Hydrol. Earth Syst. Sci. Discuss., 9, 4193–4233, 2012
www.hydrol-earth-syst-sci-discuss.net/9/4193/2012/
doi:10.5194/hessd-9-4193-2012

Hydrology and Earth System Sciences Discussions

Coupling the modified SCS-CN and RUSLE models to simulate hydrological effects of restoring vegetation in the Loess Plateau of China

G. Y. Gao[1,2], B. J. Fu[1], Y. H. Lü[1], Y. Liu[1,3], S. Wang[1], and J. Zhou[1]

[1]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 100085 Beijing, China
[2]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100 Shaanxi, China
[3]Lab for Agriculture and Environment, Institute of Remote Sensing Applications, Chinese Academy of Sciences, 100101 Beijing, China

Received: 19 March 2012 – Accepted: 21 March 2012 – Published: 29 March 2012

Correspondence to: B. J. Fu (bfu@rcees.ac.cn)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Predicting event runoff and soil loss under different land covers is essential to quantitatively evaluate the hydrological responses of vegetation restoration in the Loess Plateau of China. The Soil Conservation Service Curve Number (SCS-CN) and Revised Universal Soil Loss Equation (RUSLE) models are widely used in this region to this end. This study incorporated antecedent moisture condition (AMC) in runoff production and initial abstraction of the SCS-CN model, and considered the direct effect of runoff on event soil loss by adopting a rainfall-runoff erosivity factor in the RUSLE model. The modified SCS-CN and RUSLE models were coupled to link rainfall-runoff-erosion modeling. The effects of AMC, slope gradient and initial abstraction ratio on curve number of SCS-CN, as well as those of vegetation cover on cover-management factor of RUSLE were also considered. Three runoff plot groups covered by sparse young trees, native shrubs and dense tussock, respectively, were established in the Yangjuangou catchment of Loess Plateau. Rainfall, runoff and soil loss were monitored during the rainy season in 2008–2011 to test the applicability of the proposed approach. The original SCS-CN model significantly underestimated the event runoff, especially for the rainfall events that have large 5-day antecedent precipitation, whereas the modified SCS-CN model could predict event runoff well with Nash-Sutcliffe model efficiency (EF) over 0.85. The original RUSLE model overestimated low values of measured soil loss and under-predicted the high values with EF only about 0.30. In contrast to it, the prediction accuracy of the modified RUSLE model improved satisfactorily with EF over 0.70. Our results indicated that the AMC should be explicitly incorporated in runoff production, and direct consideration of runoff should be included in predicting event soil loss. Coupling the modified SCS-CN and RUSLE models appeared to be appropriate for runoff and soil loss simulation at plot scale in the Loess Plateau. The limitations and future study scopes of the proposed models were also indicated.

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1 Introduction

Flash flood and soil erosion affect adversely the natural and human-management ecosystems. In arid and semi-arid regions, water shortage is the key limited factor. Changes in anthropogenic (e.g., land use) and natural (e.g., climate change) forcings will further affect hydrological cycles and water availability at all scales in these regions. Therefore, modeling of the event based rainfall-runoff and soil erosion processes under different land use conditions has significant importance. It has been recognized to be fundamental to a range of applications in hydrological practices.

The Soil Conservation Service Curve Number (SCS-CN) model is a simple and empirical model with clearly stated assumptions and few data requirements to estimate runoff for a given rainfall event (Ponce and Hawkins, 1996). It accounts for the major runoff producing characteristics including soil type, land use/treatment, surface condition and soil moisture condition, and incorporates them in a single CN parameter (Ponce and Hawkins, 1996). Mishra and Singh (2003) summarized the application of the SCS-CN model in storm water modeling for single rainfall events, long-term hydrologic simulation as well as predicting infiltration and rainfall-excess rates, and discussed its potential to simulate sediment yield and transport of urban pollutants. The SCS-CN model has also been adopted by many hydrological and ecological models to determine runoff, such as CREAMS (Knisel, 1980), ANSWERS (Beaslry et al., 1980), AGNPS (Young et al., 1989), EPIC (Sharply and Williams, 1990) and SWAT (Neitsch et al., 2005).

On the other hand, the SCS-CN has its own perceived disadvantages. One of the main weak points is that there exists no explicit guideline on how to vary the antecedent moisture condition (AMC) with the antecedent rainfall of certain duration (Ponce and Hawkins, 1996). The standard SCS-CN model incorporates an empirical method to classify AMC into three distinct levels, viz., AMC I (dry), AMC II (normal) and AMC III (wet), based on the amount of 5-day antecedent precipitation (P_5). However, this method usually led to poor results and failure of SCS-CN model to predict runoff

(Mishra and Singh, 2002; Huang et al., 2007). Therefore, many studies aimed at improving the method and finding a better way to incorporate the AMC (e.g., Mishra and Singh, 2002; Mishra et al., 2006a; Michel et al., 2005; Huang et al., 2007; Sahu et al., 2010).

The Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) and its revised version (RUSLE, Renard et al., 1997) are the most widely used empirical models to predict annual soil loss at field scale resulting from sheet and rill erosion. The USLE/RUSLE models have their advantages over the physically process-based models such as WEPP and EUROSEM because they combine acceptable accuracy with a perceived ease of parameterization and use. However, their applications to storm-based events usually led to large errors (Kinnell, 2005). Risse et al. (1993) and Tiwari et al. (2000) observed that the USLE/RUSLE models overestimated low values of measured soil loss and under-predicted the high values. This result was mainly due to that runoff and soil loss were considered as separate entities without reference to any intrinsic link between them (Kinnell, 2009). In reality, the linkage between runoff and soil loss is quite fundamental as the soil lost from the areas being considered is usually that discharged across the downslope boundary with surface-water flow (Kinnell, 2010). Therefore, the accuracy of USLE/RUSLE models can be improved if they are coupled with a hydrologic rainfall-excess model.

Mishra et al. (2006b) coupled the SCS-CN method with USLE model for computing the lumped quantity of event sediment yield from a number of watersheds. The coupling in Mishra et al. (2006b) was based on three hypotheses needing further verification, especially those that the potential maximum retention parameter (S) of SCS-CN model can be expressed in terms of the USLE parameters and the sediment delivery ratio is equal to the runoff coefficient (Kinnell, 2009). In reality, the logical way to link soil loss and the parameter S should be through the effect of S in predicting runoff ratios rather than through attempts to signify S using USLE (Kinnell, 2009). To consider direct effect of runoff on predicting soil loss, Kinnell (2007) included the runoff ratio in rainfall erosivity index of RUSLE, and applied it to predict event soil loss (Kinnell, 2010; Bagarello

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et al., 2008, 2010). However, runoff and soil loss modeling was decoupled in their studies as the runoff volume was obtained from measurements, not by model prediction. In addition, the approach was only used in bare plots. Its application in plots with different vegetation types needs further investigation.

The Loess Plateau region is located in the middle reaches of the Yellow River basin in Northern China and experiences arid and semi-arid climate condition over an area greater than 600 000 km^2 (Lü et al., 2012). It is one of the most severely eroded areas in the world due to highly erodible loessial soil, steep landscape, frequent large rainfall storms in summer months, and low vegetable cover stemming from intensive cultivation and improper land uses (Zhang and Liu, 2005). In order to alleviate soil erosion and improve environmental quality in the Loess Plateau, a series of soil conservation practices such as Grain-for-Green project have being implemented to augment vegetation recovery. Vast areas of cropland in sloping areas were converted into forestland or grassland in the gully and hilly zones of the Loess Plateau, which altered the land use pattern greatly (Cao et al., 2009). The revegetation resulted in increase of vegetation cover, improvement of soil nutrient levels and recovery of soil properties (Liu et al., 2012). These changes caused significant responses in hydrological function and soil erosion to cropland abandonment for revegetation. As runoff and soil erosion in the Loess Plateau are often dominated by a few storms with high intensity or high precipitation amount in summer (Wei et al., 2009a, 2009b), it is essential to predict event runoff and soil loss under different land covers, which is of great importance for land use planning and water resources management. The SCS-CN and RUSLE models have been applied at plot (Shen et al., 2003; Huang et al., 2006, 2007; Fu et al., 2011) and watershed scales (Fu et al., 2005; Xiao et al., 2011) in the Loess Plateau. After carefully checking these studies, one can find that there is rarely study to explicitly incorporate AMC in SCS-CN model except that Huang et al. (2007) developed an equation between curve number and soil moisture to account for AMC. There is no study to include direct consideration of runoff in predicting event soil loss, and link runoff and soil loss simulation, which will be the focus of this investigation.

The objectives of this study are as follows. First is to incorporate AMC in runoff production and initial abstraction of the SCS-CN model, and consider the direct effect of runoff on event soil loss by adopting a rainfall-runoff erosivity factor in the RUSLE model. Second is to couple the modified SCS-CN and RUSLE models to link the rainfall-runoff-erosion modeling. Third is to apply the proposed approach to predict event runoff and soil loss from restoring vegetation plots in the Loess Plateau of China.

2 Model theory

2.1 Rainfall-runoff modeling

2.1.1 Original SCS-CN model

The SCS-CN method is based on the principle of the water balance and two fundamental assumptions (Mishra and Singh, 2002). The first assumption is that the ratio of direct runoff to potential maximum runoff is equal to the ratio of infiltration to potential maximum retention. The second assumption states that the initial abstraction is proportional to the potential maximum retention. The water balance equation and the two assumptions are expressed mathematically respectively, as:

$$P = I_{\mathrm{a}} + F + Q \tag{1}$$

$$\frac{Q}{P - I_{\mathrm{a}}} = \frac{F}{S} \tag{2}$$

$$I_a = \lambda S \tag{3}$$

where P is the total precipitation (mm), I_{a} is the initial abstraction before runoff (mm), F is the cumulative infiltration after runoff begins (mm), Q is direct runoff (mm), S is the potential maximum retention (mm), and λ is the initial abstraction coefficient. Combination of Eqs. (1) and (2) leads to the popular form of the original SCS-CN

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method:

$$Q = \frac{(P - I_a)^2}{P - I_a + S}, \quad \text{for } P > I_a$$
$$Q = 0, \quad \text{for } P \leq I_a \tag{4}$$

The parameter S can vary in the range of $0 \leq S \leq \infty$, and it directly linked to the curve number CN as:

$$S = \frac{25\,400}{\text{CN}} - 254 \tag{5}$$

where the CN is a dimensionless variable, and it depends on land use, hydrological soil group, hydrologic condition, and antecedent moisture condition.

2.1.2 Modified SCS-CN model

The variability of antecedent rainfall and the associated soil moisture amount is an important source of the inherent curve number variability encountered in applications of the SCS-CN method (Ponce and Hawkins, 1996). The incorporation of antecedent moisture in the original SCS-CN method in terms of three AMC levels permit unreasonable sudden jumps in the CN-variation, which results in corresponding jumps in computed runoff (Mishra et al., 2006a). To circumvent these problems, Mishra and Singh (2002) suggested an SCS-CN-based equation incorporating antecedent moisture and P_5 for computation of runoff.

Using the $C = S_r$ concept, where C is the runoff coefficient ($= Q/(P - I_a)$) and S_r is the degree of saturation, Mishra and Singh (2002) modified the original SCS-CN method for accounting antecedent moisture M as:

$$\frac{Q}{P - I_a} = \frac{F + M}{S + M} \tag{6}$$

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where M is antecedent moisture representing the amount of moisture available in the soil profile before the start of the storm (mm).

Upon substituting Eq. (6) into Eq. (1) leads to:

$$Q = \frac{(P - I_a)(P - I_a + M)}{P - I_a + M + S} \tag{7}$$

M on the day of onset of rainfall is assumed to be the amount of water infiltrated due to the antecedent 5-day rainfall ($M = F$), priori to which the soil is completely dry:

$$M = P_5 - I_a - Q \tag{8}$$

Assuming the antecedent moisture condition to be dry for 5 days before the onset of the considered rain storm, substituting Eq. (4) into Eq. (8) results in the expression of M (Mishra and Singh, 2002):

$$M = \frac{(P_5 - \lambda S_I)S_I}{P_5 + (1 - \lambda)S_I} \tag{9}$$

where S_I is the potential maximum retention corresponding to the AMC I condition (mm). Since $S_I = S + M$, it follows:

$$M = 0.5\left[-(1+\lambda)S + \sqrt{(1-\lambda)^2 S^2 + 4P_5 S}\right] \tag{10}$$

Here + sign before the square root is retained for $M \geq 0$, and $P_5 \geq \lambda S$.

In the original SCS-CN method, I_a is given by Eq. (3), which does not incorporate M. In reality, the initial abstraction, which represents losses due to interception, surface storage, evaporation, and infiltration, varies inversely with the antecedent moisture. The higher the antecedent moisture, the lower will be the initial abstraction, and vice versa

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(Mishra et al., 2006a). Mishra et al. (2006a) modified Eq. (3) to the following non-linear $I_a - S$ relation incorporating antecedent moisture:

$$I_a = \frac{\lambda S^2}{S + M} \quad (11)$$

For a completely antecedent dry condition or $M = 0$, $I_a = \lambda S$, which is the same as Eq. (3). Substituting Eq. (11) into Eq. (7), one can obtain the simulated event runoff of the modified SCS-CN method:

$$Q = \frac{(P - \frac{\lambda S^2}{S+M})(P - \frac{\lambda S^2}{S+M} + M)}{P - \frac{\lambda S^2}{S+M} + M + S} \quad (12)$$

2.2 Soil loss modeling

2.2.1 Original RUSLE model

The USLE/RUSLE models predict long-term average annual soil loss using six factors that are associated with climate, soil, topography, vegetation and management. They have also been used for time intervals shorter than the mean annual one, such as the event scale (Kinnell, 2005; Bagarello et al., 2010):

$$A_e = R_e \mathrm{KLSCP} \quad (13)$$

where A_e is the event soil loss ($\mathrm{t\,ha^{-1}}$), R_e is the event rainfall erosivity factor ($\mathrm{MJ\,mm\,ha^{-1}\,h^{-1}}$) given by the product of total kinetic energy of the rainstorm (E, $\mathrm{MJ\,ha^{-1}}$) and maximum 30-min intensity during the event (I_{30}, $\mathrm{mm\,h^{-1}}$) ($R_e = EI_{30}$), K is the soil erodibility factor ($\mathrm{t\,h\,MJ^{-1}\,mm^{-1}}$), LS is the slope-length and steepness factor, C is the cover-management factor, and P is the conservation support-practice factor.

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2.2.2 Modified RUSLE model

Many studies have indicated that the USLE/RUSLE overestimated low event soil losses and underestimated high event soil losses (Kinnell, 2005, 2007, 2010). The failure to consider runoff explicitly is a primary factor for USLE/RUSLE model to produce systematic errors in the prediction of event erosion (Kinnell, 2005). In reality, erosion is a hydrologically driven process, and it is well known that event soil loss is given by the product of the runoff amount and bulk sediment concentration for an event (Kinnell, 2005; Bagarello et al., 2010). Modern understanding of rainfall erosion processes recognizes that runoff is a primary independent factor in modeling rainfall erosion. To directly consider the effect of runoff, Kinnell (2007) proposed the event rainfall-runoff erosivity index ($Q_R EI_{30}$, Q_R is the runoff ratio) to replace the USLE/RUSLE rainfall erosivity factor (EI_{30}), and substantial improvement of prediction accuracy was obtained (Kinnell, 2007, 2010). Bagarello et al. (2008, 2010) found that the event soil loss was proportional to the power function of $Q_R EI_{30}$ term. In terms of above results, the following modified RUSLE model is used to predict event soil loss:

$$A_e = a(Q_R EI_{30})^b \mathrm{KLSCP} \tag{14}$$

where a and b are empirical coefficients.

In the modified RUSLE model, both of the effects from event rainfall and runoff on soil loss are explicitly considered. The predicted event runoff of the modified SCS-CN method is substituted into Eq. (14) to determine Q_R. In this way, the event rainfall-runoff-erosion modeling is directly coupled, which is very useful for practical application.

3 Model application

3.1 Study area

The study area is the Yangjuangou catchment (36°42′ N, 109°31′ E) located in the middle part of the Loess Plateau, Shaanxi Province, China (Fig. 1). The catchment has

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a total area of 2.02 km^2 with elevation ranging from 1050 m to 1298 m. It is a typical gully and hilly area with a gully density of 2.74 km km^{-2}, and the slope gradients range from 10° to 30° (Li et al., 2003). The area has a semi-arid continental climate with an average annual rainfall of 535 mm. The rainfall is mainly concentrated between June and September with large inter-annual variations. Soil in the study area is mainly derived from loess, which is fine silt to silt in texture. The soil type is Calcaric Cambisol characterized by a uniform texture and weak structure, and it is vulnerable to water erosion (Li et al., 2003). The average erosion rate of the Yangjuangou catchment is 90.42 t ha^{-1} yr^{-1} between 1980 and 1990 and 62.73 t ha^{-1} yr^{-1} during 1992–1996 (Li et al., 2003), and 36.41 t ha^{-1} yr^{-1} in 2006 (Wang et al., 2009).

Before the 1980s, the land use in the Yangjuangou catchment was dominated by croplands. Reforestation began in the 1980s on infertile and steep cultivated lands with low crop yields. Driven by the implementation of the Grain-for-Green project since 1998, most of the cultivated lands on steep slopes were abandoned for natural or artificial revegetation. At present, the main land use types are grassland, forestland and shrubland formed at different restoration stages. The main forest species in the Yangjuangou catchment is acacia (*Robinia pseudoacacia*), which was planted in the 1980s or after 1999. The dominant grass species are *Artemisia sacrorum*, *Stipa bungeana* and *Artemisia scoparia*. The main shrub species are *Prunus armeniaca* and *Hippophae rhamnoide*. As a result of human disturbances and changes of the natural environmental conditions, mosaic of patchy land cover is the typical landscape pattern in the Yangjuangou catchment.

3.2 Data collection

Three runoff plot groups with different land cover types were installed in the catchment in 2008 (Figs. 1 and 2). Each group included three closed runoff plots with a fixed width of 2 m and lengths of 5, 9 and 13 m, respectively. Two numbers were used to define the runoff plot. For example, plot 11, plot 12 and plot 13 indicated that these plots belonged to Group 1 and their lengths were 5, 9 and 13 m, respectively. The slope gradients of all plots were somewhat different (see Table 1).

Group 1 plots were at the initial stage of revegetation and had been abandoned for 8 yr. Group 2 and Group 3 plots had been revegetated for 25 yr. The vegetation of Group 1 plots was sparse apricot (*Armeniaca vulgaris*) planted in rows at interval distances of 2.5 or 5 m. Patchy biological crusts covered most of the soil surface of plots in Group 1. Dense native shrubs (*Spiraea pubescens Turcz.*) with an arborous layer of sparse artificial acacia covered plots of Group 2. Plots of Group 3 were dominated by dense tussock (*A. scoparia*) and beard grass (*Andropogon L.*). Liu et al. (2012) used a digital camera (Finepix S1000, Fujifilm) and a 50 × 50 cm subplot mesh to perpendicularly photograph the surface of each runoff plot. The resulting images were transferred to digital vegetation cover maps in ArcMap. The vegetation cover ratio of each runoff plot could be easily obtained from these maps. Table 1 shows the main characteristics of each runoff plot.

Twenty-seven samples of topsoil (0–10 cm) were collected from each plot group. Soil texture was analyzed using a Mastersizer 2000 particle analyser (Malvern Instruments Ltd., Worcestershire, UK). Bulk density (BD), Total Kjeldhal nitrogen (TN), total carbon (TC), total phosphorous (TP), soil organic carbon (SOC), electrical conductivity (EC) and pH were tested using standard soil testing methods (Liu et al., 1996). Soil properties of each runoff plot group are shown in Table 2.

Rainfall, runoff and erosion of the nine runoff plots were monitored during the rainy season in 2008, 2009, 2010 and 2011. Rainfall depth was measured with an accuracy of 0.2 mm using a tipping bucket rain gauge that was connected to a data logger. The runoff mixed with the sediment discharged from each plot was collected after each rainfall event and the volume was measured. After settling for 24 h, sediment was separated from water, dried in an oven at a temperature of 105 °C for 8 h and weighed. Totally, there were 21 and 16 rainfall events that produced runoff and sediment, respectively.

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3.3 Determination of model parameters

3.3.1 Parameters for rainfall-runoff modeling

There are two parameters in the original or modified SCS-CN model. One is the initial abstraction coefficient λ, and the other is the curve number CN. λ was assumed to be equal to 0.2 in its original development. However, the assumption of $\lambda = 0.2$ has frequently been questioned for its validity and applicability, invoking a critical examination of the $I_a - S$ relationship for pragmatic applications (Pronce and Hawkins, 1996; Baltas et al., 2007). Fu et al. (2011) found that the prediction accuracy for $\lambda = 0.05$ was greater than that for $\lambda = 0.2$ using SCS-CN method to simulate plot runoff of 757 rainfall events in Zizhou and Xifeng cities located in the Loess Plateau of China. Similar results have been obtained from plots or watersheds in USA (Hawkins et al., 2002), semi-arid tropical highlands of Northern Ethiopia (Descheemaeker et al., 2008) and the Three Gorges area of China (Shi et al., 2009). In this study, both of these two values ($\lambda = 0.05, 0.2$) are used in the SCS-CN model for comparison.

For the CN value, it needs the following steps to determine it with considering the effect of AMC, slope gradient and initial abstraction ratio. First, in terms of the hydrologic soil group (set to B) and hydrologic condition (determined by the measured vegetation cover), the CN_{II} value for the normal AMC (AMC II) can be determined from USDA-NRCS handbook with land cover and hydrologic soil-cover complexes of each runoff plot (see Table 9-2 in USDA-NRCS, 2004).

Second, the CN_{II} value obtained from the USDA-NRCS handbook corresponds to a slope of 5 %, and it should be adjusted to the actual slope. Huang et al. (2006) used SCS-CN method to evaluate an 11-yr runoff plot experiment with slopes ranging from 14 % to 140 % in Xifeng city located in the Loess Plateau of China, and proposed the following equation to consider the effect of slope on CN_{II} value:

$$CN_{II\alpha} = CN_{II} \frac{322.79 + 15.63\alpha}{\alpha + 323.52} \quad (15)$$

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where $CN_{II\alpha}$ is the slope-adjusted CN_{II} value, and α is the slope steepness (%).

Third, the above determined $CN_{II\alpha}$ value is the median CN value taken as a representative value for the AMC II condition. It should be converted to AMC I (dry) or AMC III (wet) condition depending on the magnitude of P_5 with the following relations (Hawkins et al., 1985):

$$CN_{I\alpha} = \frac{CN_{II\alpha}}{2.281 - 0.0128 CN_{II\alpha}} \tag{16}$$

$$CN_{III\alpha} = \frac{CN_{II\alpha}}{0.427 + 0.00573 CN_{II\alpha}} \tag{17}$$

where $CN_{I\alpha}$ and $CN_{III\alpha}$ are the slope-adjusted CN values corresponding to the AMC I and AMC III condition, respectively.

Finally, if $\lambda = 0.05$ is used in SCS-CN method, a new set of curve numbers must be developed (Hawkins et al., 2002). Hawkins et al. (2002) developed the following relationship that converted the 0.20-based CN to 0.05-based CN from model fitting results using rainfall-runoff data:

$$CN_{0.05} = \frac{100}{1.879\left[\frac{100}{CN_{0.20}} - 1\right]^{1.15} + 1} \tag{18}$$

$$S_{0.05} = 0.8187 S_{0.20}^{1.15} \tag{19}$$

where $CN_{0.05}$ and $S_{0.05}$ (mm) are the CN and potential water storage values with λ = 0.05, respectively, and $CN_{0.20}$ and $S_{0.20}$ (mm) are the values with $\lambda = 0.2$.

3.3.2 Parameters for soil loss modeling

In the original or modified RUSLE model, the six erosivity factors are determined in the following. The event rainfall erosivity factor (R_e) is calculated as follows (Brown and

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Foster, 1987):

$$R_e = EI_{30} = \left(\sum_{r=1}^{n}(e_r v_r)\right) I_{30} \tag{20}$$

where e_r and v_r are the unit rainfall energy ($\mathrm{MJ\,ha^{-1}\,mm^{-1}}$) and the rainfall volume (mm) during a time period r, respectively. The unit rainfall energy (e_r) is calculated for each time interval as (Brown and Foster, 1987):

$$e_r = 0.29[1 - 0.72\exp(-0.05 i_r)] \tag{21}$$

where i_r is the rainfall intensity during the time interval ($\mathrm{mm\,h^{-1}}$).

This study employs the method developed from EPIC by Sharply and Williams (1990) to estimate the soil erosivity K factor. The calculation formula is as follows:

$$K = \{0.2 + 0.3\exp[-0.0256 S_a(1 - S_i/100)]\}\left(\frac{S_i}{\mathrm{Cl} + S_i}\right)^{0.3} \cdot \left[1 - \frac{0.25C}{C + \exp(3.72 - 2.95C)}\right]\left[1 - \frac{0.7S_n}{S_n + \exp(-5.51 + 22.9S_n)}\right] \tag{22}$$

where S_a is the sand content (%); S_i is the silt content (%); Cl is the clay content (%); C is the organic carbon content (%); and $S_n = 1 - S_a/100$.

For each plot, a value of the topographic factor, LS, is calculated according to the following relationships (Nearing, 1997; Renard et al., 1997):

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$$L = \left(\frac{\lambda}{22.13}\right)^m \tag{23}$$

$$S = -1.5 + \frac{17}{1 + \exp(2.3 - 6.1 \sin\beta)} \tag{24}$$

$$m = \frac{F}{1+F} \tag{25}$$

$$F = \frac{\sin\beta/0.0896}{3(\sin\beta)^{0.8} + 0.56} \tag{26}$$

where λ is the slope length (m), m is the slope-length exponent, and F is the ratio of rill erosion to interrill erosion which depends on the slope angle, β (°).

Vegetation type and vegetation cover play major roles in controlling soil loss, especially in the restoration lands of arid and semi-arid regions. Many experimental studies have verified that soil loss exponentially decreased with vegetation cover ratio for a specific vegetation type (Moreno-de las Heras et al., 2009; Bartley et al., 2010; Garcia-Estringana et al., 2010; Podwojewski et al., 2011). Based on numerous observed plot data in Ansai city located in the middle part of the Loess Plateau of China, Jiang et al. (1996) proposed the following exponential functions to describe the relationship between the cover-management C factor and cover ratio of woodland and grassland:

$$C_{\text{grassland}} = \exp\left[-0.0418(V_{\text{cover}} - 5)\right] \tag{27}$$

$$C_{\text{woodland}} = \exp\left[-0.0085(V_{\text{cover}} - 5)^{1.5}\right] \tag{28}$$

where $C_{\text{grassland}}$ and C_{woodland} are the cover-management factor of woodland and grassland, respectively, V_{cover} is vegetation cover (%). The above relationships have also been verified by Zhang et al. (2003) with observation data from thirty three plots with nine types of grassland and woodland in the Loess Plateau of China. In this study, Eqs. (27) and (28) are used to determine the C factor of the nine plots. As there is no soil conservation practice for all the plots, the P factor is set to be 1 ($P = 1$).

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In the modified RUSLE model, there is no independently method to determine the introduced empirical coefficients a and b. In this study, the observed event soil loss data from all plots in 2008 are fitted by the modified RUSLE model to determine a and b. After model calibration, the modified RUSLE model is used to predict the event soil loss in the rest of three years (2009, 2010 and 2011).

3.4 Model performance evaluation criteria

In this study, the following four popular statistical criteria are used to measure the agreement between predicted and observed values of event runoff and soil loss. A good agreement indicates a good model performance, and vice versa.

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O})^2} \tag{29}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2} \tag{30}$$

$$\mathrm{NRMSE} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2}}{\overline{O}} \tag{31}$$

$$e = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \tag{32}$$

where EF is the Nash-Sutcliffe model efficiency, RMSE is the root mean square error, NRMSE is the normalized root mean square error, e is the bias, O_i and P_i are the observed and predicted runoff or soil loss of the ith rainfall event, respectively, $\overline{O}$ is the

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average observed runoff or soil loss, N is the total number of rainfall events that producing runoff or soil loss. EF = 1 indicates a perfect agreement between observed and predicted values, and its decreasing values indicate poor agreement. A higher RMSE or NRMSE value indicates poor model performance. Bias represents the average differences between the predicted and observed values.

4 Results and discussion

4.1 Prediction results of event runoff

There are four rainfall-runoff models including the original SCS-CN model ($\lambda = 0.2$), the original SCS-CN model ($\lambda = 0.05$), the modified SCS-CN model ($\lambda = 0.2$) and the modified SCS-CN model ($\lambda = 0.05$) to predict event runoff. Figures 3, 4 and 5 show the comparison between the observed and predicted event runoff of the Group 1, Group 2 and Group 3 plots, respectively. It should be noted that the runoff of one event in these figures is the average value of the three plots belonged to same group as the SCS-CN model can not consider the effect of plot length. It can be found from Figs. 3a, 4a and 5a that the original SCS-CN model ($\lambda = 0.2$) significantly underestimates the observed runoff. There are many rainfall events that produce small runoff, but the simulation results of the original SCS-CN model ($\lambda = 0.2$) for these events are almost equal to 0. The original SCS-CN model ($\lambda = 0.05$) can predict the low event runoff well, whereas it underestimates the high event runoff, especially for the rainfall events that have large P_5 (Figs. 3b, 4b and 5b). Although the predicted runoff of large rainfall events by the modified SCS-CN model ($\lambda = 0.2$) are more close to the observed results compared to the original SCS-CN model ($\lambda = 0.2$ or 0.05), the modified SCS-CN model ($\lambda = 0.2$) still underestimates the high event runoff (Figs. 3c, 4c and 5c). Furthermore, it predicts no runoff for the small rainfall event, which is similar to the original SCS-CN model ($\lambda = 0.2$). Compared to the above three models, the prediction results of the modified SCS-CN model ($\lambda = 0.05$) are in good agreement with the observations, having a ratio

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close to 1:1, as shown in Figs. 3d, 4d and 5d. This result indicates that the modified SCS-CN model ($\lambda = 0.05$) can adequately predict both the small and large event runoff well.

Table 3 compares the evaluation criteria of event runoff prediction performance of the four models. The prediction results of modified SCS-CN model ($\lambda = 0.05$) provide a greater model efficiency (EF) and a lower RMSE, NRMSE and bias compared to the original SCS-CN model ($\lambda = 0.2$ or 0.05) and the modified SCS-CN model ($\lambda = 0.2$). The EF values of the modified SCS-CN model ($\lambda = 0.05$) to predict event runoff of the Group 1, Group 2 and Group 3 plots are 0.899, 0.892 and 0.879, respectively. The bias values of the other three models are negative (most of them are less than −1 mm, see Table 3), indicating that these three models substantially underestimate the event runoff, as evident from Figs. 3, 4 and 5. The above comparison results of the model performance evaluation criteria further prove the superiority of the modified SCS-CN model ($\lambda = 0.05$) with respect to other three models.

4.2 Prediction results of event soil loss

The simulated event soil loss of the three runoff plot groups in 2008 are compared with the measurements for calibration of the modified RUSLE model (Fig. 6). The estimated values of the empirical coefficients *a* and *b* in the modified RUSLE model are 1.723 and 1.548, respectively. Figure 6 shows that the simulated event soil loss agrees well with the measured values. The EF, RMSE, NRMSE and *e* values of modified RUSLE model simulation results are 0.810, 0.163 $\mathrm{t\,ha^{-1}}$, 0.231 $\mathrm{t\,ha^{-1}}$ and 0.033 $\mathrm{t\,ha^{-1}}$, respectively. This again reflects that the modified RUSLE model is well calibrated.

Figures 7, 8 and 9 shows the comparison between the observed and predicted event soil loss of the Group 1, Group 2 and Group 3 runoff plots during the rainy season of 2009–2011, respectively. It can be found that the predicted event soil loss of the original RUSLE model depart significantly from the observed ones. In general, the original RUSLE model overestimates low event soil losses and underestimates high event soil losses (Figs. 7a, 8a and 9a), which has been also indicated by Kinnell (2005, 2007, 2010). With respect to the original RUSLE model, the predicting results of the modified RUSLE model are more satisfactory as evident from Figs. 7b, 8b and 9b. The better performance of the modified RUSLE model is also supported by its larger EF and smaller RMSE, NRMSE and e values than those of the original RUSLE model, as shown in Table 4. The EF values of the modified RUSLE model are over 0.70, whereas those of the original RUSLE are only about 0.30.

4.3 Physical interpretation of model performance

The substantial underestimation of event runoff by the original SCS-CN model ($\lambda = 0.2$) is due to that it overestimates the initial abstraction with $\lambda = 0.2$ and does not explicitly consider the effect of antecedent moisture amount in soil on production of runoff. For the rainfall events that have large P_5, considerable amount of moisture have existed in soil before the start of rainstorm, which can reduce infiltration and enhance runoff. Whereas the original SCS-CN model assumes that the soil is complete dry (Eq. 2), the effect of antecedent moisture is ignored. Therefore, even the initial abstraction can be reasonably estimated with $\lambda = 0.05$, the original SCS-CN model can only predicts the low event runoff well before which there is small or no antecedent moisture, but it still underestimates the event runoff produced by the rainfall events that have large P_5. After consideration of the antecedent moisture, the prediction performance of modified SCS-CN model can substantially improve with $\lambda = 0.05$, but there is still considerable errors for the modified SCS-CN model with $\lambda = 0.2$. Therefore, the antecedent moisture should be directly incorporated into the SCS-CN model (Eq. 6) and $\lambda = 0.05$ is suitable for the initial abstraction coefficient in the study area. Combined actions of above two factors result in the satisfactory performance of the modified SCS-CN model ($\lambda = 0.05$) compared to other three models.

In rainfall erosion, soil particle detachment is caused by raindrops impacting the soil surface and by flow shear. Sediment downslope transport is mainly driven by the interaction between raindrop impact and flow (raindrop-induced saltation and rolling) or by flow alone (flow-driven saltation and rolling) (Kinnell, 2010). Therefore, rainfall drives

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the start of soil loss, but both of the rainfall and runoff play an important role in producing sediment yield across the downslope boundary of an area. Although empirical relationships tend to exist between runoff amount and E, and between peak runoff rate and I_{30}, this implicit embedding through the EI_{30} index in the original RUSLE model can not deal with the effect of runoff on soil loss and the response of soil loss to changes in the initial soil moisture status (Kinnell, 2010). This is the reason for the failure of original RUSLE model to predict event soil loss well. The overestimation of low event soil losses and underestimation of high event soil loss by the original RUSLE model may be due to that there is a threshold that rainfall or runoff play dominant role on affecting soil loss. The detailed reason needs further investigation.

The better performance of the modified RUSLE model is attributable to two points. First, the effect of runoff is directly considered in it through the rainfall-runoff erosivity index (Eq. 14). Second, the prediction accuracy level of event runoff achieved by the modified SCS-CN model ($\lambda = 0.05$) is sufficient, which ensures the ability of $Q_R EI_{30}$ index to predict event erosion. Moreover, as indicated by Kinnell (2010), including direct consideration of runoff in the event rainfall-runoff factor enhances the ability of the modified RUSLE model to account for variations in event soil loss. It may also improve the potential of the model to react to spatial variations in runoff and soil loss results from spatial variations in soil and vegetation (Kinnell, 2010).

4.4 Advantages and limitations of the proposed approach

The proposed approach in this study coupled the modified SCS-CN and RUSLE models to link the rainfall-runoff-erosion modeling. It has the following main advantages. First, it substantially incorporates AMC in runoff production and includes direct consideration of runoff in soil loss to overcome the main weak points of the traditional SCS-CN and RUSLE models. Second, main stand and vegetation conditions of runoff plot (e.g., soil property, plot scale, plot slope, vegetation type, and vegetation cover) which are critical to runoff and soil loss are explicitly incorporated into the model parameters. Third, compared to models like WEPP and EUOSEM, the proposed approach is simple

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and almost all of the parameters can be independently determined from observations. Finally, it can satisfactorily predict event runoff and soil loss of different restoring vegetations in the Loess Plateau which has complex geographical and climatic conditions. One can expect that good results can be obtained in other regions. These advantages ensure that the proposed approach is useful for the general application.

However, there are several issues still needing further investigations. First, it is not adequate to represent antecedent moisture condition only by the antecedent rainfall (Ali and Roy, 2010), and the robust physical meaning of determining antecedent moisture amount with P_5 needs further investigation (Michel et al., 2005; Sahu et al., 2010). Many studies have indicated that the CN values are much more correlated with the soil moisture, especially the moisture of surface soil layer (Huang et al., 2007; Tramblay et al., 2010). It is necessary to estimate CN values continuously to allow representation of varying soil moisture conditions. Second, rainfall intensity and rainfall duration have great impact on the quantity of runoff, but there were not considered in the modified SCS-CN model. More efforts are needed to account for the temporal variation of rainfall, such as done in Mishra et al. (2008) and Suresh Babu and Mishra (2011). Third, it is difficult to independently determine the introduced empirical coefficients in the modified RUSLE model. Systematic field experimental studies should be conducted to install quantitative relationships between the empirical coefficients and knowable variables such as soil texture, land cover, plot length and slope. Fourth, sediment deposition due to changes in slope gradient was ignored in the modified RUSLE model. More attentions should be paid to couple the modified RUSLE model with an appropriate sediment transport model, as done in RUSLE2. Finally, further studies are needed to extend the modified SCS-CN and RUSLE models to catchment or watershed scale for long-term continuous and spatial distributed hydrologic simulation, which is very useful for evaluating the impacts of land use and climate change on hydrological cycles.

5 Conclusions

In this study, the modified SCS-CN and RUSLE models were coupled to predict event runoff and soil loss from restoring vegetation plots in the Loess Plateau of China. The effects of antecedent moisture condition on runoff production (Eq. 6) and initial abstraction (Eq. 11) were explicitly accounted for in the modified SCS-CN model. Antecedent moisture condition, slope gradient and initial abstraction ratio were incorporated to determine the curve number, and two initial abstraction coefficient values ($\lambda = 0.05$, 0.2) were used in the SCS-CN model. In the modified RUSLE model, direct effect of runoff on event soil loss was considered by adopting a rainfall-runoff erosivity index ($Q_R EI_{30}$) to replace the traditional rainfall erosivity factor (EI_{30}) (Eq. 14). The rainfall-runoff-erosion modeling was linked by determining the runoff ratio Q_R with predicted runoff of the modified SCS-CN model.

The simulation results indicated that the original SCS-CN model ($\lambda = 0.05$, 0.2) and modified SCS-CN model ($\lambda = 0.2$) underestimated the event runoff, especially for the rainfall events that have large 5-day antecedent precipitation. Compared to these three models, the modified SCS-CN model ($\lambda = 0.05$) satisfactorily predicted event runoff with Nash-Sutcliffe model efficiency (EF) larger than 0.85. The original RUSLE model overestimated low values of measured soil loss and under-predicted the high values, whereas the modified RUSLE model could well predicted both the small and large event soil loss with EF over 0.70.

It can be found from this study that the antecedent moisture should be directly incorporated into the SCS-CN model and $\lambda = 0.05$ is suitable for the initial abstraction coefficient in the study area. Direct consideration of runoff in the event rainfall-runoff erosivity can substantially improve the capacity of the RUSLE model to predict event soil loss. Coupling the modified SCS-CN and RUSLE models has great practical importance for runoff and soil loss simulation in the Loess Plateau. The limitations and future study scopes of the proposed models were also discussed in this study. This evaluation is useful to shed lights on model applications and additional model development.

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Acknowledgement. This research was financially supported by the National Natural Science Foundation of China (Grant Nos. 41101096, 40930528 and 41171156), Open Fund from State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau (Grant No. 10501-280), and the CAS/SAFEA International Partnership Program for Creative Research Teams of "Ecosystem Processes and Services".

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Table 1. Main characteristics of each runoff plot in the three groups.

	Group 1			Group 2			Group 3		
	Plot 11	Plot 12	Plot 13	Plot 21	Plot 22	Plot 23	Plot 31	Plot 32	Plot 33
Length (m)	5	9	13	5	9	13	5	9	13
Width (m)	2	2	2	2	2	2	2	2	2
Slope gradient (°)	19	19	19	25	25	25	21	22	23.5
Revegetation time (yr)	8	8	8	25	25	25	25	25	25
Main vegetation type	*Armeniaca vulgaris*			*Spiraea pubescens Turcz.*			*A. scoparia, Andropogon L.*		
Vegetation cover (%)	40.6	54.8	29.0	76.5	71.5	72.5	71.2	71.6	89.1

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Table 2. Soil properties of the three runoff plot groups.

	Group 1	Group 2	Group 3
Sand (%)	22.83	24.40	24.39
Silt (%)	72.96	71.25	71.10
Clay (%)	4.21	4.36	4.5
BD[a] ($g\,cm^{-3}$)	1.04	1.30	1.17
TN (%)	0.06	0.12	0.10
TC (%)	1.91	2.53	2.22
SOC ($g\,kg^{-1}$)	7.41	16.44	20.05
TP ($g\,kg^{-1}$)	0.61	0.65	0.62
pH	8.42	8.28	8.32
EC ($\mu s\,cm^{-1}$)	133.03	153.80	139.00

[a] BD: Bulk density.

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Table 3. Values of model performance evaluation criteria to predict event runoff of the three runoff plot groups.

Plot type	Model	EF	RMSE (mm)	NRMSE (mm)	e (mm)
Group 1	Original SCS-CN ($\lambda = 0.2$)	0.545	2.116	1.378	−1.030
	Original SCS-CN ($\lambda = 0.05$)	0.697	1.578	1.028	−0.794
	Modified SCS-CN ($\lambda = 0.2$)	0.642	1.833	1.163	−0.898
	Modified SCS-CN ($\lambda = 0.05$)	0.899	0.838	0.616	−0.115
Group 2	Original SCS-CN ($\lambda = 0.2$)	0.591	3.288	0.862	−2.094
	Original SCS-CN ($\lambda = 0.05$)	0.672	2.561	0.672	−1.427
	Modified SCS-CN ($\lambda = 0.2$)	0.719	2.141	0.561	−1.372
	Modified SCS-CN ($\lambda = 0.05$)	0.892	0.859	0.325	−0.209
Group 3	Original SCS-CN ($\lambda = 0.2$)	0.559	3.095	1.016	−1.763
	Original SCS-CN ($\lambda = 0.05$)	0.709	2.318	0.761	−1.192
	Modified SCS-CN ($\lambda = 0.2$)	0.732	1.688	0.554	−0.960
	Modified SCS-CN ($\lambda = 0.05$)	0.879	0.86	0.317	−0.202

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Table 4. Values of model performance evaluation criteria to predict event soil loss of the three runoff plot groups.

Plot type	Model	EF	RMSE ($t\,ha^{-1}$)	NRMSE ($t\,ha^{-1}$)	e ($t\,ha^{-1}$)
Group 1	Original RUSLE	0.272	0.302	0.533	−0.102
	Modified RUSLE	0.704	0.192	0.339	−0.050
Group 2	Original RUSLE	0.331	0.330	0.430	−0.036
	Modified RUSLE	0.746	0.203	0.265	−0.010
Group 3	Original RUSLE	0.373	0.347	0.409	−0.022
	Modified RUSLE	0.743	0.222	0.262	−0.012

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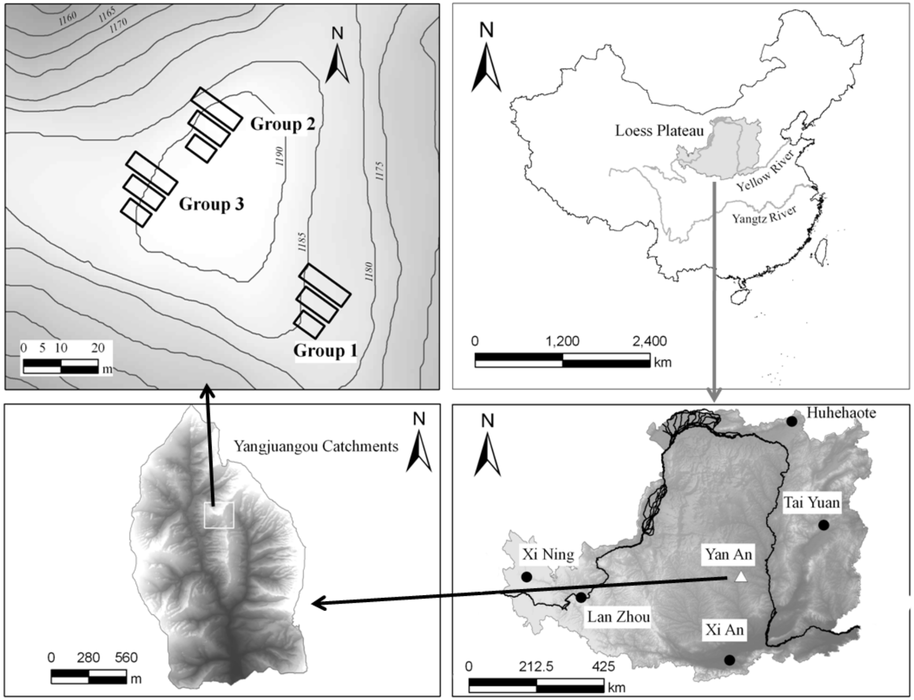

Fig. 1. Location of the study area and distribution of the three runoff plot groups.

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Group 1

Group 2

Group 3

Fig. 2. Pictures of runoff plot in the three groups.

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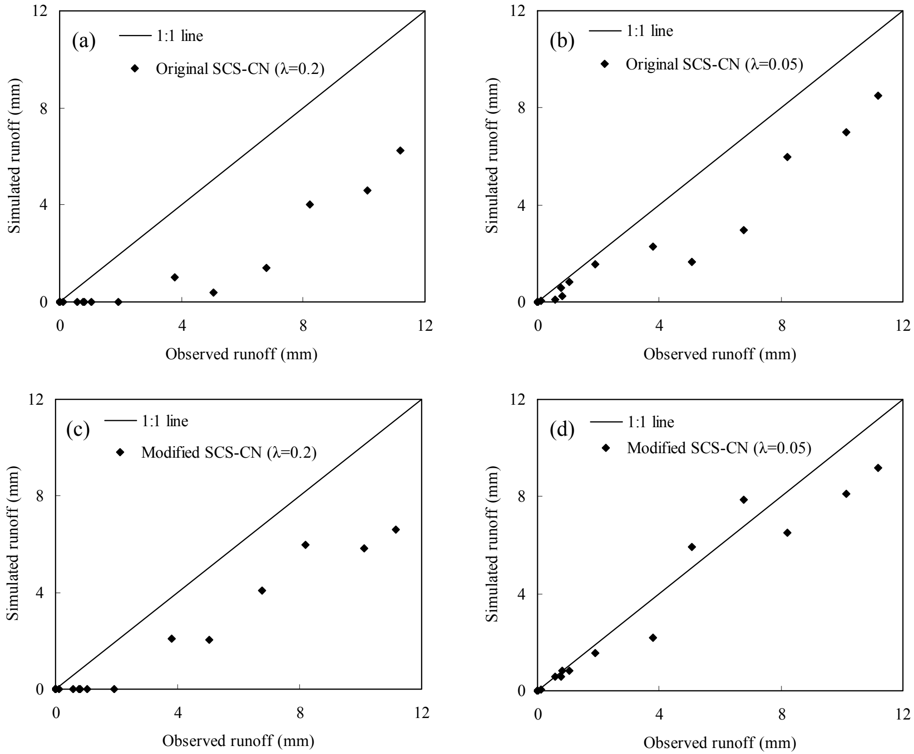

Fig. 3. Comparison between observed and predicted event runoff using **(a)** Original SCS-CN ($\lambda = 0.2$), **(b)** Original SCS-CN ($\lambda = 0.05$), **(c)** Modified SCS-CN ($\lambda = 0.2$) and **(d)** Modified SCS-CN ($\lambda = 0.05$) models for Group 1 runoff plots.

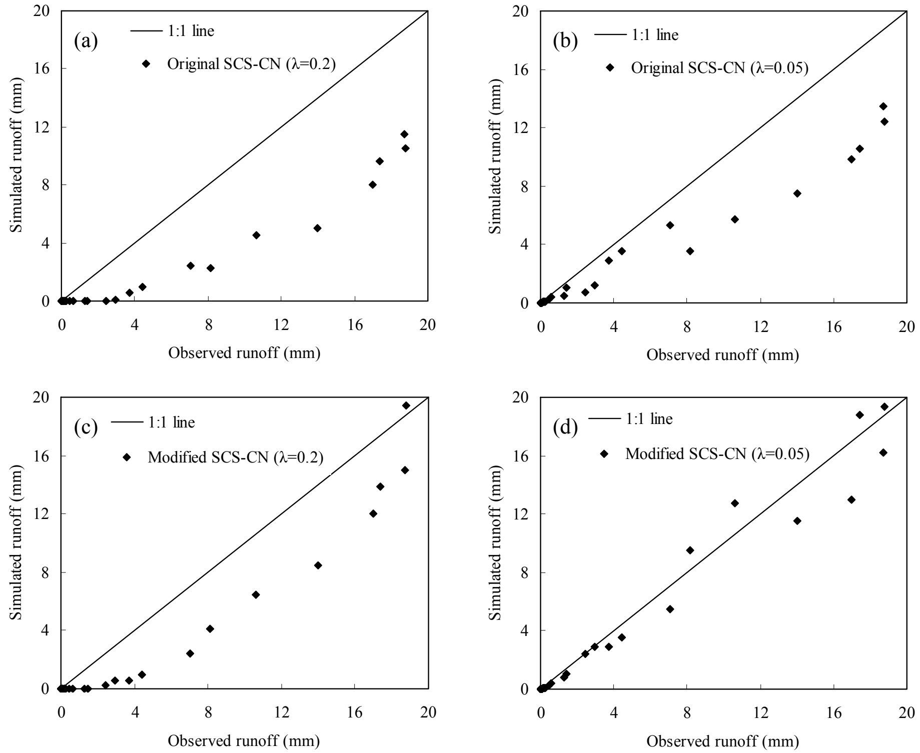

Fig. 4. Comparison between observed and predicted event runoff using **(a)** Original SCS-CN ($\lambda = 0.2$), **(b)** Original SCS-CN ($\lambda = 0.05$), **(c)** Modified SCS-CN ($\lambda = 0.2$) and **(d)** Modified SCS-CN ($\lambda = 0.05$) models for Group 2 runoff plots.

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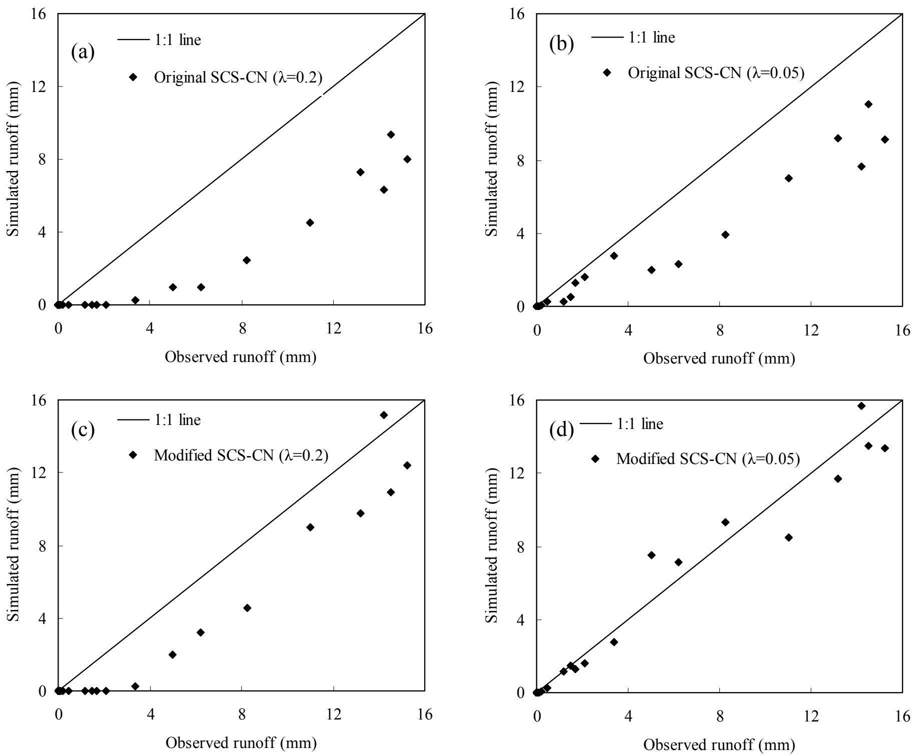

Fig. 5. Comparison between observed and predicted event runoff using **(a)** Original SCS-CN ($\lambda = 0.2$), **(b)** Original SCS-CN ($\lambda = 0.05$), **(c)** Modified SCS-CN ($\lambda = 0.2$) and **(d)** Modified SCS-CN ($\lambda = 0.05$) models for Group 3 runoff plots.

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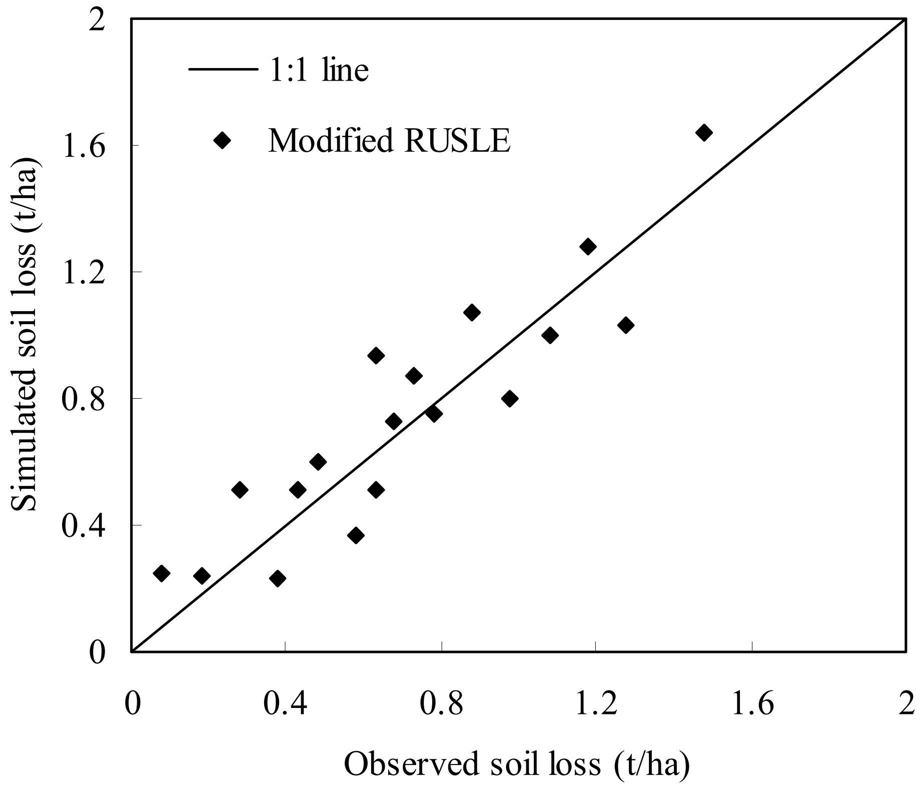

Fig. 6. Comparison between observed and simulated event soil loss using observed data of the three runoff plot groups in 2008 to calibrate the Modified RUSLE model.

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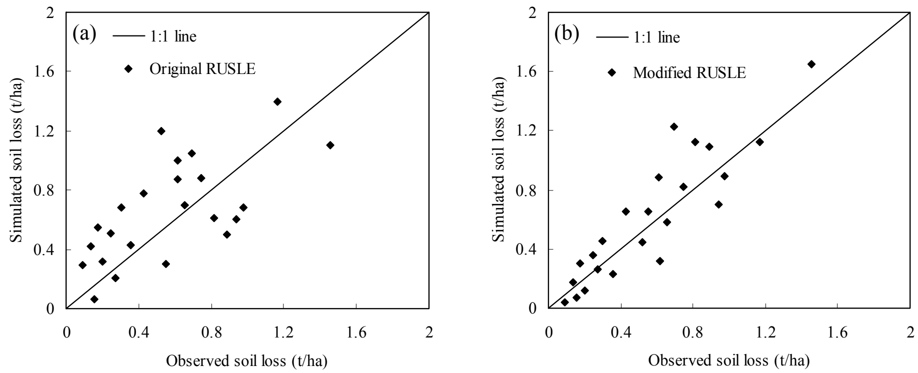

Fig. 7. Comparison between observed and predicted event soil loss during 2009–2011 using **(a)** Original RUSLE and **(b)** Modified RUSLE models for Group 1 runoff plots.

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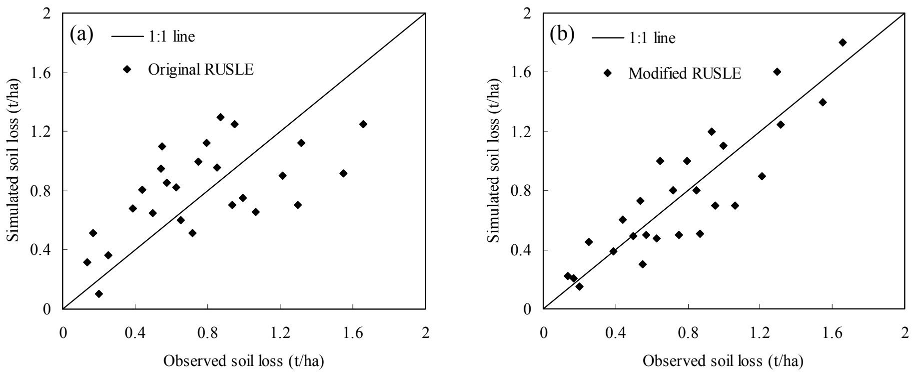

Fig. 8. Comparison between observed and predicted event soil loss during 2009–2011 using **(a)** Original RUSLE and **(b)** Modified RUSLE models for Group 2 runoff plots.

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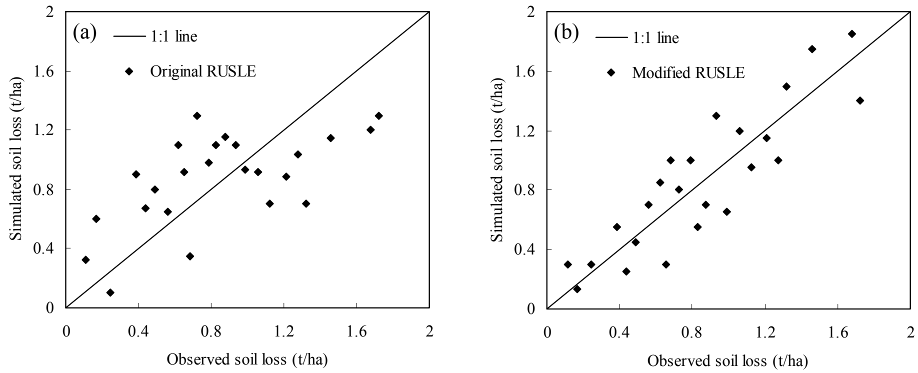

Fig. 9. Comparison between observed and predicted event soil loss during 2009–2011 using **(a)** Original RUSLE and **(b)** Modified RUSLE models for Group 3 runoff plots.

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