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Assessment of the Performance of WEPP in Purple Soil Area with Simulated Rainfall Experiments

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Abstract: The water erosion prediction project (WEPP) model is a popular water erosion prediction tool developed on the basis of the physical processes of water erosion. Although WEPP has been widely used around the world, its application in China is still insufficient. In this study, the performance of WEPP used to estimate the runoff and soil loss on purple soil (Calcaric Regosols in FAO taxonomy) sloping cropland was assessed with the data from runoff plots under simulated rainfall conditions. Based on measured soil properties, runoff and erosion parameters, namely effective hydraulic conductivity, inter-rill erodibility, rill erodibility, and critical shear stress were determined to be 2.68 mm h^{-1}, 5.54×10^6 kg s^{-1} m^{-4}, 0.027 s m^{-1} and 3.5 Pa, respectively, by using the recommended equations in the WEPP user manual. The simulated results were not good due to the low Nash efficiency of 0.41 for runoff and negative Nash efficiency for soil loss. After the four parameters were calibrated, WEPP performed better for soil loss prediction with a Nash efficiency of 0.76. The different results indicated that the equations recommended by WEPP to calculate parameters such as erodiblity and critical shear stress are not suitable for the purple soil areas, Sichuan Province, China. Although the predicted results can be accepted by optimizing the runoff and erosion parameters, more research related to the determination of erodibility and critical sheer stress must be conducted to improve the application of WEPP in the purple soil areas.

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Introduction

The Water Erosion Prediction Project (WEPP) is a process-based soil erosion prediction model developed by the U.S. Department of Agriculture. WEPP involves three models for different applications, Hillslope version, watershed version and GIS version. The Hillslope version can be used to simulate the soil erosion process happening at any locus on the slope, which consists of a climate generator, a hydrology module, an erosion module, a winter process module, an irrigation module, a soil module and a vegetation module. WEPP Hillslope has been validated on various land use patterns such as cropland, grass land, and forest land for soil loss prediction (Flanagan et al. 1997; Flanagan et al. 2007).

The WEPP simulates soil erosion on slope with rill erosion and inter-rill erosion. Rill erosion refers to soil loss occurring in rills where soil particles are detached and transported by rill flow, and inter-rill erosion refers to soil loss happening between rills where soil particles are detached mainly by raindrops and transported by shallow sheet flow to rill channels (Flanagan and Nearing 1995). The equations of sediment load, inter-rill sediment delivery to the rill, and rill erosion rate calculation were well documented in the WEPP user manual (Forster et al. 1995).

Since the main factors and processes affecting soil erosion were taken into consideration, WEPP has found worldwide applications (Tiwari et al. 2000). However, WEPP is not a real physical model as some equations are developed from the statistical analysis results. Therefore, more validation of the WEPP model in different areas is needed to improve the model. Laflen et al. (2004) reviewed the application of the WEPP model in different places and discussed WEPP's capabilities to predict runoff and erosion. Through a comparison of a large number of studies for the WEPP model on erosion prediction on farmland, roads, and cropland and in small watersheds, it was found that the WEPP- recommended equation for soil erodibility calculation was not suitable for furrow irrigation conditions (Laflen et al. 2004). Ghidey and Alberts (1996) found that WEPP could simulate runoff quite well for those >200 mm storm events, and vice versa for <100 mm storm events. Alberts and Ghidey (1997) validated the WEPP model with eight high-intensity events and also found 24% error in runoff prediction, but the error involved in erosion prediction was only 1.3%. Those results indicated that the WEPP Hillslope model had a strong capability to predict erosion for large storm events. Zhang et al. (1996) evaluated WEPP with more than 4000 runoff plot data from eight regions, and concluded that the WEPP could simulate runoff and erosion on cropland reasonably. Soto and Diaz-Fierros (1998) indicated that as to the WEPP model, although soil erosion was underestimated, the overall trend was reasonable. Larsen et al. (2007) compared the simulated results of RUSLE and WEPP model on post fire land and pointed out that the complicated effect of different factors on sediments in both models was not fully considered. The authors pointed out that WEPP model performance could be improved by reducing the effective water conductivity. Moffet et al. (2007) confirmed this conclusion and suggested to modify the rill soil equation by applying WEPP to predicting soil erosion on steep slopes.

The WEPP Hillslope version provides two operation modes: Continuous-storm and single-storm. The continuous-storm model requires at least one year's daily meteorological data while the single-storm mode needs to import the hourly precipitation data of one storm. To validate the suitability of the WEPP model in a particular region, the single-storm mode is of priority because in continuous-storm simulation, surface conditions, soil permeability and soil erodibility vary significantly, which leads to an increase in model error sources. Under single-storm conditions such as artificially simulated rainfall, test conditions can be controlled, then the parameter errors can be reduced effectively and the performance of WEPP model can be tested fully. Although WEPP has been applied in some areas in China, most of applications are based on continuous-storm simulation, and the application of single-storm simulation is scarce. The aims of this study are: 1) to determine the runoff and erosion parameters for the WEPP model; 2) to analyze the effect of parameter estimation on model performance, and 3) to compare the applications of WEPP in different areas.

1 Material and Methods

1.1 Study area

The data to validate WEPP are from the results of artificial rainfall experiments. The experiments were carried out in 2005 at the Yanting Agro-ecological Experimental Station of Purple Soil, CAS, with altitude of 105°27'E and a longitude of 31° 16'N. Topographically, the developed deep hills in this area are at the altitude of 400 - 600 m. This area has typical subtropical humid monsoon climate with average annual temperature of 17.3 ℃ and average annual rainfall of 825 mm. The main soil types in this area are paddy soil (*Anthraqui - Stagnic Luvisols* in FAO taxonomy) and purple soil (*Calcaric Regosols* in FAO taxonomy). Cropland is the main land use here, and the natural vegetation is dominated by alder (*Alnus cremastogyne*) and cedarwood (*Cypresses fineries*). The design of rainfall simulation experiments is the same as the author's previous report (Fu et al. 2009).

1.2 WEPP input files

Before running the WEPP model, four datasets including climate, soil, topography and management must be available.

1.2.1 Climate

The WEPP model requires climate data including daily precipitation, temperature, solar radiation, and wind speed and wind direction. Climate data file can be created by a stand-along program-CLIGEN 4.3 for both continuous-storm mode and single-storm mode. CLIGEN 4.3 can generate three types of climate files: continuous simulation data based on ip/tp, single-event simulation based on ip/tp and TR-55 design single storm with ip/tp data (Flanagan and Nearing, 1995). The ip/tp means intensity and time to peak intensity of rainfall. This study adopted single storm mode with ip/tp data. The climate file needs the following data: storm date, storm amount, rainfall duration, max rainfall intensity and time to peak. Table 1 is the experimental results of simulated rainfalls and the climate data for the WEPP model.

1.2.2 Soil

Listed in Table 2 are the primary soil properties including soil texture, organic matter percentage, cation exchange capacity, Albedo and Initial Saturation Level (*SAT*).

Soil properties were obtained by analyzing soil samples from the field. The WEPP Hillslope model requires importing the soil properties layer by layer. The soil depths of all the plots for artificial rainfall experiment are 400 mm, thus it only needs to generate one soil layer in the soil file.

Albedo is the fraction of Sun's radiation reflected from a surface. The parameter value imported to WEPP represents the solar radiation from a bare and dry soil surface and the model will adjust the Albedo according to the effects of soil moisture, vegetation, residue cover and snow. In this study, the Albedo was determined to be 20%.

Another parameter value which must be given in soil file is *SAT* which is the percentage of the pores filled by water at the beginning of simulation.

Table 1 Runoff (RO, mm) and Soil Loss (SL, kg m^{-2}) in simulated rainfall experiments with different Rain Intensity (RI, mm h^{-1}), Rainfall Duration (RD, hrs) and Storm Amount (SA, mm)

Events	Slope (%)	RI	RD	SA	RO	SL
502	17.62	19.6	0.98	19.25	4.40	0.07
503	17.62	37.4	0.75	28.13	17.66	0.88
504	17.62	54.0	0.46	24.56	13.68	0.96
505	17.62	74.0	0.51	37.89	24.09	1.64
506	17.62	111.7	0.35	38.91	24.92	2.55
602	26.78	19.6	0.94	18.43	4.48	0.10
603	26.78	37.4	0.66	24.67	13.50	1.03
604	26.78	54.0	0.51	27.65	12.58	1.21
605	26.78	74.0	0.32	23.65	13.54	1.58
606	26.78	111.7	0.33	36.70	22.63	2.97
702	36.38	19.6	1.00	19.52	4.85	0.12
703	36.38	37.4	0.33	12.20	5.57	0.55
704	36.38	54.0	0.59	31.61	19.97	2.53
705	36.38	74.0	0.40	29.59	19.19	2.84
706	36.38	111.7	0.36	39.71	25.14	4.35
802	46.63	19.6	1.00	19.6	4.45	0.12
803	46.63	37.4	0.52	19.28	7.87	0.70
804	46.63	54.0	0.57	30.53	14.47	1.73
805	46.63	74.0	0.41	30.64	12.82	2.11
806	46.63	111.7	0.41	45.23	28.25	6.14
902	8.74	19.6	1.12	21.94	2.73	0.04
903	8.74	37.4	0.74	27.58	4.67	0.12
904	8.74	54.0	0.67	36.24	8.95	0.24
905	8.74	74.0	0.61	45.48	16.84	0.60
906	8.74	111.7	0.44	48.83	14.03	0.66

Before each rainfall simulation test, soil moisture was measured at the depth of 15 cm, 30 cm and 40 cm from surface soil, and the values ranged from 24% to 33%, and the average value of *SAT* was then determined to be 42.45%.

Table 2 Soil properties

Parameter	Value	Parameter	Value
Rock (%)	15.78	OM (%)	8.75
Sand (%)	20.93	*CEC* (cmol kg^{-1})	23.70
Clay (%)	9.37	Albedo	0.2
Depth (mm)	400	SAT (%)	42.45

Note: Rock, percent of soil particle greater than 2 mm; OM, organic matter in the soil; SAT, initial saturation level.

Cation exchange capacity (CEC) refers to the quantity of cations adsorbed on soil particle under chemically neutral conditions (cmol/kg of soil) and it is used in the equations of parameter estimation for hydraulic conductivity. Li et al. (1991) reported the CEC for calcareous purple soil being 23.7 cmol/kg. Our simulation used this value.

1.2.3 Topography

The projective slope lengths of the five plots are 4.98 m, 4.92 m, 4.83 m, 4.7 m and 4.53 m, widths are all 1.5 m, and the slope gradients are 8.74%, 17.62%, 26.78%, 36.38% and 46.63%, respectively.

1.2.4 Management

The management file is the most complicated in all input files. In single storm mode, the initial management condition is critical which includes more than 20 parameters such as bulk density, initial plant and days since last tillage. Since all rainfall simulations were done on bare land, the content of management is simplified. Under experimental conditions, the bulk density of soil varies within the range of 1.11 - 1.66 g cm^{-3}. Here we used the average value of 1.27 g cm^{-3} for simulation. Initial plant term parameter was set as none plant, and days since last tillage was set to zero, and other terms were default.

1.3 WEPP simulation schemes

Except the four basic data, effective hydraulic conductivity, inter-rill erodibility, rill erodibility and critical shear stress are the key runoff and erosion parameters in WEPP. Two methods were used to get the values of these parameters, which resulted in two simulation schemes. In scheme A, parameters were calculated by WEPP-recommended equations with soil properties. In scheme B, the runoff and erosion parameters were calibrated in the WEPP model automatically by selecting calibration model after importing other soil and climate data first, and then they were used to run the WEPP model.

1.3.1 Scheme A

In WEPP, runoff and erosion parameters can be calculated by using two different equations according to whether the sand percentage is greater than 30%. In this study, the sand percentage is less than 30%, thus K_i is calculated as follows (Alberts et al. 1995):

$$K_i = 6054000 - 55130 \times CLAY \quad (1)$$

where, K_i is the inter-rill erodibility, kg s m^{-4}, *CLAY* is the percentage of clay.

For soils containing less than 30% sand, the equation for Kr is:

$$K_r = 0.0069 + 0.134 e^{-0.2CLAY} \quad (2)$$

For critical shear stress, when sand accounts for less than 30%, the WEPP user manual recommended the value of 3.5 Pa (Alberts et al. 1995).

The effective hydraulic conductivity is another key parameter in WEPP. The value of this parameter will be obtained by following the steps below: The first step is to determine the soil penetration as moderated according to National Engineering Handbook (USDA 2007), and the second step is to calculate the effective hydraulic conductivity with equation 9 (Alberts et al. 1995):

$$K_e = 1.17 + 0.072 \times SAND \quad (3)$$

Where, K_e is the adjusted effective hydraulic conductivity, mm h^{-1}, and *SAND* is the sand percentage.

1.3.2 Scheme B

Runoff and erosion parameters were determined by mutual calibration. Since experiments were carried out under similar conditions, the rainfall event under the conditions of moderate slope and rain intensity was used for calibration. The parameters to be calibrated are: effective hydraulic conductivity, inter-rill erodibility, critical shear stress and rill erodibility in order.

1.3.3 Index

To assess the performance of the model, a single index cannot fully reflect the relationship between the observed data and the predicted results, so multiple indices usually were applied (Willmott 1981). Commonly used indices are: correlation coefficient (R^2) between the predicted and observed values; the Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970); the root-mean-square error (RMSE) (Bhuyan et al. 2002; Willmott 1981); and the relative error between the predicted value and the observed value.

The Nash efficiency (Em) is calculated as:

$$E_m = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_{ave})^2} \quad (4)$$

where, P_i is i_{th} the predicted value; O_i is i_{th} the observed value; O_{ave} is the average of all observed events.

RMSE is calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \quad (5)$$

where, O_i is the i_{th} observed value; P_i is the i_{th} predicted value, and n is the number of rainfall events.

The relative error is used to represent the accuracy of event storm:

$$S_i = (P_i - O_i)/P_i \times 100 \quad (6)$$

where, S_i is the relative error, P_i is the predicted value, and O_i is the observed value.

2 Results

2.1 WEPP parameters

Listed in Table 3 are the model parameters used in both scheme A and scheme B. The inter-rill erodibility was the same in both schemes, and the rill erodibility, effective hydraulic conductivity and critical shear stress are distinctly different.

Table 3 Runoff and erosion parameters used for simulation in Scheme A and B

Parameter	Scheme A	Scheme B
K_e / mm h^{-1}	2.68	2.19
K_i /10^6 kg s m^{-4}	5.54	5.54
K_r / s m^{-1}	0.027	0.006
τ / Pa	3.50	10.35

Table 4 Comparison of runoff and soil loss simulated in two schemes

	Parameter	Runoff	Erosion
Scheme A	*RMSE*	5.78	3.67
	E_m	0.41	-5.30
Scheme B	*RMSE*	5.72	0.71
	E_m	0.42	0.76

Note: RMSE is the root-mean-square error, E_m is Nash efficiency

2.2 Simulation results of scheme A

In scheme A, runoff and erosion parameters were calculated with the equations that WEPP recommended. The predicted runoff was better than the average value, with the Nash efficiency of 0.41 and *RMSE* of 5.78 (Table 4). WEPP performed poorly for erosion prediction since the Nash efficiency for erosion was negative, which indicated worse results compared to the average value. Figure 1 shows the contrast of the predicted runoff and the observed runoff. The predicted runoff was

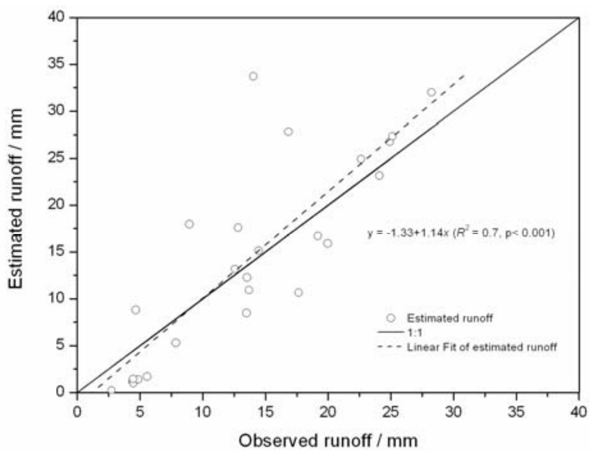

Figure 1 Comparison of the simulated runoff in scheme A with the observed runoff

a linear function of the measured runoff with the coefficient of determination (R^2) =0.7. The slope of fitted line 1.14 indicated that the simulated runoff was greater than the observed runoff. Statistical results showed that there were 14 events with under-estimated runoff, which accounted for 64% of all simulated events.

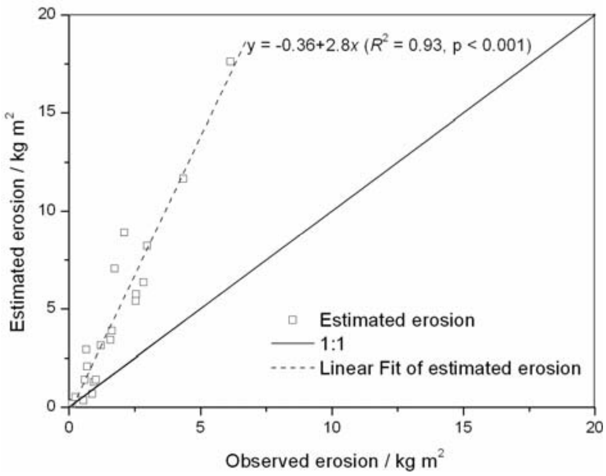

Figure 2 Comparison of the predicted erosion in scheme A and the observed soil loss

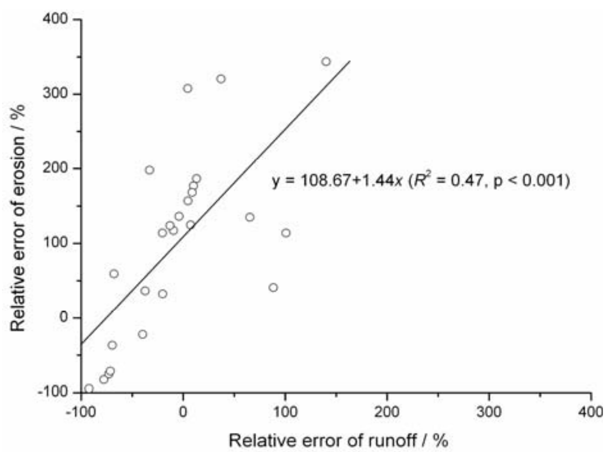

Figure 3 Comparison of the runoff simulation performance and the erosion prediction performance

Figure 2 compared the predicted erosion with the observed erosion. Stronger linear function was found between the simulated value and the observed value with the coefficient of determination (R^2) = 0.93. In low erosion events, erosion usually was under-estimated, but over-estimated in high erosion events. In contrast to runoff prediction, erosion was over-estimated in most events. The ratio of events over-estimated accounted for up to 76% of all the events.

Figure 3 compared the accuracy of runoff prediction with that of erosion prediction. There was a linear function between the relative error of runoff and that of erosion with the coefficient of determination (R^2) =0.47. Therefore, any action for improving either the runoff simulation or the erosion simulation can also enhance the performance of the whole model. The consistency of runoff and erosion simulation did not come from the WEPP model itself, but was related to the applied environment. Alberts and Ghidey (1997) found inverse trends for the runoff prediction and erosion prediction when calculating the soil erosion on maize cropland. The runoff was overestimated by 214% and the erosion was under-estimated by 11%.

2.3 Results of simulation with scheme B

Effective hydraulic conductivity, rill erodibility and critical shear stress were optimized based on the calculated values with scheme B, and resulted in the change of model performance.

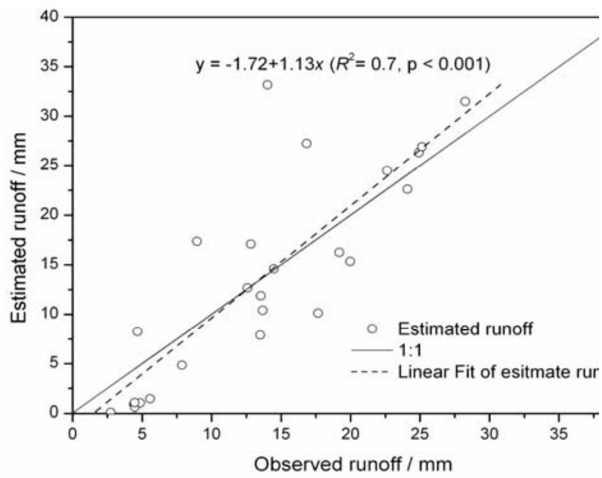

Figure 4 Comparison of the observed runoff and the estimated runoff in scheme B

The predicted results of runoff obtained a little improvement, with *RMSE* decreasing from 5.78 to 5.72 and Nash efficiency increasing from 0.41 to 0.42. However, the results of erosion simulation were improved distinctly since RMSE decreased to 0.71 and Nash efficiency increased to 0.76. Shown in Figure 4 is the simulated runoff in scheme B. There existed a linear correlation between estimated runoff and measured runoff with the coefficient of determination (R^2) = 0.7. Shown in

Figure 5 are the results of erosion prediction. Also the simulated erosion was a linear function of the measured erosion with the coefficient of determination (R^2) = 0.91.

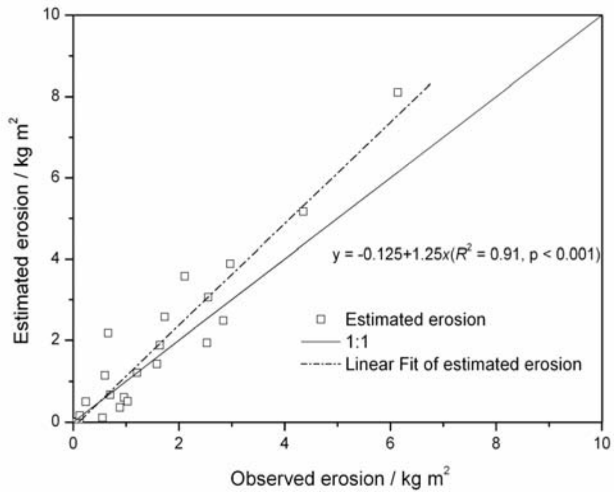

Figure 5 Comparison of the predicted erosion in scheme B and the observed soil loss

2.4 Comparison of two schemes

Shown in Figures 6-7 is the consistency of predicted runoff and erosion, respectively, for both schemes. The determination coefficient of erosion estimation with two schemes is up to 0.9, indicating a similar prediction trend. The straight linear correlation can be found for both schemes, but less erosion was predicted by scheme B than by scheme A since the ratio of predicted erosion between scheme B and scheme A was 0.44. Listed in Table 4 are the Nash efficiency and RMSE for both schemes. The runoff results of scheme A are the same as those of scheme B, with the Nash efficiency of 0.42 and 0.41. Scheme B predicted erosion more accurately than scheme A with the Nash efficiency up to 0.7, but the latter was negative. Therefore, the efficient hydraulic conductivity calculated by the equation recommended in the WEPP user manual can be used for runoff prediction without calibration, but the rill erodibility cannot be used for erosion prediction directly.

3 Discussion

3.1 Parameter estimation

Soil erodibility, effective hydraulic conductivity and critical shear stress are sensitive parameters for WEPP, and have important effect on prediction results. Most researchers preferred to use the recommended equations to calculate these parameters and someone used the parameters calibrated by WEPP automatically as Table 5 showed. For the effect of parameters calculated with WEPP recommended equations on runoff and erosion prediction, there has no consistent viewpoint can be found. Yu and Rosewell (2001) successfully predicted the erosion on bare slope in single storm events by using runoff and erosion parameters calculated with the measured soil samples. Bhuyan et al. (2002) compared the capabilities of three models — the WEPP, the

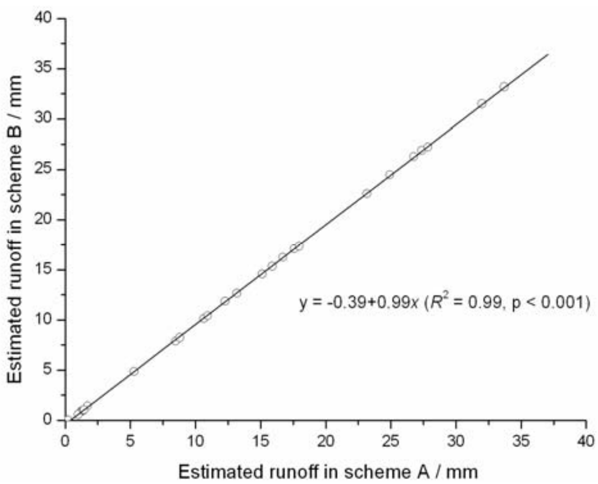

Figure 6 Comparison of predicted runoff in Scheme A and Scheme B

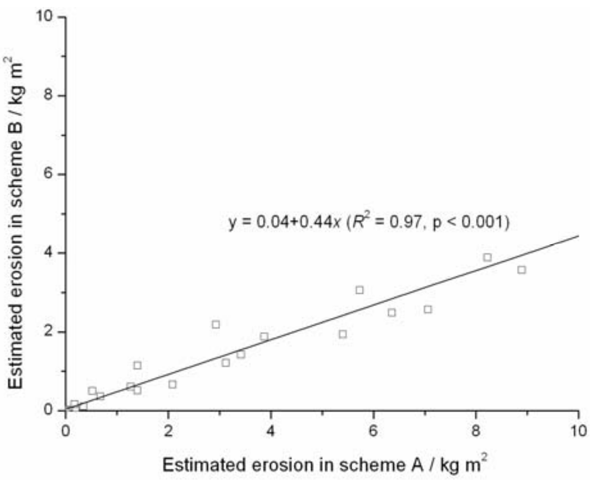

Figure 7 Comparison of predicted erosion in Scheme A and Scheme B

Table 5 Application of WEPP for croplands water and soil loss prediction in different areas

Region	Soil	Slope	Plot size	PCM	Literature
Italy	CS+FS	15%	7 m × 50m	SP	Pieri et al. 2007
Australia	Sand 42%	7.50%	100 m^2	SP	Yu et al. 2000
Norway	Sand 9.5%	13%	21 m × 8 m, 30 m × 7 m	SP	Gronsten & Lundekvam 2006
USA	Silt loam soil	1—1.5%	3 m × 15 m	Calibration	Bhuyan et al. 2002

Note: PCM means parameter calculation method, CS+FS: 10% coarse sand and 32% fine sand; SP: estimating parameters with WEPP recommended equation with soil property

Erosion Productivity Impact Calculator (EPIC), and the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) in predicting soil loss for three different tillage systems, and found that the soil loss predicted by the WEPP model was reasonably good with the observed data when runoff and erosion parameters were calibrated based on the calculated values with the equations recommended by WEPP. Pieri et al. (2007) reported under-estimated erosion predicted by WEPP on cropland in Italy because the runoff and erosion parameters were not calibrated. However, Gronsten and Lundekvam (2006) simulated runoff and soil loss using the WEPP Hillslope model in yearly and daily modes, and suggested that it was unsuitable to simulate soil erosion on those two Norwegian soils by using WEPP-recommended soil erosion parameter equations, especially for leveled soil.

In this study, two methods for parameter calculation were applied and a notable difference in model prediction was found. WEPP performed poorly when the four parameters calculated by the recommended equation were used. The results indicated that the parameters calculated by WEPP equations could not be used in the model directly to predict soil loss in the purple soil area of Sichuan Province, China. The major cause can be attributed to the variability of soil. During rainfall simulation experiments, little variation was observed in soil property and slope surface as compared to seasonal tillage. However, even under this condition, the WEPP model cannot produce good result if without parameter calibration, which suggested that the critical erosion parameters like rill erodibility were not calculated correctly. In WEPP, erodiblility was divided into two parts: the baseline erodibility and the adjusted erodibility, the baseline erodiblity is determined by soil texture, but as lots of research reported, any soil property may affect soil erodiblity (Elliot et al. 1990; Govers and Loch 1993; Mamo and Bubenzer 2001; Nachtergaele and Poesen 2002). The several easy to measure factors are texture, organic content, aggregate content, structure, pH, etc. (Bryan 2000; Elliot et al. 1990). In fact, the baseline erodiblity equation in WEPP is highly simplified since only soil texture was used for erodibility calculation. Purple soil is a highly erodible soil, with coarse texture and low organic matter content, and it is prone to shrinking-swelling, but the effect of these factors is not taken into consideration in WEPP erodiblity equations.

3.2 Model performance on purple soil cropland

WEPP was developed based on plot data from the USA. Many equations were empirical. The simulated results must be validated in environments different from where model was developed (Larsen and MacDonald 2007), which was important for model improvement.

Numerous other studies compared the WEPP applications in different storm events (Table 5). Most researchers agreed that runoff and erosion were over-estimated for low rainfall events, but under-estimated for high rainfall events (Ghidey et al. 1995; Gronsten and Lundekvam 2006; Kramer and Alberts 1995; Zhang et al. 1996). Risse et al. (1994) suggested that this result was related to the area of runoff generation. For light rainfall, just part of the plot made some contribution to runoff, but WEPP assumed that the whole plot would generate runoff. Therefore, the results were over-estimated.

The result of this study was inconsistent with what was described above. For low rainfall intensity events, runoff and erosion were both underestimated, but overestimated for high rainfall intensity events. Since the plots were small in this study, the explanation of Risse et al. (1994) cannot account for the results of our experiments. The main reason is that WEPP cannot represent all physical processes of water erosion, especially under different environmental conditions. In the WEPP model, the whole slope was divided into two parts: rill and interrill in space, then runoff and erosion were calculated based on this partition. However, this treatment was not common in the hilly areas of the Sichuan Basin, China. Farmers like to conduct tillage on flat slope without any ridge. It is unknown where the rill will occur and how it is developed. Thus, the direct application of the WEPP model could not produce satisfied results.

4 Conclusions

WEPP prediction performance was assessed for erosion on purple soil cropland by using the plot data from rainfall simulation in the field. Estimated values of the effective hydraulic conductivity, soil erodibility and critical shear stress were 2.68 mm h^{-1}, 5.54 × 106 kg s m^{-4}, 0.027 s m^{-1} and 3.5 Pa, respectively. The estimated results are not a good fit due to negative Nash efficiency for erosion. After effective hydraulic conductivity and critical shear stress were calibrated, better results of erosion were obtained as the Nash efficiency increased to 0.7. The different results indicated that the WEPP equations calculating parameters such as erodiblity and critical shear stress are not suitable to be used in purple soil areas, Sichuan Province, China. T o promote the application of WEPP in China, the further study should focus on development of f when an erosion parameters such as interrill erodibility and rill erodibility estimating equation based on soil properties.

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