This is not a peer-reviewed article.
7th World Congress on Computers in Agriculture and Natural Resources
Conference Proceedings 22-24 June 2009 (Reno, Nevada USA)
Publication Date 22 June 2009
ASABE Publication Number 701P0409e Eds F.S. Zazueta and J. Xin

Modeling Top Soil Erosion and Mass Failures in Steep Agricultural Slopes: Integrating WEPP and a Landslide Model

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Abstract. Steep agricultural hillslopes are not only subjected to soil erosion, but also have a probability of failure. In hilly country were both soil erosion and landslide processes are active, the interaction between these processes is critical. A model called WEPP-SLIP was developed that integrates erosion modeling and landslide prediction to determine sediment delivery pre and post landslide failures. Initially, WEPP is used to estimate pre-failure erosion. The landslide model then predicts where a mass failure may occur along the slope. Changes in topography and soil structure are estimated from the predicted magnitude of the landslide. The WEPP model is then used again with the new topography to predict post-failure erosion. A flume based experiment was used to validate the modeling with loess and sandy type soil representative of hilly sheep pasture land in New Zealand. Results showed a good correlation between predicted and measured erosion and runoff. In fallow conditions, post-failure erosion was shown to be smaller than pre-failure erosion due to changes in slope and soil properties resulting from the failure. The opposite is true for hillslopes covered with grass, as slope failures disturb the cover resulting in greater erosion. Flume based results indicate that sediment yields during failures were high. WEPP-SLIP can be applied for individual hillslope profiles; however, efforts are on the way to create a spatially distributed model. The model will be used to improve management practices and calculate the long term implications of mass movements in hilly slopes.

Keywords. Landslides, erosion, WEPP, steep slopes, modeling

Introduction

Shallow landslides and erosion can be detrimental to agriculture in steep hillslopes and to associated stream water quality. For example, in hilly sheep pasture lands in New Zealand, shallow landslides not only hinder grazing potential, but can also be significant post-failure sources of sediment to nearby waterways. Although there are a wide range of models that can predict erosion or shallow landslides independently, only a few can be used to predict interactions of both landslides and erosion. One of these models is the sediment transport modelling system (SHETRAN), which predicts spatially distributed shallow landslide erosion and sediment yield at large catchment scales (Burton and Bathurst, 1998). Although this model does a good job of identifying landslide potential and sediment yield for large scale applications, there is a need to better understand hillslope processes involving shallow landslide generation, topography changes, and erosion prediction of pre and post landslides. To this effect, a method was developed that uses a landslide model to identify the risk of shallow landslides on a hillslope, it uses simple rules to estimate potential changes in the slope, and applies the Water Erosion Prediction Project (WEPP) hillslope model (Flanagan and Nearing, 1995) to predict erosion on a hillslope before and after the slope failure occurs. The model was termed the WEPP-SLIP model (WEPP - Shallow Landslide Integrated Prediction model).

A flume based experiment was used to validate initial modeling with loess and sandy type soil representative of hilly sheep pasture land in New Zealand. Validation was done for each component of the model: pre-failure erosion, landslide failure predictions, mass movement, and post-failure erosion. Following validation, a comparative analysis of differences in annual total sediment yields using pre and post-failure topography was conducted. The objectives of this paper were therefore to show the feasibility of the WEPP-SLIP model concept, demonstrate its applicability, and point out limitations that need to be addressed in future development.

Materials and Methods

Model formulation

A descriptive flow chart of the proposed WEPP-SLIP model's inputs, outputs, processes and internal outputs are shown in Figure 1. The main inputs to the model are the original hillslope topography, soil properties, landcover/vegetation, and climate data (requiring specific parameters of these for the WEPP, slope stability, and mass redistribution models). Predictions of pre-failure erosion and runoff are given by

WEPP using the original hillslope topography. WEPP predictions of soil moisture are then used by the slope stability model (along with other soil and vegetation parameters) to predict occurrence of shallow landslides. The time and location of potential shallow landslides along the slope are presented as output. The mass redistribution model is then used to predict changes in topography. Finally, WEPP is run again using the new hillslope topography to predict post-failure erosion.

WEPP was selected for simulating both pre and post landslide erosion events because it is a well established physically based erosion model that has been widely used and validated for hillslope simulations. Laflen et al. (2004), for example, report on an extensive literature review of studies comparing observed soil loss to WEPP model predictions, and conclude that WEPP is well suited for a wide range of erosion predictions. Of particular interest for the landslide/erosion application is the fact that WEPP was found to work quite well in representing major storms that account for high percentages of soil loss. In a study using sixteen-hundred plot years of natural runoff plot data, it was found that WEPP preformed nearly as well as empirical models (USLE and RUSLE) without calibration of any parameters (Tiwari et al, 2000).

The occurrence of shallow landslides was predicted using the infinite slope method of slope stability analysis. This widely used method assumes that shallow landslides occurs along a soil profile resulting from two major opposing influences: the resistance of soil to shearing (shear strength) and the downslope component of soil weight, which acts to shear the soil along a potential failure plane. The ratio of this relationship is expressed as a factor of safety, F. The factor of safety can be calculated using the following equation by Skempton and DeLory (1957):

$$F = \frac{C + \left[D\rho_S - h_W\rho_W\right]g\cos^2\beta\tan\phi}{\rho_S gDSin\beta Cos\beta} \quad (1)$$

where C is the soil cohesion (N m^{-2}), D is the thickness of the overlying soil (m), φ is the angle of internal friction (-), β is the inclination of the topographic surface, ρ_w is the density of water (kg m^{-3}), ρ_s is the saturated density of the soil (kg m^{-3}), and h_w (m) is the water table height above the slip surface. F values are calculated along the hillslope topography. Values of $F < 1.5$ are assumed to indicate that the slope at a specific point is prone to failure. This model identifies where along the hillslope a landslide is likely to occur.

To determine the changes in hillslope topography following a predicted landslide event, a mass redistribution model consisting of a set of simple rules was used. Runout distance, failure length (and/or final cut depth), and final runout slope were estimated.

Runout distance can be estimated based on parameters such as triggering rainfall intensity and duration, soil properties, and the slope of the topography immediately downslope of the failure. However, for the initial WEPP-SLIP application the following simple and proven empirical equation was used (Burton and Bathurst, 1998):

$$R = \lambda\Delta y \quad (2)$$

where R (m) is the landslide runout distance, λ (-) is an empirically derived fraction (set to 0.4), and Δy is the elevation difference between the head of the slide and the point at which the deposition begins.

Various studies suggest the runout continues unconditionally if the slope slopes is greater than 10° (Burton and Bathurst, 1998; Claessens, et al., 2007). Therefore it was assumed that deposition began when the slope of the profile changed to being 10° or less.

The final deposition slope was set to 12° as observed in our studies and supported by other studies reported in literature (Johnson et al., 2000). Upper stable slopes following landslides can be back calculated for different soil types.

A simple empirical equation presented by Claessens, et al., (2007) was used to calculate the landslide depth based on soil geotechnical properties and local slope inclination:

$$S = \frac{\rho_s \cos\beta(\tan\beta - \tan\alpha)a}{C} \quad (3)$$

where S (m) is the depth of the slide, ρ_s (kg m^{-3}) is the saturated density of the soil, β (-) is the local slope angle, α (-) is the minimum local slope for debris flow movement, and a (m^2) is a dimensionless correction factor. This equation predicts the deepest possible slide and does not take into account the soil depth. A rule was therefore proposed stating that the actual slide depth will be set to 90% of the soil profile depth if the actual soil depth is less than the predicted S value.

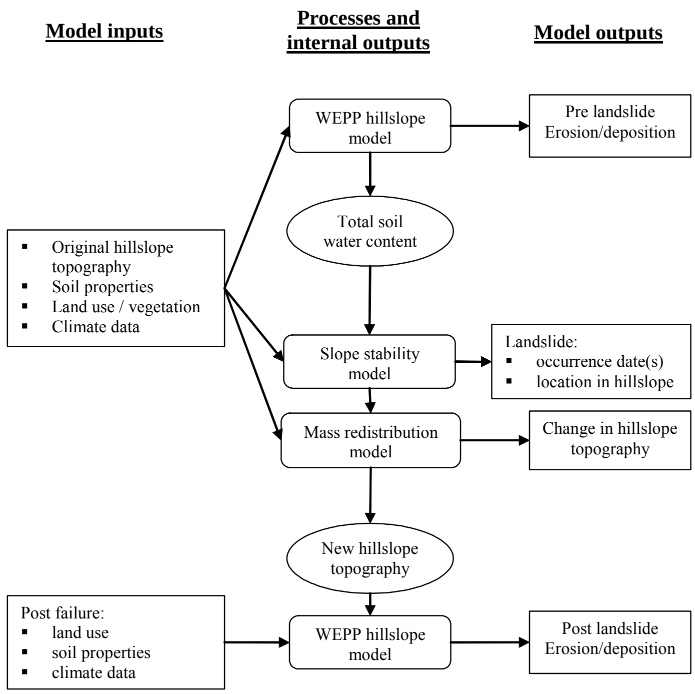

Figure 1. Integrated hillslope modeling of erosion and landslides.

Experimental setup

The WEPP-SLIP model was validated against a series of flume based erosion and landslide experiments under simulated rainfall as listed in Table 1. The experimental setup consisted of a 4 meter long compound flume where slope for the upper 2.5 meter section can be varied between 30° and 47° and slope for the lower 1.5 meter section can be varied between 5°and 10°. The loess soils were close to saturated before rainfall was applied. Runoff and sediment concentration leaving the flume were sampled at regular intervals over a period of 8 hours. Landslide occurrence, evolution, and resulting profile were recorded. Loess soils were used for experiments 1 through 10 and sandy soils were used for the last 2 experiments. Soil properties are detailed in Table 2. Pre-failure erosion was validated with experiments 1 to 8. Land slide and post-failure predictions were validated against experiments 9-12.

Table 1: Summary of experimental sloping configurations and profile preparations

Exp.	Soil	Upper slope (°)	Lower slope (°)	Soil depth (mm)	Landslide triggered	Rainfall intensity (mm hr^{-1})	Porosity
1	Loess	35	10	100	No	20	0.41-0.42
2	Loess	40	10	100	No		
3	Loess	45	5	100	No		
4	Loess	47	7	100	No		
5	Loess	35	10	100	No	40	0.41-0.42
6	Loess	40	10	100	No		
7	Loess	45	5	100	Minor		
8	Loess	47	7	100	Minor		
9	Loess	45	5	100	Yes	40	0.46-0.48
10	Loess	47	7	100	Yes		
11	Sandy	30	10	200	Yes	40	0.40– 0.41
12	Sandy	30	10	200	Yes		

Table 2: Physical properties of the soils

Selected soil properties	Unit	Loess soil	Sandy soil
Cohesion (C)	kPa	2.60	0
Angle of internal friction (φ)	°	39.00	41
Organic matter content (OM)	%	2.40	0.70
Initial moisture content (w)	%	23.00	12.00
Mean grain size (D_{50})	mm	0.075	0.57
Effective grain size (D_{10})	mm	0.010	0.20
Specific gravity (G)	kN m^{-3}	26.10	26.30
Cation exchange capacity	meq g^{-1}	0.19	NA

Results and Discussion

Pre-failure validation:

The WEPP-SLIP model was validated for pre-failure conditions using the set of experiments where no significant failure occurred (exp. 1-8). Results shown in Table 4 show a good correlation between measured and WEPP simulations of both sediment loss and runoff. In experiments 7 and 8 minor slope failures at the top of the slope caused high measured soil loss values compared to WEPP simulated values.

Table 4. Summary of measured and modeled soil loss.

Exp	Measured soil loss (kg m^{-2})	WEPP soil loss (kg m^{-2})	Measured mean runoff (l min^{-1})	WEPP mean runoff (l min^{-1})
1	4.68	4.70	0.278	0.303
2	5.03	4.92	0.311	0.332
3	5.02	4.83	0.308	0.322
4	5.24	5.13	0.340	0.316
5	12.57	14.94	0.630	0.699
6	12.85	15.77	0.657	0.711
7	22.26	14.76	0.658	0.697
8	23.64	15.19	0.665	0.696

Failure validation:

Measured slope failures were compared against WEPP-SLIP factor of safety (F) predictions at the time were the soils were fully saturated (Table 5). As expected, F values lower than 1.5 produced slope failures.

Table 5. Prediction of slope failures using a factor of safety.

Slope (°)	Soil type	Factor of safety	Actual condition
30	Sandy	0.73	Slope failure (multiple retrogressions)
45	Loess	1.31	Slope failure (one retrogression)
47	Loess	1.25	Slope failure (two retrogressions)

Predicted runout distances (using equation 2) were on average 38% smaller than measured values (Table 6). The underprediction can be attributed to the continuous rainfall during the experiment that triggered not only one landslide, but in some cases multiple retrogressions of the slide. Adjustments to the empirical equation could be made to improve predictions for these cases. Predicted maximum potential failure depths reported in Table 6 show values much higher than the actual soil profile depths. Since the predicted value is greater than the soil depth, the predicted depth is set to 0.90 times the soil depth. These new values, adjusted for actual soil depth, are comparable to observed results. Pre and post-failure slope profiles for experiments 9 and 10 are shown in Figure 2. The final runout slope was between 12 and 13 degrees for all experiments regardless of soil type. The upslope angle was between 25 and 27 degrees for loess soils and 23 degrees for sandy soils, which is comparable to values reported in literature. Although the overall predictions seem to coincide with observed results, further improvements in how landslides and mass movements are predicted are warranted.

Table 6. Predicted vs. measured landslide runout distance and failure depths.

Slope (°)	Soil type	Predicted runout (m)	Measured runout (m)	Predicted maximum depth (m)	Adjusted prediction (m)	Average measured depth (m)
30	Sandy	0.49	0.76	N/A	0.18	0.15
45	Loess	0.69	0.96	0.800	0.09	0.08
47	Loess	0.71	1.45	0.839	0.09	0.08

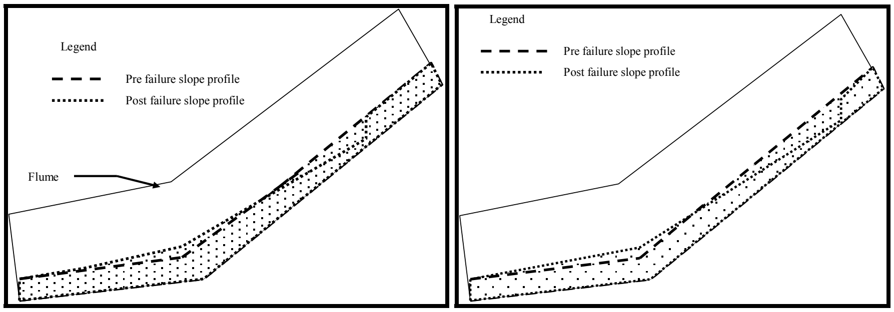

Figure 2. Pre and post-failure slope profiles for experiments 9 (left) and 10 (right).

Post-failure validation:

Post-failure validation of the WEPP-SLIP model was only done with experiments 9 and 10 (Table 7). WEPP simulations of the sandy soil did not produce erosion or correct runoff because the application of an impermeable boundary layer was not possible in a single storm simulation with WEPP. Measured values for the loess soil experiments, however, compared well to WEPP predicted values for both runoff and soil loss. Smaller soil loss measured values are probably due to the occurrence of post-failure soil armouring in the lower slope. Efforts are on the way to model potential armouring to improve simulation results.

Table 7. Summary of measured and modeled soil loss in the post-failure phase.

Exp	Measured soil loss (kg m^{-2})	WEPP soil loss (kg m^{-2})	Measured runoff (l min^{-1})	WEPP runoff (l min^{-1})
9	9.54	10.22	0.636	0.694
10	9.81	10.55	0.690	0.717

Sediment yield during failures

Sediment yield during failures were high for all experiments. For example, in experiment 10, two failures occurred at 0.35 and 1.25 hours into the experiment and sharp increases in measured sediment yields were readily observed during those events (Figure 3). WEPP-SLIP, however does not predict erosion during landslides do the the complexities in modeling to achieve this.

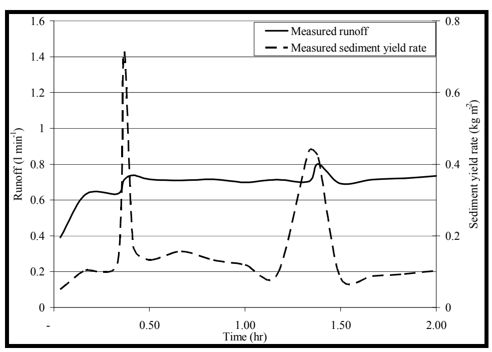

Figure 3. Measured sediment yield and runoff from experiment 10 showing sharp increase in sediment during slope failures occurring at 0.35 and 1.25 hours into the experiment.

Difference in sediment yields between pre and post-failure topography as impacted by cover

Soil loss and runoff for a year long WEPP simulation of pre and post-failure slope topography (Figure 2, exp. 9 and 10) were compared under fallow slope conditions, grass (w/sheep grazing), and regeneration of grass after failure (Table 8). WEPP was run on a daily continuous simulation mode with a total annual precipitation of 857 mm, typical of hills near Christchurch, New Zealand. Results clearly show that post-failure soil loss is lower than pre-failure soil loss if the hillslope is in fallow conditions. However, if the failure occurs in hillslopes with grass cover, pre-failure soil loss would be significantly less because failure of the slope would imply that the grass cover would be lost and therefore have to be regenerated over time. For our example, pre-failure soil loss on grass covered hillslopes would be only 0.02 kg/m^2 compared to a post-failure situation were grass had to regenerate over time yielding 0.300 kg/m^2.

Table 8. WEPP simulated pre and post-failure annual soil loss and runoff as impacted by landcover.

Exp.	Topography	Landcover	Annual soil loss (kg/m^2)	Annual runoff (mm)
9	Pre-failure	Fallow	0.452	167.45
9	Post-failure	Fallow	0.386	170.53
9	Pre-failure	Grass (w/ sheep grazing)	0.020	34.23
9	Post-failure	Grass regeneration	0.300	109.19
10	Pre-failure	Fallow	0.455	166.50
10	Post-failure	Fallow	0.387	172.21
10	Pre-failure	Grass (w/ sheep grazing)	0.020	33.70
10	Post-failure	Grass regeneration	0.302	111.65

Conclusions

The WEPP-SLIP model was validated against experimental results from a flume based study. Erosion predictions matched measured results closely. Further improvement of the landslide prediction and mass redistribution models is necessary. Soil loss during shallow landslide events is not estimated by the WEPP-SLIP model, but experimental results show that sediment yields during failures increase sharply.

Sample applications showed that if the hillslope is fallow, landslides may actually cause a reduction in future erosion because changes in topography result in reduced slope gradient and possible aromouring of soils. When the hillslope is covered with vegetation such as grass, post-failure erosion would be significantly larger.

Further research is underway to improve estimates of potential changes in topography following slope failures. WEPP-SLIP is currently a hillslope model that can be applied in a catchment on user selected transects; however, efforts are on the way to create a spatially distributed model that makes use of digital elevation models. The model will be used to improve management practices and calculate the long term implications of mass movements in hilly slopes.

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