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Assessing applicability of the WEPP hillslope model to steep landscapes in the northern Loess Plateau of China

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ABSTRACT

The Water Erosion Prediction Project (WEPP) model has been extensively evaluated at lower slope gradients, but its applicability to steep slopes is not yet known. The objectives of this study were to evaluate the WEPP model's ability to predict runoff and soil erosion on steep slopes in the hilly-gully region of the Loess Plateau of China, and to provide insights for adapting it for this region. Field runoff and soil loss data collected from six bare slope gradient plots, four bare slope length plots, and four cropped plots at the Ansai experimental station during 1985–1992 were used to calibrate, validate, and evaluate the WEPP hillslope model. Measured rainfall intensity (rainfall break point data) was directly used to minimize climate-induced prediction errors. Overall, the calibrated WEPP model predicted event, annual, and average annual runoff and soil loss for different slope gradients, slope lengths, and cropped conditions reasonably well with model efficiencies (E_{NS}) being greater than 0.5 for most cases, but there is still room for improvement. Specifically, for the slope gradient plots, simulated runoff was somewhat insensitive to slope increases at large slope gradients while measured runoff tended to increase with slope steepness due to a decrease in surface storage capacity; however, simulated average annual soil loss, though satisfactory (E_{NS} = 0.83), was slightly oversensitive to slope increases at large slope gradients. For the slope length plots, simulated average annual soil loss was overly responsive to slope length increases at steep slopes, indicating a potential deficiency in representing slope length influence in the model for large slope gradients. The use of the default 1-m rill spacing might have also affected the sensitivity of WEPP-predicted soil loss to slope gradients and lengths, because rill spacing varies with slope steepness and lengths and WEPP –predicted erosion is sensitive to rill spacing. For the cropped plots, WEPP tended to underpredict runoff and soil loss, indicating that the internal model adjustments of hydraulic conductivity and soil erodibility for the effects of factors like roots and residue need to be reexamined for use on steep slopes.

1. Introduction

The Loess Plateau is situated in the north central region of China and occupies an area of 620,000 km^2. It is covered with a thick layer (up to 200 m) of highly erodible aeolian silt deposits, which are loose, porous, fine, and rich in vertical fissures. The region has a semiarid to sub-humid climate with most precipitation falling in the summer months largely in the form of heavy storms. Vegetation cover is generally low, and land use is predominantly cultivated croplands before implementation of the Chinese government project "Conversion of steep farmland to permanent vegetation cover" in 1999, which is also called as the Grain to Green Project (GGP). The typical landscape consists of severely dissected steep round hills and long ridges. In most parts of the hilly-gully region of the Loess Plateau, the average slope gradient is greater than 15 degrees (27%), average slope length is from 100 to 200 m, and gully length density is 3 to 5 km km^{-2}. The Yellow River, famous for the highest sediment concentrations in the world, runs through the Loess Plateau and picks up about 90% of its sediment from the area. Due to frequent large rainfall storms in the summer months, steep landscape, low vegetation cover, and the highly erodible loessial soil, the Loess Plateau had been one of the most severely eroded areas in the world for most parts of the last century. Specifically, in about 47% of the Loess Plateau (291,640 km^2) soil erosion rates were more than 5000 t km^{-2} yr^{-1}. Each year 1.6 billion tonnes of suspended

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sediment were delivered out of the Loess Plateau (1950's and 1960's), of which 0.4 billion tonnes were deposited in the lower reaches of the Yellow River. Due to this sediment deposition, the riverbeds in the lower reaches of the Yellow River continued to rise at a rate of 80–100 mm yr^{-1} in the 1970's and 1980's (Xu, 2003). At present, the riverbeds in the lower reaches are 4–12 m above the surrounding ground levels, raising serious threats to life and property in the region during flood events.

In order to control soil erosion in the Loess Plateau and to alleviate accretion in the lower reaches of the Yellow River, the Chinese government has sponsored several soil conservation campaigns in the Loess Plateau since the 1960′s by building reservoirs, check dams, and bench terraces, as well as restoring vegetation, leading to considerable reduction in sediment loads overtime (Yue et al., 2014; Wang el al., 2016; Li et al., 2018). Meanwhile, numerous studies have been conducted to study soil erosion control measures in the Loess Plateau and to understand sediment transport in the Yellow River basin (e.g., Laflen et al., 2000; Xu, 1999; Ran et al., 2008; Liu et al., 2008; Zhang et al., 2010; Yue et al., 2014; Wang et al., 2016; Li et al., 2017; Wang et al., 2017; Li et al., 2018; Wu et al., 2019). Erosion models and prediction technology have been studied rigorously in China. Since the 1980s, great efforts have been made to adopt the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) in the mainland of China (Wang, 2007; Pan and Feng, 2010; Kinnell et al., 2018; Zhang et al., 2019). As a result, many regional soil loss prediction models at the hillslope scale based on various modifications of the USLE were developed to predict soil erosion for various physiographic regions (Zheng et al., 2004; Pan and Feng, 2010; Qin et al., 2018a; Zhang et al., 2019). A new Chinese Soil Loss Equation (CSLE) was developed and used in a soil erosion survey in China (Liu et al., 2002).

The Water Erosion Prediction Project (WEPP) model, which unlike USLE, is a physically-based continuous simulation erosion model (Nearing et al., 1989; Laflen et al., 1991; Flanagan and Nearing, 1995; Flanagan et al., 2007), has been parameterized and validated extensively for gentle slopes (Zhang et al., 1996; Ghidey and Alberts, 1996; Shen et al., 2009; Tiwari et al., 2000; Yu and Rosewell, 2001; Laflen et al., 2004; Amore et al., 2004; Flanagan et al., 2012). Yu and Rosewell (2001), after evaluated WEPP soil loss predictions with measured soil losses from natural runoff plots of three slope lengths varying from 21 to 62 m, concluded that WEPP was able to predict the effects of slope length on soil loss for the study site in Australia. Zhang (2016) validated the WEPP model along a 200 m long, concave hillslope (1 to 4% slope) in central Oklahoma, U.S., using ^{137}Cs-derived spatially distributed erosion data. He reported that the downslope erosion patterns predicted by WEPP using the 1-m default rill spacing did not match those derived by the ^{137}Cs technique and that three different input rill spacing's had to be used to match the ^{137}Cs erosion patterns along the hillslope, indicating the importance of the rill spacing input parameter (Zhang, 2016).

Several studies were conducted to evaluate the WEPP model's applicability to Chinese physiographic conditions in different climate regions. Miu et al. (2004 and 2005) tested WEPP in the upper region of the Yangtze River basin in southern China and reported that WEPP could simulate the erosion process satisfactorily for single rain events in the region. Shi et al. (2006) evaluated the WEPP model for the Ansai experimental field station in the northern Loess Plateau, with emphasis on evaluating the ability of CLIGEN (CLImate GENerator) of the WEPP model to create daily climate input data for use in soil erosion prediction in the region. They reported that CLIGEN was adequate for generation of climate data for predicting runoff and soil erosion for the station.

To date there has been no systematic evaluation of the WEPP model's ability to predict runoff and soil loss at various slope gradients and slope lengths and for different crops in the Loess Plateau, especially on steep slopes and for major crops in the region. As mentioned earlier, the WEPP model was mainly parameterized and validated for gentler slopes (< 20%) at relatively low soil erosion rates, and evaluations on steep slopes at high soil erosion rates would provide useful information on how the model performs under these conditions. This knowledge could help determine whether the erosion science used in WEPP is sound and applicable to severely eroded conditions on steep slopes and provide insights on how to improve the model if its performance is less than satisfactory.

The objective of this study was to assess the WEPP model's ability to predict runoff and soil erosion in the hilly-gully region of the Loess Plateau using field runoff and soil loss data collected from six bare slope gradient plots, four bare slope length plots, and four cropped plots at the Ansai experimental field station during 1985–1992, during which 62 erosive rainstorm events occurred. This research was intended not only to broaden the scope of the WEPP model's application, but also to provide insights for improving it and for developing Chinese versions of process-based soil erosion prediction models.

2. Materials and methods

2.1. Site description

The Ansai experimental field station was established in 1973 near Xinghe village (36°51′N and 109°19′E) in the central Loess Plateau of China. Elevation ranges from 1068 to 1309 m above mean sea level. The station has a temperate and semi-arid climate with an average annual temperature of 8.8 °C, and average annual precipitation from 1985 to 1992 of 530 mm, with 69% concentrated in June, August and September. Typical soil at the station is loessial soil (fine-silty and mixed) and classified as a Calcic Cambisols (USDA Taxonomy), with silt content being close to 70% and organic matter < 0.5% (Table 1). Due to the highly erodible conditions, soil erosion was very severe at the research station with erosion rates up to 14,000 t km^{-2} yr^{-1} (Zhao et al., 2013).

2.2. Plot description and treatment

There were two groups of field plots: bare fallow and vegetated plots. All plots were 5 m wide and uniform in slope steepness. There were 10 runoff plots in the bare group, among which six were slope gradient treatment plots (5°, 10°, 15°, 20°, 25° and 28°) and four were slope length treatment plots (10, 20, 30 and 40 m). All of the slope gradient treatment plots were 20 m long, and all of the slope length treatment plots had a 30° (58%) slope. All bare plots were maintained as continuous bare fallow under conventional tillage. The soil was turned over with a spade to about 0.2 m deep in mid-April each year. In order to keep the vegetation cover below 5% in the bare plots, weeds were hand pulled or hoed as needed during the entire experiment.

There were four cropped plots, which were 20 m long at a 25° (47%) slope each. Cropping systems were in a four-year rotation of buckwheat, potato, soybean, and millet. The rotation was permutated for each plot so that all four crops were grown each year. Tillage operations and planting and harvesting dates for each crop are given in Table 2. Crop residue was removed from plots at harvest.

Table 1
Selected soil physical and chemical properties at the Ansai Station.

Soil depth m	Organic matter	Clay %	Silt	Sand	Cation exchange capacity $cmol_c\,kg^{-1}$
0.0 - 0.2	0.413	12.2	67.3	21.5	6.70
0.2 - 0.3	0.380	13.2	68.7	18.1	6.13
0.3 - 1.0	0.330	12.8	68.8	18.4	6.42

Table 2
Tillage operations and crop management.

Crop	Tillage	Planting date	Harvest date
Buckwheat	Turn soil over with a spade to a 0.2-m depth in mid-April each year, and hoe or pull weeds by hand to keep vegetation cover < 5% as needed. All plant residues were removed following harvest.	Late July	Early October
Potato		Late May	Early October
Soybean		Late April	Late October
Millet		Mid April	Early October

2.3. Climate data

Daily weather data measured at the Ansai station from 1985 to 1992 were used. The observed data included daily breakpoint rainfall data, maximum and minimum air temperatures, solar radiation, wind velocity, wind direction, and dew point temperature. To minimize climate-induced uncertainty in runoff and soil loss predictions, measured breakpoint rainfall data (reading off charts of cumulative rainfall depth) along with other measured weather data were used to compile the climate input files for the WEPP model (v2006.5).

2.4. Calibration of hydraulic conductivity and soil erodibility parameters

WEPP-predicted runoff is very sensitive to effective hydraulic conductivity (K_{eff}) and soil erosion is sensitive to rill erodibility (K_r) and critical hydraulic shear stress (τ_c) of the soil (Nearing et al., 1990). Similar to the method used by Zhang (2004), K_{eff} was varied manually to minimize the sum of squared errors (SSE) between annual measured runoff and predicted runoff. A response curve for K_{eff} is plotted in Fig. 1A as an example, showing that runoff was sensitive to K_{eff} and a global optimum of K_{eff} at which SSE reached its minimum could be easily identified. Using optimized K_{eff} as an input value, K_r and τ_c were further optimized in a similar fashion by minimizing SSE between annual measured and predicted soil losses (Fig. 1B). Two sets of K_{eff}, K_r, and τ_c were calibrated: one for the slope gradient treatment and another for the slope length treatment. For the slope gradient treatment, the slopes of 5°, 15°, and 25° were used in the calibration, and the slopes of 10°, 20°, and 28° were used for validation. Similarly, for the slope length treatment, the 10- and 30-m plots were used for calibration, and the 20- and 40-m plots were used for validation. Reasons for the separate calibrations are discussed later.

2.5. Crop parameters

Four crops (buckwheat, potatoes, soybeans, and millet) were grown on the four cropped plots each year in rotation. Plant growth parameters were taken either from the WEPP internal plant parameter databases or from the Environmental Policy Impact Calculator (EPIC) (Sharpley and Williams, 1990) if unavailable in the WEPP database. The main parameter values used in this study are given in Table 3.

2.6. Evaluation measures

The relative error and Nash-Sutcliffe model efficiency (E_{NS}) were used in this study. Model efficiency, as defined by Nash and Sutcliffe (1970), is a good measure of agreement between model prediction and measured data, and is calculated as:

$$ME = 1\text{-}\frac{\sum (Y_{obs} - Y_{pred})^2}{\sum (Y_{obs} - Y_{mean})^2}$$

where Y_{obs} is the observed value, Y_{pred} is the predicted value, and Y_{mean} is the measured mean.

The E_{NS} can range from -∞ to 1. When E_{NS} equals 1, the model produces the exact same value as each data point of the measured data. A value of 0 indicates that a single measured-mean value is as good an overall predictor as the model. Negative E_{NS} values indicate that the model is a worse predictor than the mean value of the measured data.

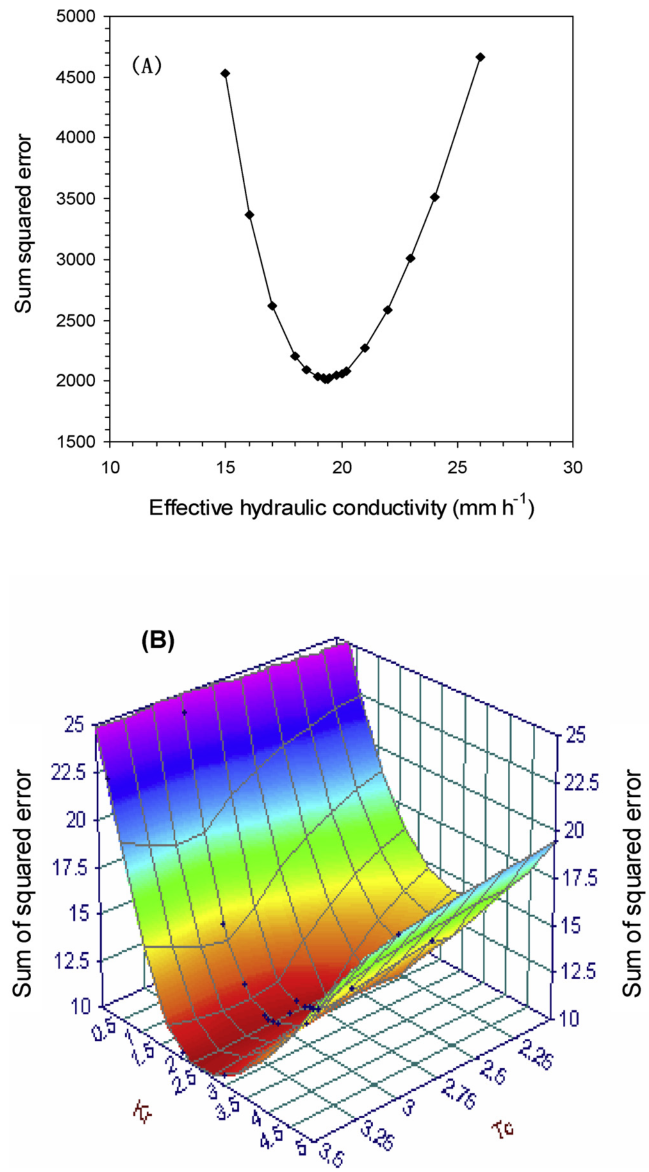

Fig. 1. (A) Response of sum of squared errors (SSE) between measured and simulated annual runoff to effective hydraulic conductivity, K_{eff}; (B) Response of SSE between measured and simulated annual soil loss to rill erodibility, K_r, and soil critical hydraulic shear stress, τ_c.

3. Results and discussion

3.1. Parameter calibration and validation

An example response curve (surface) is shown for runoff (soil loss) in Fig. 1. The results corroborated that runoff prediction by the WEPP model was sensitive to effective hydraulic conductivity (K_{eff}), and soil

Table 3
Selected plant growth parameters for the four crops.

Crops	WA*	HI	TOP	TBS	DMLA	DLAI	HMX	RDMX
	kg MJ^{-1}		°C	°C			m	m
Buckwheat	25	0.23	25	5	3	0.49	1	1
Potato	30	0.95	17	7	5	0.6	1.2	2
Soybean	25	0.30	25	10	5	0.9	0.8	2
Millet	35	0.25	30	10	2.5	0.85	1.2	2

* WA = biomass energy ratio, HI = harvest index, TOP = optimal temperature, TBS = base temperature, DMLA = maximum potential leaf area index, DLAI = fraction of growing season when leaf area starts declining, HMX = maximum crop height, RDMX = maximum root depth.

loss prediction was sensitive to rill erodibility (K_r) and soil critical hydraulic shear stress (τ_c). These three key parameters were calibrated separately for the slope gradient treatment as well as for the slope length treatment. The reasons for the separate calibrations are twofold. First, the separate calibrations provide an opportunity to reveal potential errors associated with model structure and internal parameter estimation. If two sets of the calibrated parameter values for the same soil, tillage management, and climate are very different (i.e., equifinality), it would indicate that there exist potential errors in measured data, model structure, process representation, internal parameter estimation because the calibrated parameters are responsible for all errors and uncertainties of the whole systems. Second, with the separate calibration, the model's responses to slope gradient or slope length can be characterized and quantified more precisely, because errors associated with the key relevant parameters are minimized in each specific calibration.

Estimates of the three parameters calibrated for the slope gradient treatment were: K_{eff} = 19.3 mm h^{-1}, K_r = 0.025 s m^{-1}, and τ_c = 2.6 Pa. The measured and calculated annual runoff and soil loss using these three calibrated values were close, and their scatter plots were near the 1:1 line with an E_{NS} of 0.91 for runoff (Fig. 2A) and an E_{NS} of 0.79 for soil loss (Fig. 2B), indicating that the model fitted the measured annual data well. The calibrated values of the soil erodibility parameters were very close to those determined by Zhang and Liu (2005) for a similar loessial soil from the southern Loess Plateau. To validate the model calibration, the WEPP model was then run for the 10°, 20°, and 28° plots (note that the 5°, 15°, and 25° plots were used for the calibration). Model efficiencies for predicted annual runoff and soil loss during validation were 0.92 and 0.76, respectively, which were similar to those during calibration, indicating that the three calibrated parameters performed well for the slope gradient treatment.

In the parallel calibration using measured annual data from the slope length plots (10- and 30- m long at 30°), the three calibrated values were: K_{eff} = 22.1 mm h^{-1}, K_r = 0.022 s m^{-1}, and τ_c = 3.5 Pa. Prediction model efficiencies were 0.88 for annual runoff and 0.74 for annual soil loss during calibration, and 0.88 and 0.76 during validation (using data from the 20- and 40-m long plots at 30° slope gradient), respectively. The E_{NS} values from the calibration and validation plots were close, indicating that the calibrated parameter values performed well for the slope length treatment.

The two sets of the calibrated parameter values determined under the slope gradient and slope length studies were close but slightly different. The greater K_{eff} from the slope length treatment might be caused by longer infiltration time as water flows downslope over a longer slope length and /or greater soil erosion at a greater slope angle of 30° for that treatment. The loessial soil was prone to surface seal formation during rainfall (Luk and Cai, 1990), and greater soil erosion would tend to counter sealing by eroding the less pervious thin seal layer from the soil surface. Shainberg et al. (1992) reported that the final infiltration rates during a rainfall event tended to be greater at higher slopes due to greater soil erosion. The slight disagreement between the two sets of the calibrated erodibility parameter values was indicative of a potential

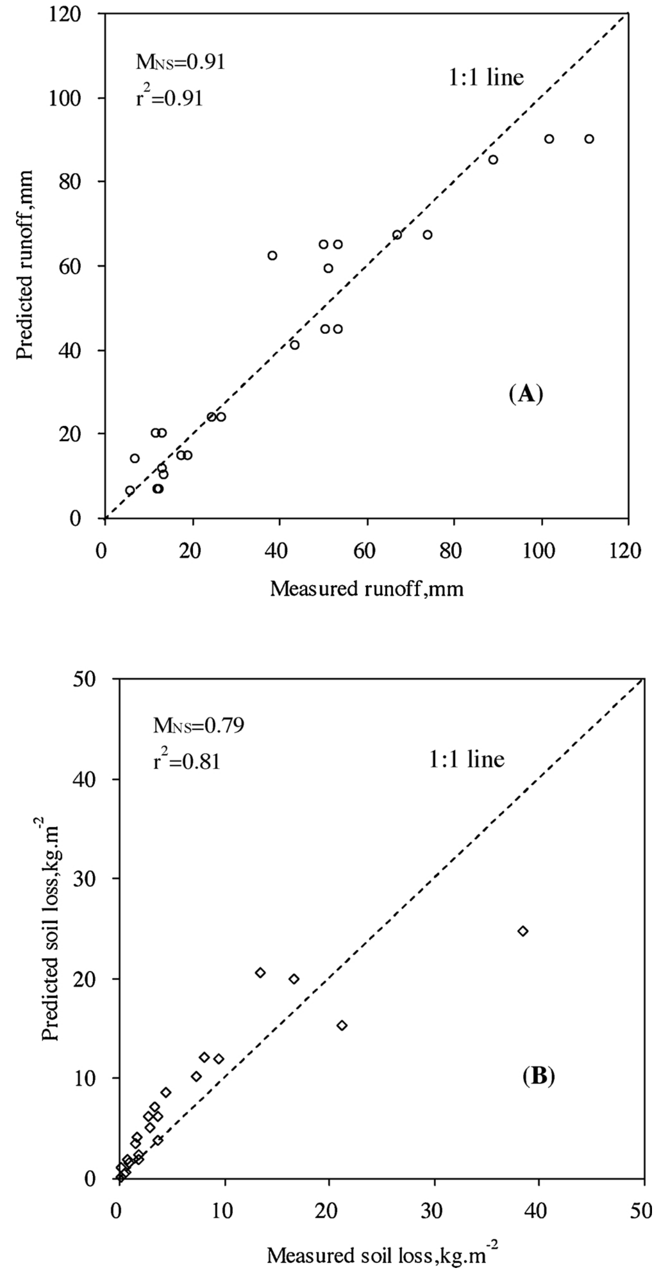

Fig. 2. Scatter diagrams between predicted and measured annual runoff (A) and soil loss (B) on the calibration plots.

inadequacy of the WEPP model in its formulation in representing the effects of slope steepness and slope length on soil erosion, especially at high slope gradients. To gain insights into model behavior, the two sets of the calibrated values as well as their averages were used to predict annual runoff and soil loss for all plots in both slope gradient and slope length treatments. The E_{NS} values calculated for the WEPP model predictions of the annual runoff and soil loss values are provided in Table 4. Model efficiencies for the slope gradient treatment plots were fairly close for both sets of the calibration values. However, considerable differences for the soil loss predictions existed for the slope length treatment plots, when using the two different sets of calibrated erodibility parameters. These results indicate that the WEPP model may have a deficiency in representing the slope length effect on soil loss at steep slope gradients (see more discussion later).

Table 4
Model efficiency (E_{NS}) of annual runoff and soil loss predictions under three different calibrations.

Treatment	Variable	Slope gradient calibration	Slope length calibration	Average values of the two calibrations
Slope gradient	Runoff	0.912	0.880	0.902
	Soil loss	0.772	0.743	0.782
Slope length	Runoff	0.847	0.879	0.871
	Soil loss	0.553	0.758	0.688

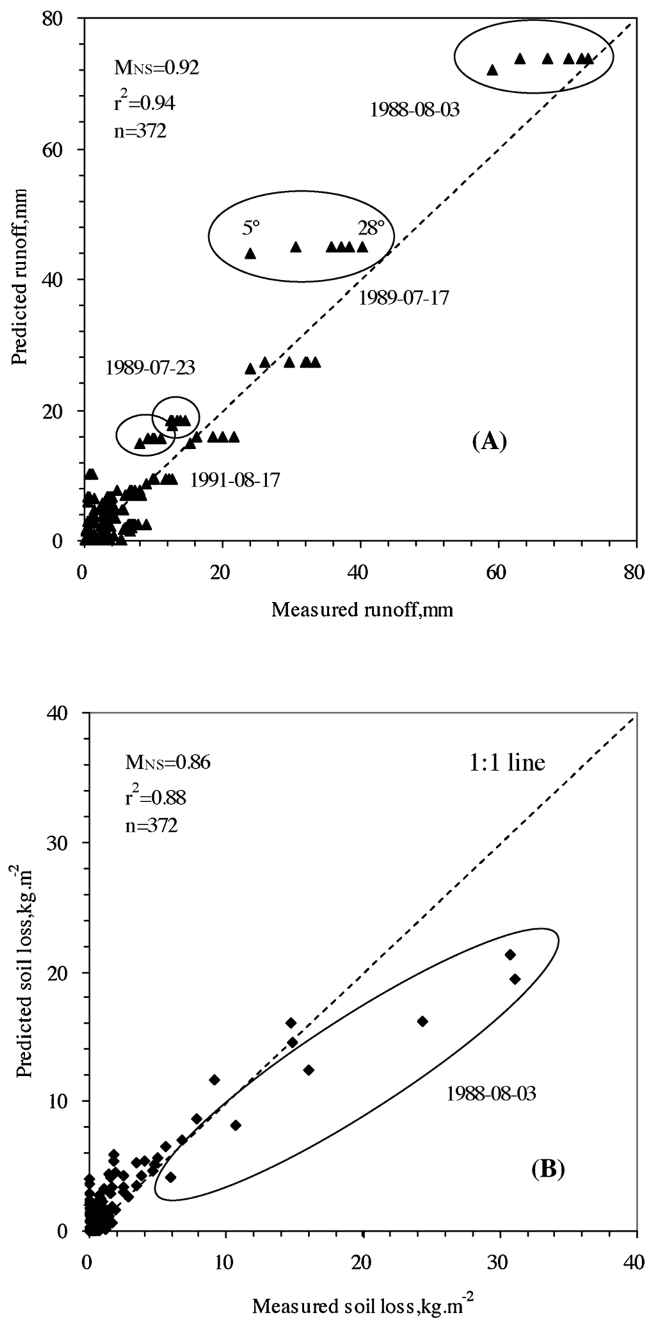

Fig. 3. Predicted versus measured event runoff (A) and event soil loss (B) on the six slope gradient treatment plots (date format: yyyy-mm-dd).

3.2. Simulated event and average-annual runoff and soil loss

3.2.1. Slope gradient treatment

The three key parameters calibrated for the slope gradient treatment using annual data were used to simulate event and average-annual runoff depths and soil loss rates for the six slope gradient plots. The measured and simulated event runoff and soil loss were close to the 1:1 line, with an E_{NS} of 0.92 for runoff depths (Fig. 3A) and a E_{NS} of 0.86 for soil loss rates (Fig. 3B). The results showed that the WEPP model simulated event runoff quite reasonably; however, it tended to overpredict surface runoff for storm events having high maximum 30-min rainfall intensity (I_{30}). As indicated in Fig. 3A, the runoff depths of the four events having the greatest I_{30} in the records were slightly overpredicted (the maximum 30-min intensity was around 60 mm h^{-1} for the four storms). The measured event runoff increased with slope steepness primarily due to the decrease in the surface storage capacity, but the simulated runoff was somewhat insensitive to slope increases, suggesting that the effects of slope steepness on surface runoff storage was not well represented at steep slopes. For example, for the 7/17/1989 event, the measured runoff was 24 mm on 5° and 38 mm on 28°, while the WEPP-predicted runoff was 44 and 45 mm, respectively.

The event soil loss was reasonably simulated by the model (Fig. 3B), except for the extreme event on 8/03/1988, in which 138-mm rain fell within one day and the I_{30} reached to 56 mm h^{-1}. The WEPP model underpredicted soil loss for this extreme event at all six slopes. This can be explained by the fact that only downward scouring by concentrated flow is simulated in WEPP while rill headcutting and sidewall slumping are not explicitly modeled. Headcutting and sidewall slumping during active rill formation are important forms of rill erosion on steep slopes in the Loess Plateau, especially during large erosive storms (Zheng and Tang, 1997; Shen et al., 2015, 2016; Qin et al., 2018b). Zhang (2016) also reported that WEPP-predicted soil loss was quite sensitive to rill spacing, which often varies with slope steepness. In this study, the 1-m default rill spacing was used in all simulations, and an inadequate representation of rill spacing at the different slopes might have affected the response of the WEPP-predicted soil loss to slope steepness.

Measured and simulated average-annual runoff and soil loss are plotted in Fig. 4 with an E_{NS} of 0.62 for runoff and an E_{NS} of 0.83 for soil loss. Average annual runoff and soil loss could provide useful insights into the model's overall response to slope gradient changes, since the climate factor was largely averaged out. The simulated runoff increased with slope gradient only from 5° to 10°, while the measured runoff increased up to 20° (Fig. 4A), indicating that the effects of slope steepness on surface water storage are not well simulated in WEPP, especially at high slope gradients. WEPP seemed to consistently overpredict average-annual soil loss (Fig. 4B), and the overprediction appeared to increase as slope gradient increased. This result indicated that the model's soil loss prediction response to slope gradient change was slightly over sensitive under steep slope conditions.

3.2.2. Slope length treatment

Similar to the slope gradient treatment, the three key parameter values calibrated for the slope length treatment were used in WEPP model simulations. The predicted event runoff and soil loss for all four slope length plots are shown in Fig. 5. The measured and simulated event runoff depths were close to the 1:1 line, with an E_{NS} of 0.92 (Fig. 5A). Event soil loss was slightly less well simulated with an E_{NS} of 0.85 for all events. Similar to the slope gradient treatment, the event soil loss from the extreme event on 8/03/1988 was underpredicted (Fig. 5B). Again, this may be because the rill headcutting and sidewall slumping processes, which are common in heavy storms, are not explicitly simulated in the WEPP model.

Measured and simulated average-annual runoff depths and soil loss rates are plotted in Fig. 6. The E_{NS} for both predicted runoff and soil loss were negative, even though the determination coefficients (r^2) of the linear regressions were high. Although small sample sizes may have an

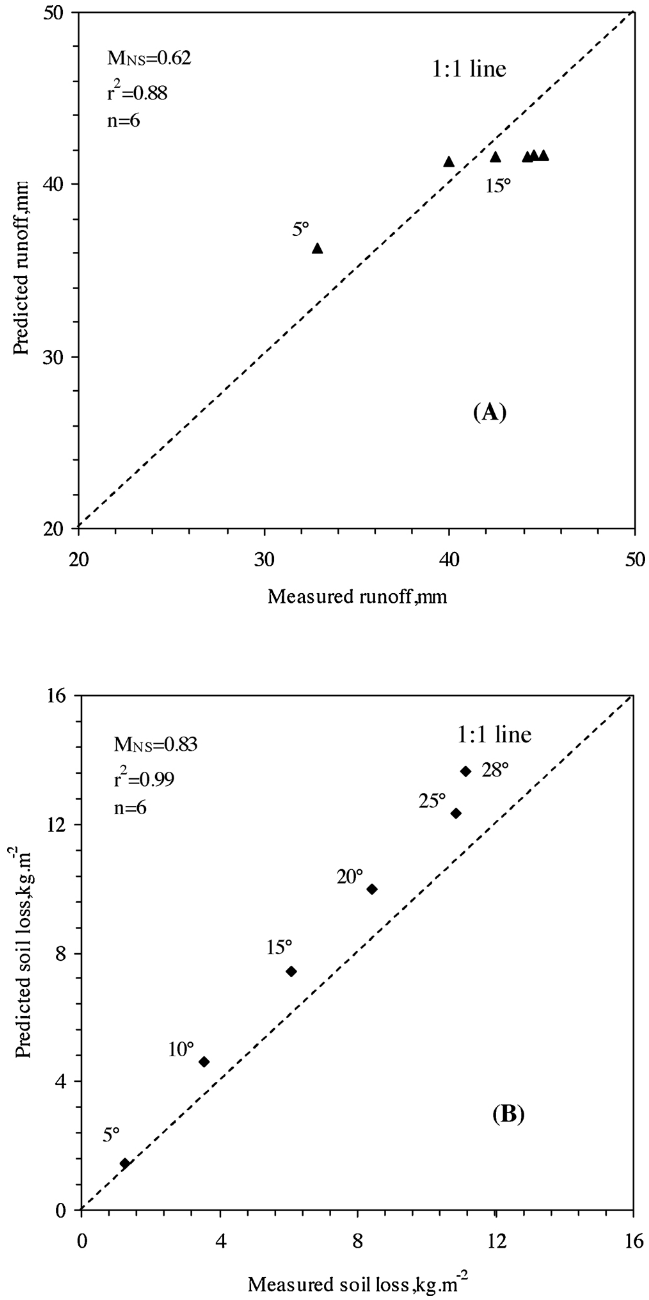

Fig. 4. Predicted versus measured average annual runoff (A) and average annual soil loss (B) on the six slope gradient treatment plots.

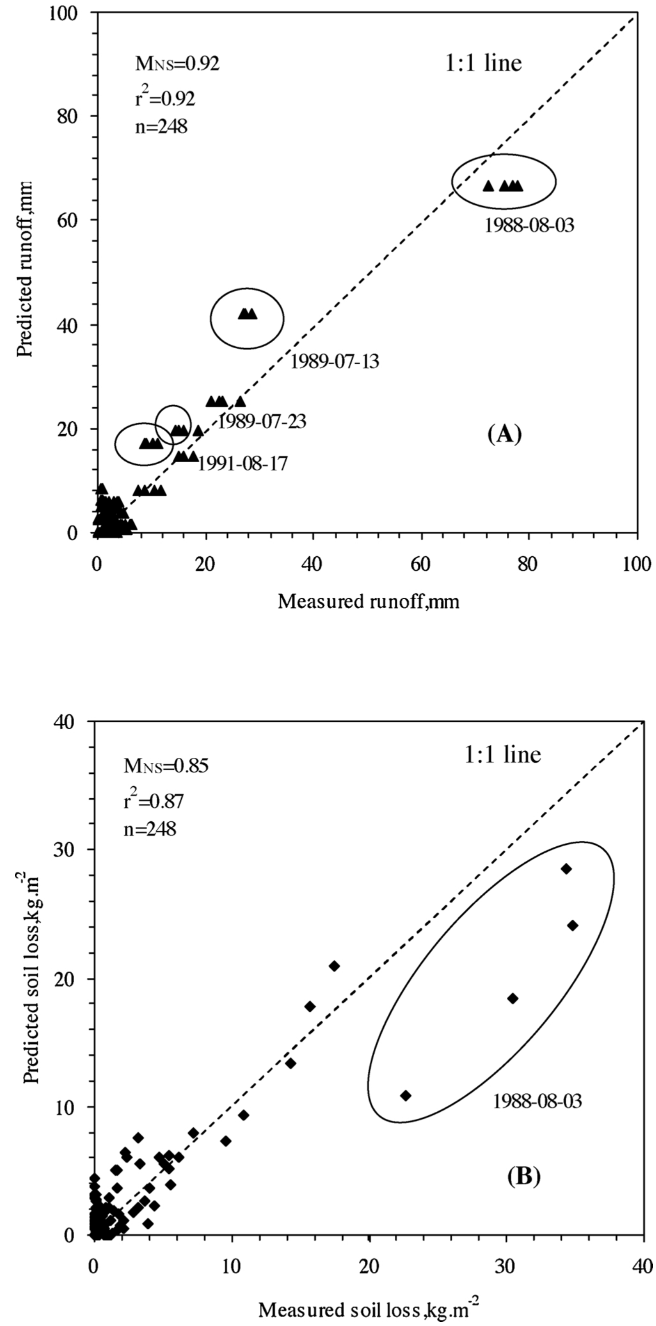

Fig. 5. Predicted versus measured event runoff (A) and event soil loss (B) on the four slope length treatment plots (date format: yyyy-mm-dd).

unfavorable effect on E_{NS} (McCuen et al., 2006), the negative E_{NS} values here are indicative of a potential problem or bias of the WEPP model for representing the effects of slope length on runoff and soil loss. The measured average-annual runoff tended to decrease from 40 to 34 mm as slope length increased, while the simulated runoff was insensitive to slope length changes (see more discussion later). It is sensible that the duration of the runoff process increases as the slope length increases, resulting in longer infiltration time for longer slope lengths and therefore less runoff volumes. The simulated soil loss was overly responsive to slope length increases at steep slopes, such as at the 30° (58%) slope used in the experiment. This model bias resulted in the negative E_{NS} value for soil loss, even though the r^2 was 0.99. The overestimation increased as slope length increased at the 28° (54%) slope, indicating that caution is warranted when applying the WEPP model on long, very steep profiles, especially under tilled fallow conditions. Additional erosion processes representation for rill detachment that includes headcutting and sidewall slumping may be necessary in the WEPP model logic to improve its performance under these type conditions.

3.3. *Characterizing slope gradient and length influences on runoff and soil loss*

3.3.1. *Slope gradient influence*

Cumulative distributions of annual runoff increase per 1° slope gradient increase are plotted in Fig. 7 for the five slope groups. The increases of measured annual runoff per 1° slope gradient increase consistently decreased as slope steepness increased, and the increases were reversed or became negative for slopes changing from 25° to 28° (Fig. 7A). This observed phenomenon was not caused by a difference in the projection area (the projected plot length was 20 m for all of the slope gradient plots), but may be explained in principle as follows. In

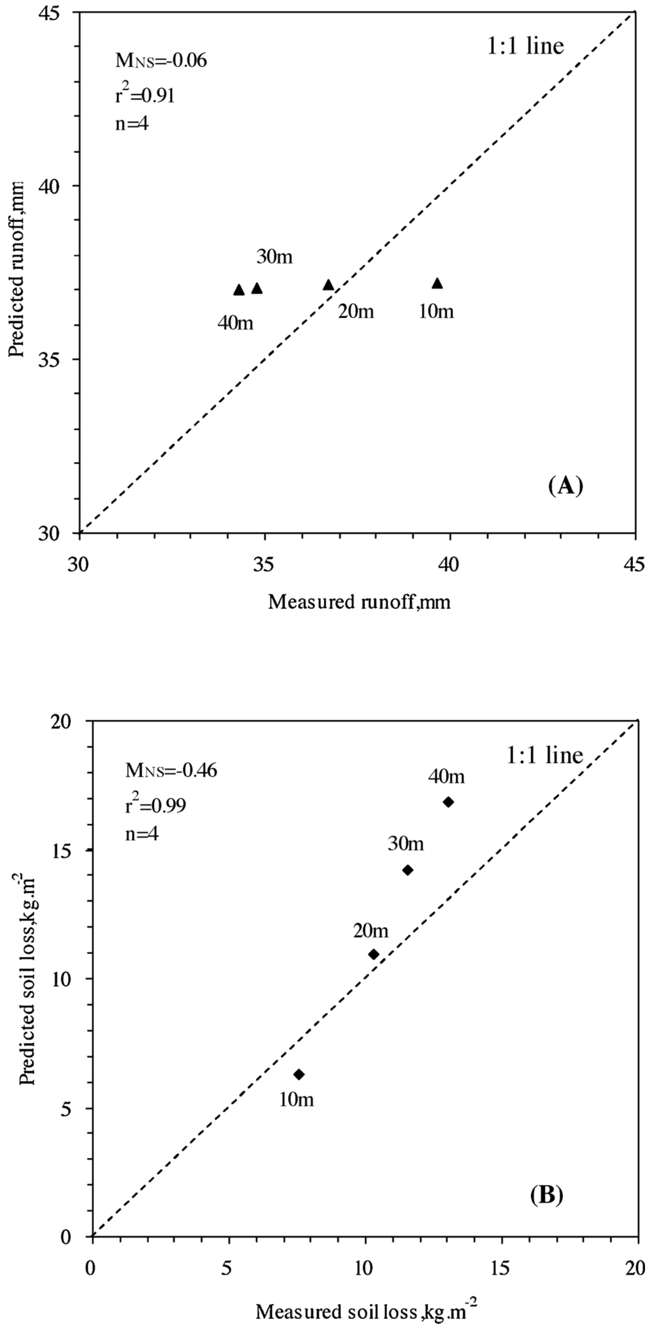

Fig. 6. Predicted versus measured average annual runoff (A) and average annual soil loss (B) on the four slope length treatment plots.

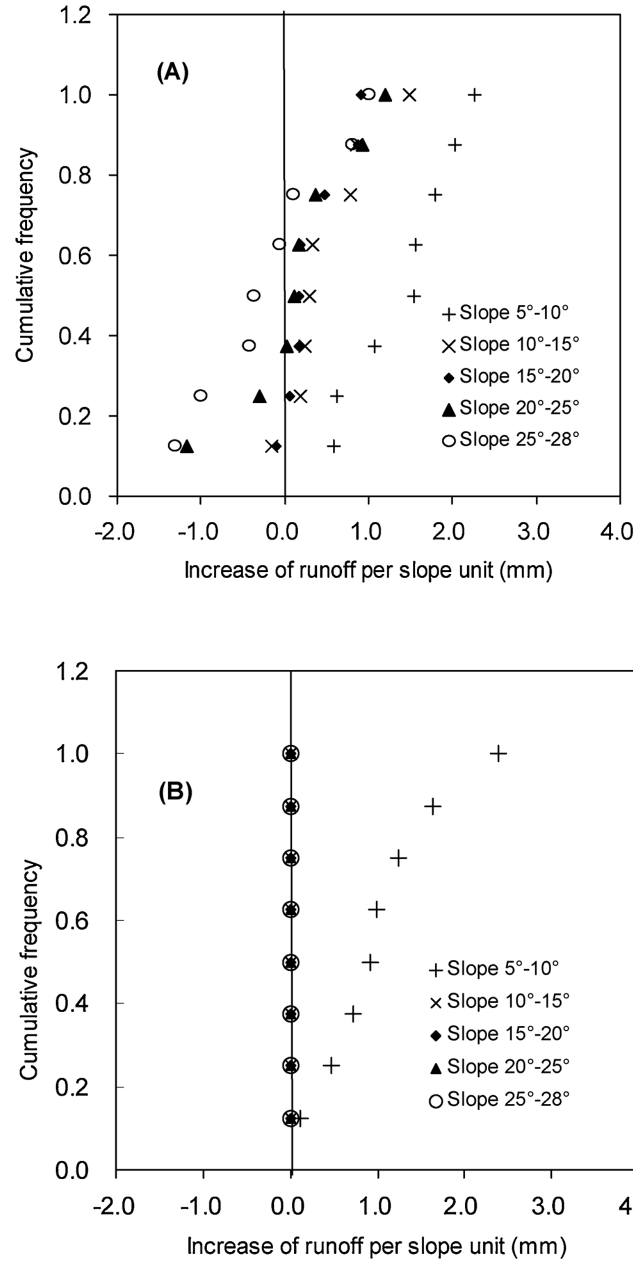

Fig. 7. Cumulative distribution of runoff increases per 1° slope increase for five slope groups for measured annual runoff (A) and simulated annual runoff (B).

general, the surface water storage capacity decreases as slope steepness increases for any given surface roughness condition, and the rates of the capacity loss (or efficiency of surface water retention) should decrease as slope steepness increases. There is another mechanism coming into play as slope increases. As mentioned earlier, the loessial soil is very susceptible to surface seal formation during a storm, and the hydraulic conductivity of the surface seal is often several orders lower than the underneath unsealed soils (Luke and Cai, 1990; Zhang and Miller, 1996). Greater soil erosion rates at steeper slopes would disrupt seal formation more effectively and therefore enhance water infiltration and reduce runoff (Shainberg et al., 1992). The importance of this mechanism would increase as soil loss increases, i.e., as slope gradient increases. In contrast to the measured data, the WEPP-simulated annual runoff only increased as slope increased from 5° to 10° and remained unresponsive to slope changes up to 28° (Fig. 7B). The lack of the runoff response to slope change in WEPP was potentially because: 1) the effects of slope steepness on surface water storage capacity were not adequately simulated by the model at the higher slope gradients; and 2) the erosion of the soil surface seal layer and the subsequent effect on enhancing infiltration is not simulated by WEPP.

Cumulative distributions of measured and simulated annual soil loss for the five slope groups are shown in Fig. 8. The increases of the measured annual soil loss per 1° slope degree increase tended to decrease as slope steepness increased, as indicated by the leftward shifts of the distributions as slope increased from 5° to 28° (Fig. 8A). This decreasing pattern (leftward shift from 5° to 28°) was well represented by the WEPP model (Fig. 8B). However, the influence of slope steepness on soil loss, as represented by the soil loss increase per 1° slope degree increase, was over-simulated by the model since the distributions for each slope group in Fig. 8B were shifted to the right compared with those in Fig. 8A for most slope groups and years (except for the year with the most soil loss). This finding was in agreement with the

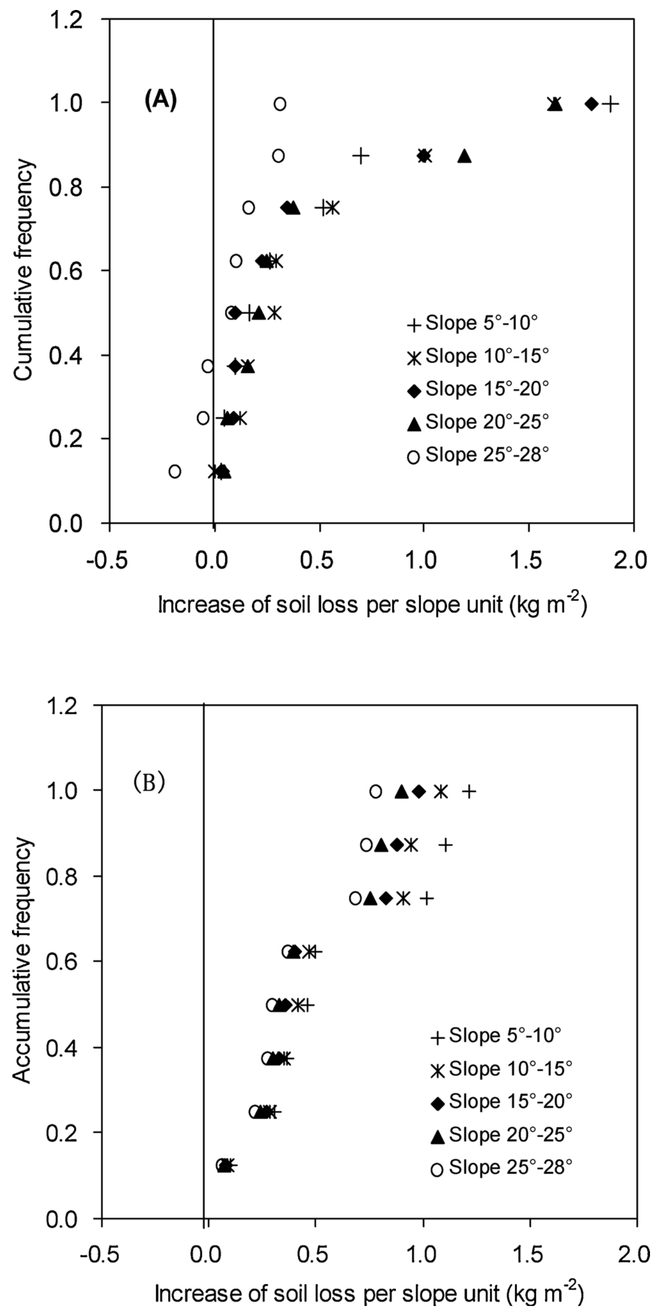

Fig. 8. Cumulative distribution of soil loss increases per 1° slope increase for five slope groups for measured annual soil loss (A) and simulated annual soil loss (B).

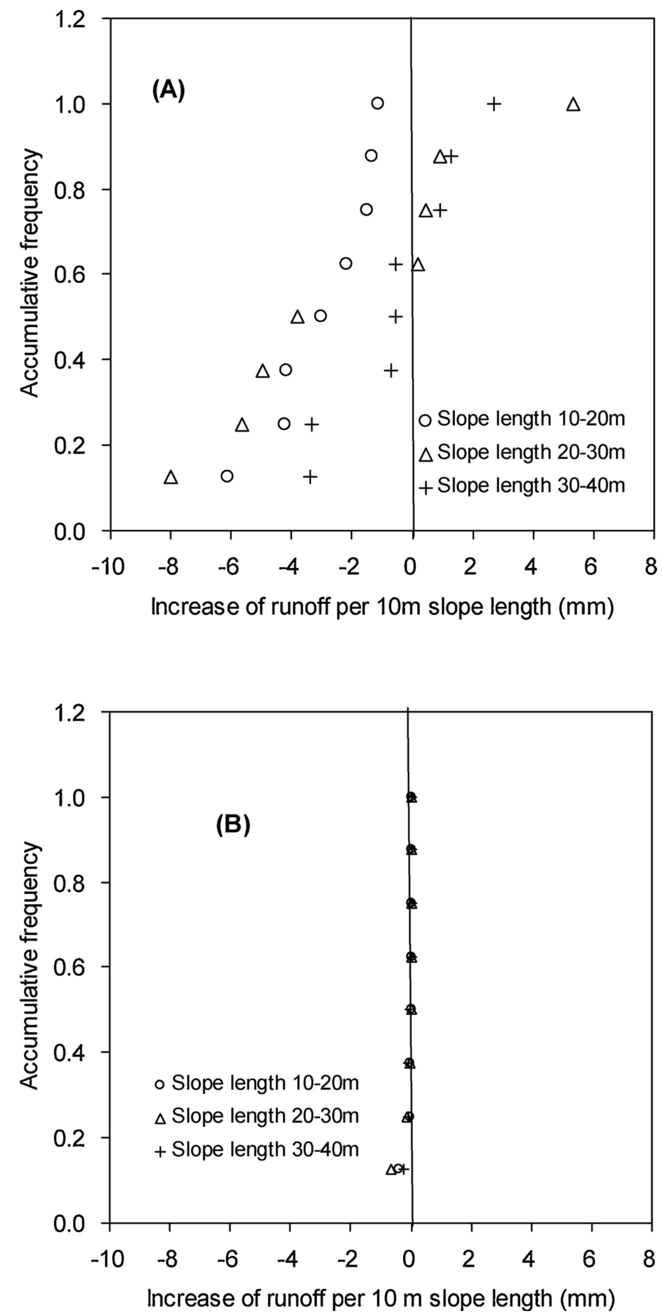

Fig. 9. Cumulative distribution of runoff increases per 10-m increase in slope length for measured annual runoff (A) and simulated annual runoff (B).

conclusion drawn from Fig. 4B.

3.3.2. *Slope length influence*

Measured annual runoff depths decreased as slope length increased for most years (Fig. 9A), as indicated by the negative runoff depths per 10-m increase in slope length. This decreasing trend may be explained by two major mechanisms. First, the travel time of overland flow increases as slope length increases. The longer travel time ought to result in more water infiltration, especially when the surface is rough. Secondly, spatial variability of hydraulic conductivity such as the presence of preferential flow pathways may be responsible. Since overland flow depth increases with slope length, a deeper overland flow or surface ponding enhances infiltration not only by increased hydraulic heads but also by supplying more water to more macropores or to larger areas having greater infiltration capacity (Zhang et al., 1995). The WEPP-simulated annual runoff depth exhibited small decreases as slope length increased only for a few years. The lack of slope length response is probably because the macropore flow phenomenon is not explicitly simulated in WEPP and the effective hydraulic conductivity within a plot or overland flow element is assumed uniform.

There was a tendency that the increases of measured annual soil loss rates per 10-m increase in slope length became smaller as slope length became longer (Fig. 10A). This pattern was clearly simulated by the WEPP model (Fig. 10B). However, the simulated increases in soil loss per 10-m increase were greater than the measured increases for most years, as indicated by the rightward shifts of the distributions in Fig. 10B relative to those in Fig. 10A. The right shifts indicated that the WEPP-simulated annual soil loss was overly sensitive to slope length, and the same was true for simulated event soil loss (distributions not

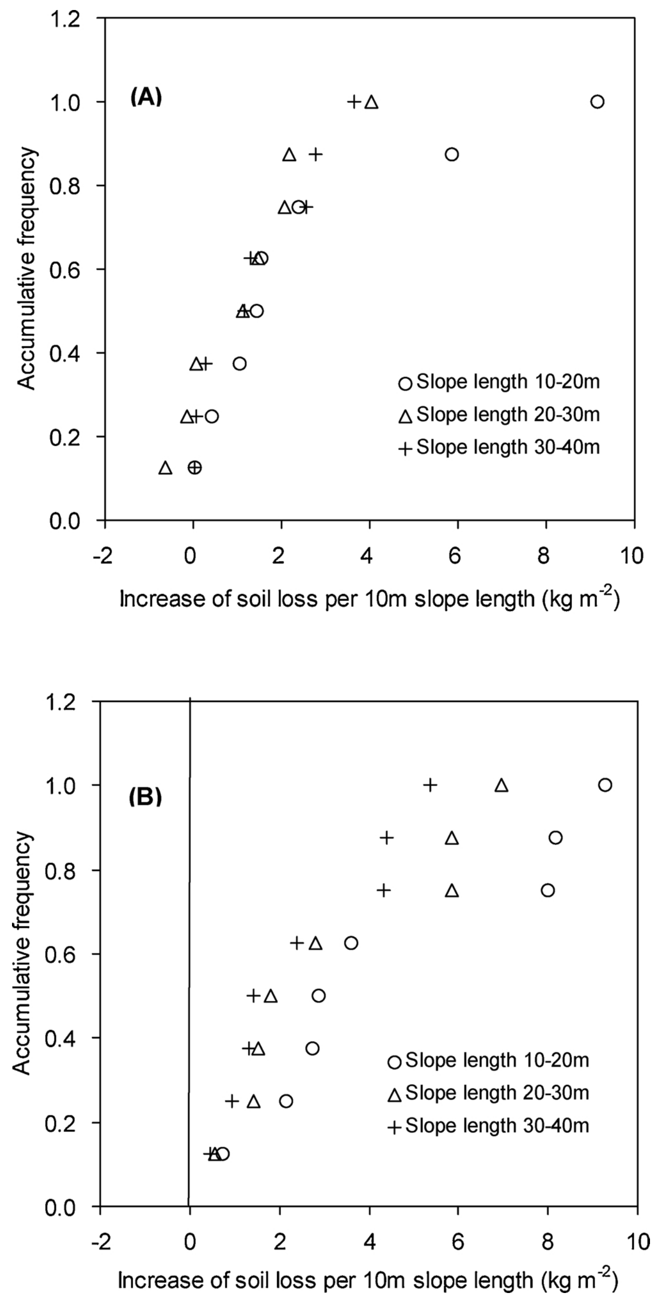

Fig. 10. Cumulative distribution of soil loss increases per 10-m increase in slope length for measured annual soil loss (A) and simulated annual soil loss (B).

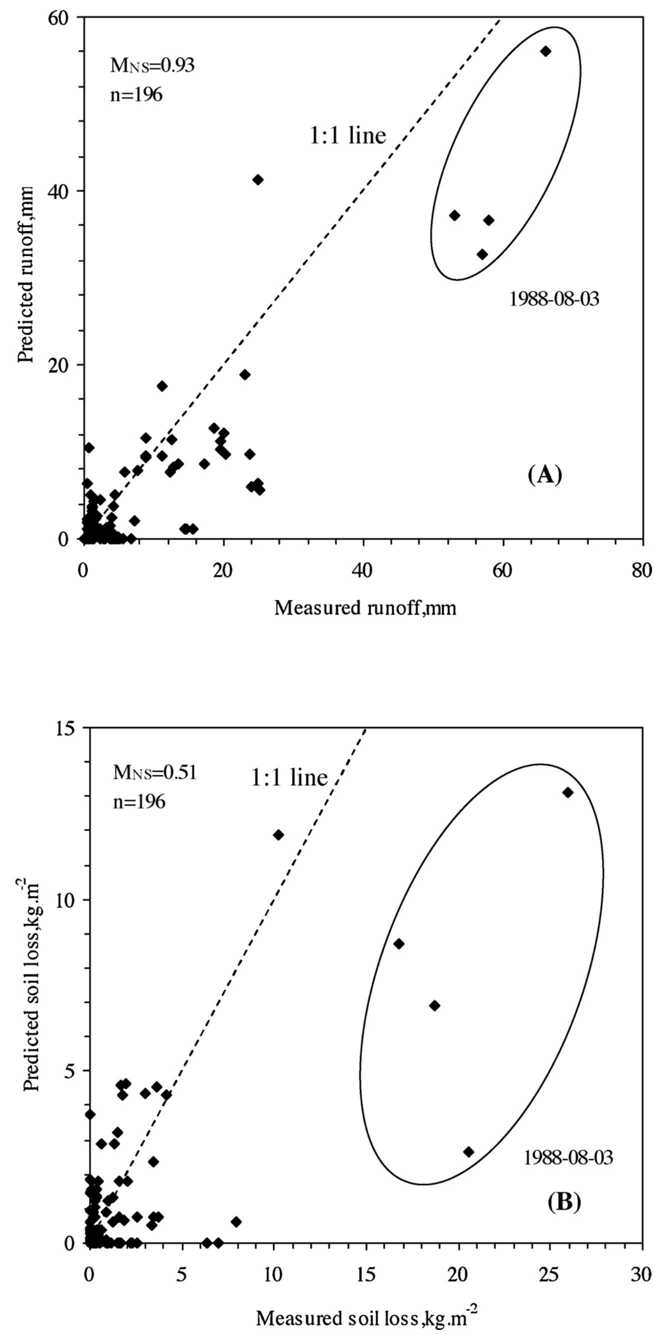

Fig. 11. Scatter diagrams between measured and simulated event runoff (A) and event soil loss (B) for all cropped plots (date format: yyyy-mm-dd).

shown). This conclusion is in agreement with the one drawn from Fig. 6B.

3.4. Runoff and soil loss prediction under cropped conditions

The four cropped plots, which were 20 m long at a 25° (47%) slope gradient, had the same type of soil as the bare plots. Since the two sets of the parameter values calibrated for the slope gradient treatment and for the slope length treatment were close, the average values (K_s = 20.7 mm h^{-1}, K_r = 0.0235 s m^{-1}, and τ_c = 3.1 Pa) were used in the simulations for the cropped plots. The calibrated baseline values of these three parameters are internally adjusted in the WEPP model to account for their temporal changes as affected by surface sealing and crusting, soil consolidation, tillage operations, residue and vegetation cover, live and dead roots, and others (Flanagan and Nearing, 1995; Zhang et al., 1995).

WEPP model prediction efficiency (E_{NS}) for event runoff depths for all cropped plots was 0.93 (Fig. 11A), and for event soil loss was 0.51 (Fig. 11B). WEPP generally predicted event runoff reasonably well for the cropped plots. However, the event soil loss values were not predicted as well, especially for the extreme event on 8/03/1988 in which soil loss was grossly underpredicted.

Measured and simulated annual runoff depths and soil loss values are shown in Fig. 12, with an E_{NS} of 0.62 for runoff and an E_{NS} of 0.48 for soil loss. The WEPP model tended to underpredict annual runoff for most years, especially for 1988. Due to the underprediction of soil loss for the storm on 8/03/1988, the annual soil loss in 1988 was consequently underpredicted by the model (Fig. 12B). Model efficiencies for event and annual runoff and soil loss predictions are listed by crops in Table 5. Overall, the WEPP model simulated runoff better than soil loss for all four crops. Soil loss was best simulated for buckwheat and most

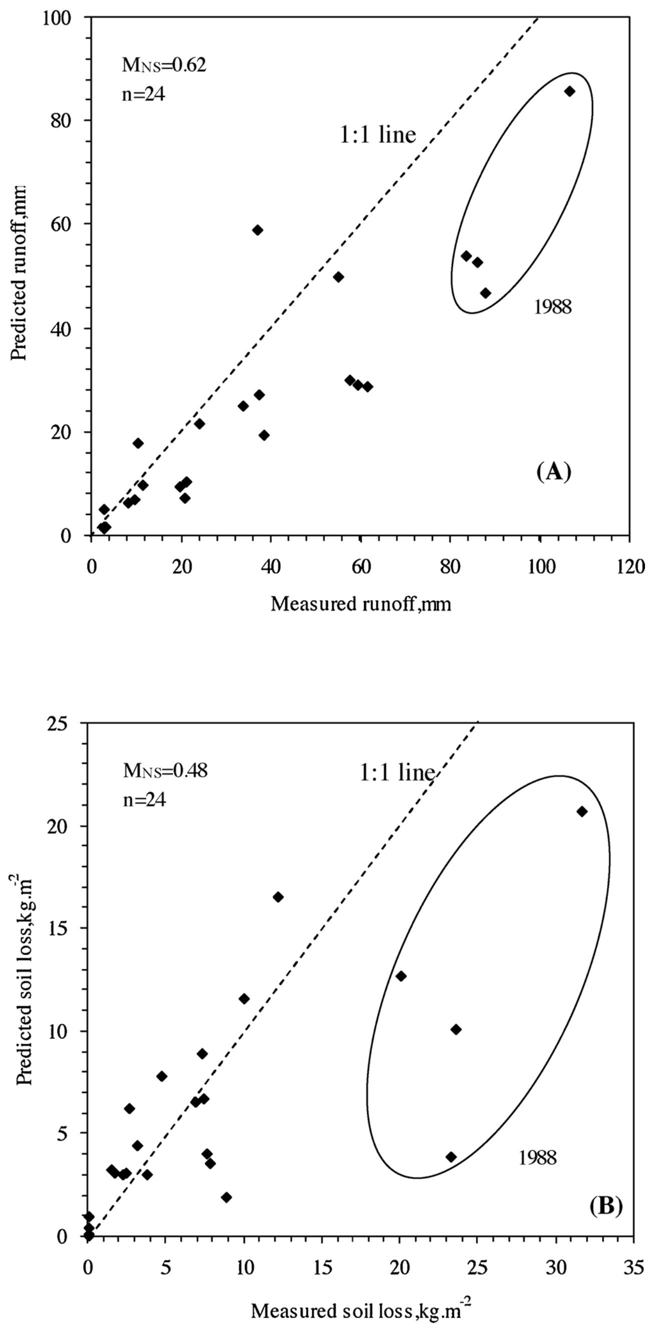

Fig. 12. Scatter diagrams between measured and simulated annual runoff (A) and annual soil loss (B) for all cropped plots.

Table 5
Model efficiency (E_{NS}) of event and annual runoff and soil loss predictions for four crops.

Crop	Event prediction		Annual prediction	
	Runoff	Soil loss	Runoff	Soil loss
Buckwheat	0.81	0.68	0.86	0.71
Potato	0.67	0.57	0.56	0.64
Soybean	0.63	0.49	0.45	0.41
Millet	0.69	0.13	0.52	−0.29

poorly for millet. To improve runoff and soil loss predictions, crop growth parameters need to be better calibrated for the region.

The average-annual runoff depth and soil loss rate for buckwheat were well simulated with a relative error of 1.3 and 3.5%, respectively (Table 6). However, the average annual runoff and soil loss for the other three crops were underpredicted. Since the baseline K_{eff} was calibrated to the bare conditions and the calibrated runoff was fairly close to the measured runoff under the bare conditions (Fig. 4A), the underprediction of runoff under cropped conditions might indicate that the K_{eff} adjustments implemented in WEPP to account for the effects of cover and precipitation depth need to be further evaluated (see detailed adjustments in Zhang et al., 1995). Since the crop yields and above ground biomasses of the four crops were unavailable, the crop parameters were not adjusted and the performance of WEPP crop simulation was not evaluated. An over-prediction of total crop biomass would lead to over-adjustment of the crop effect on runoff reduction. Thus, the effects of the crop adjustments on infiltration enhancement in the WEPP model cannot be definitely evaluated in this study. However, it is sure that the underprediction of runoff would be at least partially responsible for the underprediction of soil loss (Table 6).

Table 6
Measured and simulated average-annual runoff and soil loss for four crops.

Crop	Measured	Predicted	Relative error
		Runoff, mm	%
Buckwheat	39.3	39.8	1.3
Potato	35.5	21.1	−40.7
Soybean	36.1	19.6	−45.7
Millet	36.1	20.3	−43.8
		Soil loss, kg m^{-2} yr^{-1}	
Buckwheat	10.3	10.6	3.5
Potato	6.9	5.5	−19.8
Soybean	7.0	4.5	−35.6
Millet	7.6	3.1	−59.6

Similar to the C (crop management) factor in the USLE, the ratio of annual soil loss from the cropped plot (20-m long at 25° slope gradient) to that from the corresponding bare plot (20-m long at 25°) was calculated for each crop and year to reflect the effectiveness of crop management on soil loss reduction. The average ratios for the measured soil loss were 0.78 for buckwheat, 0.56 for potato, 0.47 for soybeans, and 0.61 for millet; while the ratios for the predicted soil loss were 0.48, 0.45, 0.15, and 0.07, respectively. These results indicate that the soil erodibility adjustments implemented in the WEPP model (see Flanagan and Nearing, 1995) to account for the effects of roots, surface residues, and other factors may need further examination using more data from steep slopes. Additionally, plant growth and residue decomposition parameters need to be developed for typical crops and conditions in China, and biomass and cover conditions need field measurements for calibration/validation, at the same time that runoff and soil loss measurements are being collected.

4. Conclusions

The WEPP hillslope model was evaluated using runoff and soil loss data collected from six bare slope gradient plots, four bare slope length plots, and four cropped plots during 1985–1992 on a loessial soil at the Ansai experimental field station in the central Loess Plateau of China. The measured rainfall breakpoint data were directly used in the calibration and evaluation to minimize rainfall intensity representation errors. Three key parameters (effective hydraulic conductivity, rill erodibility, and soil critical hydraulic shear stress) were calibrated and validated with annual runoff and soil loss data separately for the slope gradient treatment and for the slope length treatment. Model efficiencies (E_{NS}) calculated for the validation plots were 0.92 for annual runoff and 0.76 for annual soil loss for the slope gradient treatment and were 0.88 and 0.76 for the slope length treatment, respectively, indicating that the separate calibrations worked well for each treatment. However, there were small differences between the two sets of calibrated values, suggesting that a deficiency exists in representing the influences of slope length on soil loss in the WEPP model, especially at steep slope gradients.

For the slope gradient treatment, WEPP model prediction efficiencies (E_{NS}) were 0.92 and 0.88 for event runoff and soil loss, respectively; and were 0.62 and 0.83 for average-annual runoff and soil loss, respectively, indicating that the WEPP model's response of soil loss to slope steepness was satisfactory. However, measured runoff tended to increase with slope steepness primarily due to the decrease in surface storage capacity, but the simulated runoff was somewhat insensitive to slope change at high slope gradients. The WEPP model tended to overpredict average-annual soil loss, and the overprediction seemed to increase with slope gradient increase, indicating that the model's response of soil loss to slope gradient was, though acceptable, slightly oversensitive under steep slope conditions. This oversensitivity might stem from inadequate representation of rill spacing using a constant, 1-m default value. Generally speaking, rill spacing decreases as slope steepness increases, and lesser soil loss would be predicted for a smaller rill spacing by WEPP due to reduced shear stress of water flowing in each rill (Zhang, 2016).

For the slope length treatment, WEPP model prediction efficiencies (E_{NS}) for event runoff and soil loss were 0.92 and 0.85, respectively. However, the E_{NS} values for both average-annual runoff and soil loss were negative. The measured average-annual runoff tended to decrease as slope length increased; while the simulated runoff was insensitive to slope length changes, suggesting potential deficiencies in simulating recess infiltration and in representing spatially variable infiltration rates. The simulated soil loss was overly responsive to slope length increases, indicating a potential deficiency in representing the influence of slope length on soil loss at steep slopes. One possible reason could be an inadequate representation of rill spacing variations along the hillslope profiles. Measured rill spacing should be used in WEPP model simulation to improve model prediction.

For all cropped plots, E_{NS} values were 0.93 for event runoff prediction, 0.51 for event soil loss, 0.62 for annual runoff prediction, and 0.48 for annual soil loss prediction. The WEPP model tended to underpredict average-annual runoff and soil loss for 3 out of the 4 crops. The underprediction may be caused by several factors, including poor plant growth and residue decomposition parameterization, and over-adjustments of hydraulic conductivity and soil erodibility for the effects of factors like plant roots, cover and residue in the WEPP model. Plant growth and residue decomposition parameters need to be developed and validated for crops and plot conditions in China. Additionally, WEPP model internal adjustments to hydraulic conductivity and erodibilities may need to be further evaluated for use under steep slope conditions.

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