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SENSITIVITY ANALYSIS OF THE WEPP HILLSLOPE PROFILE EROSION MODEL

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ABSTRACT

Sensitivity analysis was performed on the hillslope profile erosion model developed by the USDA-Water Erosion Prediction Project. The erosion model calculates soil loss and sediment yield caused by rill and interrill erosion on complex shaped hillslope profiles. Sensitivity analysis of a physically based simulation model is used for assessing the rationality of the model, to provide insight into the overall physical system which the simulation model represents, and to help identify research needs. Changes in predicted soil erosion and sediment yield as a function of changes in soil, plant residue and canopy, hillslope topography, and hydrologic input variables were assessed. Dominant factors related to model response were precipitation, rill erodibility, rill residue cover, and rill hydraulic friction factors. Saturated hydraulic conductivity and interrill erodibility were moderately sensitive parameters. Other factors which had less influence on output were canopy height, interrill cover, soil bulk density, antecedent moisture, peak rainfall intensity, time to peak rainfall intensity, rill width and spacing, and sediment characteristics. Slope length, gradient, and slope shape effects on soil loss and sediment delivery were also discussed.

INTRODUCTION

The USDA-Water Erosion Prediction Project (WEPP) was initiated in 1985 to develop new generation soil erosion prediction technology for use in soil and water conservation planning and assessment (Foster and Lane, 1987). The hillslope profile version of the technology was designed to estimate rill and interrill soil losses and sediment yields from a complex shaped slope profile. The WEPP hillslope model is based on fundamentals of hydrologic and erosion science and is process-based and computer-driven. The purpose of this study was to perform a detailed sensitivity analysis of the WEPP hillslope model to assess the overall influence of input parameters to the predicted soil loss estimates provided by the model. This analysis also provides insight into the factors which are most important to assess and ultimately control soil erosion under various environmental conditions.

Development of a physically based model requires two general steps: 1) development of the model equations, algorithms, and structure from existing theories and basic principles; and 2) evaluation of the model (Beck, 1983). The evaluation process includes at least three steps: 1) validation of the model by comparison of results to measured data; 2) sensitivity analysis of the model response to input parameters; and 3) evaluation of confidence limits for the model predictions. Sensitivity analysis is an evaluation of the relative magnitudes of changes in the model response as a function of relative changes in the values of model input parameters. A detailed evaluation of a model's response can yield a great deal of insight into the nature of the model. Also, to the degree that the model accurately represents the physical system which it simulates, sensitivity analysis can provide insight into the factors which influence the response of the physical system. As pointed out by McCuen and Snyder (1983), sensitivity analysis provides a method for examining the response of a model in a way that eliminates the influence of error related to natural variation of the model input parameters. The rationality of the model and the influence of input error can thus be evaluated in detail.

The purpose of this study was to evaluate the response of the WEPP hillslope profile erosion model relative to changes in input parameters. Sensitivity analysis was conducted on soil, plant, hydrologic, and slope profile parameters of the model. The approach was to use an average linear sensitivity coefficient for the change in model response relative to the values of input parameters which represent the extremes in the physical conditions. These are generally the cases of most interest (McCuen and Snyder, 1983). Two forms of the model were used: the single storm version of the WEPP hillslope model which includes both the hydrology and erosion models; and the erosion model from the WEPP hillslope model independent from the hydrology model. The use of both forms of the model helped to better delineate the factors which influenced the erosion model from those which influenced the overall hydrology and erosion computations. A detailed description of the WEPP erosion model was given by Nearing et al. (1989) and the single storm model is described in Lane and Nearing (1989).

It should be noted that validation of the WEPP models is not complete. This sensitivity analysis was not performed on the final version of WEPP. The results

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reported herein reflect our best current prediction capabilities.

METHODS

SENSITIVITY ANALYSIS

Parameters considered in the sensitivity analysis for the erosion model are listed in Table 1, along with the base value used in the analyses. Unless otherwise noted in the tables and figures of results, the base values of the parameters were used. Single storm parameters are listed in Table 2.

The sensitivity parameter, S, is given by

$$S = [(O_2 - O_1) / O_{12}]) / [(I_2 - I_1) / I_{12}] \qquad (1)$$

where I_1 and I_2 are the least and greatest values of input used, respectively. I_{12} is the average of I_1 and I_2. O_1 and O_2 are the output for the two input values, and O_{12} is the average of the two outputs. The parameter S represents a relative normalized change in output to a normalized change in input, which allows a means of comparing sensitivities for input parameters which have different orders of magnitude. The parameter S will be a function of the chosen input range for nonlinear response. In some of the results presented herein, more than one S value is given for more than one input range. The range of inputs over which S was calculated is reported in Table 1 for each of the parameters.

Three limitations to current methods in sensitivity analysis were discussed by McCuen and Snyder (1983):

1. The linear form of the sensitivity parameter does not reflect sensitivity of the variable over the entire range of the parameter because of the non-linear response of the model. However, as pointed out by McCuen and Snyder (1983), the sensitivity which represents the extremes of the physical conditions is often of primary interest.
2. The sensitivity parameter is a univariate parameter, which implies that there is no interaction between variables. This can be a serious limitation which can lead to misinterpretations of the model. A variable which is insensitive with a given set of companion inputs might be quite sensitive with another set of inputs.

TABLE 1. Erosion model parameters and constant values used for sensitivity analysis

Parameter	Units	Base value	Range of test
Clay	%	20.0	0.0 - 100.0
Sand	%	30.0	0.0 - 100.0
Slope length	m	50.0	10.0 - 300.0
Slope gradient	m/m	0.05	0.005 - 0.10
Rainfall intensity	mm/hour	60.0	30.0 - 300.0
Runoff (Q_e)	mm/hour	50.0	20.0 - 90.0
Rill spacing	m	1.0	0.25 - 5.0
Rill cover	%	0.0	0.0 - 100.0
Interrill cover	%	0.0	0.0 - 100.0
Canopy cover	%	0.0	0.0 - 100.0
Canopy height	m	0.0	0.0 - 10.0
Incorporated residue	t/ha	0.0	0.0 - 10.0
Rill erodibility (K_r)	s/m	0.003	0.0002 - 0.03
Interrill erodibility (K_o)	kg s/m^4	2.0 x 10^6	0.5 x 10^6 - 0.5 x 10^6
Critical shear	Pa	1.0	0.0 - 10.0

TABLE 2. Single storm model input parameters and base values used for sensitivity analysis

Category	Parameter	Units	Base value
Profile	Length	m	50.0
	Average slope	%	9.0
	End slope	%	9.0
	Upper slope	%	0.0
Management	Canopy height	m	0.1
	Canopy cover	%	10.0
	Interrill cover	%	10.0
	Rill cover	%	10.0
Climate	Precipitation	nm	100.0
	Duration	hour	1.0
	Normalized time to peak (t_p)	non-dimensional	0.5
	Intensity (i_p)	non-dimensional	2.0
Soil	Rill erodibility (K_r)	s/m	0.003
	Interrill erodibility (K_i)	kg s/m^4	2.0 x 10^6
	Saturation (initial)	dec	0.50
	Bulk density	g/ml	1.35
	Saturated hydraulic conductivity	mm/ hour	2.40
	Sand	%	25.0
	Silt	%	50.0
	Clay	%	25.0
	Organic matter	%	2.00
	Cation exchange capacity	meq	10.0

3. The sensitivity parameter is single-valued. A probability distribution of the output as a function of input parameter distributions might better describe sensitivity. This third point is related to confidence limit analysis mentioned above.

In addition to the three limitations listed above, the value of sensitivity analysis is limited by the "goodness" of the model. The power of a prediction model is that it integrates a number of interdependent processes to simulate a larger system. The effect is synergistic: the resulting product which a model represents is greater than the sum of the independent components. Still, current knowledge dictates the relationships in the model. There is always an inherent bias toward current scientific knowledge, and specifically that knowledge represented in the model.

EROSION AND HYDROLOGY MODEL OVERVIEW

The WEPP hillslope profile model used in the analysis was described in detail in Lane and Nearing (1989). The WEPP hydrology model is driven by four hydrologic input variables: rainfall amount (mm), rainfall duration (hrs), normalized peak rainfall intensity (non-dimensional), and normalized time to peak intensity (non-dimensional). A disaggregation model uses the storm information to generate time-intensity or breakpoint data which is used to calculate infiltration and total runoff volume for the storm as a function of soil infiltration parameters. Infiltration is calculated using a Green-Ampt infiltration equation. Peak rates of runoff are calculated with either the kinematic wave equations or by an approximate routing method which is based on regression equations that approximate the kinematic wave solutions (Hernandez et al., 1989). The approximate routing method was evaluated in this study and the results are reported below.

The erosion model used in the hillslope profile model was reported in detail by Nearing et al. (1989). The model uses a steady-state sediment continuity equation for predicting rill and interrill erosion processes. Net detachment in rills is considered to occur when the hydraulic shear stress of flow exceeds the critical shear stress of the soil and when sediment load in a rill is less than the sediment transport capacity of the rill flow. Net deposition is calculated when the sediment load is greater than the transport capacity. Rill detachment rate is dependent upon the ratio of sediment load to transport capacity, rill erodibility, hydraulic shear stress, surface cover, below ground residue, and consolidation. Rill hydraulics are used to calculate shear stresses and a simplified transport equation, calibrated with the Yalin transport equation, is used to compute transport capacity in rills. Interrill erosion is represented as a function of rainfall intensity, residue cover, canopy cover, and interrill soil erodibility. The model has capabilities for estimating spatial distributions of net soil loss and is designed to accommodate spatial variability in topography, surface roughness, soil properties, hydrology, and land use conditions on hillslopes.

SENSITIVITY TO SOIL PARAMETERS

Sensitivities to rill erodibility, interrill erodibility, and critical hydraulic shear were determined using the erosion model for six slope length-slope gradient pairs (Table 3). Sensitivity to interrill erodibility is greatest for shorter slopes and lower slope gradients where rill erosion accounts for a smaller relative fraction of the total soil detached and where sediment loads are low relative to transport capacity of the flow. In other words, interrill erosion is important in detachment limiting cases where rilling is less significant.

Rill detachment rate is a function not only of rill erodibility, but also of the amount of sediment in the flow. When relative interrill contributions to sediment load are high, rill contributions are less than they would be if interrill contributions are low. This compensating process is the reason for the low sensitivity to interrill erodibility when rilling is active.

Sensitivity to interrill erodibility is also a function of storm intensity (Tables 4 and 5). Interrill contribution to sediment load increases proportional to the square of rainfall intensity; whereas runoff, and hence rill erosion, increases more linearly proportional to excess rainfall. Interrill sensitivity was greater and rill sensitivity was less for the 100 mm/hr storm compared to the 50 mm/hr storm.

Sensitivity to spacing between rills was tested with the erosion model (Table 3). Overall the sensitivity to rill spacing was not great, except for the very long slope lengths and higher slope gradient. The WEPP model uses a default value of one meter for rill spacing, which is a reasonable approximation for many cases and represents an intermediate value in terms of response range (fig. 1).

Sensitivity to soil texture is high, as shown by results from both the erosion model and single storm model (Table 6). Sensitivity to soil texture is caused by five major factors which are calculated based on clay, silt, and/or sand fractions:

1. erodibility parameters,
2. infiltration parameters,
3. hydraulic friction factors,
4. rill widths, and
5. transportability of the sediment.

TABLE 3. Measure of sensitivity* for erodibility and rill spacing parameters of erosion model

Length (m)	Gradient (%)	Sensitivity (S) to: K_i†	K_r‡	τ_r§	Rill space‖	K_i#	Rill space**
22.13	5.0	0.2970	0.4691	-0.3632	-0.0346	0.4609	-0.0237
22.13	9.0	0.2155	0.6194	-0.4857	-0.1145	0.3308	-0.1075
50.0	5.0	0.1588	0.4806	-0.4698	-0.0667	0.2921	-0.1390
50.0	9.0	0.1176	0.6228	-0.5468	-0.1473	0.2046	-0.1966
200.00	5.0	0.0483	0.3451	-0.4289	-0.0621	0.1315	-03138
200.00	9.0	0.0374	0.4679	-0.2222	-0.1403	0.0888	-0.3454

$$* \quad S = \frac{\dfrac{(\text{sediment load})_1 - (\text{sediment load})_2}{\overline{(\text{sediment load})}_{1,2}}}{\dfrac{(\text{variable})_1 - (\text{variable})_2}{\overline{(\text{variable})}_{1,2}}}$$

† S measured between $K_i = 0.5 \times 10^6$ and $2.0 \times 10^6 (kg{\cdot}s{\cdot}m^{-4})$.

‡ S measured between $K_r = 0.001$ and $0.01 (s{\cdot}m^{-1})$.

§ S measured between $t_c = 0.0$ and 10.0 Pa.

‖ S measured between rill space = 0.5 and 5 m.

S measured between $K_i = 0.5 \times 10^6$ and $5.0 \times 10^6 (kg{\cdot}s{\cdot}m^{-4})$.

** S measured between rill space = 0.5 and 2 m.

TABLE 4. Measure of sensitivity* for soil file parameters of single storm model with 50 mm storm and 0% end slope

Variable	Value	Detachment area $\left(\frac{kg}{m^2}\right)$	Sedi. delivery $\left(\frac{kg}{m}\right)$	Sensitivity of detachment (S)	Sensitivity of sediment delivery (S)
Rill erodibility	0.0002 0.003 0.03	0.899 3.74 9.65	40.0 114.0 149.0	0.84	0.58
Interrill erodibility	0.5×10^6 2.0×10^6 5.0×10^6	3.44 3.74 4.30	107.0 114.0 126.0	0.14	0.10
Saturation (init.)	0.10 0.50 0.90	3.43 3.74 4.31	101.0 114.0 135.0	0.14	0.18
Bulk density	1.0 1.35 1.70	3.81 3.74 3.76	117.0 114.0 115.0	-0.025	-0.033
Saturated hydraulic conductivity	0.24 2.4 24.00	4.30 3.74 1.13	136.0 114.0 14.0	-0.60	-0.83

$$* \quad S = \frac{\dfrac{(\text{output})_1 - (\text{output})_2}{\overline{(\text{output})}_{1,2}}}{\dfrac{(\text{variable})_1 - (\text{variable})_2}{\overline{(\text{variable})}_{1,2}}}$$

TABLE 5. Measure of sensitivity* for soil file parameters of single storm model for 100 mm storm with 0% end slope

Variable	Value	detachment area $\left(\frac{kg}{m^2}\right)$	Sedi. delivery $\left(\frac{kg}{m}\right)$	Sensitivity of detachment (S)	Sensitivity of sediment delivery (S)
Rill erodibility	0.0002	2.95	138.0	0.78	0.60
	0.003	8.66	331.0		
	0.03	23.06	534.0		
Interrill erodibility	0.5×10^6	7.44	288.0	0.24	0.22
	2.0×10^6	8.66	331.0		
	5.0×10^6	11.12	414.0		
Saturation (init.)	0.10	8.33	317.0	0.063	0.071
	0.50	8.66	331.0		
	0.90	9.22	355.0		
Bulk density	1.0	8.73	334.0	-0.009	-0.006
	1.35	8.66	331.0		
	1.70	8.69	333.0		
Saturated hydraulic conductivity	0.24	9.24	356.0	-0.26	-0.30
	2.4	8.66	331.0		
	24.00	5.50	194.0		

$$* \quad S = \frac{\dfrac{(\text{output})_1 - (\text{output})_2}{\overline{(\text{output})}_{1,2}}}{\dfrac{(\text{variable})_1 - (\text{variable})_2}{\overline{(\text{variable})}_{1,2}}}$$

The results of the single storm model shown in Table 6 reflect the sensitivity to texture in terms of all of the above except erodibility, which was held constant. When the sensitivity to infiltration was excluded, as it is when the erosion model by itself is executed, the sensitivity to texture reduced slightly, but remains high.

Much of the sensitivity to texture is caused by the rill friction factor calculation. When rill friction factor was set internally to a constant value of 1.0 for all textures, sensitivity to texture reduces tremendously. The sensitivity to texture became negligible when only transportability was a factor, as shown in Table 6 wherein rill width was set at 15 cm for all cases. The conclusion, therefore, is that texture is important to model response, and that the greatest sensitivity comes about in the rill hydraulic friction factor term. Hydraulic friction is a dominant factor in calculation of rill shear stresses which are used to calculate rill erodibility and sediment transport capacity.

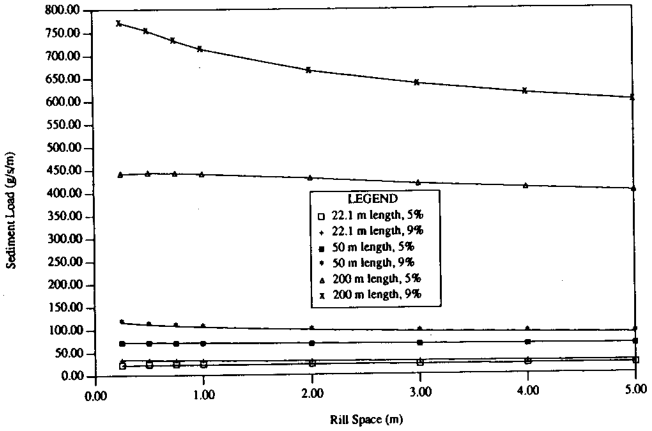

Figure 1–Effect of rill spacing on soil loss for a range of slope lengths and gradients.

Saturated hydraulic conductivity was the infiltration parameter which produced the greatest variation in model response (Tables 4 and 5). Sensitivity to infiltration parameters was greater for the low intensity storm than for the higher intensity storm. This is reasonable since a greater relative proportion of the rainfall from the higher intensity storm will become runoff than will that for the low intensity storm. Initial saturation and bulk density are used by the model to calculate the suction term for the Green-Ampt equation. The model was relatively insensitive to those parameters, being more sensitive to initial saturation than to bulk density.

The sensitivity analyses on the single storm model shown in Tables 4 and 5 are for complex, "S-shaped", slope profiles, where slopes at top and bottom of the profile were zero and average slope over the entire profile was 9%. The detachment values given are for net soil detachment over the areas of net detachment, excluding depositional areas. The delivery values are for sediment leaving the end of the slope profile per unit width for the storm event. Sensitivity to the parameters for detachment differed from those for sediment delivery. Sediment delivery at the end of the profile was more influenced by transport capacity than was the detachment over the area of net detachment. This fact is reflected in the results of the analysis. The detachment parameters, rill and interrill erodibility, produced a greater sensitivity for detachment than for delivery. The infiltration parameters affected runoff and hence transport capacity of the flow in addition to detachment rates in rills. The sensitivity for delivery by those parameters was greater than sensitivity for detachment. Also, sensitivity to the infiltration parameters was greater for the smaller storm event, again where transport tended more toward being a limiting process.

SENSITIVITY TO PLANT AND RESIDUE PARAMETERS

Sensitivities to plant canopy and surface residue were calculated for the erosion (Table 7) and single storm (Tables 8 and 9) models. Canopy cover influenced interrill

TABLE 6. Measure of sensitivity, S, to soil texture

	Sensitivity values			
Particle Size Class	Variable factors:* Infiltration Friction factor Rill width Transportability	Variable factors: Friction factor Rill width Transportability	Varible factors: Rill width Transportability	Variable factors: Transportability
clay (silt=0)†	0.63	0.52	-0.028	-0.028
clay (sand=0)	0.25	0.25	0.051	-0.028
silt (clay=0)	0.46	0.30	-0.079	0.00
silt (sand=0)	-0.25	-0.25	-0.051	0.028
sand (clay=0)	-0.46	-0.30	0.079	0.00
sand (silt=0)	-0.63	-0.52	0.028	0.028

* Factors in the model which were allowed to vary with texture.
† Sensitivity to clay for case when silt held constant at 0%.

Table 7. Measure of sensitivity, S*, for plant and residue parameters of erosion model

Slope length (m)	Slope gradient (%)	Sensitivity (S) to:						
		Canopy† cover	Canopy‡ height	Interrill§ cover	Rill‖ cover (wheat)	Interrill# & rill (wheat)	Rill‖ cover (corn)	Interrill# & rill (corn)
22.1	5.0	-0.2050	0.0587	-0.2272	-0.2871	-0.6983	-0.6004	-0.8797
22.1	9.0	-0.1478	0.0426	-0.1629	-0.3323	-0.6131	-0.4911	-0.8110
50.0	5.0	-0.1085	0.0314	-0.1192	-0.4001	-0.6151	-0.6783	-0.8248
50.0	9.0	-0.0801	0.0232	-0.0878	-0.4170	-0.5667	-0.6122	-0.7769
200.0	5.0	-0.0327	0.0095	-0.0357	-0.5328	-0.5884	-0.7723	-0.8005
200.0	9.0	-0.0253	0.0074	-0.0276	-0.5234	-0.5662	-0.7483	-0.7876

* $$S = \frac{\dfrac{(\text{sediment load})_1 - (\text{sediment load})_2}{(\text{sediment load})_{\overline{1,2}}}}{\dfrac{(\text{variable})_1 - (\text{variable})_2}{(\text{variable})_{\overline{1,2}}}}$$

† Canopy cover: S measured between 0 and 100%.

‡ Canopy height: S measured between 0.0 and 2.0 m.

§ S measured between interrill cover = 0 and 100%.

‖ S measured between rill cover = 0 and 100%.

detachment but not rill detachment. The trends in sensitivity to canopy cover were therefore similar to those for interrill erodibility and in general the sensitivities were low. Again, shorter slopes and lesser slope gradients were the conditions for which sensitivity was greatest. The effect of canopy height on model response was minimal.

Interrill cover was also a relatively lesser factor than rill cover for soil loss sensitivity. Rill surface cover was a major factor in predicted detachment and sediment delivery. Ground cover in rills greatly reduced the shear stress which acts on the soil and hence reduced detachment rates and sediment transport capacity of the flow. The trends in sensitivity values for rill cover was similar to those for rill erodibility and were of the same general magnitude. The rill cover effect is reflected in the WEPP model in terms of a hydraulic friction factor for the surface cover, which affects both detachment and transport capacities of the flow through the partitioning of the flow shear stress. This again indicated the importance of accurate representation of rill hydraulic friction factors for soil loss and sediment delivery estimates generated by the model.

TABLE 8. Measure of sensitivity* for management file parameters of single storm model for 50 mm storm and 0% end slope

Variable	Value	detachment area $\left(\frac{kg}{m^2}\right)$	Sedi. delivery $\left(\frac{kg}{m}\right)$	Sensitivity of detachment (S)	Sensitivity of sediment delivery (S)
Canopy	0.1	2.98	90.2		
height†	1.0	3.09	92.4	0.034	0.023
(m)	2.0	3.17	94.1		
Canopy	5.0	3.77	114.0		
cover†	50.0	3.50	106.0	-0.111	-0.117
(%)	90.0	3.09	92.4		
Interrill	0.0	3.83	116.0		
cover	50.0	3.52	107.0	-0.054	-0.059
%	100.0	3.44	103.0		
Rill	0.0	6.07	206.0		
cover	50.0	1.20	27.8	-0.818	-0.882
(%)	100.0	0.608	12.9		

* $$S = \frac{\dfrac{(\text{output})_1 - (\text{output})_2}{(\text{output})_{\overline{1,2}}}}{\dfrac{(\text{variable})_1 - (\text{variable})_2}{(\text{variable})_{\overline{1,2}}}}$$

† Canopy cover = 90.0%.

‡ Canopy height = 1.0 m.

TABLE 9. Measure of sensitivity* for management file parameters of single storm model for 100 mm storm with 0% end slope

Variable	Value	detachment area $\left(\frac{kg}{m^2}\right)$	Sedi. delivery $\left(\frac{kg}{m}\right)$	Sensitivity of detachment (S)	Sensitivity of sediment delivery (S)
Canopy	0.1	6.83	264.0		
height†	1.0	7.23	278.0	0.057	0.052
(m)	2.0	7.57	290.0		
Canopy	5.0	8.77	335.0		
cover†	50.0	8.04	309.0	-0.11	-0.10
(%)	90.0	7.23	278.0		
Interrill	0.0	9.13	347.0		
cover	50.0	7.62	295.0	-0.12	-0.11
%	100.0	7.23	279.0		
Rill	0.0	13.52	550.0		
cover	50.0	3.24	106.0	-0.77	-0.80
(%)	100.0	1.76	60.5		

* $$S = \frac{\dfrac{(\text{output})_1 - (\text{output})_2}{(\text{output})_{\overline{1,2}}}}{\dfrac{(\text{variable})_1 - (\text{variable})_2}{(\text{variable})_{\overline{1,2}}}}$$

† Canopy cover = 90.0%.

‡ Canopy height = 1.0 m.

SENSITIVITY TO HYDROLOGIC PARAMETERS

The erosion model requires two hydrologic inputs, rainfall intensity and runoff rate. The model was very sensitive to both (Table 10). Intensity was particularly important on the low slope gradients and short slopes, i.e.,

TABLE 10. Analysis of erosion model sensitivity for hydrologic parameters

Length (m)	Gradient (%)	Sensitivity to intensity* (S)	Sensitivity to runoff† (S)	Sensitivity to intensity and‡ runoff (S)
22.13	5.0	0.7809	0.6918	1.2940
22.13	9.0	0.661	0.7204	1.2357
50.0	5.0	0.5394	0.8115	1.2177
50.0	9.0	0.4431	0.8083	1.1595
200.0	5.0	0.2183	0.9304	1.1238
200.0	9.0	0.1756	0.8975	1.0709

* Runoff constant at 120 mm/ hour, S measured between 30 and 180 mm/ hour of intensity.

† Intensity constant at 60 mm/ hour, S measured between 25 and 150 mm/hour of runoff.

‡ Runoff rate 5/ 6 of intensity, S measured between 30 and 150 mm/ hour.

where interrill detachment was important. As mentioned above, the rainfall intensity term drives the interrill erosion rates in the erosion model. Runoff rates were important on all ranges of slope lengths and gradients. The results show the major importance of good hydrologic estimates for the model in order to produce reasonable erosion estimates.

Four hydrologic parameters are required to drive the single storm version of the hillslope profile model: 1) precipitation amount, 2) rainfall duration, 3) time to peak rainfall intensity, tp (normalized to total rainfall duration), and 4) peak rainfall intensity, ip (normalized to average rainfall intensity). These parameters are input through the climate file for the model. Sensitivity to the four parameters for two storm amounts is given in Table 11 using the kinematic wave solution for peak runoff computations and in Table 12 using the approximate method (see METHODS section above). The dominant parameter is precipitation amount for both soil loss (detachment over area of net detachment) and sediment delivery from the end of the complex slope profile. Duration was also important, especially in terms of sediment delivery. Storms of higher intensity (i.e., storms of shorter duration with the same total precipitation amount) produced greater peak runoff amounts and more soil loss and sediment yield. Normalized time to peak intensity and normalized peak intensity (both nondimensional) were less sensitive parameters.

Comparison between the results using the kinematic wave solution and those using the approximate method indicated some difference in peak runoffs, but only small differences in predicted soil losses and sediment loads. Runoff volume was the same with both methods.

SENSITIVITY TO SLOPE PROFILE PARAMETERS

UNIFORM SLOPES

Soil loss from uniform slopes was calculated for a range of slope lengths and gradients using both the erosion model and the single storm model. Comparisons of the WEPP model results were made to relationships in the Revised

TABLE 11. Measure of sensitivity* for climate file parameters of single storm model with 0% end slope using kinematic wave equations

Variable	Value	detachment area ($\frac{kg}{m^2}$)	Delivery ($\frac{kg}{m}$)	Sensitivity of detachment	Sensitivity of delivery	Runoff volume (mm)	Peak runoff
Precipitation (mm)	20.0	0.881	10.2	1.12	1.19	7.42	21.40
	100.0	8.66	331.0			85.83	173.07
	200.0	20.5	871.0			293.27	356.86
Duration§ (hr)	0.5	10.1	429.0	-0.220	-0.750	90.29	346.40
	1.0	8.66	331.0			85.83	173.07
	6.0	6.93	96.0			61.23	25.04
Time to peak (t_p)§	0.01	8.99	332.0	-0.014	0.0	85.73	150.34
	0.5	8.66	331.0			85.83	173.07
	1.0	8.75	332.0			85.86	168.36
Peak intensity (i_p)§	1.0	10.18	316.0	-0.145	-0.011	85.75	91.86
	2.0†‡	8.75	332.0			85.86	168.36
	10.0	7.21	327.0			86.33	775.32
	20.0	7.11	330.0			86.46	1338.40
Duration‖ (hr)	0.5	4.20	157.0	-0.459	-1.06	40.40	160.89
	1.0	3.74	114.0			36.17	80.76
	6.0	1.85	8.63			14.64	9.10
Time to peak (t_p)‖	0.01	3.88	104.0	-0.015	0.047	35.76	62.80
	0.5	3.74	114.0			36.17	80.76
	1.0	3.77	114.0			36.32	79.94
Peak Intensity (i_p)‖	1.0†	4.20	85.8	-0.167	0.174	35.85	41.77
	2.0†‡	3.77	114.0			36.32	79.94
	10.0	3.36	144.0			38.11	358.20
	20.0	3.36	150.0			38.80	603.58

$$* \quad S = \frac{\dfrac{(\text{output})_1 - (\text{output})_2}{(\text{output})_{\overline{1,2}}}}{\dfrac{(\text{variable})_1 - (\text{variable})_2}{(\text{variable})_{\overline{1,2}}}}$$

† $t_p = 1.0$.

‡ Sensitivity calculated between $i_p = 2.0$ and $i_p = 10.0$.

§ Precipitation = 100 mm.

‖ Precipitation = 50 mm.

Universal Soil Loss Equation (RUSLE) (Renard, 1990). The slope factor predicted by WEPP, unlike RUSLE, is dependent on slope length (Table 13). Slopes of longer lengths showed a greater effect of slope gradient than did shorter slopes. The reason for this was that the gradient effect was greater as transport became limiting. Even in the extreme (transport limiting) case WEPP predictions for slope effects are not as great as those proposed by RUSLE (fig. 2). Little data exists to validate the slope gradient effect on longer slopes.

Slope length effect was a function of gradient (fig. 3). The WEPP results agree with RUSLE in that the "L" factor was greater on steeper slopes, however, length effects from WEPP were less than those predicted by RUSLE even for cases with high rill to interrill erosion ratios. The limiting case for the slope length effect is where only interrill erosion is active, which occurs on flat slopes. In that case, the slope length factor is 1. In RUSLE the ratio, ß, is defined as the ratio of rill to interrill sediment contribution and is calculated as a function of slope gradient. The ß value for a 5% slope in RUSLE is 0.46. WEPP predicts that ß is also a function of slope length. For a 5% slope the ratio of rill to interrill erosion (for moderate rill and interrill erodibilities) ranges from 0.20 to over 3.2 as slope length varies from 5 to 300 meters (Table 14).

The slope exponent, m, for RUSLE is a function of the calculated ß for the slope gradient. The equation for L in RUSLE is

$$L = (l_s / 72.6)^m \qquad (2)$$

where l_s is slope length in feet. The results of the sensitivity analysis of the WEPP model showed that the

TABLE 12. Measure of sensitivity* for climate file parameters of single storm model with 0% end slope using the approximate method for runoff

Variable	Value	detachment area $\left(\frac{kg}{m^2}\right)$	Delivery $\left(\frac{kg}{m}\right)$	Sensitivity of detachment	Sensitivity of delivery	Runoff volume (mm)	Peak runoff
Precipitation (mm)	20.0	0.880	10.3	1.12	1.19	7.42	21.56
	100.0	8.78	332.0			85.83	166.13
	200.0	20.75	880.0			185.75	346.25
Duration§ (hr)	0.5	10.36	436.0	-0.2332	-0.759	90.29	328.06
	1.0	8.78	332.0			85.83	166.13
	6.0	6.96	95.1			61.23	24.78
Time to peak (t_p)§	0.01	9.04	332.0	-0.010	1.53×10^{-3}	85.73	147.23
	0.5	8.78	332.0			85.83	166.13
	1.0	8.86	333.0			85.86	162.04
Peak intensity (i_p)§	1.0†	10.33	314.0	-0.180	-0.037	85.75	88.15
	2.0†‡	8.86	333.0			85.86	162.04
	10.0	6.96	317.0			86.33	848.60
	20.0	6.39	299.0			86.46	1707.84
Duration‖ (hr)	0.5	4.26	158.0	-0.466	-1.06	40.40	152.69
	1.0	3.78	112.0			36.17	76.34
	6.0	1.85	8.51			14.64	8.99
Time to peak (t_p)‖	0.01	3.91	103.0	-0.011	0.047	35.76	60.53
	0.5	3.78	112.0			36.17	76.34
	1.0	3.83	113.0			36.32	75.43
Peak Intensity (i_p)‖	1.0†	4.26	82.9	-0.130	0.160	35.85	39.43
	2:0†‡	3.83	113.0			36.32	75.43
	10.0	3.22	140.0			38.11	408.39
	20.0	2.98	135.0			38.80	829.77

$$* \quad S = \frac{\dfrac{(\text{output})_1 - (\text{output})_2}{(\text{output})_{\overline{1,2}}}}{\dfrac{(\text{variable})_1 - (\text{variable})_2}{(\text{variable})_{\overline{1,2}}}}$$

† $t_p = 1.0$.

‡ Sensitivity calculated between $i_p = 2.0$ and $i_p = 10.0$.

§ Precipitation = 100 mm.

‖ Precipitation = 50 mm.

TABLE 13. Slope factors predicted by WEPP and those used in RUSLE

Slope (%)	Slope factor predicted by WEPP							
	5m	10 m	25 m	50 m	100 m	200 m	300 m	RUSLE
0.5	0.144	0.126	0.095	0.073	0.056	0.043	0.041	0.084
1.0	0.375	0.320	0.234	0.178	0.136	0.105	0.101	0.138
2.5	0.701	0.589	0.469	0.400	0.346	0.305	0.296	0.300
5.0	0.820	0.768	0.711	0.674	0.639	0.606	0.609	0.569
7.5	0.937	0.919	0.898	0.884	0.870	0.861	0.858	0.838
10.0	1.040	1.051	1.065	1.074	1.083	1.089	1.094	1.17
15.0	1.221	1.284	1.363	1.419	1.461	1.524	1.552	1.99
20.0	1.382	1.493	1.634	1.727	1.816	1.942	2.013	2.79

length factor followed this relationship very closely (r^2 = 0.99, Table 15). However, the exponents, m, were lower than those for the RUSLE. Table 15 gives m values calculated by the RUSLE method for low (1/2 ß), medium (ß), and high (2 ß) rill to interrill ratios. (The ß values in RUSLE may be adjusted if the soil is more susceptible to either rill or interrill erosion than the "average" soil.) The m values calculated by WEPP, for what was a medium ratio of rill to interrill erosion, were within the range of m values calculated by RUSLE, but definitely on the lower end of the range.

A summary of slope exponent (m) values was given by Foster (1982) as shown in Table 16. The exponents ranged in value from 0.0 to 0.9 from 14 sets of natural runoff plots. The exponents predicted by WEPP were reasonable when compared with those experimental values. Until the reasons for the wide range of potential slope exponent values can be better defined, it will be difficult to improve the model's estimates with regards to slope length or gradient. The model predicted relationships which were well within expected ranges as indicated by the experimental data, and it followed the recognized trends in effects due to slope length, slope gradient interactions and due to differing rill to interrill erosion ratios.

The WEPP model predicted a different slope length effect for sediment delivery than for soil loss when deposition was active, as discussed below in the section on complex slopes, which was a physically meaningful response. If some of the runoff plots from which the exponent values from Table 16 had even a small amount of deposition, some of the higher slope exponents from the experimental data could be explained. This will become clearer in the discussion below regarding effect of slope length on sediment delivery from complex slopes.

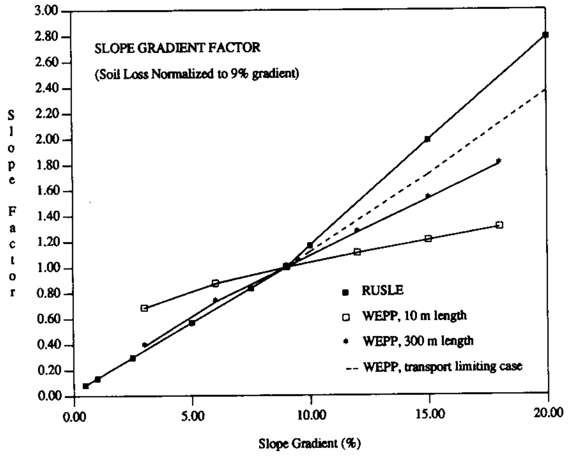

Figure 2–Effect of slope gradient on soil loss estimates using the single storm erosion model with uniform slopes.

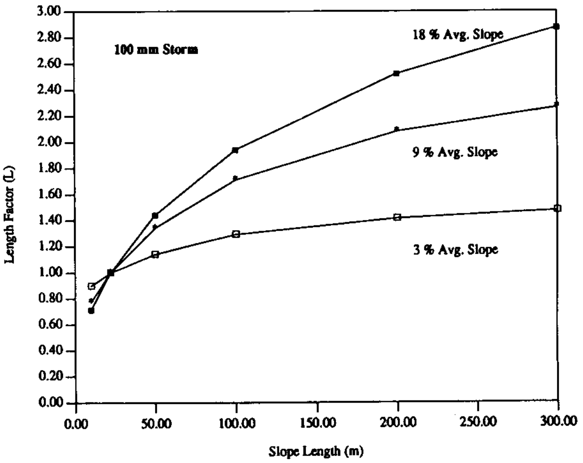

Figure 3–Effect of slope length on soil loss estimates using the single storm erosion model with uniform slopes.

COMPLEX SLOPES

A major difference between the RUSLE and the WEPP model is that WEPP predicts deposition. It is recognized that a significant portion of soil detached on a slope profile is deposited on the toe of the slope. WEPP calculates soil loss and sediment delivery (sediment yield). Figure 4 shows the results for soil loss over the area of net soil loss and sediment delivery from the profile for a complex ("S-shaped") hillslope with zero slope at the top and a range of slopes at the end, S_e. The slope inflection point was halfway down the slope (inflection point distances herein are reported as fractions of the total slope length). Average soil lost over the area of net soil loss was a function of the average slope over the hillslope and practically independent of the slope at the end, S_e, of the profile. However, the slope at the end of the profile plays a dominant role in the amount of sediment leaving the slope profile. The end slope, S_e, acts as a "control gate" for the sediment leaving the field. If transport capacity at the end of the hillslope is very low, sediment is deposited and less leaves the field than is detached. If slope, and hence transport, is high at the end of the hillslope most or all of the detached soil leaves the field.

The effect of slope length was much different in terms of sediment delivery than it was in terms of soil loss (fig.

TABLE 14. Rill and interrill soil loss and ratio, β, for 5% gradient

Slope length	Rill erosion rate	Interrill erosion rate	Rill to interrill loss ratio β_{WEPP}
(m)	($g/m^2/s$)	($g/m^2/s$)	
5	0.110	0.555	0.20
10	0.237	0.555	0.43
25	0.528	0.555	0.95
50	0.853	0.555	1.53
100	1.238	0.555	2.23
200	1.624	0.555	2.93
300	1.826	0.555	3.29

TABLE 15. Slope length exponents for WEPP and RUSLE

		RUSLE				
Slope gradient	β_{USLE}	$(m)_{\beta/2}$	$(m)_{\beta}$	$(m)_{2\beta}$	m*	r^2
5.0	0.67	0.25	0.40	0.57	0.32	0.99
10.0	1.07	0.35	0.52	0.68	0.41	0.99
15.0	1.37	0.41	0.58	0.73	0.46	0.99
20.0	1.59	0.44	0.61	0.76	0.49	0.99

* Using "standard" values of Table 1 with varying slopes.

5). The effect here was actually much the same as for storm size, which was discussed above. The longer slope produced more runoff and a higher sediment carrying capacity at the slope ends, and consequently a smaller fraction of the total sediment load was shown to be deposited on the longer slopes. Sediment delivery estimates will become more important in the future with increased interest in surface water quality associated with sediment leaving the hillslope.

A complex ("S-shaped) profile can be characterized in the WEPP model by the length, the slope at the top (usually zero), the average slope, the slope at the end, and the location of the inflection point. Figure 6 shows the effect of the location of the inflection point on soil loss and sediment delivery. The effect on soil loss was moderate. Calculated soil loss over the area of net soil loss was less when the inflection point was located towards the top of the slope for the case where average slope over the entire profile was held constant. The effect on sediment delivery was negligible when the end slope was low and deposition occurred. For the case where deposition did not occur, as when endslope was 6%, the effect was similar to that for soil loss, as would be expected. The differences in slope inflection point location shown in figure 6 were extreme (ranging from 0.2 to 0.8). Errors in soil loss predictions caused by inaccurate slope profile shape descriptions will not be large unless gross errors in the inputs are present.

Slopes may have multiple inflection points. Figure 7 shows the results of an analysis on a complex, "double-S", shaped profile where the slope at the mid-point was the same as the slope at the end point. The trends and conclusions which were true for the single "S" profile are also valid for the double "S" profile. The effect of end slope on sediment delivery is more pronounced for the double "S" profile because more deposition takes place due to the flat mid-section.

Table 16. Length of slope data summary* from Foster (1981)

Location	Slope %	Row direction	Cropping	Slope length (ft)	Length of record (yr)	Average exponent of L[†]
Zanesville, OH	12	Contour	C.corn	36,73,145	7	0.27
Clarinda, IA	8	U&D[‡]	C.corn	158,315,630	7	0.31
Clarinda, IA	9	U&D	C.corn	73,145	11	0.36
Bethany, MO	8	Contour	C.corn	73,145	10	0.36
Bethany, MO	10	U&D	C.corn	90,180,270	9	0.90
Dixon Sp, IL	5&9	Contour	C,W,L	35,70,140	8	0.39
Arnot, NY	18	Contour	C.corn	73,145	8	0.45
LaCrosse, WI	3-18	U&D	C.barley C,W,M	36,73	5	0.45
Lacrosse, WI	16	Contour	C.corn	36,73,145	6	0.50
Marcellus, NY	17	Contour	C,C,O,M C,O,M	36,73,145	7	0.60
Hays, KS	5	U&D Contour	C.wheat	36,73,145	10	0.00
Temple, TX	4	U&D	C.corn	36,73,145	15	0.00
Tyler, TX	9	Contour	C.cotton	36,73,145	25	0.54
Gutherie, OK	7.7	U&D	C.cotton	36,73,145	25	0.68

* Wischmeier, W. H. 1956. Distributed at a joint SEA-SCS workshop held at Purdue University, Lafayette, IN.

† Exponent of L when fitted to 108 years of annual soil losses = 0.48.

‡ Legend: U&D - Rows up and down hill; C. - continuous cropping; C - corn; W - wheat; L - Legume; O - oats; M - meadow.

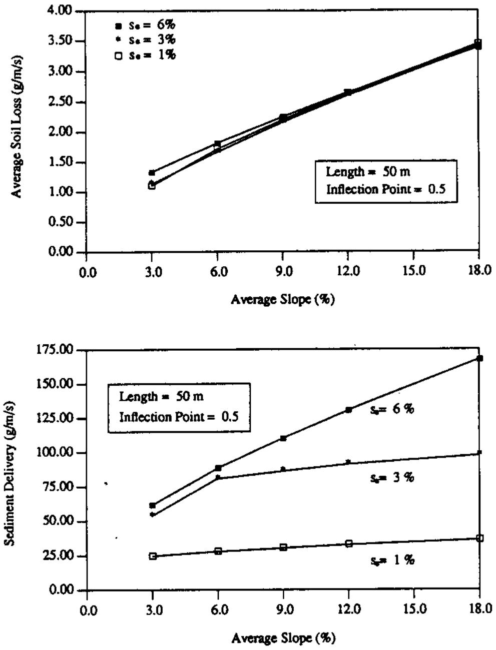

Figure 4–Effect of average slope gradient on on-site soil loss and off-site sediment delivery for a range of end slope gradients. Inflection point is relative to the total slope length.

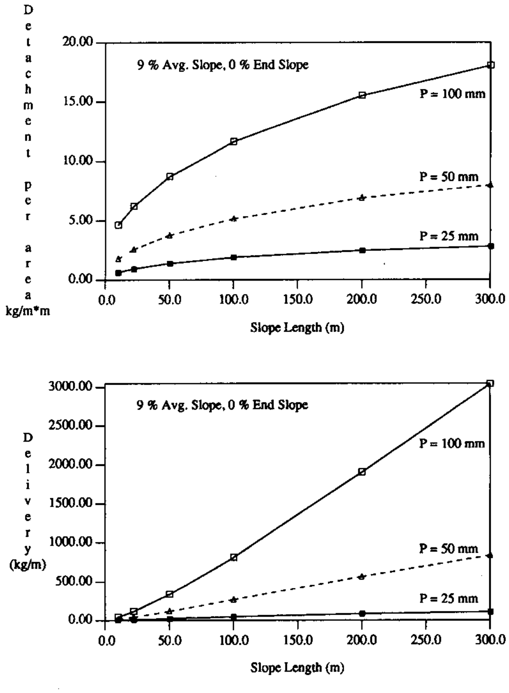

Figure 5–Effect of slope length on on-site soil loss and off-site sediment delivery for average rainfall intensities of 25, 50, and 100 mm/hr occurring over a one-hour period.

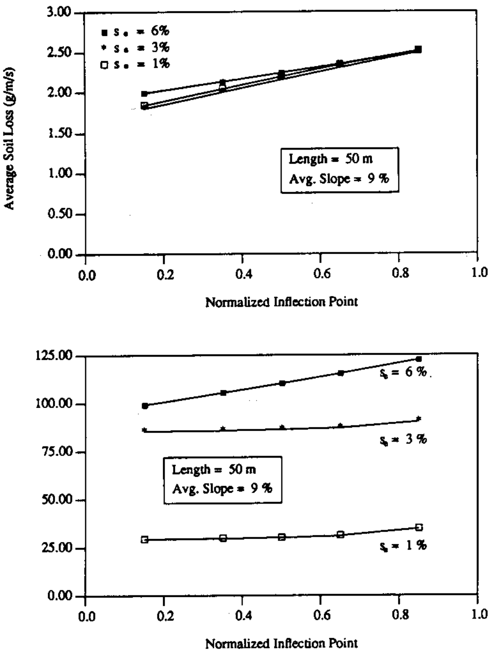

Figure 6–Effect of inflection point location on on-site soil loss and off-site sediment delivery for a range of end slope gradients. Inflection point distance is relative to the total slope length.

SUMMARY OF SENSITIVITY ANALYSES

A summary of the sensitivity analyses for the erosion model are presented in Table 17 and for the single storm model in Table 18. Hydrologic factors are key to obtaining good soil loss estimates from the model as shown in both tables. Factors related to rill detachment and transport are also very important. Rill erodibility, critical hydraulic, surface cover in the rills, and rill hydraulic friction factors are major factors in terms of model response. Texture is an important soil property for the model. Much of the sensitivity to texture is introduced through the prediction of rill hydraulic friction factors. Saturated hydraulic conductivity and interrill erodibility fall into the moderately sensitive range of the parameters. However, the influence of these factors on predictions depend on specific conditions. Interrill erodibility is important on short, flat slopes. Saturated conductivity is more important for shorter, less intense storms and less important for the larger storms. Interrill cover is important when interrill erosion is great; its response is similar to the interrill erodibility term. Plant canopy cover is not a dominant factor. Its influence, again, is greater on short flat slopes, but not as great as interrill cover or erodibility. Canopy height is relatively insignificant. Terms related to the suction term of the infiltration equation, those being bulk density and

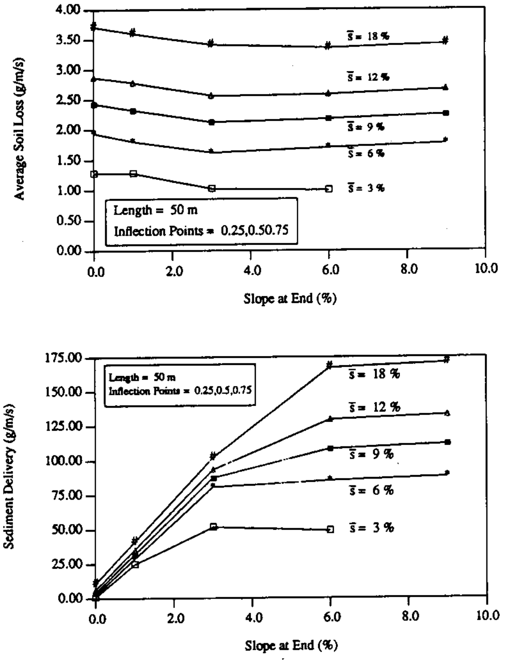

Figure 7–Effect of end slope gradient on on-site soil loss and off-site sediment delivery for a range of average slope gradients for the case of a "double-S" shaped profile.

TABLE 17. Summary of average sensitivity values (S) for erosion component

Parameter	Average S value*
Intensity & runoff	1.1836
Ground cover (corn)	-0.8134
Runoff	0.8100
Rill cover (corn)	-0.6504
Ground cover (wheat)	-0.6080
Rill erodibility	0.5008
Intensity	0.4697
Critical shear	-0.4194
Rill cover (wheat)	-0.4155
Incorporated residue	-0.3843
Soil friction factor †	0.3565
Interrill erodibility	0.2515

* Sensitivity values averaged over sediment loss from slope lengths of 22.13, 50.0, and 200 m at slope gradients of 5 and 9%.

† Sensitivity values averaged over sediment loss from slope lengths of 50 m and 5% gradient.

‡ Sensitivity values averaged over sediment loss from K_i values of $0.5 \times 10^6 - 5.0 \times 10^6$ kg•s•m^{-4}.

§ Sensitivity values averaged over sediment loss from rill space values of 0.5 and 5 m.

TABLE 18. Summary of average sensitivity values (S) for detachment per area in single storm component

Parameter	Average S value
Precipitation	1.12
Rill erodibility*	0.81
Rill cover	-0.794
Sand fraction	-0.455 to -0.630 †
Clay fraction	0.245 to 0.630 †
Silt fraction	-0.245 to 0.455 †
Saturated hydraulic conductivity	-0.43
Rainfall duration‡	-0.344
Interrill erodibility*	0.19
Peak rainfall intensity	-0.156
Canopy cover	-0.111
Initial soil saturation*	0.1015
Interrill cover	-0.087
Canopy height	0.0455
Bulk density*	-0.017
Time to peak rainfall intensity	-0.0130

* End slope = 0%.

† Dependent on fraction of other size classes.

‡ At constant total precipitation.

saturation, do not have a major influence on the output. Peak rainfall intensity, time to peak rainfall intensity, rill spacing and width, and sediment transportability do not play a major role in these soil loss predictions.

REFERENCES

Beck, M.B. 1983. Sensitivity analysis, calibration, and validation. In *Mathematical Modeling of Water Quality: Streams, Lakes, and Reservoirs*, ed. G.T. Orlob, 425-467. New York: John Wiley & Sons.

Foster, G.R. and L.J. Lane. 1987. User requirements: USDA-Water Erosion Prediction Project (WEPP). NSERL Report No. 1, National Soil Erosion Research Laboratory, USDA-Agric. Res. Service, West Lafayette, IN.

Foster, G.R. 1982. Relation of USLE factors to erosion on rangeland. In *Proc. Workshop on estimating erosion and sediment yield on rangelands,* ed. K.G. Renard, 17-35. USDA-Agric. Res. Service, Agric. Reviews and Manuals, ARM-W-25. Oakland CA, 94612.

Hernandez, M., L.J. Lane and J.J.Stone. 1989. Surface runoff. In USDA-Water Erosion Prediction Project: Profile model documentation, ed. L.J. Lane and M.A. Nearing. NSERL Report No. 2, National Soil Erosion Research Laboratory, USDA-Agric. Res. Service, West Lafayette, IN 47907.

Lane, L.J. and M.A. Nearing, ed. 1989. USDA-Water Erosion Prediction Project: Profile model documentation. NSERL Report No. 2, National Soil Erosion Research Laboratory, USDA-Agric. Res. Service, West Lafayette, IN 47907.

McCuen, R.H. and W.M. Snyder. 1983. *Hydrologic Modeling: Statistical Methods and Applications.* Englewood Cliffs, NJ: Prentice-Hall.

Nearing, M.A., G.R. Foster, L.J. Lane and S.C. Finkner. 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. (In press) *Transactions of the ASAE.*

Renard, K.G., ed. 1990. The Revised Universal Soil Loss Equation. (In Review).