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Sediment Transport in Irrigation Furrows

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ABSTRACT

Sediment data were collected in southern Idaho irrigation furrows. Irrigation furrows allow detailed study of sediment transport relationships because of gradually decreasing flow rates in long, uniform, pre-formed rills. The measured trends of rapidly increasing sediment transport (load) with distance at the inflow ends of furrows (due to high erosion rates), maximum load near mid-furrow, and then decreasing load (due to net deposition) follows the expected basic processes. However, the measured high rates of sediment deposition are not predicted by transport relationships of the type used in the WEPP model. Also, the measured wide variation in sediment load over time on a field cannot be explained by sediment transport capacity concepts. An alternative sediment transport theory, not based on transport capacity, fit the furrow transport data better with fewer parameters and more consistent coefficients.

INTRODUCTION

Irrigation furrows present an excellent opportunity to study sediment transport processes in small channels (rills) in field soils. Furrows are relatively straight and prismatic and furrow inflows are constant with time. As water infiltrates, flow rates decrease fairly linearly with distance along a furrow. At some point along the furrow, the capacity of the flow to transport the accumulated sediment decreases and net deposition occurs. Consequently, the relationship between flow rate (or shear) and sediment load can be determined. Irrigation furrow sediment load field data were used to evaluate the concept of sediment transport capacity. The primary goal was to evaluate the form of the relationships, rather than specific transport capacity equations.

It is generally assumed that furrow erosion processes are similar to rill erosion processes that occur under rainfall. There are similarities in the processes, but there are also differences in the conditions (Trout and Neibling, 1993). Most rainfall erosion occurs during a few highly erosive events, while furrow erosion occurs at low-to-moderate rates during several irrigations with controlled water application. Rill inflows carry sediment from interrill areas and water flows over prewetted soil. Rill flows increase in the downstream direction. Furrows are irrigated from the upslope end with fairly clean water and advancing flows rapidly wet dry soils. Flow rates decrease in the downstream direction as water infiltrates. Most irrigation furrows are on slopes of less than 3%, while most rill erosion research is carried out on slopes greater than 3%. However, in spite of the controlled inflows and relatively low slopes, in some areas with highly erodible soils, there is significant furrow irrigation-caused erosion damage (Koluvec et al. 1993).

Sediment Transport Processes

Most models of sediment transport assume that a flow has a capacity to carry sediment at a steady-state rate, termed the transport capacity, in which particle settling and deposition on the bed and detachment and entrainment from the bed are in equilibrium, resulting in no net change in load. The transport capacity is a function of the hydraulics of the flow - commonly represented by shear or shear velocity, and the characteristics of the sediment - primarily particle sizes and densities. Most of the transport theory was developed to predict erosion and sedimentation in large streams with coarse, non-cohesive bed materials.

Scientists trying to model rill and interrill erosion and deposition on agricultural fields have adopted similar methodologies based on a transport capacity (Foster, 1982; Alonso et al. 1991), even though flow and soil conditions are quite different. For example, in the process-based Water Erosion Prediction Project (WEPP) model (Nearing et al. 1989), transport capacity is calculated by an adaptation of the Yalin equation (Finkner et al., 1989) and this capacity establishes the limit for load. Net soil particle detachment and entrainment in the flow, and thus erosion, is reduced as the sediment load approaches the transport capacity:

$$D_f = D_c(1 - G/T_c), \quad (\text{for } G < T_c) \qquad (1)$$

where D_f is the net soil detachment/entrainment or deposition (kg m^{-2} s^{-1}), D_c is the detachment capacity of the flow (kg m^{-2} s^{-1}), G is the sediment load (kg m^{-1} s^{-1}), and T_c is the sediment transport capacity (kg m^{-1} s^{-1}).

Where sediment load exceeds the transport capacity, deposition occurs at a rate determined by the excess load above transport capacity and the fall velocity of the sediments:

$$D_f = (V_f/q)(T_c - G), \quad (\text{for } G > T_c) \qquad (2)$$

where V_f is the effective fall velocity for the sediments (m s^{-1}), and q is the flow discharge per unit width (m^2 s^{-1}).

These equations predict that sediment load in a flow over erodible soil will increase (assuming shear exceeds the critical shear for the soil) at a decreasing rate and asymptotically approach the transport capacity. If shear decreases, due to a slope or flow rate decrease, such that T_c is less than G, deposition will occur.

In irrigation furrows, these relationships result in the trends depicted in Figure 1. Particle detachment and entrainment (erosion) rate begins high due to high flow rates

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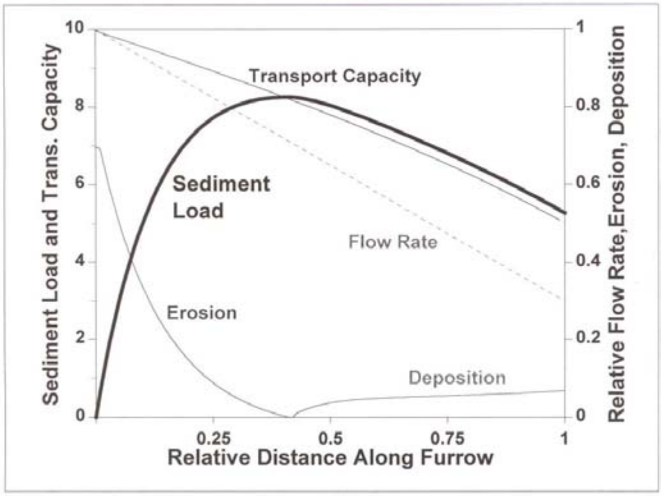

Figure 1. Relative variation in erosion, deposition, transport capacity, and sediment load along an irrigation furrow with uniform slope and decreasing flow rate with distance.

(and shear) and low sediment loads, decreases as the sediment load increases, and net erosion stops when either shear decreases below critical shear or load equals transport capacity. Furrow transport capacity continuously decreases, because of decreasing flow rate, forcing sediment to deposit. Load exceeds transport capacity slightly because of the lag created by particle fall velocity.

Data Collection

Sediment transport rates were measured on two fields (beans, 0.013 m/m slope, 204 m length; corn, 0.0052 slope, 254 m length) located near Kimberly, Idaho (Portneuf silt loam soils - coarse-silty, mixed, mesic Durixerollic Calciorthids). Data were collected from each field during 5 or 6 irrigations. Three constant inflow rates (medium, low (80% of medium) and high (120% of medium)) were applied to each of four replicate furrows. Flow rates at the end of each quarter of the furrow length were measured with trapezoidal, long-throated flumes. One-liter water samples were collected at each flume periodically for sediment concentration analysis. Trout (1996) gives details of the methodology and results of the field tests.

Furrow Erosion and Sediment Transport Model

A simple, steady state soil erosion and deposition model was developed based on the erosion and sediment transport relationships used in the WEPP model. The spreadsheet model divides a furrow into 100 equal length increments, and estimates wetted perimeter and flow cross-sectional area for each segment, based on a furrow geometry model (Trout, 1991) with geometric parameters determined from the furrow shape measurements, and flow rate interpolated from measured inflow and outflow rates. Detachment capacity is calculated from

$$D_c = K_r(\tau_f - \tau_c)\ b \qquad (3)$$

where K_r is the rill soil erodibility coefficient (kg^{1-b} m$^{-(2-b)}$ s$^{-(1-2b)}$), τ_f is the flow shear stress (tractive force) acting on the soil (Pa), τ_c is the critical shear stress for the soil (Pa), and b is the empirical exponent (set equal to 1 in WEPP).

Transport capacity was calculated from:

$$T_c = k_t\ \tau_f^{\,d} \qquad (4)$$

where k_t is the an empirical transport coefficient (calculated from the Yalin Eq in WEPP), d is the an empirical transport exponent (1.5 in WEPP).

In the model, net erosion or deposition is calculated from Eqs. 1 or 2, based on load, G, in the previous increment, and load is cumulative erosion and deposition in the upstream sections. Coefficients for Eqs. 3 and 4 were selected by trial and error such that the model best fit the measured load data.

RESULTS

The measured sediment load for both fields, all irrigations, and all three flow rate treatments increased in the first quarter of the field, reached a maximum in or near the second quarter, and decreased in the third and fourth quarters (Fig 2). The trends show that erosion was concentrated primarily in the first quarter and deposition occurred in the third and fourth quarters. Fifty to 75% of the soil eroded in the first quarter deposited in the third and fourth quarters. These general erosion, sediment load and deposition trends agree with the theory described above.

Transport Capacity and Shear

Where sediment load is decreasing, the load should be equal to the transport capacity plus an amount that results from sediment deposition lag, given by (2). Figure 2 shows that the erosion rate was high enough in all cases that the transport capacity was reached in or near the second quarter, and load decreased in the downstream half of the furrow as the flow rate decreased.

Assuming the deposition lag is small, the data from the ends of the second, third and fourth quarters can be used to analyze the relationship between sediment transport capacity and flow rate or shear. Figure 3 shows the relationship between measured sediment load and flow rate. The exponent of the relationships (2 and 3) are at the high end of the range presented by Kemper et al. (1985) for furrow data. Using a derivation from Trout (1991) that shear in furrows is approximately proportional to flow rate to the 3/8 power, results in sediment load being proportional to shear to the fifth and eighth power for the two fields, respectively. This is a much more sensitive relationship than that proposed by Finkner et al. (1989) and used in WEPP (shear to the 1.5 power). The low exponent used in WEPP would result in greatly underestimated on-field deposition. This could not be verified using the WEPP model because that model predicts no on-field deposition for the experimental conditions (Bjorneberg et al. 1999).

The analysis thus far has ignored the effects of sediment deposition lag. The iterative spreadsheet furrow erosion model includes deposition lag and accounts for its effects. Shear in the model was partitioned as described in Trout and Bjorneberg (2002). Transport parameter values, k_t and d, (Eq. 4), and the erodibility coefficient, K_r, were selected by trial and error so the model fit (visually) the measured data at the mid-furrow, three-quarters, and outflow end locations. Since in no case did data indicate that erosion was limited by critical shear, critical shear was arbitrarily set at the lowest

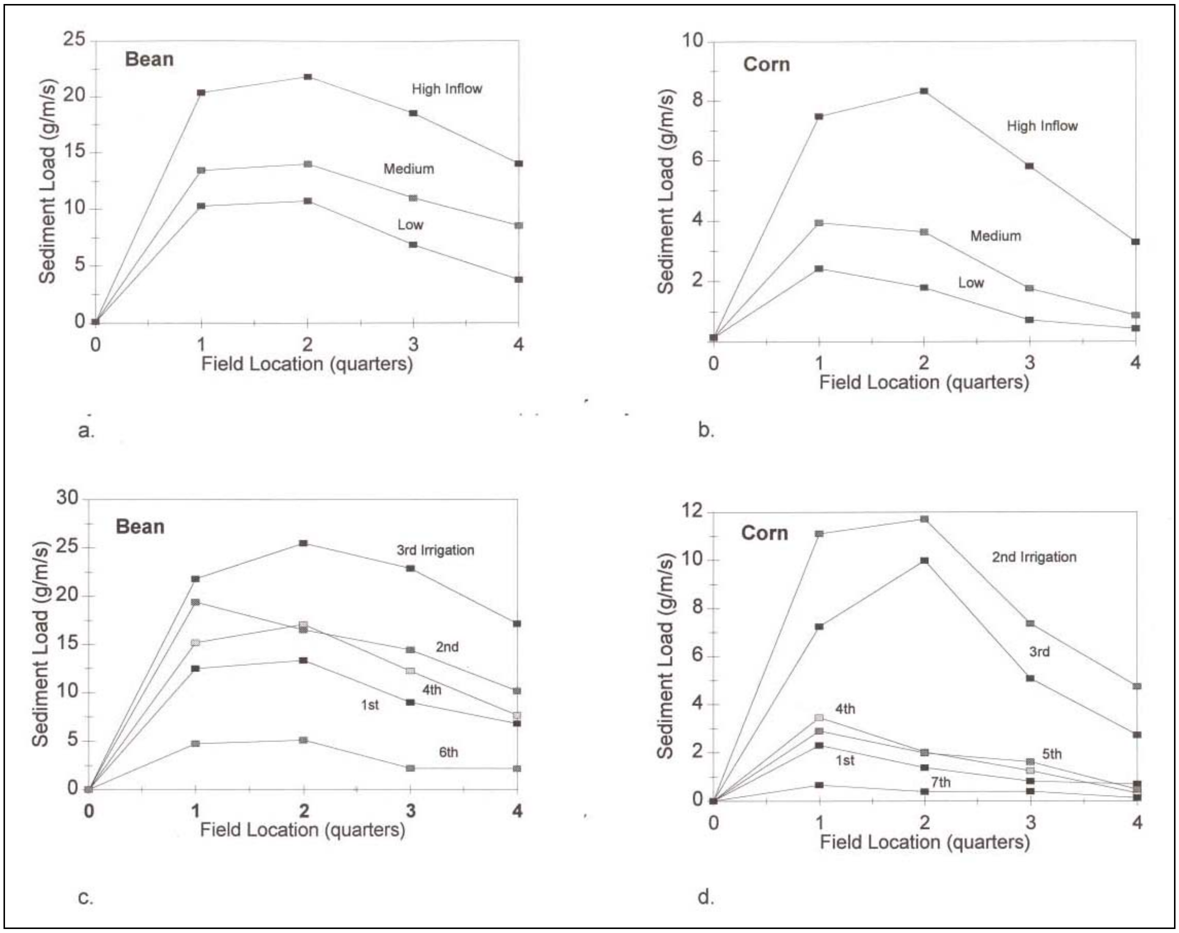

Figure 2. Measured sediment load along the furrows, (grams sediment per meter wetted perimeter per second). (average for 4 replications and all irrigations (a and b) or treatments (c and d)). a) Bean, by Inflow Rate treatment b) Corn, by Inflow Rate treatment c) Bean, by Irrigation number d) Corn, by Irrigation number

Table 1. Sediment Transport Coefficients derived by trial and error visual fit of the iterative furrow erosion model to the data. (d = sediment transport exponent).

	Bean (d = 2)					Corn (d = 4)				
Irrig No.	**---------------Inflow----------------**				**Error†**	**---------------Inflow-------------**				**Error†**
	Low	Med.	High	Combined		Low	Med.	High	Combined	
1	35	30	23	30	0.26	25	10	12	15	0.08
2	24	18	16	19	0.25	70	90	100	90	0.25
3	55	60	48	60	0.38	350	130	120	150	0.25
4	70	70	55	65	0.26	250	100	60	100	0.09
6	15	19	17	17	0.07	200	110	55	100	0.13
7						400	50	13	50	0.03

† Avg. Sediment Load Error (g/furrow/s) = Avg[ABS(predicted - measured)] for 3 locations x 3 flow rate treatments.

measured value at which erosion occurred (0.35 Pa). Average sediment particle fall velocity was set at 0.00009 m/s.

Figure 4 shows two typical examples of model-predicted sediment load and measured load, along with the model parameters used and the measured flow rates. Shear partitioning substantially increased the variation in effective shear with flow rate resulting in the fitted transport exponent decreasing substantially. Including deposition lag caused the exponent to increase slightly (ie: ignoring deposition lag results in a small underestimation of the exponent value). Table 1 lists the fitted transport coefficients for all irrigations and flow rates. Acceptable fits could be achieved in most cases with d values of 2 for the bean field and 4 for the cornfield (as compared to the WEPP value of 1.5). The reason for the different exponent values on the two fields is unknown and unexpected. These parameter values are very sensitive to the way the shear is partitioned. Note that shear is not partitioned in WEPP rills.

Transport Coefficient

A disturbing aspect of the sediment load:shear relationships for the measured data is that the transport coefficient values varied widely from irrigation to irrigation. The sediment load variation is evident in Figs. 2(c) and 2(d). On the bean field, with d held constant at 2 and all flow rate treatments combined, k_t varied between 17 in the final irrigation and 65 in the fourth irrigation. The corn field k_t values varied from 15 to 150. The coefficient tended to be high mid-season and low early and late in the season. The coefficients were similar for each of the three flow rate treatments within any irrigation. Figure 3 also shows the large k_t value variations from irrigation to irrigation with about the same flow rate (and presumably, shear) values. By the presented relationships (Eq. 1 - 4) sediment load in the downstream sections of the furrows where deposition is occurring, should only depend upon transport capacity and particle fall velocity. The transport coefficient, which is primarily dependent on soil sediment sizes and densities, should not vary greatly through the season. In WEPP, the soil-dependent aspects of k_r are a function only of the soil texture and do not vary with time.

Sediment load also varied with time during each irrigation. Sediment concentration in the flows on the lower half of the field peaks early in the runoff at a location and decreases with time (Fig 5). This variation is not related to flow rate. Flow rate approached a steady-state value within 100 minutes after the flow reached a location. This trend has been noted previously (Kabir and King, 1981, Brown et al., 1988, Trout and Neibling, 1993), but has been attributed to a decrease in effective erodibility of the perimeter soil with time as initially loose particles are flushed out and a stable perimeter seal forms. If only erodibility varied with time, the distance to reach transport capacity would vary, but load would eventually approach the same limiting transport capacity. However, these data indicate that the transport capacity also varies with time during an irrigation such that, as the erodibility changes, the furrow length to reach transport capacity remains fairly constant.

Alternative Sediment Load Relationship

The general sediment transport theory, based on transport capacity, cannot explain the large variation in sediment load in the lower half of the furrows from irrigation to irrigation and with time during an irrigation. The data suggest that sediment load, even where net deposition is occurring and transport capacity should be controlling load, is still related to soil erodibility.

An erosion/transport theory that better fits these data is one in which 1) there is no limiting transport capacity, 2) sediment detachment and entrainment is not diminished by the load, and 3) deposition rate is a function of sediment concentration in the flow rather than concentration above some transport capacity. Net erosion or deposition rate becomes simply the difference between detachment capacity and deposition rate and both processes occur simultaneously and independently. By this theory, net soil erosion, D_f, would equal

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

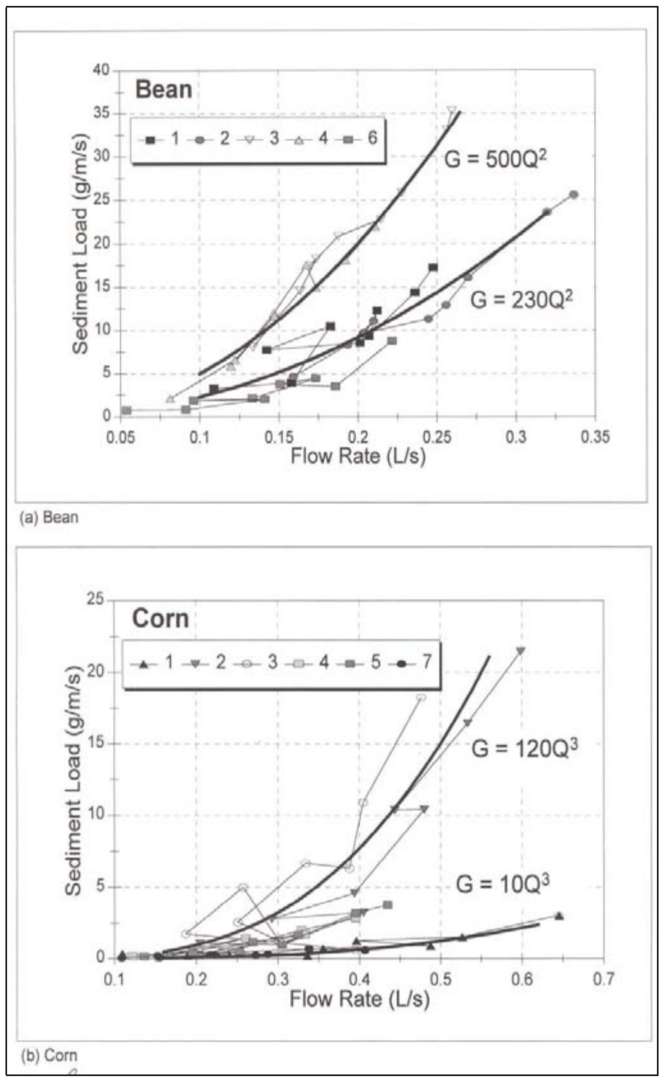

Figure 3. Average sediment load, G, vs. flow rate, Q. Data for each irrigation (3 inflow rates x 3 locations) are connected. Curves are visually-fit power functions. a) Bean, b) Corn

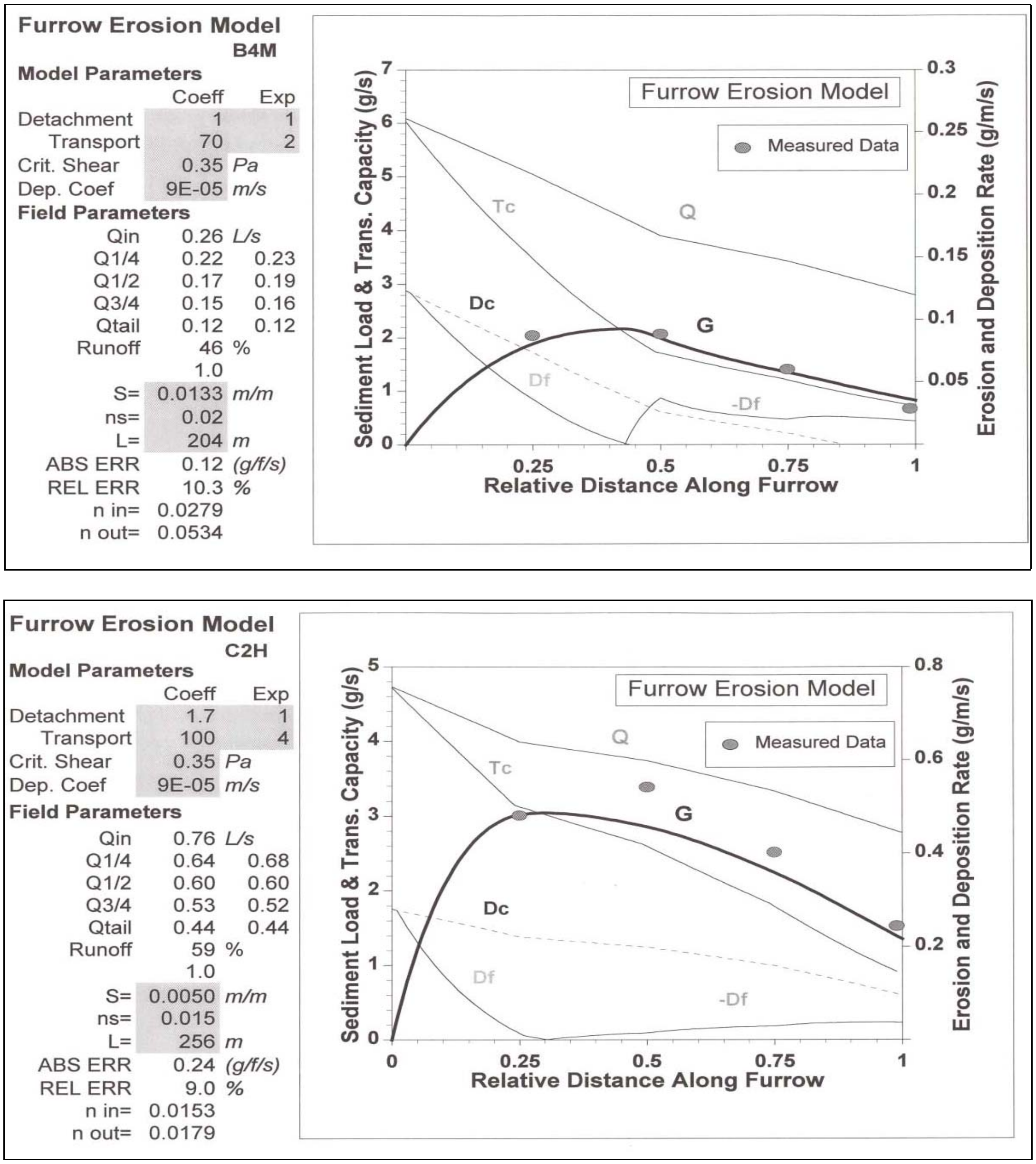

Figure 4. Furrow Erosion Model-predicted detachment capacity, D_c, erosion rate , D_f, deposition rate, -D_f, transport capacity (T_c), and sediment load, G, for two sample cases. Q is the interpolated flow rate between measurement points (L/s - right axis), and the filled circles are the measured load data. Measurements are on a per-furrow basis. Model parameters are shown on the left. a) Bean, 4th irrigation, Medium inflow rate; b) Corn, 2nd irrigation, High inflow rate.

Table 2 shows visual best fit parameters developed from the iterative erosion model using this proposed relationship. This model was able to match the field measured load better than with the transport capacity relationships with only one parameter, the soil erodibility coefficient, K_r, varying between irrigations. With these relationships, K_r determines the rate of erosion and peak load, and fall velocity, V_f, determines the deposition rate. The V_f values that gave the best fit were 0.00005 m s^{-1} for the bean and 0.00007 m s^{-1} for the corn. This variation in V_f values between the two fields, which have very similar soils, is not expected. Note also that, in this analysis, the critical shear value was reduced to 0. This was necessary to predict net deposition at the tail end of the furrows where shear was low. Very low or 0 critical shear in irrigation furrows in cohesive but unstable soils has been proposed by Kemper et al. (1985).

As variations in soil erodibility can account for variation in sediment load from irrigation to irrigation with this alternative model, a time variant K_r could also account for changes in load during an irrigation. Wide variation with time in soil erodibility, which depends on soil aggregate stability and cohesiveness, is much easier to rationalize than wide variation in sediment transportability.

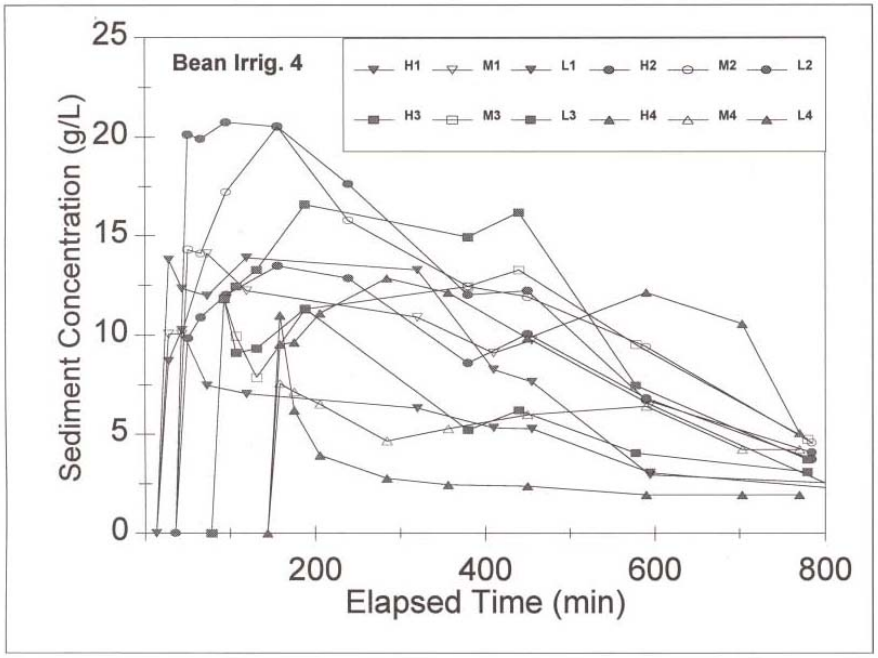

Figure 5. Variation in sediment concentration with elapsed time during bean irrigation no. 4. [Label letter represents inflow rate (L = low, etc.); label number represents field location (1 = first quarter, etc.)] (from Trout, 1996).

Table 2. Visually fitted parameters for the proposed furrow erosion relationships.

Irrig No.	Bean (all flow rates) (V_f = 0.00005 m/s, τ_c = 0, and b = 1)		Corn (all flow rates) (V_f = 0.00007 m/s, τ_c = 0, and b = 2)	
	K_r	Error[†]	K_r	Error[†]
1	0.45	0.15	0.09	0.08
2	0.4	0.29	0.7	0.36
3	0.9	0.25	0.7	0.19
4	0.8	0.24	0.4	0.05
5	0.2	0.06	0.35	0.04
7			0.08	0.02

[†] Avg. Sediment Load Error (g/furrow/s) = Avg.[ABS(predicted - measured)] for 3 locations x 3 flow rate trmts.

Recirculating infiltrometer studies (Trout et al., 1995, Trout, 1990) support the concept that deposition in furrows is not limited by transport capacity. In these studies, all water and sediment was continuously recycled through 6 m long furrow sections. According to the transport capacity concept, sediment concentration in the recirculating water (constant flow rate) should increase to the transport capacity and remain at that level for the duration of the experiment. In fact, the sediment concentration in the recirculating water increased rapidly (less than 15 min) and remained high for a while (1 to 6 hours), and then tended to decrease gradually with time, even though no sediment was removed from the system. Late in the runs (after 4 to 10 hrs of irrigation) essentially all of the sediment had deposited on the bed and the recirculating water was nearly clear. I attribute the clearing of the water to the combination of 1) reduced erodibility of the furrow perimeter soils due to the formation of a surface seal stabilized by soil water suction, and 2) the gradual deposition of transported sediment as particles move toward the bed by gravity and with infiltrating water and as they enter low velocity eddies caused by form roughness (aggregates on the furrow bed and non-uniformities in the furrow shape) that allow them to settle out.

Is this variance from the commonly held concept of transport capacity unique to furrow irrigation? Because deposition in furrows occurs under more gradual conditions than often occurs in rills, load may be controlled by different factors. Furrow conditions also allow the transport process to be studied in a new way. Rill transport is not normally studied under conditions in which gradual spacial changes in flow rate results in deposition. Although river sediment transport processes, where the concept of transport capacity is commonly used, do involve gradual spatially-varying processes, they generally involve non-cohesive bed sediments for which erodibility would not change with time.

CONCLUSIONS

Irrigation furrows present an excellent laboratory to study sediment transport relationships of cohesive soils. Variations in measured sediment loads in furrows over space and time are not explained by commonly used sediment transport theory based on transport capacity. Transport equations used in the WEPP model greatly underpredict sediment deposition in irrigation furrows. A simple transport relationship that decouples sediment detachment/entrainment from load fits the collected data fairly well.

REFERENCES

Alonso, C.V., W.H. Neibling and G.R. Foster. 1981. Estimating sediment transport capacity in watershed modeling. Trans. ASAE, 24(5):1211-1220.

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. ASAE 42(6):1733-1741.

Brown, M.J., W.D. Kemper, T.J. Trout and A.S. Humpherys. 1988. Sediment, erosion and water intake in furrows. Irrig. Sci. 9:45-55.

Flanagan, D.C. 1993. Evaluation of the WEPP deposition component. Paper #93-2107 presented at the 1993 summer ASAE meeting. 15pp.

Finkner, S.C., M.A. Nearing, G.R. Foster and J.E. Gilley. 1989. A simplified equation for modeling sediment transport capacity. Trans. ASAE 32(5):1545-1550.

Foster, G.R. 1982. Modeling the erosion process. pp. 297-308 In Haan, C.T., H.P. Johnson and D.L. Brakensiek, eds. Hydrologic modeling of small watersheds. ASAE Monograph No. 5. ASAE, St. Joseph, MI.

Kabir, J. and L.G. King. 1981. A numerical model of furrow irrigation sediment transport. ASAE Paper #81-2529 presented at the ASAE Winter meeting. ASAE. St. Joseph, MI

Kemper, W.D., T.J. Trout, M.J. Brown and R.C. Rosenau. 1985. Furrow erosion and water and soil management. Trans. ASAE 28(5):1564-1572.

Koluvec, P.K., K.K. Tanji and T.J. Trout. 1993. Overview of soil erosion from irrigation. J. Irrig. Drainage Engr. ASCE 119(6):929-946.

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. Trans. ASAE 32(5):1587-1593.

Trout, T.J. 1990. Surface seal influence on surge flow furrow infiltration. Trans of the ASAE. 33(5):1583-1589.

Trout, T.J. 1991. Furrow geometric parameters. J. Irrig. Drainage Engr. ASCE 117(5):613-634 with errata in 118(1):199-200.

Trout, T.J. 1996. Furrow erosion and sedimentation: on field distribution. Trans ASAE. 39(5):1717-1723.

Trout, T.J. and D.L. Bjorneberg. 2002. Sediment Transport in Irrigation Furrows. SSSAJ (in process).

Trout, T.J. and W.H. Neibling. 1993. Erosion and Sedimentation Processes on irrigated fields. J. Irrig. Drainage Engr. ASCE 119(6):947-963.

Trout, T.J., R.E. Sojka and R.D. Lentz. 1995. Polyacrylamide effect on furrow erosion and infiltration. Trans. ASAE. 38(3):761-765.