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Evaluating WEPP-Predicted Furrow Irrigation Erosion

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Abstract

The Water Erosion Prediction Project (WEPP) model allows users to predict furrow irrigation erosion. However, an initial model evaluation showed that 1) WEPP default erodibility values had to be reduced for simulating furrow irrigation erosion and 2) the WEPP model overpredicted sediment transport capacity. Therefore, the purpose of this study was to investigate the applicability of the governing equations used in the WEPP model to calculate sediment detachment and transport. Sediment detachment data were collected from 53 irrigation furrows, 9 m long, on a Portneuf silt loam with flow rates varying from 2 to 50 L min^{-1} among furrows. Hydraulic shear measured in irrigation furrows varied from 0.4 to 1.7 Pa, which is less than the 2.6 to 8.8 Pa shear measured during WEPP rainfall simulation on the same soil. The linear relationship between shear and detachment rate used by the WEPP model may be appropriate for predicting both rainfall and furrow irrigation erosion as long as separate erodibility values are identified for furrow irrigation. A power function relating shear and detachment rate may allow one relationship to be used for both the low shear conditions in irrigation furrows and the high shear conditions in rills during intense rain storms. Although transport capacity could not be thoroughly evaluated with this data set, sediment detachment seemed to be limited by factors other than transport capacity,. Additional model evaluation is needed with data from other soils before changes to the model can be recommended or the model can be implemented for predicting furrow irrigation erosion.

Keywords. Furrow irrigation erosion, WEPP, Erosion simulation.

Introduction

The Water Erosion Prediction Project (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). Furrow irrigation erosion in the WEPP model is assumed to be identical to 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.

Sediment detachment by flowing water in rills is calculated by:

$$D_c = K_r(\tau - \tau_c) \tag{1}$$

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 the soil critical shear (Pa) (Flanagan and Nearing, 1995). Detachment rate is a linear function of hydraulic shear with slope equal to the rill erodibility and x-intercept equal to the soil critical shear. Hydraulic shear is calculated by:

$$\tau = \gamma RS \tag{2}$$

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 soil critical shear represent erodibility characteristics of freshly tilled soil. These two erodibility parameters were determined on 33 sites across the United States during WEPP rainfall simulations (Elliot et al., 1989). They can also be calculated based on soil texture and organic matter content (Flanagan and Nearing, 1995).

Predicting transport capacity is critical for predicting soil loss from a field. Transport capacity affects both sediment detachment and deposition in the WEPP model. Transport capacity is calculated by the following equation:

$$T_c = k_t\tau^{3/2} \tag{3}$$

where T_c is transport capacity (kg m^{-1} s^{-1}) and 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).

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An initial evaluation of furrow irrigation erosion prediction by the WEPP model showed that infiltration and soil loss correlated poorly with measured values when simulations were conducted over a growing season using calibrated hydraulic and erodibility parameters (Bjorneberg et al., 1999). Furthermore, cumulated predicted soil erosion across a field did not match cumulated measured erosion because transport capacity was overpredicted and therefore no deposition was predicted. This initial study did not evaluate the equations used by the WEPP model to predict soil erosion. Thus, prediction errors may have resulted from fundamental problems with the equations used in the model or from improper adjustment of erodibility parameters by the model. Therefore, the objective of this study was to determine if the detachment (Eq. 1) and transport capacity (Eq. 3) relationships used in the WEPP model apply to furrow irrigation.

Methods and Materials

Field measurements were conducted on a fallow field with Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) at the Northwest Irrigation and Soils Research Laboratory near Kimberly, ID. The field was disked and roller harrowed before furrows were formed with a cultivator (0.76 m spacing). The surface soil was dry (<50g kg^{-1}) and loose prior to irrigation on 12 July, 1999. Field slope was approximately 1%.

The field was irrigated with 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). Small trapezoidal flumes were placed in irrigation furrows 9 m from the gated pipe; the same length as rill plots used during WEPP rainfall simulation studies (Elliot et al., 1989). Sediment detachment is the main mechanism in these short furrows; little if any sediment should deposit. To obtain a wide range of hydraulic shears, inflow rates were randomly set on 53 furrows and varied from 2 to 50 L min^{-1} among furrows. Flow rate and sediment concentration in each furrow were measured four and seven hours after the irrigation began to allow runoff rate and sediment concentration to reach a quasi-steady state. Sediment concentration was measured by pouring a 1-L sample from flume outflow into an Imhoff cone (Sojka et al., 1992). Top-width and depth of furrow flow was also measured when sediment samples were collected. Top-width and depth were used to calculate cross-section area, wetted perimeter and hydraulic radius assuming a parabolic furrow shape.

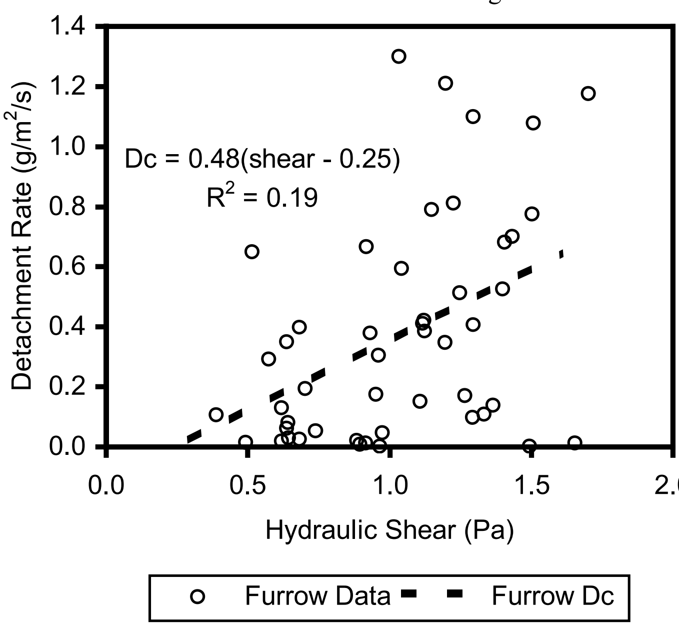

Figure 1. Detachment rate measured in irrigation furrows.

Hydraulic shear was calculated for each furrow using Eq. 2. Sediment transport rate (mass per time) was calculated by multiplying furrow flow rate by sediment concentration. Sediment detachment rate, D_c in Eq. 1, was calculated by dividing the transport rate by the wetted furrow area (i.e. furrow length times wetted perimeter). Sediment transport rate and detachment rate were both plotted against hydraulic shear. These relationships from furrow irrigation data were compared with data from the WEPP rainfall simulation on Portneuf silt loam (Elliot et al., 1989).

Results and Discussion

Data from this furrow irrigation study showed that detachment rate was significantly related to hydraulic shear, but the linear regression only explained 19% of the variability in detachment rate (Fig. 1). This relationship does not include the second set of flow and sediment measurements (seven-hour reading) because the linear relationship was not statistically significant (P=0.4).

Hydraulic shear calculated for irrigation furrows in this study varied from 0.4 to 1.7 Pa, which is less than the 2.6 to 8.8 Pa calculated for rill plots during WEPP rainfall simulation on the same soil, resulting in different shear-detachment rate relationships for WEPP and furrow irrigation data (Fig. 2). Sediment transport rate data also show that the furrow irrigation and WEPP data sets were different (Fig. 3). Flow rates from 7 to 35 L min^{-1} were added to rills during WEPP rainfall simulations, which were within the range of those used during this study (2 to 50 L min^{-1}). The rill slopes for WEPP rainfall simulations, however, varied from 5.1 to 5.6% compared to 1% field slope for this study. Greater slope explains greater hydraulic shear, detachment rate and transport rate, but does not explain why different relationships occurred. The WEPP model does not adjust the detachment rate relationship (Eq. 1) for slope, only soil conditions. These data indicate that furrow irrigation and rainfall erosion conditions are different.

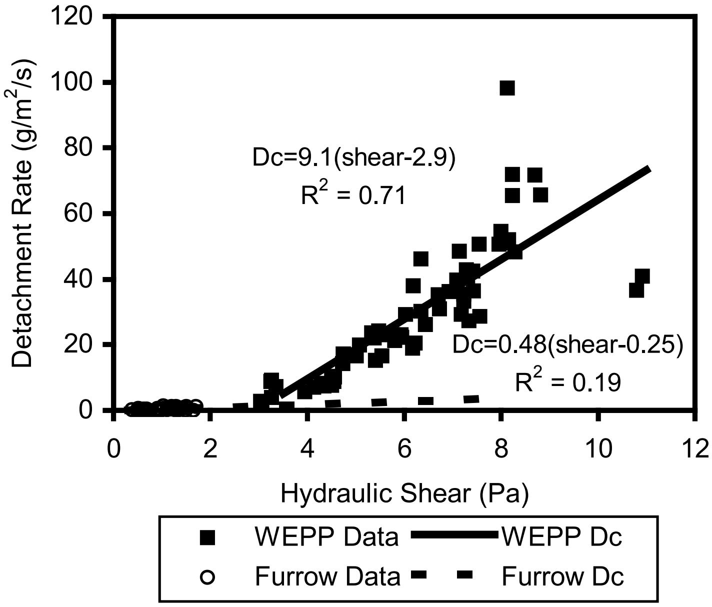

Figure 2. Comparison of sediment detachment rates from furrow irrigation and WEPP rainfall simulation.

Soil critical shear (Eq. 1) equals the x-intercept on the regression lines in Figure 2. The critical shear for the WEPP data was 2.9 Pa, indicating that sediment should not be detached when hydraulic shear in a furrow is less than 2.9 Pa. The greatest hydraulic shear calculated for the furrow irrigation was only 1.7 Pa, even though the greatest furrow flow rates would be considered excessive for fields in this area. The regression line slope (rill erodibility) for the furrow irrigation data was also less than the slope for the WEPP data, which means less sediment was detached in furrows per unit increase in hydraulic shear than during WEPP rainfall simulation.

Rill erodibility for the furrow irrigation data (0.00048 s m^{-1}) was slightly greater than the rill erodibility calibrated by WEPP simulations for two different furrow irrigated fields with Portneuf silt loam (0.0003 s m^{-1}), but much less than the WEPP default rill erodibility of 0.02 s m^{-1} (Bjorneberg et al., 1999). The calibrated critical shear of 1.2 Pa reported by Bjorneberg et al. (1999), however, was about 5 times greater than the critical shear from linear regression (0.25 Pa). The fields used by Bjorneberg et al. (1999) for calibration had been continuously cropped as compared to two years of fallow for this study. Lack of crop residue and growing plants would have resulted in less organic matter in the surface soil, possibly increasing the rill erodibility and decreasing the critical shear on this field.

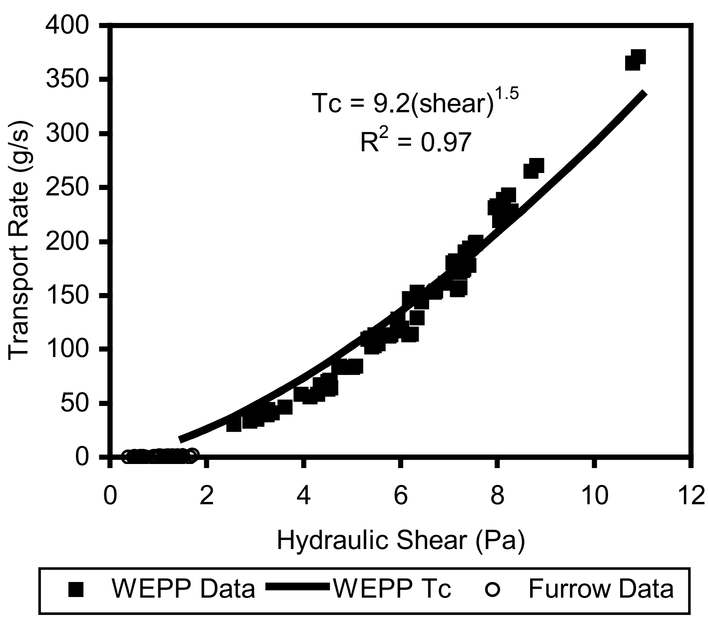

Figure 3. Sediment transport rates from furrow irrigation and WEPP rainfall simulation.

A combined linear regression of the furrow irrigation and WEPP rainfall simulation data resulted in 0.0062 s m^{-1} rill erodibility and 1.1 Pa critical shear with R^2 = 0.82 [D_c=6.2(τ-1.1) with D_c in

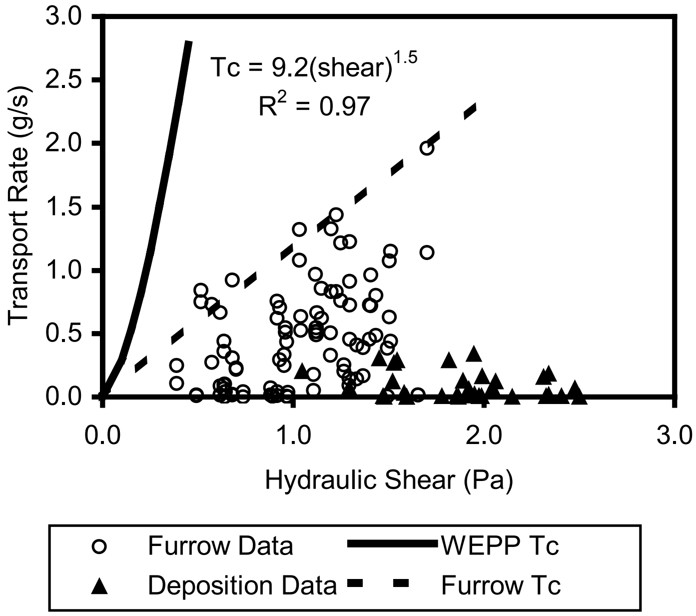

Figure 4. Sediment transport rate from furrow irrigation showing apparent upper limit (dashed line) and transport rate when deposition occurred during a separate study (▲).

g s^{-1} m^{-2}]. Using these values, detachment rate would be too low for higher shear values (i.e. >8 Pa) and zero when shear is less than 1.1 Pa, which often occurred during furrow irrigation (Fig. 1). A better visual fit occurred with the following power function:

$$D_c = 0.26(\tau)^{2.4} \qquad (4)$$

with the same coefficient of determination (R^2 = 0.82). A single power function may be more appropriate for both the high shear conditions occurring in rills during intense rainfall and the low shear conditions occurring in irrigation furrows. This would eliminate the need to define separate shear–detachment rate relationships for rainfall and furrow irrigation.

Sediment transport capacity could not be thoroughly evaluated with these data because there was no way to ensure that transport capacity was reached (i.e. measure deposition). However, sediment transport rate in irrigation furrows seemed to have an upper limit that was much lower than transport capacity based on WEPP data (Fig. 4). Transport rate may not have reached transport capacity in these short furrows or sediment detachment may have been limited by some soil characteristic, such as armoring, rather than the transport capacity of the furrow stream. Unpublished sediment transport data from other furrow irrigation erosion studies at the Northwest Irrigation and Soils Research Lab show that sediment deposition occurred when transport rates were less than an apparent transport capacity for a given hydraulic shear (Fig 4). Sediment deposition may be independent of transport capacity, but further study of this concept is needed.

Summary

Sediment detachment in irrigation furrows was measured at shear values less than the critical shear calculated from WEPP rainfall simulation data on the same soil. The detachment rate relationship used by the WEPP model may be appropriate for predicting both rainfall and furrow irrigation erosion, but separate erodibility values need to be identified for furrow irrigation. A power function between shear and detachment rate may be more appropriate than the linear relationship used by the WEPP model. Sediment detachment, deposition and transport in irrigation furrows need to be further investigated before the WEPP model can be modified or recommend for use with furrow irrigation.

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