M. Dukes ed. St Joseph Mich: ASABE
ASABE Publication Number 711P0810cd

2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Conference Presentation

Paper Number: IRR10-9629

The Current State of Predicting Furrow Irrigation Erosion

D.L. Bjorneberg, Supervisory Research Agricultural Engineer

USDA Agricultural Research Service, Kimberly, ID

T.S. Strelkoff, Research Hydraulic Engineer

USDA Agricultural Research Service, Maricopa, AZ

A.J. Clemmens, Center Director

USDA Agricultural Research Service, Maricopa, AZ

J. Lee, Research Associate

USDA Agricultural Research Service, Kimberly, ID

Written for presentation at the
5th National Decennial Irrigation Conference
Sponsored jointly by ASABE and the Irrigation Association
Phoenix Convention Center
Phoenix, Arizona
December 5 - 8, 2010

Abstract.

There continues to be a need to predict furrow irrigation erosion to estimate on- and off-site impacts of irrigation management. The objective of this paper is to review the current state of furrow erosion prediction technology considering four models: SISL, WEPP, WinSRFR and APEX. SISL is an empirical model for predicting annual soil loss from furrow irrigated fields. SISL could potentially be a useful model if a new method was developed to calculate base soil loss for areas other than southern Idaho where it was developed. The WEPP model uses physically-based equations to predict erosion in irrigation furrows, which are assumed to be the same as rills. Primary difficulties with the WEPP model are defining erodibility parameters for furrow irrigation and over-prediction of transport capacity. WinSRFR provides detailed evaluation of furrow hydraulics and sediment detachment, transport and deposition in an individual furrow during a single irrigation event using similar equations as WEPP. Initial evaluations of WinSRFR are promising and development continues to fully simulate the mix of aggregate sizes found in furrow soil and furrow flow. The APEX model uses empirical relationships to predict soil loss from small watersheds. Preliminary evaluation of the APEX model indicated reasonable correlation with measured soil loss in a 170 ha irrigated *watershed. All of these methods require further development and/or evaluation before they can be widely applied to furrow irrigated land. In selecting a predictive tool, it should be noted that an empirical equation may be as good as a physically based equation if we cannot quantify the parameters for the physically based equation.*

Keywords. Furrow Irrigation, Erosion Model, SISL, WEPP, WinSRFR, APEX.

Introduction

Water flowing in irrigation furrows can erode soil and transport sediment and associated nutrients off the field. Significant erosion reduces crop productivity in fields and degrades water quality of receiving water bodies. Crop yields in southern Idaho were decreased at least 25% on the inflow end of fields that had been eroded from 80 years of furrow irrigation (Carter et al., 1985, Carter, 1993). Annual soil loss of 1 to 141 Mg ha^{-1} were measured in southern Idaho (Berg and Carter, 1980), with greater losses occurring on row crop fields with field slopes >2%. Evans et al. (1995) also measured soil loss of 40 to 100 Mg ha^{-1} from furrow irrigated hops on a 3.5% slope. Sediment and associated nutrients in furrow irrigation runoff from fields can impair water quality and exceed standards of the receiving water body (Bjorneberg et al., 2002).

The need to predict furrow irrigation erosion has been realized for a long time (Gardner and Lauritzen, 1946; Mech and Smith, 1967). Early attempts focused on calculating a critical, or non-erosive, stream size (Hamad and Stringham, 1978). Gardner and Lauritzen (1946) concluded that “It should be apparent that there does exist an analytical approach toward the solution of the erosion problem that will prove to be valuable to farmers in the design of their irrigation systems”. Mech and Smith (1967) proposed that furrow irrigation erosion may be predicted by modifying factors in a rainfall equation to fit irrigation conditions, adapting channel stability and sediment transport concepts, or developing a new furrow irrigation erosion equation.

The quest for a furrow irrigation erosion model or prediction equations continues today. In contrast to rainfall induced flow in rills, furrow inflow water typically contains little sediment and proceeds to detach and transport sediment. Furthermore, as water infiltrates in furrows, flow decreases with distance, reducing the amount of sediment that the water can transport, resulting in sediment deposition on the lower end of the field (Trout, 1996). Simulating on-site and off-site impacts require models to consider different mechanisms. On-site impacts require simulation of detachment and deposition within the field, not just total soil loss from the field. Simulating off-site impacts should consider soil loss from multiple fields with various crops and management practices within a watershed. The objective of this paper is to review the current state of furrow erosion prediction technology.

Models for Predicting Furrow Irrigation Erosion

Surface Irrigation Soil Loss (SISL) Model

A simple empirical furrow irrigation erosion prediction tool called SISL (Surface Irrigation Soil Loss) was developed by the Idaho Natural Resources Conservation Service in the 1990’s. SISL was based on annual soil loss measurements collected from over 200 field-years in southern Idaho. The SISL equation has similar form as the universal soil loss equation, or USLE, (Wischmeier and Smith, 1978). A base soil loss is selected from a table according to crop type and field conditions. This base value is then multiplied by several factors to account for previous crop, soil erodibility, irrigation management and conservation practices (Bjorneberg et al., 2007). The SISL equation is:

$$SISL = BSL*KA*PC*CP*IP \qquad (1)$$

where, SISL is annual surface irrigation soil loss from a field (tons a^{-1} yr^{-1}, NRCS uses English units), BSL is the base soil loss rate (tons a^{-1} yr^{-1}), and KA, PC, CP and IP are dimensionless adjustment factors for soil erodibility, prior crop, conservation practice, and irrigation practice, respectively.

An evaluation of SISL using data from six production fields near Kimberly, ID, along with previously published furrow irrigation erosion data from Kimberly, ID and Prosser, WA, showed that the model predicted the relative effects of conservation practices rather well, but absolute differences between measured and predicted values were often large (Bjorneberg et al., 2007). For example, the coefficients of determination of 0.55 and 0.88 between measured and predicted soil loss indicate that the relative effects of conservation practices were predicted reasonably well for the two-year data set (Figure 1). However, measured soil loss was about 10 times greater than predicted for the 1999 data, indicating that the model did not adequately represent specific field conditions. The model also does not account for the actual amount of applied irrigation water, number of irrigations, or amount of runoff because this information is embedded within the BSL. This limits the application of this model to areas with “typical” furrow irrigation practices similar to southern Idaho. A more flexible method is needed for calculating the BSL based field length, slope, soil erodibility, and estimated runoff for this model to be applied in other regions. Furthermore, the conservation practices available in SISL do not represent the wide variety of tillage and management practices that occur in the field.

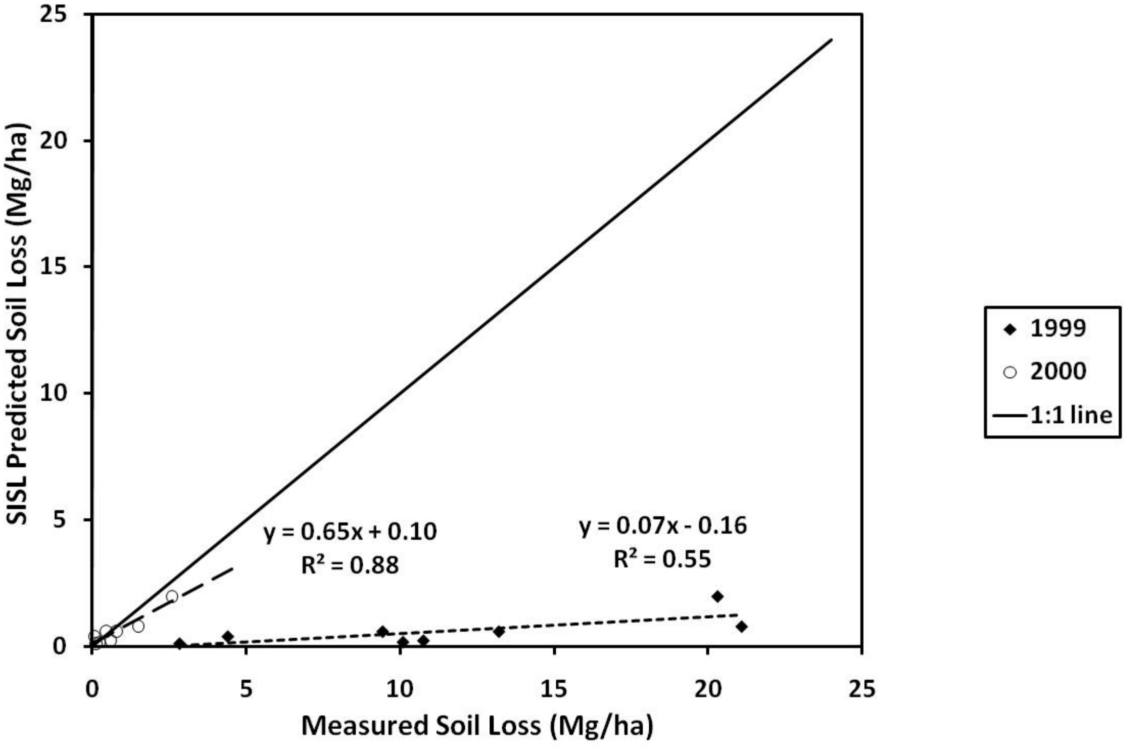


Figure 1. Relationship between measured and SISL predicted soil loss for a southern Idaho tillage study. Data taken from Bjorneberg et al. (2007).

Water Erosion Prediction Project (WEPP) Model

The Water Erosion Prediction Project (WEPP) model was first released in 1995. It represents new erosion prediction technology for simulating sediment detachment, transport and deposition. The WEPP model was the first comprehensive water erosion prediction tool to include furrow irrigation erosion by assuming that furrow erosion was the same as rill erosion. The WEPP model calculates soil detachment capacity by water flowing in furrows by

$$D_c = K_r (\tau - \tau_c) \qquad (2)$$

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 soil critical shear (Elliot and Laflen,1993). No sediment is detached until the hydraulic shear exceeds the critical shear value for the soil. Sediment detachment also does not occur if the sediment transport rate exceeds the transport capacity of the furrow flow, which is also a function of hydraulic shear.

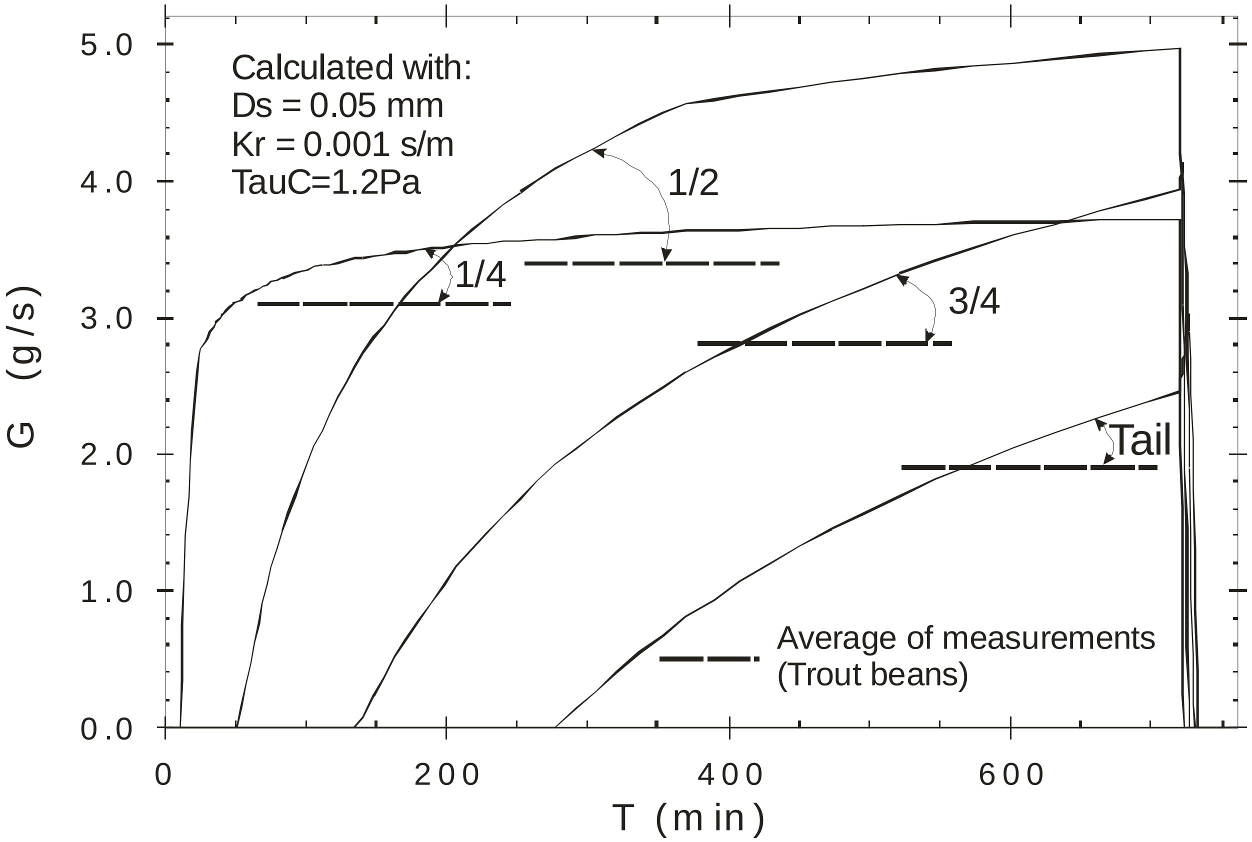
A limited evaluation of the WEPP model for furrow irrigation on a single soil type showed that erodibility parameters calibrated for furrow irrigation were much lower than the default values defined by WEPP rainfall simulations for the same silt loam soil. The model also over-predicted transport capacity and therefore did not accurately predict deposition on the lower end of furrow irrigated fields (Bjorneberg et al., 1999). For the WEPP model to be effectively used on furrow irrigated fields, furrow soil erodibility parameters need to be better defined and sediment transport capacity prediction needs to be improved. Additional studies would be beneficial to determine if similar results occur on different types of soils.

WinSRFR

SRFR is a one-dimensional model for simulating water flow in borders, basins and furrows during a single irrigation event. It allows all flow characteristics to vary with time and distance down the furrow. At every computational time step, the flow depths and velocities are calculated at a sequence of points within the surface stream. Only a single furrow is simulated so any variability among furrows must be simulated separately to estimate erosion from an entire field. SRFR has been incorporated into WinSRFR, which is integrated surface irrigation software for design, evaluation and operational analyses, as well as simulation. WinSRFR can be downloaded from the ARS Arid-Land Agricultural Research Center website.

SRFR uses many of the same fundamental erosion equations as WEPP, but they are applied to the furrow flow hydraulics calculated by SRFR for each time and distance step in the furrow. SRFR uses soil-specific erodibility (K_r) and critical shear (τ_c) parameters similar to WEPP. These parameters are measured or estimated for the given soil. The Laursen (1958) formula was chosen to predict transport capacity in SRFR because: (a) it predicts both suspended and bed load, (b) some silt-sized particles were included in its experimental database, and (c) it was developed through a classic exercise in dimensional analysis with final results confirmed empirically. Maintaining the theoretical basis of the original analysis, Strelkoff and Clemmens (2005) modified the Laursen formula to include silt sizes finer than those in Laursen's database. SRFR calculates transport capacity at each time and distance step in the furrow by applying the modified Laursen formula to predicted hydraulic variables.

The initial erosion component added to SRFR predicted the behavior of only a single soil aggregate size that represent the actual mix of sediments in the furrow bed and suspended in the flowing water (Strelkoff and Bjorneberg, 2001). Figure 2 illustrates the potential of SRFR-based erosion simulation. Calculated sediment-load hydrographs are displayed for four points in a furrow. These hydrographs are compared with average sediment transport values measured in the field by Trout (1996). The input value of erodibility for the simulation (Kr=0.001s m^{-1}) was calibrated from a comparison between measured and calculated hydrographs at the first quarter point, before transport capacity typically limits sediment detachment.



Simulation: TJTBN71.015
File: TJTBn71L.cdr

Figure 2. SRFR Simulated sediment transport hydrographs at quarter points in furrows compared to average measured transport rates from Trout (1996). Figure taken from Strelkoff and Bjorneberg (2001).

Evaluation of furrow erosion prediction with SRFR was promising, but the results were highly dependent on the choice of the single aggregate size. For example, a small increase in aggregate size can lead to the prediction of no sediment loss from the furrow. Simulating a mix of particle sizes would lead to more gradual changes in predicted sediment load (Strelkoff et al., 2002). In a cooperative study, Dr. G. Duan in the Civil Engineering department at the University of Arizona is viewing furrow erosion in a theoretical as well as a laboratory context. This effort has produced a complex mathematical model (Zhang et al., 2010), which takes into account the changes in bed configuration as a result of erosion and deposition, and also the changes in fluid properties induced by the suspended sediment. A parallel experimental study has focused on the erosion and transport in a laboratory flume. The Strelkoff and Clemmens (2005) modifications to Laursen’s transport capacity formula will be evaluated as well as soil erodibility and critical shear.

Erosion prediction within WinSRFR continues to be refined and improved to simulate detachment, transport and deposition of a mix of aggregate sizes. Further evaluation is expected within the next few years.

Erodibility Parameters

Defining erodibility parameters for furrow irrigation as input for WEPP or SRFR has been problematic for Portneuf silt loam. Default values in the WEPP model that were developed from rainfall simulations were much greater than calibrated values for furrow irrigation (Bjorneberg et al., 1999). Subsequent attempts to define rill erodibility and critical shear have not been successful. Controlled tests were conducted on 2-m long furrow segments in a recently tilled field near Kimberly, Idaho. A constant inflow rate was applied to the furrow until sediment concentrations reached steady state (about 60 min). Hydraulic shear was calculated from a furrow profile measurement after the last sediment concentration sample was collected. Data collected during these tests did not give an acceptable relationship between hydraulic shear and sediment transport rate (Figure 3) so rill erodibility and critical shear could not be calculated with equation 2. Sediment detachment or deposition at the beginning and end of these short furrow segments may have had a greater proportional effect on sediment transport than detachment by flowing water. An earlier test on fifty, 10-m long furrows had a similar poor relationship (r^2=0.19). Clearly, more research is needed to define erodibility parameters for physically-based furrow irrigation erosion prediction.

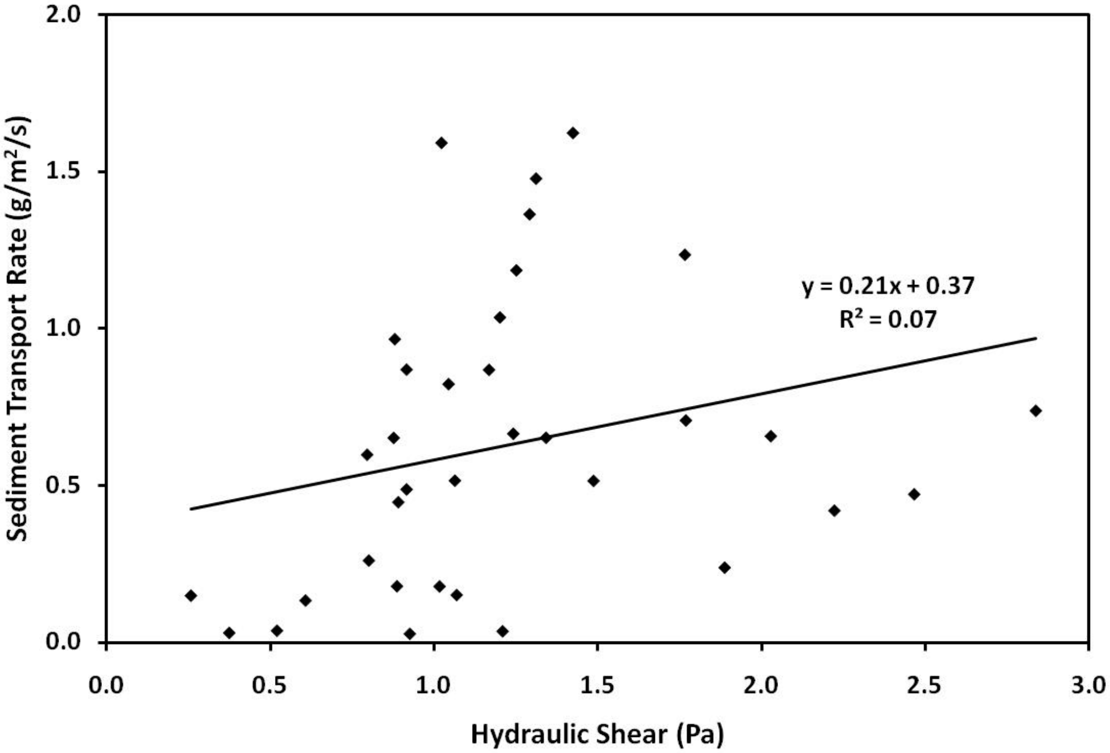


Figure 3. Relationship between hydraulic shear and final sediment transport rate for 2-m long furrow segments in southern Idaho.

Agricultural Policy/Environmental eXtender (APEX) Model

The APEX model predicts runoff, sediment, nutrient and pesticide losses from small watersheds on a daily time step. A watershed is divided into uniform subareas and a routing component simulates flow from one subarea to another. The individual field simulation component of APEX is taken from the Environmental Policy Integrated Climate (EPIC) model, which was developed in the early 1980's to assess the effect of soil erosion on crop productivity (Williams, et al., 1984).

APEX does not directly calculate runoff for irrigation events; rather the user specifies the runoff fraction. Runoff volume and peak runoff rate for irrigation events are calculated from the runoff fraction and irrigation application rate, which is manually input or automatically calculated. In other words, the user defines how much runoff will occur.

Erosion is calculated from the following equation, which has similar form as the USLE:

$$Y=X*EK*CVF*PE*SL*ROKF \tag{3}$$

where Y is the sediment yield in t ha^{-1}, X is the energy factor, EK is the soil erodibility factor, CVF is the crop management factor, PE is the erosion control practice factor, SL is the slope length and steepness factor, and ROKF is the coarse fragment factor (Williams et al., 2008). The energy factor, X, is calculated from one of six optional equations with rainfall or runoff as the energy source.

To test APEX application in an irrigated watershed, the modified USLE (MUSLE) was chosen because it uses runoff volume and peak runoff rate to calculate X as follows:

$$X=1.586*(Q*q_p)^{0.56}*WSA^{0.12} \tag{4}$$

where Q is the runoff volume in mm, q_p is the peak runoff rate in mm h^{-1}, and WSA is the watershed area in ha. Data from a furrow irrigation erosion test using three inflow rates on a fallow field at Kimberly, Idaho showed a good correlation between $Q*q_p$ and total soil loss on a log-log scale ($r^2=0.78$, n=9). Comparisons of data from six commercial fields used for SISL evaluation (Bjorneberg et al., 2007) also had correlations with $r^2>0.5$, indicating that MUSLE may be a better predictor of furrow irrigation erosion than hydraulic shear.

An evaluation of the APEX model is being conducted using data from a 170 ha irrigated watershed that was monitored as part of the Upper Snake-Rock Conservation Effects Assessment Project (Bjorneberg et al., 2008). Crop and irrigation factors were adjusted so predicted evapotranspiration matched potential ET calculated at a local Agrimet station (http://www.usbr.gov/pn/agrimet/). Each field was defined as a subarea and we assumed no deposition or erosion occurred as runoff was routed through the watershed. Runoff fractions for each crop were assigned based on field data from southern Idaho (Berg and Carter, 1980).

Data from 2008 were used to calibrate the model and data from 2006 and 2007 were used for initial validation. The simulation of 2008 data showed that annual soil loss was under predicted. As an easy calibration step, the PE factor in equation 3 was set to 1.64 so predicted annual soil loss nearly equaled measured soil loss for 2008. (PE should be <1 since it is an erosion control practice.) Using PE=1.64 resulted in annual predicted soil loss that was 2% greater, 6% greater and 1 less than measured for 2006, 2007 and 2008, respectively. Predicted monthly soil loss correlated reasonably well with measured values for the 2006 and 2007 irrigation seasons (Figure 4). These results indicate that further evaluation of the APEX model should be conducted to determine if this or similar models can be applied in irrigated watersheds.

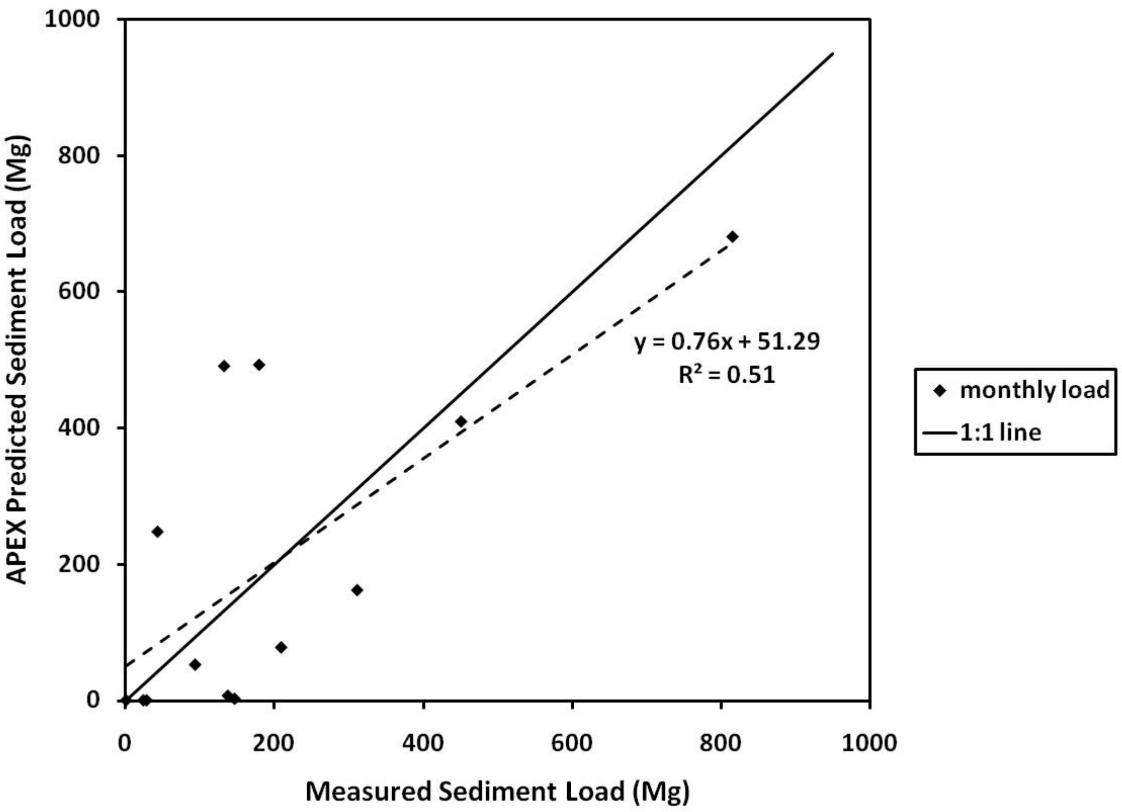


Figure 4. Correlation between measured and APEX-predicted monthly soil loss for 2006 and 2007 irrigation seasons (April through October) in a 170 ha irrigated watershed.

Conclusion

Current methods for predicting furrow irrigation erosion require more development and/or validation before they can be widely applied. WEPP and APEX models were developed primarily for rainfall erosion, and irrigation erosion was made to fit that structure. SRFR and SISL were developed specifically for surface irrigation, but do not simulate the effects of crop production or tillage management practices. The SISL model is acceptable for conditions similar to typical southern Idaho irrigation practices, but cannot account for different irrigation rates and the wide variety of tillage practices used. WEPP and WinSRFR require a technique for defining soil erodibility parameters for physically-based detachment equation. WinSRFR, however, simulates the hydraulics of furrow flow at discrete distance and time steps during an irrigation event, providing more detailed information about irrigation management effects on soil erosion. APEX uses empirical relationships to predict erosion from user defined runoff fractions of irrigation water. Preliminary model evaluation indicated reasonable correlation with measured soil loss in a 170 ha irrigated watershed and justifies continued evaluation. In selecting a predictive tool, it should be noted that an empirical equation may be as good as a physically based equation if we cannot quantify the parameters for the physically based equation.

References

Berg, R.D. and D.L. Carter. 1980. Furrow erosion and sediment losses on irrigated cropland. J. Soil Water Cons. 35(6):267-270.

Bjorneberg, D.L., D.T. Westermann, N.O. Nelson, and J.H. Kendrick. 2008. The Upper Snake-Rock CEAP watershed: Conservation practice effectiveness in an irrigated watershed. J. Soil Water Cons. 63:487-495.

Bjorneberg, D.L., C. Prestwich, and R.G. Evans. 2007. Evaluating the surface irrigation soil loss (SISL) model. Applied Eng. in Agriculture. 23:485-491.

Bjorneberg, D.L., D.T. Westermann, and J.K. Aase. 2002. Nutrient losses in surface irrigation runoff. J. Soil Water Cons. 57:524-529.

Bjorneberg, D.L., T.J. Trout, R.E. Sojka, and J.K. Aase. 1999. Evaluating WEPP-predicted infiltration, runoff and soil erosion for furrow irrigation. Trans. of the ASAE 42:1733-1741.

Carter, D.L. 1993. Furrow irrigation erosion lowers soil productivity. J. Irr. Drainage Eng. 119(6):964-974.

Carter, D.L. R.D. Berg, and B.J. Sanders. 1985. The effect of furrow irrigation erosion on crop productivity. Soil Sci. Soc. Am. J. 49(1):207-211.

Elliot, W. J. and J. M. Laflen. 1993. A process-based rill erosion model. Transactions of the ASAE 36(1):65-72.

Evans, R.G., B.N. Girgin, J.F. Chenoweth, M.W. Kroeger. 1995. Surge irrigation with residues to reduce soil erosion. Ag. Water Man. 27:283-297.

Gardner, W and C.W. Lauritzen. 1946. Erosion as a function of the size of the irrigation stream and the slope of the eroding surface. Soil Science 62:233-242.

Hamad, S.N. and G.E. Stringham. 1978. maximum nonerosive furrow irrigation stream size. J. Irr. Drainage. Div., Proceedings of the ASCE 104(IR3):275-281.

Laursen, E.M. 1958. The total sediment load of streams. J.Hydr. Div. ASCE 84:1530 1-6.

Mech, S.J. and D.D. Smith. 1967. Water erosion under irrigation. *Irrigation of Agricultural Lands* Agronomy Monograph No. 11. American Society of Agronomy, Madison, WI. p 950-963.

Strelkoff, T.S. and D.L. Bjorneberg. 2001. Hydraulic modeling of irrigation-induced furrow erosion. In D.E. Stott, R.H. Mohtar, and G.C. Steinhardt (eds.) Sustaining the Global Farm: Selected papers from the 10th International Soil Conservation Organization Meeting. Published by the International Soil Conservation Organization in cooperation with USDA-ARS and Purdue University. p. 699-705.

Strelkoff, T. S., Fernandez-Gomez, R., Mateos, L., Giraldez, J. V., and A.J. Clemmens. 2002. On tracking sediment particle sizes in furrow-irrigation induced erosion for modeling phosphorus transport. Proceedings 2002 USCID/EWRI Conference—Energy, Climate, Environment and Water, San Luis Obispo, July 10-13, 2002. p.423-433.

Strelkoff, T.S. and A.J. Clemmens. 2005. Transport capacity for eroded silts in irrigation furrows, J. Hydr. Engineering, ASCE, 131(10): 921-926

Trout, T.J. 1996. Furrow irrigation erosion and sedimentation: On-field distribution. Trans. ASAE 39:1717-1723

Williams, J.W., R.C. Izaurralde, and E.M. Steglich. 2008. Agricultural Policy/Environmental eXtender Model: Theoretical Documentation. Version 0604 BREC Report # 2008-17. pp.130. (Available at http://epicapex.brc.tamus.edu/downloads/user-manuals)

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. of the ASAE 27:129-144.

Wischmeier and Smith. 1978. Predicting rainfall-erosion losses: A guide to conservation planning. Agriculture Handbook 537. U.S. Dept. of Agriculture, Washington, DC.

Zhang, S.Y, Duan, J.D., and T. Strelkoff. 2010. Simulation of unsteady flow and soil erosion in irrigation furrows, Proceedings of ASCE EWRI 2010 Congress in Providence, Rhode Island, May 2010, 10 pp.