A Process-Based Model (WEPP) for Simulating Soil Erosion in the Andes

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Soil erosion by water represents a major threat to the long-term productivity of hillside agriculture in the Andes. To help combat this threat, researchers need a quantitative understanding of the hydrologic and physical processes that drive soil loss. They also need to understand how these processes interact with land use and management to either diminish or increase soil loss. This understanding, however, is not easily obtained in a cultural and physical environment as diverse and complex as the Andes, particularly given the paucity of experiments and data needed to quantify soil erosion for the myriad land-use systems in the region.

To better understand soil erosion and its impact in the Andes, we have begun a multi-institutional and multidisciplinary effort based on a systems research approach. This approach is designed to take advantage of existing simulation models, using existing experimental data to the extent possible for model calibration and model testing. New experiments and other data collection activities will be pursued as this approach helps us to identify gaps in available data sets and possibly inaccuracies in process descriptions incorporated in present models. With time, we expect the iterative process of experimentation and model evaluation to increase our understanding of the major processes that cause soil erosion. We also expect the systems research approach to result in improved simulation models that can be used to help predict how conservation measures—or the lack of them—might affect soil productivity on a site-specific basis.

A process-based simulation model we have begun to evaluate under Andean conditions is one recently developed by the Water Erosion Prediction Project (WEPP) of the U.S. Department of Agriculture (Flanangen and Nearing, 1995). The WEPP model mathematically describes the processes of soil particle detachment, transport, and deposition due to hydrologic and mechanical forces acting on a hillslope profile. It is considered to possess state-of-the-art knowledge of erosion science, and has become an important analytical tool for global change studies (Favis-Mortlock et al., 1996).

The purpose of this study is to provide a first approximation of the capability of the WEPP model for simulating soil loss in an Andean environment. We will do this by comparing model predictions of runoff and soil loss to data measured from fallow runoff plots during a 154-d study in the eastern Andes of Peru.

Materials and Methods

Model description

The WEPP erosion model is a continuous simulation computer program that calculates runoff and erosion on a daily basis. Erosion processes may be simulated at the level of a hillslope profile or at the level of a small watershed. Our evaluation, however, is restricted to the hillslope profile version (v 98.4). The major inputs for running the hillslope profile version need to be specified in four data files: weather, slope, soil, and management.

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The weather file requires daily values for precipitation, maximum and minimum temperature, and solar radiation. In addition to rainfall amount, the model requires three variables related to rainfall intensity that are used to compute rainfall excess rates and thus runoff. These are (1) rainfall duration, (2) the ratio of time to peak rainfall intensity to rainfall duration, and (3) the ratio of maximum peak intensity to average intensity.

With the WEPP model, a user can simulate differences in soil types or management along the length of a hillslope through the use of overland flow elements (OFE). An OFE is a specified section of the hillslope with a region of homogeneous soils and management. Up to 10 OFEs can be defined for one hillslope of a given width. The number of OFEs to include in a simulation is specified in the slope file, along with the length and slope characteristics of each OFE.

The soil file contains information on the physical characteristics of the surface soil and subsoil for each OFE. The surface soil parameters required are the effective hydraulic conductivity (Green and Ampt effective conductivity), interrill erodibility (sheet erosion mostly caused by raindrop impact), rill erodibility (small eroded channels), critical shear stress (rill detachment threshold parameter), and albedo (fraction of solar radiation reflected back to the atmosphere). For each soil layer, the inputs required are cation exchange capacity (CEC) and percentages of sand, clay, organic matter (OM), and rock fragments. Up to eight soil layers to a maximum profile depth of 1.8 m may be defined in the soil file.

The management file contains information needed to define initial conditions, tillage practices, plant growth parameters, and residue management and crop management. It is the file with the largest number of parameters.

Runoff plot study

Measurements of runoff and soil loss were obtained from a runoff plot study conducted during the first 6 mo of 1991 in San Ramon, Peru (Pastor, 1992). In this study, 30 runoff plots, each 10 m long and 4 m wide, were set up on slopes of 30, 35, 40, 45, 50, and 60%. At each of the six slope sites, five plots with the following management systems were installed: (1) clean fallow, (2) natural grass vegetation, (3) sweetpotato (*Ipomoea batatas*) planted in rows along the contour with hilling, (4) sweetpotato planted in rows along the contour without hilling, and (5) sweetpotato planted up and down the slope with hilling. Treatments were not replicated, meaning there was only one set of observations for each unique combination of slope and management system. There were also fairly large differences in the infiltration properties of the soils (Entisols) across slope sites. Infiltrometer measurements in the field showed infiltration was 21.0 mm/hr on the 30-35% slopes, 12.4 mm/hr on the 40-45% slopes, 215.0 mm/hr on the 50% slope, and 104.7 mm/hr on the 60% slope.

Runoff and soil losses were measured after each rainfall from 21 Jan to 24 Jun 1991. There were 62 rainfall events during this 154-d period, each producing measurable runoff and soil loss. The total rainfall for the period was 1,053 mm. Total runoff and soil loss measured for all treatments and slopes are shown in Table 1 (note the sweetpotato contour treatment represents the mean of plots with and without hilling). The greatest runoff and soil loss occurred from the clean fallow plots. Any discernible impact of slope on runoff and soil loss apparently was masked by the differences in soil infiltration properties across slopes. The 50% slope, because of more rapid infiltration, actually produced less runoff and soil loss than the 30-45% slopes.

Model analysis

Our analysis of the WEPP model in this initial study focuses on measured and simulated data obtained from the clean fallow plots only. Soil is often left bare

Table 1. Runoff and soil loss measured for four different management systems at six locations with different slopes in San Ramon, Peru, from 21 January to 24 June 1991 (Pastor, 1992).

	Slope (%)						
Treatments	30	35	40	45	50	60	Treatment mean
	Runoff (mm)						
Natural vegetation	42.18	41.57	38.25	52.84	25.77	27.77	**38.06**
Sweetpotato/contour[a]	30.95	26.24	26.29	29.36	21.83	29.67	**27.39**
Sweetpotato/up-down[b]	59.10	44.69	38.52	33.53	23.39	34.58	**38.97**
Clean fallow	62.85	50.99	43.40	60.05	48.38	41.30	**51.16**
Slope mean	**48.77**	**40.87**	**36.62**	**43.95**	**29.84**	**33.33**	38.90
	Soil loss (mg ha^{-1})						
Natural vegetation	0.44	0.48	1.10	0.86	0.45	0.79	**0.69**
Sweetpotato/contour[a]	0.61	0.80	0.98	1.42	0.65	1.06	**0.92**
Sweetpotato/up-down[b]	2.42	3.33	3.21	4.01	1.82	3.96	**3.13**
Clean fallow	14.88	13.03	11.38	7.74	3.12	8.39	**9.76**
Slope mean	**4.58**	**4.41**	**4.17**	**3.51**	**1.51**	**3.55**	**3.62**

[a] Sweetpotato planted in rows along the contour.

[b] Sweetpotato planted in rows up and down the slope.

between crops, thus it is important to quantify the vulnerability of exposed soil to the erosive forces of natural rainfall. Also, we thought it better to first parameterize and evaluate the performance of the model for bare soil where there would be no expected interaction between residue cover and plant growth. If the model cannot be shown to simulate soil loss realistically from bare soil, then it would not be expected to do so for other management systems.

Our analysis of WEPP in this study is also restricted to results averaged across slopes. There was insufficient information about the on-site soil properties to parameterize the WEPP model for each slope site. Therefore, we evaluate the performance of the model by averaging both measured and simulated data across slopes. That is, WEPP model input files were set up to simulate by slope, but the simulated output values were averaged across slopes before comparing them to measured data, which were also averaged across slopes.

For evaluating model performance, we followed the suggestion of Nearing et al. (1994) to compare the frequency distributions of the measured and simulated events rather than make event-by-event comparisons. Although the WEPP model should eventually be evaluated by comparing outcomes on an event-by-event basis, such a comparison is not valid in this study. The reason is that critical input parameters for soil properties and rainfall intensity were not measured on site and could only be approximated.

Model inputs

The weather file for simulating erosion from the clean fallow plots was assembled using daily rainfall recorded in pluviometers at the experimental site. Daily temperature and solar radiation values were obtained from the CIP-San Ramon weather station located about 1 km from the experimental site. Rainfall intensity was not recorded at the site, so we estimated values for the duration and intensity parameters using statistical relations derived from recorded values at the CIP-San Ramon weather station.

Slope input files were assembled for each of the six slopes by specifying one OFE with a slope length of 10 m and a plot width of 4 m. Soil input files were made identical for each of the slope sites. Soil profile parameters for soil depth, texture, OM, CEC, and rock fragments were based on measurements taken from a nearby site (La Torre, 1985). Surface soil parameters were estimated using either empirical relations described in the WEPP User Summary (Flanagan and Livingston, 1995) or by calibrating simulated runoff and soil loss to measured data from only the 30% slope. Input values for surface soil parameters were 7.0 mm/h for effective hydraulic conductivity, 2.0 x 10^6 kg s/m^4 interrill erodibility, 0.002 s/m for rill erodibility, and 4.0 N/m^2 for critical shear stress. The management input files were also made identical for each slope with parameters set to simulate bare soil.

Results and Discussion

One of the most notable discrepancies between WEPP model simulations and measured data was in the number of rainfall events that resulted in runoff and soil loss. Whereas field measurements showed that each of the 62 rainfall events produced some runoff and soil loss, although often in only small amounts (Figures 1A and 1B), the WEPP model produced runoff and soil loss values for only 16 of the events. Closer analysis revealed that the model failed to pick up the less intense or smaller rainfall events that produced measured runoff values of less than 1 mm or soil loss values of < .1 t/ha.

The failure of the model to simulate the smaller events was judged not significant as the measured data clearly showed that any substantial soil loss only occurred when rainfall exceeded 10 mm (Figure 1B) or runoff exceeded 1 mm (Figure 1C). Furthermore, we were able to demonstrate in a sensitivity analysis that the model would reproduce more of the measured runoff and soil loss events by adjusting the rainfall intensity parameters of specific rainfall events. Thus, if the on-site rainfall duration and intensity parameters had been known with more certainty, the model output may have more accurately reflected the observed number of events.

The cumulative frequency distributions for runoff and soil loss measured during all 62 events are provided in Figure 2, expressed as the probability that any one event will exceed a given runoff or soil loss

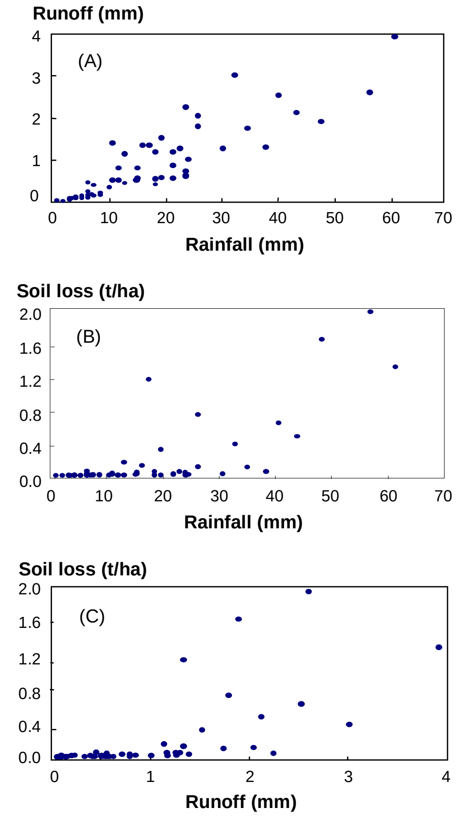

Figure 1. Measured data from fallow plots showing the relations between (A) rainfall and runoff, (B) rainfall and soil loss, and (C) runoff and soil loss. Runoff and soil loss values represent the mean across slopes for each event.

amount. These distributions represent the same data presented in Figure 1. Here, however, the highly skewed nature of the data is more apparent; relatively few events produced most of the runoff and soil loss. For example, only 4 of the 62 events resulted in a combined soil loss of 6.0 t/ha, whereas the cumulative soil loss from all events amounted to 9.8 t/ha.

The cumulative frequency distributions for simulated runoff and soil loss are also shown in Figure 2. These were calculated using the simulated output for the 16 events reproduced by the model together with zero values for the other 46 events not reproduced by the model. For that reason the simulated distributions indicate that most of the events would not have produced runoff exceeding 1 mm or soil loss exceeding 0.1 t/ha, values similar to those indicated by the measured distributions. When these values were exceeded, the simulated distribution of events similarly reflected the measured distribution.

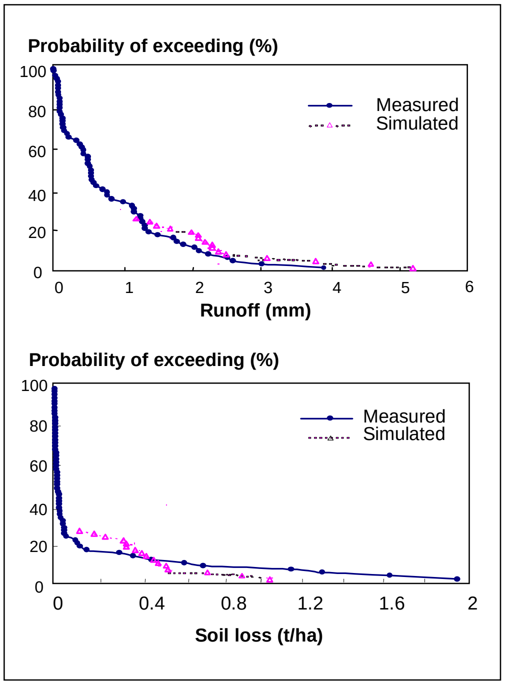

Figure 2. Measured and simulated cumulative frequency distributions showing the probability of exceeding a given runoff or soil loss from fallow plots.

For runoff, the simulated distribution was shifted to the right of the measured distribution, indicating the model tended to overpredict runoff. For soil loss, the model tended to overpredict small values (distribution shifted to the right), but underpredict large values (distribution shifted to the left). This same trend in overpredicting small values and underpredicting large values is common when evaluating many erosion models with measured data. Nearing (1998) attributes the trend to limitations in capturing the random component of measured erosion data with a deterministic model. Although measured and simulated distributions were somewhat similar, the model underestimated the 154-d totals for runoff and soil loss. We attribute that to the failure of the model to reproduce all events. The total measured runoff was 51.2 mm compared with 40.4 mm for the simulation. The total measured soil loss was 9.8 t/ha compared with 7.6 t/ha for the simulation.

In addressing some of the uncertainty regarding input parameters, we found both runoff and soil loss to be quite sensitive to rainfall and surface soil parameters. To illustrate, Figure 3 shows how runoff and soil loss would vary with the duration or intensity of a 61-mm rainfall event for two soils with different effective hydraulic conductivity values. The 61-mm rainfall was the largest recorded during the runoff plot study. In general terms, the model indicates that the difference in soil loss between a 4- or 6-h event could be as much as 20 t/ha. Likewise, an 8-h event might result in no soil loss on a soil with good infiltration properties, but erode more than 10 t/ha if infiltration is poor. The measured soil loss for this event was 1.3 t/ha. Clearly, it is important to have reliable estimates of parameters like rainfall intensity and effective hydraulic conductivity if the model is to provide realistic estimates of runoff and soil loss.

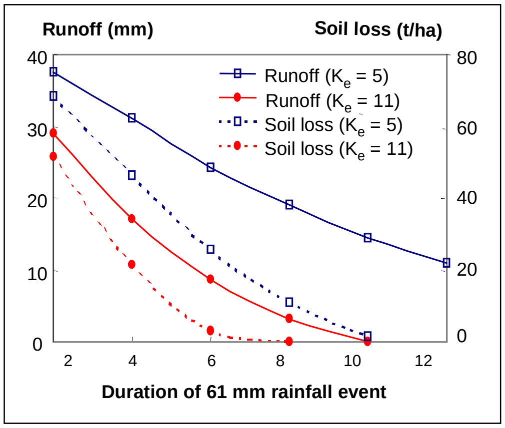

Figure 3. Sensitivity of simulated runoff and soil loss due to variation in the duration of a 61 mm rainfall event for two soils with different effective hydraulic conductivity values (K_e).

Conclusions

This initial analysis of the WEPP erosion model has shown that it can be an effective tool for studying the hydrologic and erosion processes that drive soil loss in the Andes. The model should be particularly valuable for focusing on the quantitative relations and interactions between soil, weather, topography, slope, and management factors that determine runoff, soil loss, and deposition on a site-specific basis. Nevertheless, we must caution that this study should not be seen as a validation of the WEPP model for Andean conditions. More rigorous testing of model assumptions is needed. That will require more complete experimental data sets than the one used in this study.

The results presented in this study represent our first attempt at working with the WEPP model and collating the type of measured data needed to parameterize and evaluate the model. The runoff plot study used in this analysis was certainly not ideal for model testing as shown by the lack of some on-site measurements needed to parameterize the model. It did at least start us on the road toward a better understanding of model assumptions and data input needs. As part of an ongoing regional effort, we are gathering experimental data from other historical runoff plot studies in the Andes. We will continue to evaluate the WEPP model with these data. As the need and opportunity arise, we will also conduct new experiments using the WEPP model to help us focus on improved understanding of processes.

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