 0{\cdot}00023)\text{COVER} \qquad (R^2 = 0{\cdot}86). \tag{8}$$

From equation (7), under wet antecedent conditions, cover will cause CN-CALC to reduce by 4 units as cover increases from bare to 100%. A larger trend is evident for dry conditions with CN-CALC reducing by 25 units as cover increases from bare to 100%, as shown in equation (8). The intercept of equation (8), namely 83, represents the curve number under dry antecedent conditions for a bare soil (i.e. CN_1 in equation 4).

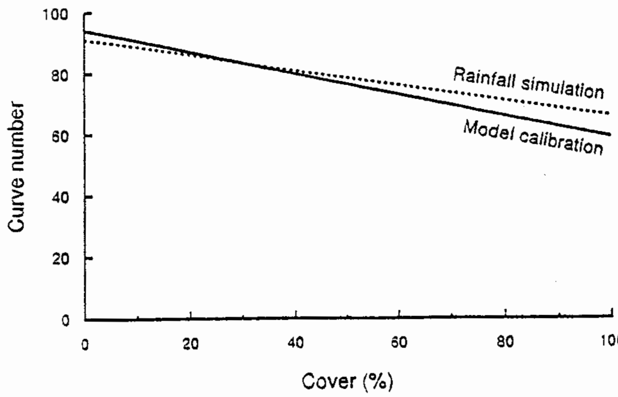

Fig. 3. Relationships between curve number and crop residue cover derived from model calibration and rainfall simulation.

Comparison between calculated and calibrated curve numbers

Relationships between CN-CALC and cover (equation 8) and CN-CALIB and cover (equation 5) for average antecedent conditions are presented in Fig. 3. The intercept of the CN-CALC *v.* cover relationship increased from 83 (as presented in equation 8) to 91 due to the change in antecedent conditions from dry to 'average'. 'Average' antecedent conditions assume a soil water content of 50% of saturation substituted into equation (3), with S_{mx} from equation (4) and S substituted into equation (2). CN-CALC is less than CN-CALIB when cover is less than 30%. CN-CALC is greater than CN-CALIB when cover is greater than 30%. The maximum difference between CN-CALC and CN-CALIB is 7 units at 100% cover.

Table 1 presents average annual runoff from PERFECT using the relationships in Fig. 3 and measured runoff for the nine tillage and amendment treatments considered in Part I of this study. There is little difference between measured runoff and predicted runoff using either CN-CALC or CN-CALIB for the amendment treatments (manure and straw). Average annual runoff was underpredicted by approximately 15% using CN-CALC for the bare soil treatments. However, the trends in runoff for the tillage and amendment treatments are similar for both CN-CALIB and CN-CALC.

Table 1. Comparison of average annual runoff (mm) using calibrated curve numbers, curve numbers calculated from rainfall simulator data and measured data for nine tillage and amendment treatments

Treatment	Measured	CN from model calibration	CN from rainfall simulation
Zero tillage, bare soil	217	210	180
Zero tillage+manure	133	132	124
Zero tillage+straw	67	70	73
Shallow tillage, bare soil	205	195	168
Shallow tillage+manure	120	124	118
Shallow tillage+straw	73	68	70
Deep tillage, bare soil	173	172	148
Deep tillage+manure	124	114	106
Deep tillage+straw	66	64	64

The statistics for daily runoff prediction are presented in Table 2. The values of root mean square error (RMSE) are similar for both CN-CALIB and CN-CALC.

Discussion and conclusions

In the past, the derivation of curve numbers from rainfall simulator data has caused erratic results. The likely explanation for the inconsistent results is the difficulty in quantifying the effects of antecedent soil water content and cover on the derived value of S and hence curve number. The approach illustrated in this paper permits the explicit consideration of these factors.

It is difficult to obtain a value for S under 'average' antecedent conditions when 'average' antecedent conditions are not clearly defined. This problem is highlighted in Fig. 1, which shows the range of curve numbers for different antecedent conditions. However, the effects of antecedent soil water content on S are reduced under dry conditions when the relative soil water content is zero (Equation 3). Therefore, a derived value of S under dry conditions is actually the value of S_{mx}. This implies that S and hence the curve number is only limited by the maximum infiltration rate of the soil. In contrast, under wet conditions the reduced soil water deficit can cause large variability in derived curve numbers.

Table 2. Comparison between root mean square error (mm) for daily runoff prediction using either calibrated curve numbers or curve numbers calculated from rainfall simulator data for nine tillage and amendment treatments

Treatment	Calibrated CN	CN from rainfall simulator
Zero tillage, bare soil	6	5
Zero tillage + manure	5	5
Zero tillage + straw	4	4
Shallow tillage, bare soil	7	7
Shallow tillage + manure	6	6
Shallow tillage + straw	5	4
Deep tillage, bare soil	7	7
Deep tillage + manure	5	6
Deep tillage + straw	5	5

The relationships between curve number and antecedent soil water depicted in Fig. 1 can be used to adjust a curve number derived under dry conditions (CN_1) to a curve number under average antecedent conditions (CN_2). This approach requires an assumption of a soil water content that represents average antecedent conditions. In this study, 50% of soil water content at saturation was used and resulted in a CN-CALC under bare conditions of 91, which is close to the CN-CALIB value of 94. This approach is different to previous work where curve numbers for a range of antecedent soil water conditions have been obtained with the median value providing an estimate of CN_2. By using this approach, the value of CN_2 under bare conditions is approximately 85 (Fig. 2). The approach used in this paper, involving rainfall simulation on a dry soil and then adjustment of the curve number from CN_1 to CN_2, has some physical basis. Under dry conditions, the maximum infiltration rate of the soil, rather than soil water deficit, limits the volume of runoff. Therefore, the effects of soil water deficit on runoff are minimal and have been explicitly accounted for.

The use of rainfall simulator data obtained under dry conditions is also supported by the regression equations for wet and dry conditions (equations 7 and 8). An R^2 value of 0·86 was obtained for the relationship between cover and curve number under dry conditions. This is in contrast to the poor R^2 value of 0·16 obtained under wet conditions. Therefore, in this study, values of CN_1 should be more reliable. The hard-setting nature of the Alfisol would be favourable in determining CN_1 since the surface layer would influence the maximum infiltration rate.

The use of a constant rain intensity during the rainfall simulation may influence these results. The accuracy of CN-CALC values under dry conditions derived from rainfall simulator experiments at different rainfall rates or for different soils is yet to be determined.

Relationships between curve number and cover obtained from rainfall simulation show a nearly linear response (equations 7 and 8). However, the slopes of the relationships between curve number and cover that were derived from calibration (equation 5) and simulator data (equations 7 and 8) were different. In equation (5), the curve number under bare conditions declines by 35 at 100% cover. This is in contrast to the decline of 25 units that was shown in equation (8). However, differences between these relationships would be compensated by the difference between the values of CN-CALC (91) and CN-CALIB (94) for bare conditions. For example, Fig. 3 reveals that at 50% cover, CN-CALC is 78·5 (91−12·5) and CN-CALIB is 76·5 (94−17·5).

The final decision to use a rainfall simulator to derive curve numbers would be purely economic because experimental runoff plots are expensive to establish and maintain. In this study, curve numbers derived from rainfall simulators provided similar results to those obtained from model calibration against experimental runoff data.

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