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Evaluating WEPP Predicted On-field Furrow Irrigation Erosion

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ABSTRACT

The Water Erosion Prediction Project (WEPP) model has the ability to predict erosion from furrow-irrigated fields. A previous evaluation showed that WEPP-predicted infiltration and soil loss correlated poorly with field measurements. Our objective was to further evaluate the WEPP model for furrow irrigation by comparing on-field distribution of measured and predicted infiltration, runoff and soil loss. We used data from three fields with Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) near Kimberly, ID. Single-event WEPP simulations were used so predicted erosion could be evaluated without the effects of daily model adjustments to effective hydraulic conductivity, critical shear and rill erodibility. Single-event simulations showed that the model could only adequately predict infiltration and runoff within a field when effective hydraulic conductivity was calibrated for each irrigation. However even with accurate furrow flows, the WEPP model could not adequately predict sediment detachment, transport, and deposition within a field. Comparing measured and predicted on-field distribution of soil loss indicated that transport capacity was over-predicted by the model because deposition was only predicted when detachment was greatly over-predicted. More thorough investigation of the WEPP model programming and more detailed furrow erosion field data are needed to develop an accurate simulation model for furrow irrigation erosion.

INTRODUCTION

The Water Erosion Prediction Project (WEPP) model includes an irrigation component for estimating soil loss for stationary sprinkler systems and furrow-irrigated fields. Sprinkler irrigation erosion is simulated with the same equations as rainfall. For furrow irrigation, infiltration is calculated in a separate component using a two-dimensional approximation of the Green-Ampt infiltration equation as presented by Fok and Chiang (1984) and as described in the WEPP technical documentation (Flanagan and Nearing, 1995). Runoff volume and peak runoff rate are calculated using conservation of mass and kinematic wave theory. A rectangular runoff hydrograph is used with the constant flow rate equal to the peak runoff rate. Effective runoff duration is then calculated by dividing runoff volume by peak runoff rate. These three parameters (effective duration, peak runoff rate and runoff volume) are used in the steady-state erosion component to predict sediment detachment, transport and deposition.

The WEPP model categorizes soil erosion into rill and interrill processes. Interrill erosion involves soil detachment and transport by raindrops and shallow sheet flow. Rill erosion processes describe soil detachment, transport and deposition in rill channels (Flanagan and Nearing, 1995). Identical processes predict furrow erosion in the WEPP model as rill erosion under rainfall conditions. Detachment in rills only occurs when hydraulic shear exceeds the soil critical shear and sediment load is less than rill transport capacity. If sediment load exceeds transport capacity, sediment deposition occurs.

Soil detachment by flowing water in rills is calculated by

$$Dc = Kr(\tau - \tau_c) \quad (1)$$

where D_c is detachment rate for clear water (kg $s^{-1}m^{-2}$), K_r is rill erodibility (s m^{-1}), τ is hydraulic shear of flowing water (Pa), and τ_c is critical shear (Pa) (Elliot and Laflen, 1993; Flanagan and Nearing, 1995). Detachment rate is a linear function of shear with slope equal to the rill erodibility (K_r) and x-intercept equal to the critical hydraulic shear (τ_c). Hydraulic shear is calculated by

$$\tau = \gamma RS \quad (2)$$

where γ is the specific weight of water (N m^{-3}), R is the hydraulic radius of the rectangular rill (m), and S is the hydraulic gradient, which approximately equals the slope of the rill bottom.

Baseline rill erodibility and critical shear represent erodibility characteristics of freshly tilled soil. These two parameters were determined for several characteristic soils during WEPP rainfall simulations. They can also be calculated based on soil texture and organic matter content. Rill erodibility and critical shear are adjusted daily in the WEPP model by multiplying the baseline values by adjustment factors. Adjustment factors account for freezing and thawing; temporal changes in roots, sealing and crusting; and residue incorporation (Flanagan and Nearing, 1995). The rill erodibility adjustment factor is less than or equal to 1.0 while the critical shear adjustment factor is greater than or equal to 1.0. Therefore, baseline rill erodibility is the maximum rill erodibility and baseline critical shear is the minimum critical shear.

The amount of soil detached in a rill is affected by the sediment concentration of water flowing in the rill. Net soil detachment is calculated by:

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$$D_f = D_c(1 - G/T_c) \quad (3)$$

where D_f is net detachment rate (kg $s^{-1}m^{-2}$), G is sediment load in the rill (kg m^{-1} s^{-1}), and T_c is transport capacity of the rill (kg m^{-1} s^{-1}). Transport capacity is calculated by the following equation:

$$T_c = k_t \tau^{3/2} \quad (4)$$

where k_t is a transport coefficient ($m^{1/2}$ s^2 $kg^{-1/2}$). The transport coefficient is calibrated from the transport capacity, calculated by a modified Yalin equation, at the end of a uniform slope using a method described by Finkner et al. (1989).

When sediment load exceeds the transport capacity, deposition occurs. Net deposition in a rill is calculated by

$$D_f = \beta V_f(T_c - G)/q \quad (5)$$

where V_f is effective sediment fall velocity (m s^{-1}), q is flow rate per unit rill width (m^2 s^{-1}), and ß is a raindrop-induced turbulence coefficient set equal to 1.0 for furrow irrigation (Flanagan and Nearing, 1995).

An initial evaluation of furrow irrigation prediction by the WEPP model showed that infiltration and soil loss correlated poorly with measured values (Bjorneberg et al., 1999). The objective of the initial study was to evaluate the WEPP model from a users point of view rather than evaluate the erosion science. Baseline rill erodibility and critical shear defined by WEPP field tests had to be greatly reduced before the model predicted any soil loss. Soil loss from entire fields was not adequately predicted even though baseline erosion parameters (rill erodibility and critical shear) were calibrated by comparing predicted and measured soil loss for the upper end of two furrow-irrigated fields. These results indicated that sediment transport and deposition might not be accurately predicted. Therefore, our objective was to further evaluate the WEPP model for furrow irrigation by comparing on-field distribution of measured and predicted infiltration, runoff and soil loss.

MATERIALS AND METHODS

Field Measurements

Data from three different fields were used for this evaluation. All fields were Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) and located at the Northwest Irrigation and Soils Research Laboratory near Kimberly, ID. Field 1 was fallowed in 1998 after being in grass for the previous seven years. Grass was killed by herbicide in the fall of 1997. The field was disked, roto-tilled and roller harrowed in the spring of 1998. Soil was not tilled again until furrows were formed two days before the monitored irrigation on August 5, 1998. Field 1 was 110-m long with a 1.0% slope (table 1). Data for fields 2 and 3 were taken from Trout (1996). Field 2 was 204-m long with 1.3% slope. It was moldboard plowed, roller harrowed and planted to dry bean (*Phaseolus vulgaris* L.). Field 3 was 256-m long with 0.52% slope (table 1). This field was disked in the fall, roller harrowed in spring and planted to corn (*Zea mays* L.).

All three fields were irrigated with siphon tubes or gated pipe using water from the Twin Falls Canal Company (electrical conductivity of 0.5 dS m^{-1}, sodium adsorption ratio of 0.4 to 0.7). Two constant inflow rates (30 and 40 Lpm), replicated on three furrows, were used on field 1. Fields 2 and 3 had three different inflow rates (low, medium and high), replicated on four furrows, for each irrigation. A medium inflow rate was chosen before each irrigation and high and low, inflow rates were 20% above and below the medium inflow rates, respectively (Trout, 1996). Presented data are the means of the replicates for each flow rate and irrigation.

Irrigation furrows on all fields were divided into four equal-length sections (1/4, 1/2, 3/4 and field end). Furrow flow rate was monitored at the end of each section using small, trapezoidal, long-throated flumes. Sediment concentration samples were collected from the flume discharge and poured into 1L Imhoff cones. Sediment volume was read after settling for 30 minutes (Sojka et al., 1992). Flow rates and sediment concentrations for field 1 were measured at 15, 45 and 75 minutes after runoff started at each monitoring station and then approximately 1.5 and 2.5 h later. Total irrigation time was 7.5 h. For fields 2 and 3, measurements occurred at 15 min, 30 min, 1 h, 2 h, 4 h, 6 h and 8 h after runoff started at each monitoring station and at the end of each 12 h irrigation.

WEPP Model Simulations

As an initial test, an eight-year simulation was conducted for field 1 using seven years of grass and one year of fallow. Field 1 provided an opportunity to test the model with few management effects since no tillage occurred during the first seven years and no crop was grown during the fallow year.

WEPP version 98.4 was used in continuous simulation mode. An eight-year climate file was produced using weather data from a local automated weather station. Calibrated baseline effective hydraulic conductivity (2.7 mm h^{-1}), critical shear (1.2 Pa) and rill erodibility (0.0002 s m^{-1}) from the earlier study were used (Bjorneberg et al., 1999). No soil loss is predicted when WEPP-default critical shear (3.5 Pa) and rill erodibility (0.0215 s m^{-1}) values are used.

The WEPP model adjusted effective hydraulic conductivity whereas rill width was fixed at 0.1 m rather than calculated by the model. Predicted infiltration, runoff, peak runoff rate and soil loss were compared with measured values for the one irrigation during the fallow year (eighth year). Irrigations were not monitored during the previous years.

Table 1. Field conditions and tillage management.

Field	Crop	Slope (m/m)	Length (m)	Previous Crop	Tillage
1	fallow	0.010	110	grass	disk, roto-till, roller harrow
2	dry bean	0.0133	204	potato	moldboard plow, roller harrow
3	corn	0.0052	256	peas	fall disk, roller harrow

Single-event simulations were used because effective hydraulic conductivity and baseline rill erodibility and critical shear could be input for each irrigation, eliminating the effects of daily adjustments by the model. Since the WEPP model is not configured to simulate a single furrow irrigation event, single-event simulations were conducted by simulating one irrigation event during a one-year simulation. Measured 1998 weather data were used for the climate file. A field cultivator tillage operation was added to the management scenario the day before irrigation so rill erodibility and critical shear adjustment factors were 1.00 and 1.07, respectively. Therefore, erodibility parameters and effective hydraulic conductivity nearly equaled baseline values on the day of irrigation.

Single-event simulations were conducted for irrigations on all three fields. For a given irrigation, effective hydraulic conductivity was adjusted until infiltration and runoff were predicted reasonably well for the two or three inflow rates used during that irrigation. Then, one simulation was conducted using the calibrated baseline rill erodibility (0.0003 s m^{-1}) and critical shear (1.2 Pa) from the earlier study (Bjorneberg et al., 1999). At least three additional simulations were conducted with various rill erodibility-critical shear combinations, chosen by trial and error, so that: 1) erosion for the upper quarter was accurately predicted, 2) erosion at the end of the field was accurately predicted, and 3) deposition was predicted.

RESULTS AND DISCUSSION

The WEPP model poorly predicted infiltration and runoff for the last year of the eight-year simulation on field 1. Predicted infiltration or runoff depths were not within the 95% confidence interval of measured values for any portion of the field (Table 2). Measured infiltration was three to four times greater than predicted. Runoff measured at the end of the field was approximately 30% of the predicted value for the 40 Lpm inflow rate and only 5% of the predicted value for the 30 Lpm inflow rate.

Peak runoff rate, which is the steady-state runoff rate used by the model, was greater than average measured final runoff rate for each furrow segment and inflow rate (Table 3). Predicted soil loss, however, was much less than the average measured soil loss (Table 3). In fact, no soil loss was predicted for the 30 Lpm inflow rate. However, predicted values were within the 95% confidence intervals of measured data because coefficients of variation for measured soil loss ranged from 70 to 160%. In other words, predicted soil loss would always fall within the confidence interval as long as soil loss was under-predicted.

Single Event Simulations

Predicted infiltration and runoff for the single event simulations closely matched measured values when the effective hydraulic conductivity was calibrated for each irrigation. Predicted infiltration and runoff were within 10% of average measured values for field 1 when the calibrated effective hydraulic conductivity of 10 mm h^{-1} was used (Table 4). For fields 2 and 3, predicted infiltration and runoff were also generally within 10% of measured values (Table 5). All but three of the predicted runoff and infiltration values were within the 95% confidence interval for field measurements. Predicted peak runoff rate was typically 10 to

Table 2. Measured and predicted infiltration and runoff for the fallow year of the eight-year simulation on field 1 with 30 and 40 Lpm inflow rates. Baseline effective hydraulic conductivity was 2.7 mm h^{-1}.

	Infiltration				Runoff			
Furrow	Measured		Predicted		Measured		Predicted	
Segment	30 Lpm	40 Lpm	30 Lpm	40 Lpm	30 Lpm	40 Lpm	30 Lpm	40 Lpm
	(mm)							
1/4	122	103	30*	31*	332	470	437*	596*
1/2	122	103	30*	31*	105	183	203*	283*
3/4	115	103	30*	31*	36	88	125*	178*
end	107	100	30*	31*	6	43	87*	126*

* Predicted value was not within the 95% confidence interval of measured values.

Table 3. Measured and predicted final runoff rate and soil loss for the fallow year of the eight-year simulation on field 1 with 30 and 40 Lpm inflow rates. Baseline effective hydraulic conductivity was 2.7 mm h^{-1}, rill erodibility was 0.0003 s m^{-1} and critical shear was 1.2 Pa.

	Final Runoff Rate				Soil Loss			
Furrow	Measured		Predicted		Measured		Predicted	
Segment	30 Lpm	40 Lpm	30 Lpm	40 Lpm	30 Lpm	40 Lpm	30 Lpm	40 Lpm
	(Lpm)				(kg)			
1/4	26	35	28	37	1.4	11.1	0.0	0.4
1/2	20	31	25	35*	3.1	8.4	0.0	0.9
3/4	12	25	24*	33	0.4	9.6	0.0	1.5
end	4	18	22*	31	0.2	8.7	0.0	2.3

*Predicted value was not within the 95% confidence interval of measured values.

Table 4. Predicted infiltration, runoff and final runoff rate for single event simulations on field 1 with 30 and 40 Lpm inflow rates. Baseline effective hydraulic conductivity was 10.0 mm h^{-1}.

Furrow Segment	Infiltration 30 Lpm	Infiltration 40 Lpm	Runoff 30 Lpm	Runoff 40 Lpm	Final Runoff Rate 30 Lpm	Final Runoff Rate 40 Lpm
	----- (mm) -----		----- (mm) -----		------ (Lpm) ------	
1/4	110	111	343	493	23	32
1/2	110	111	116	191	15	25*
3/4	110	111	41	91	9	18
end	106	110	7	41	3	11

* Predicted value was not within the 95% confidence interval of measured values.

Table 5. Measured and single-event predicted field-end infiltration and runoff for high, medium and low inflow rates from fields 2 (dry bean) and 3 (corn). Effective hydraulic conductivity was calibrated for each irrigation.

	Infiltration						Runoff					
	Measured			Predicted			Measured			Predicted		
Irrigation	High	Med	Low	High	Med	Low	High	Med	Low	High	Med	Low
Field 2	(mm)											
1	32	34	32	33	33	33	33	22	16	32	24	16
2	33	32	30	32	32	32	45	33	25	46	34	24
3	29	29	27	30	30	30	37	27	21	36	26	18
4	34	32	33	33	33	32	27	18	11	28	17	11
6	38	36	38	38	37	36	24	15	6	24	14	8
Field 3												
1	68	67	69	67	66	64	34	18	3	35	19	8*
2	44	46	45	48	47	46	40	24	15	37	24	14
3	39	37	34	37*	36	36	38	23	16	41	23	15
4	42	41	38	40	39	38	19	12	8	20	13	7
5	33	35	34	34	33*	33	28	17	10	27	18	11
7	41	39	36	40	39	38	25	13	9	26	13	6

* Predicted value was not within the 95% confidence interval of measured values.

Table 6. Measured and single-event predicted field-end runoff rates for high, medium and low inflow rates from fields 2 (dry bean) and 3 (corn). Effective hydraulic conductivity was calibrated for each irrigation.

	Final Runoff Rate					
	Measured			Predicted		
Irrigation	High	Med	Low	High	Med	Low
Field 2	(Lpm)					
1	12	8	6	10*	8	6
2	16	12	10	15*	11*	8*
3	14	10	8	12*	9*	6
4	10	7	5	9*	6*	4
6	9	6	3	8	5	3
Field 3						
1	24	14	7	20	12	6
2	27	18	12	20*	14*	9*
3	24	15	11	22*	13*	9
4	14	10	7	12	8	6
5	18	12	8	15*	11	7
7	16	9	6	15*	8	5

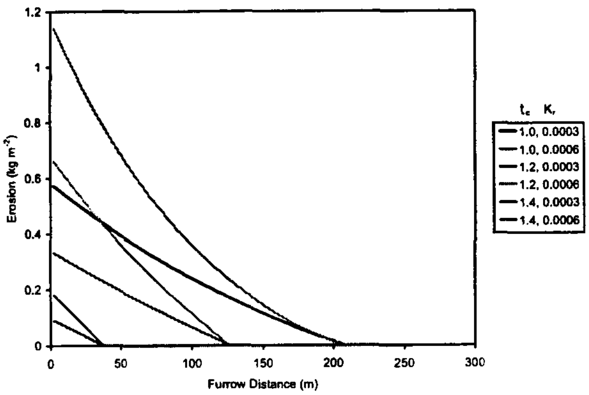

Figure 1. On-field distribution for various critical shear and rill erodibility combinations.

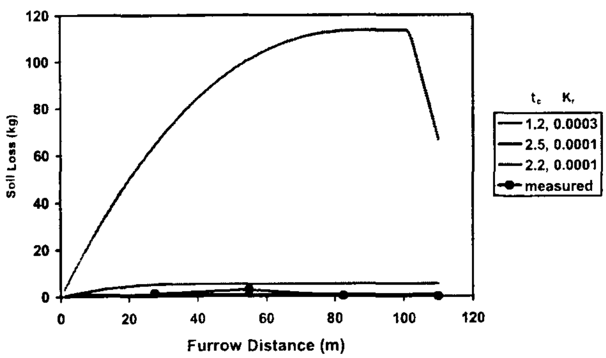

Figure 2. Erosion distribution for field 1 (fallow) with 30 Lpm inflow rate and Keff =10 mm h^{-1}.

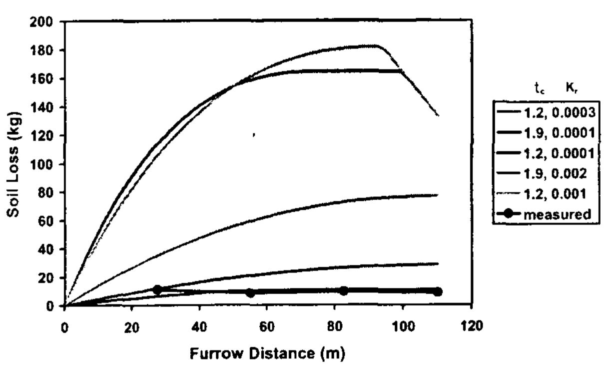

Figure 3. Erosion distribution for field 1 (fallow) with 40 Lpm inflow rate and Keff = 10 mm h^{-1}.

20% less than the average measured final flow rate. Several of the predicted values, however, were not within the 95% confidence of field measurements (Table 6). This indicates that the model hydraulic component can accurately predict furrow flow if parameters are properly defined.

Increasing critical shear decreases the furrow distance over which detachment occurs (shifts line to the left) (Figure 1). Increasing rill erodibility increases erosion per unit length of furrow, which increases the line slope (Figure 1). However, a single rill erodibility and critical shear combination could not represent the on-field erosion distribution. To predict soil loss at the lower end of the field, erosion had to be under-predicted at the upper end. Similarly, accurately predicting soil loss for the upper quarter of a field resulted in over-predicting soil loss at the end of the field.

Figures 2-5 are examples of measured and predicted on-field erosion and deposition for selected irrigation events. Detachment occurs where the line slope is positive and deposition occurs where the line slope is negative. A horizontal line indicates that neither detachment nor depositions are occurring. The black lines on the figures represent measured soil loss. The gray lines on all figures represent predicted soil loss for τ_c =1.2 Pa and K_r = 0.0003, the calibrated erosion parameters from the earlier study (Bjorneberg et al., 1999). Red lines show accurate end-of-field predictions, while blue lines show accurate upper-quarter predictions. Additional erodibility parameter combinations are also shown to demonstrate predicted detachment and deposition distribution. The distance over which predicted detachment occurred was decreased by increasing critical shear. Increasing rill erodibility increased detachment per unit length. Based on Figures 2-5, it is clear that field measured sediment transport and deposition cannot be represented by the WEPP model with a single set of parameters.

Detachment continues to be predicted until either 1) predicted transport capacity is reached and deposition begins as occurs at about 150 m in Figure 3 with τ_c = 1.2 Pa and K_r = 0.001 s m^{-1} or 2) predicted shear decreases below the critical shear as occurs at about 50 m in Figure 5 with τ_c = 1.8 Pa and K_r = 0.0006 s m^{-1} (red line) or 0.006 s m^{-1} (brown line). Predicted soil loss at the field end is equal for all erodibility parameter combinations that result in deposition (Figures 3, 4 and 5), indicating that transport capacity was over-predicted at the end of the field. At the furrow position when predicted deposition began, predicted soil loss was double or triple measured soil loss, further indicating that transport capacity was over-predicted.

Transport capacity is over-predicted because either the transport coefficient or the shear is too large, or equation 4 is not applicable for furrow irrigation. Since shear stress is a hydraulic parameter, it should be adequately predicted as long as infiltration and flow rate are accurately predicted. However, it is difficult to identify exactly where the problem occurs since transport capacity, shear, flow depth and other hydraulic and erosion parameters are not output by the model.

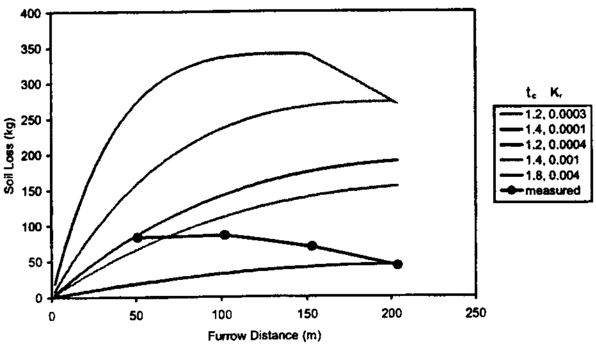

Figure 4. Erosion distribution for irrigation 1 on field 2 (dry bean) with high inflow rate and Keff = 1.2 mm h-1.

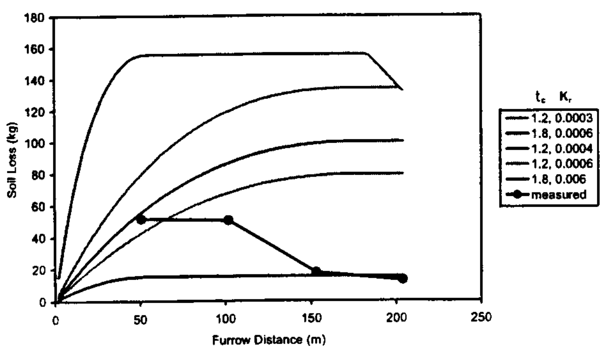

Figure 5. Erosion distribution for irrigation 1 on field 2 (dry bean) with low inflow rate and Keff = 1.7 mm h^{-1}.

CONCLUSIONS

Single-event WEPP model simulations of furrow irrigation showed that the model does not accurately predict sediment detachment, transport, or deposition within a field. Infiltration and runoff were accurately predicted for irrigation as long as effective hydraulic conductivity was calibrated for that irrigation. The WEPP model could not match measured on-field erosion distribution because transport capacity appeared to be grossly over-predicted. Single-event simulations allowed soil loss predictions to be evaluated without the effects of daily adjustments to effective hydraulic conductivity, critical shear and rill erodibility. More thorough investigation of the WEPP model programming and more detailed furrow erosion field data are needed to develop an accurate simulation model for furrow irrigation erosion.

REFERENCES

Bjorneberg, D.L., T.J. Trout, R.E. Sojka and J.K. Asae. 1999. Evaluating WEPP Predicted Infiltration, Runoff and Soil Erosion for Furrow Irrigation. Transactions of the ASAE 42(6):1733-1741.

Elliot, W.J. and J.M. Laflen. 1993. A Process-Based Rill Erosion Model. Transactions of the ASAE 36(1):65-72.

Finkner, S.C., M.A. Nearing, G.R. Foster and J.E. Gilley. 1989. A Simplified Equation for Modeling Sediment Transport Capacity. Transactions of the ASAE 32(5):1545-1550.

Flanagan, D.C. and M.A. Nearing, eds. 1995. USDA-Water Erosion Prediction Project: Technical Documentation. NSERL Report No. 10. West Lafayette, Ind.: USDA-ARS-NSERL.

Fok, Y.S. and S.H. Chiang. 1984. 2-D Infiltration Equations for Furrow Irrigation. J. Irrig. Drainage Eng. 110(2):208-217.

Sojka, R.E., D.L. Carter and M.J. Brown. 1992. Imhoff Cone Determination of Sediment In Irrigation Runoff. Soil Sci. Soc. Am. J. 56(3):884-890.

Trout, T.J. 1996. Furrow Irrigation Erosion and Sedimentation: On-Field Distribution. Transactions of the ASAE 39(5):1717-1723.

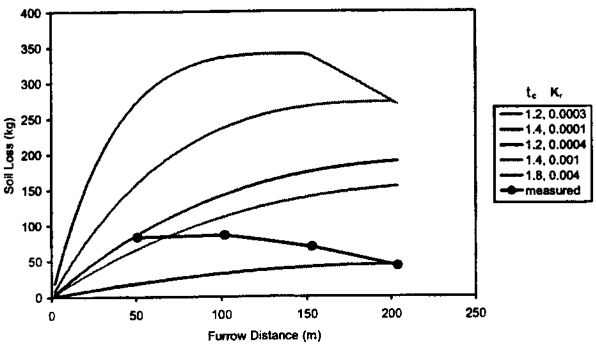

Figure 4. Erosion distribution for irrigation 1 on field 2 (dry bean) with high inflow rate and Keff = 1.2 mm h-1.

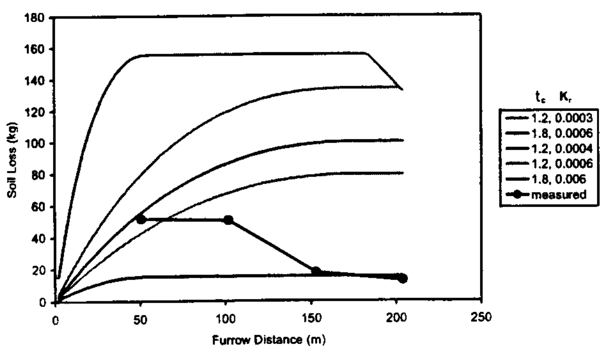

Figure 5. Erosion distribution for irrigation 1 on field 2 (dry bean) with low inflow rate and Keff = 1.7 mm h^{-1}.

CONCLUSIONS

Single-event WEPP model simulations of furrow irrigation showed that the model does not accurately predict sediment detachment, transport, or deposition within a field. Infiltration and runoff were accurately predicted for irrigation as long as effective hydraulic conductivity was calibrated for that irrigation. The WEPP model could not match measured on-field erosion distribution because transport capacity appeared to be grossly over-predicted. Single-event simulations allowed soil loss predictions to be evaluated without the effects of daily adjustments to effective hydraulic conductivity, critical shear and rill erodibility. More thorough investigation of the WEPP model programming and more detailed furrow erosion field data are needed to develop an accurate simulation model for furrow irrigation erosion.

REFERENCES

Bjorneberg, D.L., T.J. Trout, R.E. Sojka and J.K. Asae. 1999. Evaluating WEPP Predicted Infiltration, Runoff and Soil Erosion for Furrow Irrigation. Transactions of the ASAE 42(6):1733-1741.

Elliot, W.J. and J.M. Laflen. 1993. A Process-Based Rill Erosion Model. Transactions of the ASAE 36(1):65-72.

Finkner, S.C., M.A. Nearing, G.R. Foster and J.E. Gilley. 1989. A Simplified Equation for Modeling Sediment Transport Capacity. Transactions of the ASAE 32(5):1545-1550.

Flanagan, D.C. and M.A. Nearing, eds. 1995. USDA-Water Erosion Prediction Project: Technical Documentation. NSERL Report No. 10. West Lafayette, Ind.: USDA-ARS-NSERL.

Fok, Y.S. and S.H. Chiang. 1984. 2-D Infiltration Equations for Furrow Irrigation. J. Irrig. Drainage Eng. 110(2):208-217.

Sojka, R.E., D.L. Carter and M.J. Brown. 1992. Imhoff Cone Determination of Sediment In Irrigation Runoff. Soil Sci. Soc. Am. J. 56(3):884-890.

Trout, T.J. 1996. Furrow Irrigation Erosion and Sedimentation: On-Field Distribution. Transactions of the ASAE 39(5):1717-1723.