Use of soil moisture data and curve number method for estimating runoff in the Loess Plateau of China

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Abstract:

The Soil Conservation Service curve number (CN) method commonly uses three discrete levels of soil antecedent moisture condition (AMC), defined by the 5-day antecedent rainfall depth, to describe soil moisture prior to a runoff event. However, this way may not adequately represent soil water conditions of fields and watersheds in the Loess Plateau of China. The objectives of this study were: (1) to determine the effective soil moisture depth to which the CN is most related; (2) to evaluate a discrete and a linear relationship between AMC and soil moisture; and (3) to develop an equation between CN and soil moisture to predict runoff better for the climatic and soil conditions of the Loess Plateau of China. The dataset consisted of 10 years of rainfall, runoff and soil moisture measurements from four experimental plots cropped with millet, pasture and potatoes. Results indicate that the standard CN method underestimated runoff depths for 85 of the 98 observed plot-runoff events, with a model efficiency $E$ of only 0.243. For our experimental conditions, the discrete and linear approaches improved runoff estimation, but still underestimated most runoff events, with $E$ values of 0.428 and 0.445 respectively. Based on the measured CN values and soil moisture values in the top 15 cm of the soil, a non-linear equation was developed that predicted runoff better with an $E$ value of 0.779. This modified CN equation was the most appropriate for runoff prediction in the study area, but may need adjustments for local conditions in the Loess Plateau of China. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS SCS CN method; soil moisture; runoff; Loess Plateau

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INTRODUCTION

The wind-deposited loess soils in the middle reaches of the Yellow River of China are among the most erodible in the world and cover about 620,000 km$^2$ in five provinces. Approximately 280,000 km$^2$ of this area has annual soil losses averaging 40 to 50 Mg ha$^{-1}$, with high values of 100 to 200 Mg ha$^{-1}$. These large quantities of eroded sediment are transported to the Yellow River, where they degrade water quality and rapidly fill reservoirs. This severe erosion problem is caused by the high intensity of summer rainstorms, steep slopes, and sparse vegetative covers that contribute to increase the amount of runoff. In order to decrease soil erosion, maintain land productivity and improve environmental quality in the Loess Plateau, a series of soil conservation practices is being implemented. These include tree plantations, establishment of pasturelands, and construction of terraces and dams. An appropriate method to predict surface runoff from different land uses is essential for the design of these soil conservation works.

The curve number (CN) method, developed by the USDA–Soil Conservation Service (USDA–SCS, 1972), for estimating surface runoff from a single rainfall event, is widely accepted in the world. Although originally developed for the design of soil conservation structures, the CN method has evolved beyond its original objective and has been adopted for urbanized and forested watersheds (USDA–SCS, 1986) and as an integral part of more complex simulation models such as CREAMS (Knisel, 1980), EPIC (Sharpley and Williams, 1990), SWAT (Arnold et al., 1990), PERFECT (Littleboy et al., 1992), and AGNPS (Young et al., 1994). The advantages of this method include its simplicity and the use of a single parameter, CN (Ponce and Hawkins, 1996; Bhuyan et al., 2003), which represents soil, land use, antecedent soil moisture, and hydrological conditions of a field or watershed.

The CN method has been evaluated in the Loess Plateau of China (Luo et al., 2002; Xu et al., 2002; Zhang et al., 2003a and b), and a common problem encountered is the absence of significant relationship between the 5-day antecedent rainfall depth and measured CN values, resulting in large errors in runoff volume estimation (Luo et al., 2002; Zhang et al., 2003a and b). Determination of the antecedent moisture condition (AMC) plays an important role in selecting the appropriate CN value. The
CN method uses the 5-day antecedent rainfall amount prior to a rainfall event to select three levels of AMC: dry (AMC1), average (AMC2), and wet (AMC3), and a correction for growing and dormant seasons. The CN value is adjusted for the AMC level to account for the effect of soil moisture conditions on runoff depth. The use of three discrete AMC levels implies a sudden jump in the CN value from one level to another (Hawkins, 1978). Values of CN can be determined experimentally based on measured rainfall and runoff depth from experimental plots or watersheds. Measured values of CN are not limited to the three categories defined by the 5-day AMC, but can assume the whole spectrum of CN values (Rallison and Cronshey, 1979). Other methods have been proposed to refine the AMC in order to improve runoff estimation by the CN method. The antecedent precipitation index (API), developed by Kohler and Linsley (1951), is often used to select the most appropriate AMC level. Perrone and Madramootoo (1997) used the API, based on the 15-day antecedent rainfall, to determine a value of CN:

\[
API = \sum_{j=1}^{15} k^j P_j
\]  

where \(P\) is the precipitation on the \(j\)th day before a runoff event and \(k\) is a decay constant (<1). The API is commonly used because it uses readily available precipitation data. However, there is no physical basis for the relationship between the API and the actual soil ACM (Singh, 1989). In addition, the relationship between API and CN was developed for the humid climate of eastern Canada and may not be applicable to regions with different climatic conditions.

Improved knowledge of antecedent moisture would greatly enhance rainfall runoff prediction (Wood, 1976; Michele and Salvadori, 2002). Because soil moisture is the most important factor defining the initial abstraction of the CN method, an alternative solution to characterize the AMC would be to use direct measurements, or estimated values, of soil moisture prior to a rainfall event, rather than using antecedent rainfall. Saxton (1992) proposed a definition of AMC that is a step function of soil moisture in the top 15 cm of the soil (SM15), where AMC1 corresponds to an SM15 less than 60% of field capacity (FC), AMC2 to an SM15 ranging from 60% to 100% of FC, and AMC3 to an SM15 greater than FC. In the case of Saxton (1992), soil water content was estimated from a simplified soil water budget based on rainfall and lake evaporation. The approach of Saxton (1992) has the advantage, over that of the API method, of allowing the determination of an AMC value that is independent of the rainfall characteristics. However, that approach still suffers from step changes of the CN value at specific soil moisture values.

Koelliker (1994) proposed a concept where CN varies linearly with the soil water content in the top 30 cm of the soil (SM30). The slope and intercept of the linear equation are found by regression using values of CN1, CN2 and CN3 corresponding to 50%, 70% and 90% of FC respectively. Above 90% of FC the CN is assumed to be equal to CN3. This method offers the advantage of avoiding abrupt changes between CN values resulting from changes in AMC. A continuous relationship between CN and soil moisture in the top 100 cm (SM100) has also been implemented in the EPIC (Sharpley and Williams, 1990) and SWAT (Arnold et al., 1990) models. This relationship is highly non-linear and requires values of FC, wilting point, total porosity, and two shape parameters. In Oklahoma, Jacobs et al. (2003) used remotely sensed soil moisture to adjust the CN for estimating runoff from five watersheds, ranging from 2.8 to 601.6 km², and characterized by a sub-humid climate. They developed a non-linear function defining CN from the soil moisture in the upper 5 cm of soil. Using their CN, instead of the CN of the standard method, reduced by nearly 50% the root-mean-square error and the mean absolute error on runoff volume.

Soil moisture appears to be a better criterion than the 5-day antecedent rainfall depth to select an appropriate AMC value. However, it is not clear which soil depth is best to determine AMC; the literature reviewed mentioned soil depths of 5, 15, 30 and 100 cm. Also, several relationships have been proposed to relate CN to AMC, from a simple change by steps, to linear or more complex functions.

The objectives of this study were: (1) to determine the effective soil depth over which soil moisture is most related to the measured CN; (2) to evaluate a discrete (Saxton, 1992) and a linear (Koelliker, 1994) relationship between CN and soil moisture to improve the estimation of runoff volume, and (3) to develop a relationship between CN and soil moisture to predict runoff better for the climatic and soil conditions observed in the Loess Plateau of China. These objectives will be achieved using measured rainfall, runoff, and soil moisture data obtained from test plots located in an experimental watershed during a 10-year period.

THE CURVE NUMBER METHOD

The CN method (USDA–SCS, 1972) is based on a water balance and two fundamental hypotheses. The first hypothesis states that the ratio of direct runoff to potential maximum runoff is equal to the ratio of infiltration to potential maximum retention. The second hypothesis is that the initial abstraction is some fraction of the potential maximum retention. Expressed mathematically, the water balance is

\[
P = I_a + F + Q
\]

and the two hypotheses are:

\[
\frac{Q}{P - I_a} = \frac{F}{S}
\]

and

\[
I_a = \lambda S
\]
The value of evaporation is 1570 mm (Xu, 2004). The climate in the area of the experimental site is semi-arid with average temperature of 8°C and annual precipitation of 485 mm, of which 62% falls from June to September.

The standard CN method assigns a value of 0-2 to the initial abstraction ratio (λ = 0.2). However, values of λ ranging from 0-0 to 0-3 have been reported in a number of studies over various geographical locations of the USA and other countries (Springer et al., 1980; Cazier and Hawkins, 1984; Ramasastri and Seth, 1985; Bosznay, 1989). With λ = 0.2, Equation (5) reduces to the well-known SCS CN equation (USDA–SCS, 1972):

\[
Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{for } P > 0.2S \tag{6a}
\]
\[
Q = 0 \quad \text{for } P \leq 0.2S \tag{6b}
\]

The value of S is defined as

\[
S = \frac{25400}{CN} - 254 \tag{7}
\]

where CN ranges from 0 to 100. A CN₂ value is determined from land cover, land management, and the hydrologic soil group using a table from USDA–SCS (1972). The CN₂ from that table corresponds to an average moisture condition and is adjusted based on the 5-day prior rainfall depth considering whether the crop is in the dormant or growing season.

When experimental rainfall and runoff data are available, measured values of CN can be obtained from Equation (7) after S has been back calculated from Equation (6) (Hawkins, 1973):

\[
S = 5[(P + 2Q) - \sqrt{(4Q + 5P)]} \tag{8}
\]

**MATERIALS AND METHODS**

**Site description**

This study was conducted in a 4.7 km² experimental watershed located at 109°47'E and 37°31'N, 4.8 km from the city of Suide in the Loess Plateau of China (Figure 1). The climate in the area of the experimental site is semi-arid with normal (1957–2000) annual temperature of 8°C and annual precipitation of 485 mm, of which 62% falls from June to September. The average annual lake evaporation is 1570 mm (Xu, 2004).

From a loess parent mantle, 10 to 100 m deep, the soil cover developed as silty loam soils (FAO–UNESCO, 1988). Soil physical and chemical properties vary very little with the position along the hillslopes of the experimental watershed (Zhu, 1989). Soil particle size distribution and physical characteristics are very similar within the 0–30 cm layer, with average values of 30-1% for sand, 61-9% for silt, 8-0% for clay, 0-45% for organic matter, 1-34 Mg m⁻³ for soil bulk density, 0-058 cm³ cm⁻³ for wilting point, 0-212 cm³ cm⁻³ for field capacity (Yang and Shao, 2000), and 5-0 mm h⁻¹ for the minimum infiltration rate (Yang et al., 2005).

**Field experiments and data collection**

This experiment consisted of four experimental plots (Table I) and four corresponding control plots. All plots were 20 m in length, 10 or 15 m in width, and slopes ranged from 40-4 to 57-7%. These steep slopes are representative of the cultivated fields of the region, which are always greater than 30%, and can be as high as 100% (Zhu, 1989). Millet and potatoes are the main crops, with pasture used for sheep.

Each experimental plot was border dyked, and surface runoff was collected at the downstream end of each plot by a funnel-type collector and directed into two aluminium containers (0-6 m in diameter and 1-2 m deep) connected in series such that one-third of the first container overflow was collected by the second container (Figure 2). Beside each experimental plot was a control plot with the same characteristics (soil, vegetative cover, management practices, etc.). These control plots were used to measure soil water content in the soil profile. Soil water content measurements were not done in the experimental plots to avoid modifications of the infiltration characteristics that could cause errors in measured runoff.

Because most rainfall and runoff occurred between June and October of each year, measurements were taken...
only during that period. Daily weather data (rainfall, temperature, wind speed, humidity, solar radiation), from a weather station located 100 m from the experimental plots, were obtained during the study period, and daily actual evapotranspiration was calculated by applying appropriate crop coefficients to the reference evapotranspiration computed by the Penman method (Doorenbos and Pruitt, 1977). Rainfall and runoff volumes were compiled on a per-storm basis by The Yellow River Administration Committee of the Ministry of Water Resources (1961, 1963, 1965, 1967, 1970). Because of the reduced surface area exposed to rainfall for sloping plots, measured runoff depths from all plots were adjusted to that of an equivalent horizontal plot by

\[ R_m = \frac{R'_m}{\cos \theta} \]  

where \( R_m \) (mm) is the corrected runoff depth, \( R'_m \) (mm) is the measured runoff depth, and \( \theta \) (rad) is the slope.

The theoretical CN₂ values, determined for each plot based on vegetation, land use and soil group using the table in USDA–SCS (1972) were 76 for millet, 79 for corn, and 81 for potatoes. During the 10 years of the experiment, the mean rainfall depth of a runoff generating pasture, and 81 for potatoes. During the 10 years of the experiment, the mean rainfall depth of a runoff generating storm event was 20.5 mm and the mean runoff depth 3.37 mm (Table II).

Soil water measurements were taken by gravimetric method every 5 days from the soil surface down to a depth of 100 cm. Additional measurements were taken 2 to 3 h after the end of each runoff event to make sure the soil water profile was at equilibrium. Soil water content measurements were done by 10 cm increments from depths of 10 to 100 cm, and were replicated at three locations in the plots: upstream, middle, and downstream of the plots. Statistical comparisons of soil water contents from these three positions did not show significant differences at the 0.05 probability level. For each measurement depth and date, a single soil water content value was computed by averaging the three replicated measured values. From these averaged measurements, values of SM₁₅ (0–15 cm), SM₃₀ (0–30 cm), SM₆₀ (0–60 cm) and SM₁₀₀ (0–100 cm) were computed. The SM values measured just after a runoff event and the regular 5-day measurements were used to estimate the SM values just before the beginning of a runoff event, providing an estimate, therefore, of the antecedent moisture content to be used with the CN method (USDA–SCS, 1972). The SM values at the beginning of a runoff event were obtained as follows. (1) If the beginning of a runoff-generating storm occurred after no more than 24 h of a regular 5-day interval soil water content measurement, then the SM values were calculated from the regular soil water content values measured at the beginning of storm events. (2) Otherwise, they were calculated using the following procedure: first, the 5-day interval soil moisture profile measured before a runoff event was adjusted to take into account soil water changes due to actual evapotranspiration and rainfall that occurred between that measurement and the beginning of the runoff event; second, the depth of infiltration \( D_i \) was determined by comparing the adjusted soil water content profile to that measured after the runoff event; third, assuming that the infiltrated water was uniformly distributed over the infiltration depth, the SM values at the beginning of a runoff event were calculated as

\[ SMB_d = SMR_d - \frac{ET^c - P^*}{D_i} = SME_d - \frac{P - R}{D_i} \]  

where SMB, SMR and SME (mm) are average soil moistrures in the profile at the beginning of a runoff event (SMB), measured on a regular 5-day interval prior to a runoff event (SMR), and at the end of a runoff event (SME), \( d \) is the depth of the profile considered, i.e. 15, 30, 60 or 100 cm, \( P \) (mm) and \( R \) (mm) are respectively the precipitation and runoff during the runoff event, \( ET^c \) (mm) and \( P^* \) (mm) are respectively the crop evapotranspiration and precipitation between measurement of SMR and estimation of SMB, and \( D_i \) (mm) is the depth of evapotranspiration depletion soil

<table>
<thead>
<tr>
<th>Plot</th>
<th>Average no. runoff events per year</th>
<th>Rainfall depth (mm)</th>
<th>Average rainfall intensity (mm h⁻¹)</th>
<th>Runoff depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>1</td>
<td>4.3</td>
<td>21.9</td>
<td>17.8</td>
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<tr>
<td>2</td>
<td>4.3</td>
<td>21.9</td>
<td>17.8</td>
<td>9.0</td>
</tr>
<tr>
<td>3</td>
<td>6.8</td>
<td>19.8</td>
<td>15.3</td>
<td>10.8</td>
</tr>
<tr>
<td>4</td>
<td>5.3</td>
<td>19.7</td>
<td>15.0</td>
<td>13.2</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>20.5</td>
<td>15.9</td>
<td>10.8</td>
</tr>
</tbody>
</table>

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water determined by comparing the adjusted soil water profiles without rainfall. If $D_i$ was less than $d$, then $D_i$ was set to $d$; otherwise, $D_i$ kept its actual value.

**Data analysis**

Comparisons between the runoff depths measured and estimated by the proposed methods were done with the coefficient of determination $R^2$, the slope and intercept of the regression equations (procedure REG in SAS (1998)), and the model efficiency $E$ (Nash and Sutcliffe, 1970; Risse et al., 1994):

$$E = 1 - \frac{\sum_{i=1}^{n} (R_i - R_i^*)^2}{\sum_{i=1}^{n} (R_i - \overline{R})^2}$$ (11)

where $R_i$ (mm) is the measured runoff depth for storm event $i$, $R_i^*$ (mm) is the estimated runoff depth for storm event $i$, $n$ is the total number of storm events, and $\overline{R}$ (mm) is the average of measured runoff for all storm events. The model efficiency $E$ is a complement to $R^2$ because $E$ compares predicted and observed values to the 1:1 line rather than to the best linear regression line. Model efficiency will always be less than $R^2$; and lower $E$ values indicate larger differences between predicted and observed values.

For non-linear models between SM and CN, shape parameters were optimized using PEST-ASP (Doherty, 2002), with the minimum least-square error (LSE) as the objective function:

$$LSE = \min \sum_{i=1}^{n} (R_i - R_i^*)^2$$ (12)

This objective function was chosen for its ability to produce stable estimates of the parameters (McCuen and Synder, 1986).

**RESULTS AND DISCUSSION**

**Standard curve number method**

For each plot-runoff event, the runoff depths were estimated from the CN values of the SCS handbook (USDA–SCS, 1972) and the measured 5-day antecedent rainfall depth and compared with the measured runoff depths in Figure 3. This figure shows that the standard CN method underestimates most of the small runoff events, and about half of the events greater than 10 mm. This underestimation by the standard CN method can also be seen by the regression slope of 0.771 and the intercept of $-0.679$ (Table III). Underestimation of runoff events by the USDA–SCS (1972) method has been reported by Van Mullen (1991) for rangeland and by King et al. (1999) for cropland. The standard CN method underestimated the runoff depths for 85 of the 98 plot-runoff events, with a low $E$ value of 0.243.

Several factors might cause the standard CN method to underestimate runoff depth, but the AMC is considered one of the most influential (Bhuyan et al., 2003; Jacobs et al., 2003).

Based on measured rainfall and runoff depths, actual values of CN ($CN_m$) were calculated using Equations (6), (7), and (8). Measured and tabulated CN values are shown in Figure 4 as a function of the 5-day antecedent rainfall depth. This figure shows that there is no evident relationship between $CN_m$ and the 5-day AMC, and that tabulated CN values are almost always less than measured values, which confirms the underestimation of runoff depth. Based on data from over 800 station-years in Kansas, Koelliker (1987) evaluated the 5-day AMC and found that AMC2 is not a reasonable assumption for the average soil moisture condition; the probability of an AMC2 condition occurring prior to a runoff-generating storm was only 7%, instead of 50% (Hjelmfelt et al., 1982). These observations explain the underestimation of runoff depth by the standard SCS method, since it underestimates the AMC value, which results in underestimated runoff. Therefore, the 5-day AMC used by the standard CN method is not a reasonable

<table>
<thead>
<tr>
<th>Method</th>
<th>SM</th>
<th>$\lambda$</th>
<th>Linear regression</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Intersect</td>
<td>Slope</td>
</tr>
<tr>
<td>CN</td>
<td>n.a.</td>
<td>0.2</td>
<td>-0.679</td>
<td>0.771</td>
</tr>
<tr>
<td>Saxton</td>
<td>0.2</td>
<td>0.2</td>
<td>-0.594</td>
<td>0.535</td>
</tr>
<tr>
<td>Koelliker</td>
<td>0.2</td>
<td>1.277</td>
<td>1.106</td>
<td>0.708</td>
</tr>
<tr>
<td>Method 1</td>
<td>0.2</td>
<td>1.120</td>
<td>0.967</td>
<td>0.776</td>
</tr>
<tr>
<td>Method 2</td>
<td>0.2</td>
<td>1.073</td>
<td>0.963</td>
<td>0.740</td>
</tr>
<tr>
<td>Method 3</td>
<td>0.001</td>
<td>0.157</td>
<td>0.864</td>
<td>0.791</td>
</tr>
</tbody>
</table>

*Note: all statistics based on 98 plot-runoff events.*

*b Method 1: Equation (14) with SM equal to SM$_{15}$ ($\lambda = 0.2$).*

*c Method 2: Equation (14) with SM equal to SM$_{10}$ ($\lambda = 0.2$).*

*d Method 3: Equation (14) with SM equal to SM$_{15}$ ($\lambda = 0.001$).*
assumption for most storms in the study area. Because in the CN method the soil moisture is directly related to the initial abstraction (Sharpley and Williams, 1990; Saxton, 1992; Koelliker, 1994; Jacobs et al., 2003), the relationship between CNm and soil moisture at different soil depths need to be examined to determine the effective soil depth that affects most CN values.

Relationships between curve number and soil moisture

The effect of the theoretical CN2 values involved in the study, i.e. 81 for millet, 79 for pasture, and 76 for potatoes, was removed by expressing CNm as the ratio CNm/CN2. Figure 5 shows the relationships between CNm/CN2 and SM15, SM30, SM60, and SM100. A non-linear relationship can be seen between CNm/CN2 and SM15, and CNm/CN2 and SM30, but SM60 and SM100 do not appear to be strongly related to CNm/CN2. The depth of infiltration, determined by comparing adjusted soil...
moisture profiles with those measured after the storms, showed that the mean depth of infiltration was 42 cm, ranging from 10 to 80 cm. Therefore, it is reasonable that SM₆₀ and SM₁₀₀ have little impact on CNₘ/CN₂. The remainder of this paper will, therefore, focus on AMC in relation to SM₁₅ and SM₃₀.

Approaches of Saxton (1992) and Koelliker (1994)

Runoff depths measured and estimated by the AMC–SM₁₅ relationship of Saxton (1992) are compared in Figure 6. This figure shows some improvements over Figure 3, with less scatter and a reduced underestimation in the 5–10 mm range of measured runoff. These visual observations are confirmed by an $R^2$ of 0.673, compared with 0.486 for the standard CN method, and an $E$ value of 0.428, compared to 0.243 (Table III). However, the slope of the regression line is 0.535 and the intercept $-0.594$, which implies that the Saxton (1992) approach underestimated most runoff events.

Estimated runoff depths computed with the linear AMC–SM₃₀ relationship of Koelliker (1994) are compared with measured values in Figure 6. Compared with Saxton (1992), the Koelliker (1994) approach improved runoff estimation for most runoff events, with more points close to the 1:1 line. That better performance can be seen in Table III, where the slope of the regression line is 1.106 but the intercept is $-1.277$, which still means an underestimation of small runoff events. The $E$ value resulting from the Koelliker (1994) approach shows only a small improvement over that of Saxton (1992), i.e. 0.445 versus 0.428. Because of their low $E$ values, and generally poor performance, the Koelliker (1994) and Saxton (1992) approaches have limited applications in the study area. From Figure 5, we can see that CNₘ/CN₂ increases non-linearly, in a convex fashion, with SM₁₅ and SM₃₀, rather than by steps (Saxton 1992) or linearly (Koelliker 1994). This observation points to the possibility of improving runoff prediction by a non-linear AMC–SM₁₅, or AMC–SM₃₀, equation that could be parameterized for the conditions of the Loess Plateau.

An equation for adjusting curve number for the Loess Plateau

An improved value of CN for a given soil moisture condition can be determined by multiplying the SCS handbook CN₂, taken as a reference value, by a soil moisture function:

$$CN = CN₂ f(SM)$$

where SM is soil moisture (SM₁₅ or SM₃₀) and $f(SM)$ is a non-linear function. After several trials, we determined a two-parameter ($a₁$ and $a₂$) equation for CN:

$$CN = CN₂ \frac{SM}{a₁ + a₂ SM}$$

Similar to Saxton (1992) and Koelliker (1994), we assumed that CN₁ corresponded to SM equal to a fraction $f₁$ of FC (SM = $f₁FC/100$), and CN₃ to SM equal to a fraction $f₃$ of FC (SM = $f₃FC/100$), such that Equation (14) results in

$$CN₁ = CN₂ \frac{f₁(FC/100)}{a₁ + a₂[f₁(FC/100)]}$$

$$CN₃ = CN₂ \frac{f₃(FC/100)}{a₁ + a₂[f₃(FC/100)]}$$

From Equation (15a) and (15b), $a₁$ and $a₂$ can be determined thus:

$$a₂ = CN₂ \frac{f₃CN₁ - f₁CN₃}{CN₁CN₃(f₃ - f₁)}$$

$$a₁ = \frac{(CN₂ - a₂CN₁)f₁FC}{100CN₁}$$

Figure 6. Measured versus estimated runoff depth by two published methods
Replacing $a_1$ and $a_2$ of Equation (14) by their respective values of Equations (16a) and (16b) relates the actual CN to the tabulated CN, the antecedent soil moisture SM$_{15}$ or SM$_{30}$, and two fractions of FC, i.e. $f_{r_1}$ and $f_{r_3}$. Knowing FC, CN$_1$, CN$_2$ and CN$_3$ for each experimental plot, Equations (14), (16a) and (16b) were optimized for $f_{r_1}$ and $f_{r_3}$ using the 98 measured and estimated runoff depths. The advantage of rewriting Equation (14) in terms of $f_{r_1}$ and $f_{r_3}$ is that the values of $f_{r_1}$ and $f_{r_3}$ can be easily determined for other land uses and soil types in the Loess Plateau.

The non-linear approach described above was termed Method 1 when using SM$_{15}$ and Method 2 when using SM$_{30}$, with $\lambda = 0.2$ in both cases. For Method 1, optimized values of $f_{r_1}$ were 42% for CN$_1$ and 100% for CN$_3$, whereas $f_{r_3}$ values of 45% and 100% were obtained for Method 2. Parameters $a_1$ and $a_2$ vary according to the vegetative cover, as shown in Table IV. Runoff depths, measured and estimated by Methods 1 and 2, are shown in Figure 7, with statistics in Table III. Method 1 performed better than Method 2 in estimating runoff depths with $E$ values of 0·660 and 0·608 respectively, and $R^2$ of 0·776 and 0·740 respectively. However, the difference in the performance of Methods 1 and 2 remains small, with the latter having an intercept of the linear regression slightly closer to 0·0 (Table III). Because the infiltration depth averaged 42 cm for the 98 storm events considered, soil moisture conditions were not likely very different between the 0–15 and the 0–30 cm soil depths, resulting in little variation in runoff depth whether SM$_{15}$ or SM$_{30}$ was used. The small effect of SM$_{15}$ or SM$_{30}$ on runoff can also be seen in Figure 5. Considering the visual and statistical criteria used, SM$_{15}$ is better than SM$_{30}$ to define AMC in the study area. Compared with the Saxton (1992) and Koelliker (1994) approaches, Method 1 produced better estimated runoff values. The slope of the regression line between measured and estimated runoff values is 0·967, compared with 0·535 for Saxton (1992) and 1·106 for Koelliker (1994), whereas $E$ was increased to 0·660, compared with 0·428 and 0·445 respectively.

However, use of Method 1 still resulted in an underestimation of runoff depth for small events, with an intercept of the linear regression of −1·120. Underestimation of small runoff for small storm events might be inherent to the SCS method due to the adoption of the 0·2 value for the initial abstraction ratio, defined in Equation (5) (Mishra and Singh, 1999). Therefore, the value of 0·2 for the initial abstraction ratio might not be appropriate for the climatic and soil conditions prevailing in the Loess Plateau.

In order to improve the CN method, we optimized $\lambda$, as well as $f_{r_1}$ and $f_{r_3}$, in Equations (14), (16a) and (16b) (Method 3). This optimization assumed that the CN$_2$ values of the USDA–SCS (1972) handbook are reference values not affected by the initial abstraction ratio, and

<table>
<thead>
<tr>
<th>Vegetative cover</th>
<th>CN$_2$</th>
<th>$\lambda$</th>
<th>AMC$_1$ (% of FC)</th>
<th>AMC$_3$ (% of FC)</th>
<th>$a_1$</th>
<th>$a_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1: SM$_{15}$ and $\lambda = 0.2$</td>
<td>Millet</td>
<td>76</td>
<td>0.2</td>
<td>45</td>
<td>100</td>
<td>0·076</td>
</tr>
<tr>
<td></td>
<td>Pasture</td>
<td>79</td>
<td>0·2</td>
<td>45</td>
<td>100</td>
<td>0·066</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>81</td>
<td>0·2</td>
<td>45</td>
<td>100</td>
<td>0·060</td>
</tr>
<tr>
<td>Method 2: SM$_{30}$ and $\lambda = 0.2$</td>
<td>Millet</td>
<td>76</td>
<td>0·2</td>
<td>42</td>
<td>100</td>
<td>0·067</td>
</tr>
<tr>
<td></td>
<td>Pasture</td>
<td>79</td>
<td>0·2</td>
<td>42</td>
<td>100</td>
<td>0·059</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>81</td>
<td>0·2</td>
<td>42</td>
<td>100</td>
<td>0·053</td>
</tr>
<tr>
<td>Method 3: SM$_{15}$ and $\lambda = 0.001$</td>
<td>Millet</td>
<td>76</td>
<td>0·001</td>
<td>73</td>
<td>100</td>
<td>0·255</td>
</tr>
<tr>
<td></td>
<td>Pasture</td>
<td>79</td>
<td>0·001</td>
<td>73</td>
<td>100</td>
<td>0·223</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>81</td>
<td>0·001</td>
<td>73</td>
<td>100</td>
<td>0·202</td>
</tr>
</tbody>
</table>

Figure 7. Measured versus estimated runoff depth by Methods 1 and 2
representing the effect of soil and cover characteristics on the runoff process. The optimized parameters, presented in Table IV in terms of λ, AMC1 and AMC3, show a λ value of 0.001, much less than the standard value of 0.2, but still in the 0.0–0.3 range observed by other researchers. Values of λ ranging from 0.000 to 0.042 were obtained by Mishra and Singh (1999) for three watersheds less than 1 km² in the USA and for one 3124 km² watershed located in India, respectively. Whereas AMC3 is constant for Methods 1, 2, and 3, the value of AMC1 increased from 42–45% for Methods 1 and 2 to 73% for Method 3. Compared with Method 1, the increased AMC1 of Method 3 indicates a lower CN, which does not necessarily result in less runoff because the value of λ is much lower for Method 3 than for Method 1. The combined effect of λ and AMC can be seen in Figure 8, which shows the relationships between rainfall and runoff estimated by Methods 1 and 3 for two soil moisture conditions, SM = 0.20 and 0.10 cm³ cm⁻³, and a field cropped with millet. The main effect of the reduction of λ from 0.2 (Method 1) to 0.001 (Method 3) is to increase runoff for small rainfall events while leaving runoff relatively unchanged for larger rainfalls.

A comparison of measured and estimated runoff depths by Method 3, presented in Figure 9, shows that the runoff estimation for small events is much improved over Methods 1 and 2, with observation points close to the 1:1 line even for runoff depths between 10 and 30 mm. The statistics in Table III confirm the predictive capacity of Method 3 with an intercept of 0.157, a slope of 0.864, \( R^2 = 0.791 \), and a model efficiency of 0.779. Apart from the regression slope, which deviates slightly more from the 1:1 line than Method 2, the other statistics are better than those obtained with any of the other four methods. Therefore, based on the results obtained from the experimental site, the use of SM₁₀ with a non-linear equation and a value of λ of 0.001 (Method 3) is the most appropriate for runoff prediction with the CN method in the study area, and possibly in the Loess Plateau.

Because Method 3 was developed on land with slopes of 40.4–57.7%, it needs to be validated for other slope conditions. Since soil and climatic conditions vary in the Loess Plateau, Method 3 may need to be adjusted for local conditions.

The difficulty with the proposed approach is the knowledge of soil moisture prior to a rainfall event. In theory, soil moisture can be estimated from a simple soil water balance based on rainfall and potential evapotranspiration. Such a soil water balance has been developed and used in the Loess Plateau and other regions of the world for different purposes, such as irrigation design (Huang et al., 2004; Papajorgji and Shatar, 2004), water-use efficiency estimation (Fan et al., 2005; Huang et al., 2005), crop yield simulation (Kang et al., 2001), and runoff prediction (Mishra and Singh, 2003). The combination of the CN method and Equation (14) can be used to improve runoff estimation in the study area as a part of more complex simulation models such as SWAT (Arnold et al., 1990) and AGNPS (Young et al., 1994). These two models have been tested by the Chinese Agricultural and Forestry Ministry for estimating runoff, soil erosion and pollutant losses in the Loess Plateau, but their use resulted in large errors for runoff estimation (Zhang et al., 2003a and b; Zhang and Zhen, 2004). Incorporating Method 3 in these models may contribute to reduce the simulation error when used in the study area.

**CONCLUSIONS**

A 10-year experiment, consisting of four plots and three land uses, i.e. millet, pasture and potatoes, was conducted to develop a relationship between CN and the antecedent soil moisture to predict runoff better for the climatic and soil conditions observed in the Loess Plateau of China. The following conclusions can be drawn from this study:
1. The standard CN method underestimated the runoff depths of 85 out of the 98 plot-runoff events, with a model efficiency of 0.243.

2. We observed a non-linear relationship between the measured CN values and soil moisture in the 0–15 cm (SM15) and the 0–30 cm (SM30) soil depths.

3. A discrete and a linear relationship between CN and SM15 and SM30 were evaluated, resulting in a model efficiency of 0.428 for the discrete approach and 0.445 for the linear approach. These approaches have limited application in the study area.

4. A non-linear equation was developed between CN and SM15 based on observed values, and its application to runoff prediction resulted in a model efficiency of 0.660.

5. Model efficiency was increased to 0.779 by using an optimized value of the initial abstraction ratio of 0.001 instead of the standard value of 0.2. That method appears to be the most promising for runoff prediction in the study area of the Loess Plateau, but may need adjustment for variations of soil, climatic and topographic conditions.

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