FURROW IRRIGATION EROSION AND SEDIMENTATION: ON-FIELD DISTRIBUTION

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ABSTRACT. *Erosion created by furrow irrigation is a serious problem in some states and has resulted in reduced crop yields. Most furrow erosion assessments have been based on measured sediment discharge from the field, which results in an average erosion rate for the whole field. However, erosion theory predicts that the erosion rate should decrease with distance from the head (inflow) end of the furrow. The purpose of this study was to quantify soil erosion and deposition distribution within furrow irrigated fields. Within-field sediment discharge measurements on two silt loam fields in southern Idaho showed that over half of the soil that eroded from the head end of the furrows deposited on the lower portions of the field as furrow flow rates decreased. Erosion rates on the upper quarter of uniformly-sloped furrows were 6-20 times greater than average rates from the field. The measurements demonstrate the need to measure erosion rates on the head ends as well as for the whole field, and explain visible erosion damage from head ends where field average erosion rates are not high.* ***Keywords.*** *Irrigation, Furrow, Erosion.*

Of the 15 million hectares of irrigated land in the U.S., 21% are affected by soil erosion (Koluvec et al., 1993). High rates of furrow irrigation-induced erosion have been measured in Washington, Idaho, Wyoming, and Utah (Koluvec et al., 1993). On many of the fields, the field average erosion rates were near or above the allowable erosion rate for sustainable production (the soil "T" value). Eighty years of excessive furrow-induced erosion in southern Idaho has resulted in a 25% decrease in crop yield potential (Carter, 1993).

Furrow erosion assessments have usually been based on measured sediment discharge from the outflow ends of furrows or fields. These discharge measurements are used to calculate the average soil loss per unit field area (Mg/ha). However, erosion rates on a field vary widely. Erosion and sediment transport capacity increase with the shear or velocity of the flow, which in turn increase with the flow rate and furrow slope (Trout and Neibling, 1993).

In irrigation furrows, the flow rate decreases along the furrow as water is infiltrated. Typically, 50 to 80% of the furrow inflow infiltrates before it reaches the furrow end, resulting in a corresponding flow rate decrease along the furrows. Thus, for uniformly sloped furrows, both erosion rates and sediment transport capacity should decrease along the furrows as flow rates decrease. Figure 1 depicts a theoretical distribution of soil erosion and deposition along an irrigation furrow. For the depicted conditions (erodible soil, uniform slope, 30% runoff), much of the erosion occurs on the upper one-third of the furrow length, and much of the eroded soil is deposited along the lower one-half.

In south-central Idaho, the long-term effects of differential erosion are visually evident. When the 300 to 450 mm of Portneuf topsoil is eroded away, a lighter-colored, high calcium subsoil is exposed. About 75% of furrow-irrigated fields show exposed subsoils in the head-end portions, often covering about one-third of the field area (Carter et al., 1985) (fig. 2). Crop yields from these eroded sections were decreased 20 to 50%, depending on the crop (Carter et al., 1985).

Although differential erosion on furrow irrigated fields is expected and the results are evident, it is not well-documented. Mech (1949) measured sediment loss from

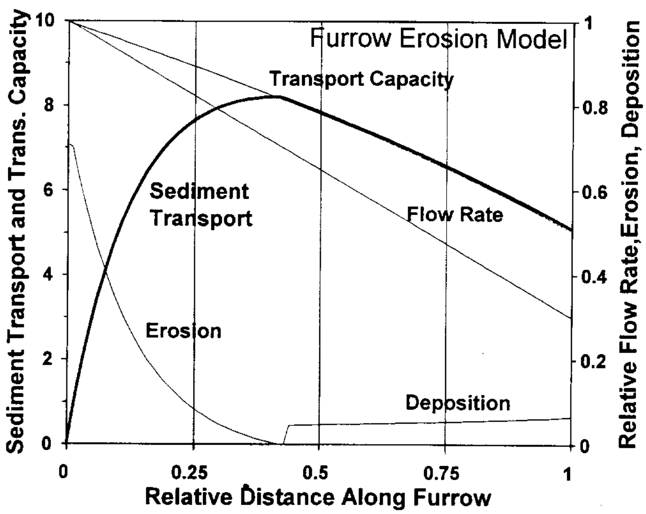

Figure 1–Theoretical variation of erosion, deposition, and sediment transport along an irrigation furrow. Erosion is high at the head end and decreases with distance as flow rate decreases and sediment transport increases. Transport capacity decreases with flow rate and when the increasing transport reaches the decreasing capacity, deposition occurs.

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Figure 2–Aerial photo of an irrigated field in south central Idaho with an eroded (light soil color) upper end. (Photo Credit: David Carter)

the upper one-third of a 275 m long field nearly 100 times higher than the loss from the tail end of the field. These results overstate the norm because less than 10% of the inflow reached the tail end of the field. Brown (1985) and Kemper et al. (1985) measured differential erosion and deposition on furrow-irrigated fields, but variations in slope along the furrows prevented clear interpretation of the results. The objective of this research was to measure the distribution of soil erosion and deposition along subsections of uniformly sloped furrows. The collected data were also compared with sediment transport models in another article (Trout, 1997).

METHODS

Sediment transport was measured at five points along irrigation furrows on two fields during the summer of 1994. Both fields were located on the USDA-ARS South Research Farm near Kimberly, ID, and contained Portneuf silt loam soils (coarse-silty, mixed, mesic Durixerollic Calciorthids). Slopes were uniform in the furrow direction. Field and cropping information are given in table 1.

A plot of 12 adjacent wheel-compacted furrows on each field was split into four, 3-furrow blocks. A "medium" furrow inflow rate was selected before each irrigation, with the rate expected to irrigate the furrows with a moderate advance time (2 h) and moderate runoff (35%). "High" and "low" flow rates, 20% above and below the medium rate, were applied to the other two furrows in each block. The three inflow rates were applied in random order to the first block and the order repeated in the remaining three blocks. The order was changed each irrigation.

Irrigation water from the Twin Falls Canal Company (EC = 0.5 dS/m, SAR = 0.4 – 0.7) was applied to the bean field from gated pipe with Aqua Control spigots, and to the corn field from a concrete ditch with siphon tubes. Inflow rates were kept constant by maintaining a constant head in the gated pipe and concrete ditch with an overflow weir at the end of the pipe and ditch. Furrow inflows were set and measured periodically with a 3.78 L (1 gal) bucket and stopwatch.

The furrows were divided into four equal-length sections (1/4, 2/4, 3/4, and tail section), and measurement stations were established at the downstream end of each section. Flows were measured with small fiberglass trapezoidal long-throated flumes (Powlus 60° V-notch furrow flumes). Sediment concentration samples were collected with small troughs pressed against the tail end of the flumes, and were poured into 1 L Imhoff cones. Sediment volume in the cones was read after 30 min of settling (Sojka et al., 1992). During each irrigation, eight sediment samples from the cones were collected and analyzed gravimetrically for sediment content. The gravimetric measurements were linearly regressed with the cone readings to determine cone calibration. The calibration, which did not vary with field, treatment, or time, was:

$$\text{Sediment Concentration (g/L)} = 0.83 \times \text{Cone sediment volume (mL)} \quad (1)$$

Flow rates and sediment concentrations were measured 15 min, 30 min, 1 h, 2 h, and approximately 4 h, 6 h, and 8 h after water arrived at each measuring station, and at the end of each 12 h irrigation. Inflow sediment concentration was never greater than 0.2 g/L. Sediment transport rate was calculated as the product of flow rate and sediment concentration, and the transport rate was multiplied times the intervening sampling time intervals to determine the sediment mass passing each measurement point. Erosion and deposition for each furrow section was calculated as the difference between sediment inflow and outflow from the section divided by the irrigated area (furrow section length × spacing).

RESULTS

Sediment transport trends along the furrows were consistent for all flow rates and irrigations on both fields (fig. 3). Transport amount increased along the first quarter of the field, remained fairly constant in the second quarter, and then decreased in the third and fourth quarters. These data show that nearly all the erosion was from the upper end of the furrows. Somewhere in or near the second quarter the maximum sediment transport was reached, beyond which net

Table 1. Field conditions, layout, and schedules

Crop	Length (m)	Slope (m/m)	Furrow Spacing (m)	Previous Crop	Field Preparation	Planting Date	Cultivation Dates	Irrigation Dates (**Bold** = measured)
Dry Beans	204	0.0133	1.12	Potato	Moldboard plow, roller harrow	6/2	7/5	**6/8, 7/1, 7/14, 7/25,** 8/3, **8/10**
Field Corn	256	0.0052	1.52 (0.76 × 2)	Peas	Fall disk, roller harrow	5/25	6/16 7/11	**6/2, 6/23, 6/30, 7/15, 7/27,** 8/7, **8/17,** 8/27, 9/7

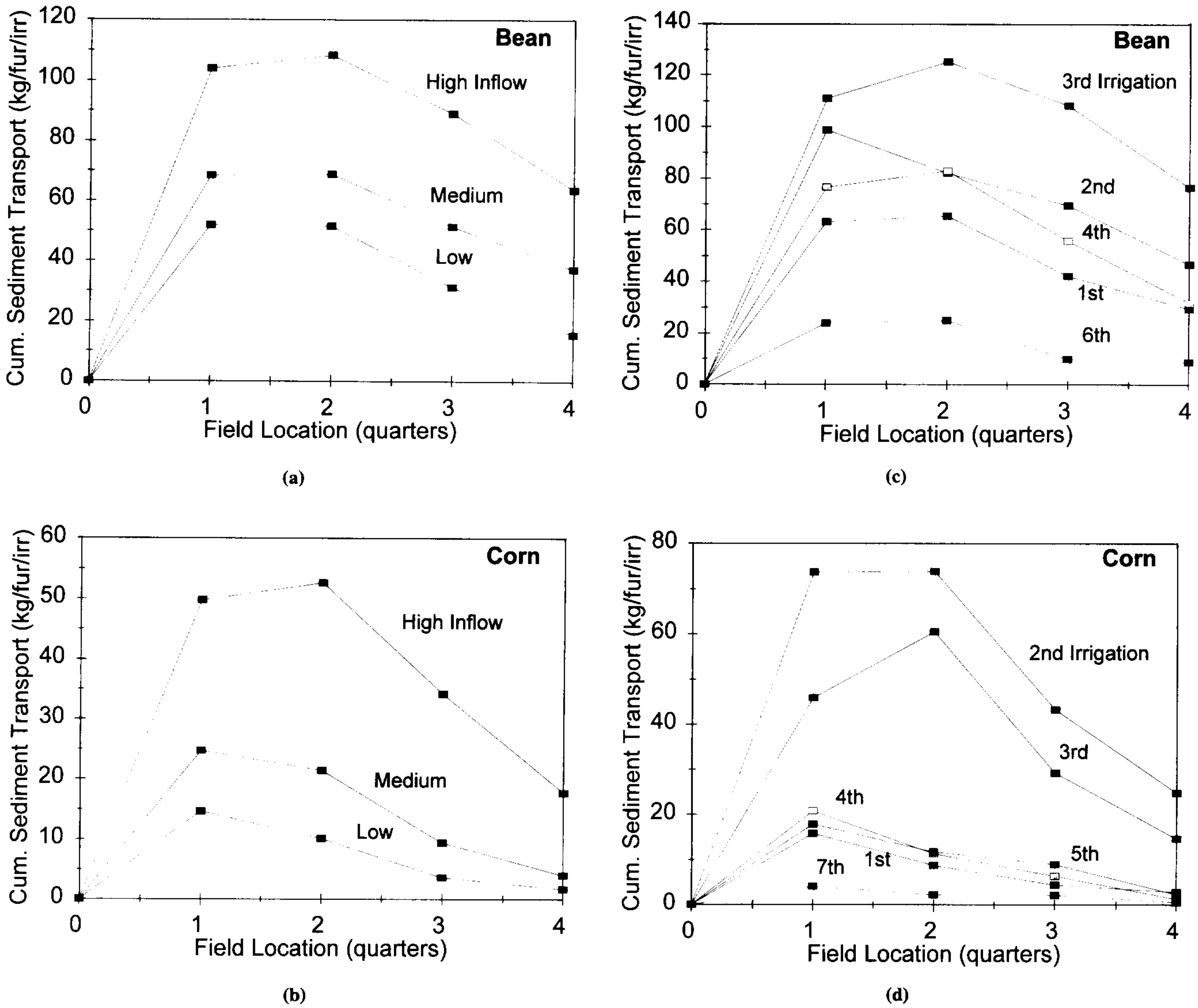


Figure 3. Measured cumulative sediment transport along the furrows (kg/furrow/irrigation) [average for four replications and all irrigations (a and b) or treatments (c and d)].

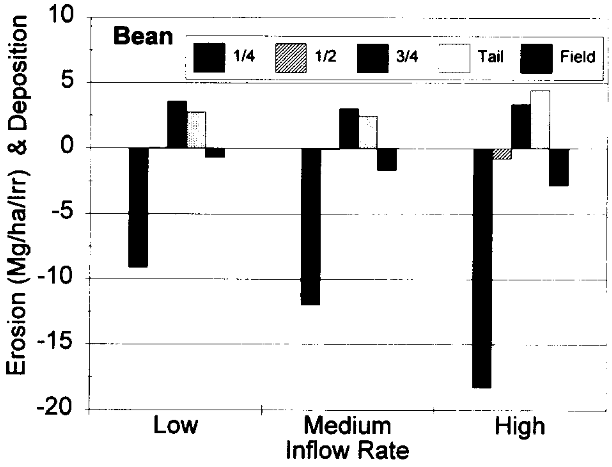
deposition began (fig. 4). This implies that the sediment transport capacity of the flow was reached and net deposition resulted from the decreasing flow rate along the furrow.

On the bean field, approximately 25% of the soil eroded from the first quarter deposited in each of the third and fourth quarters. The remaining 50% left the field with the tailwater. Thus, the erosion rate (Mg/ha) in the first quarter of the field was about eight times the field average (two times greater sediment discharge from 1/4 the area). On the corn field, about 50% of the soil eroded from the first quarter deposited in the third quarter, about 25% deposited in the fourth quarter, and 25% ran off. Thus, the first quarter erosion rate was about 16 times the field average.

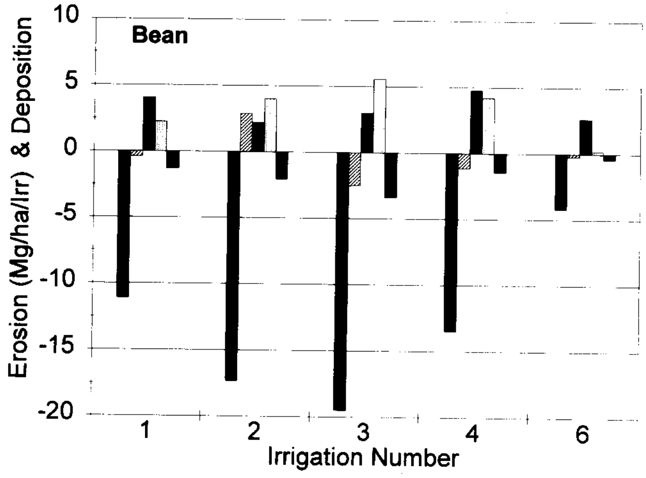
The primary factor in the wide variation in the ratio of first quarter erosion to field average erosion (erosion ratio) was the tailwater runoff percentage (table 2 and fig. 5). As the runoff percentage (the ratio of runoff to inflow volume) increases, the water is able to transport a larger portion of the eroded sediment off the field. Erosion-ratio values can theoretically range from a value equal to the inverse of the portion of the field eroding (i.e., 4 if 1/4 of the field is eroding) when runoff is high enough that no sediment deposits, to infinity if there is no runoff. The erosion ratio can be used to estimate the erosion damage in the upper portions of a field when only outflow sediment discharge is known.

Erosion from the upper 1/4 and sediment transport at all locations increased with flow rate (table 2, figs. 3 and 4). The approximately 20% increase in inflow rate between the low-to-medium and medium-to-high treatments resulted in a 30% and 50% increase, respectively, in upper 1/4 erosion (kg/m/furrow) on the bean field and a 70% and 100% increase on the corn field. This greater-than-proportional flow rate effect implies that the exponent of an erosion vs. flow rate relationship would be between 2 and 3. Kemper et al. (1985) estimated an exponent value between 1.1 and 1.7.

Sediment transport at the tail end was also proportional to outflow rates to the 2-to-3 power (Trout, 1997). Average field erosion, based on sediment outflow measurements, was much more sensitive to inflow rate with relationship exponent values between 4 and 6. This is because runoff rates varied much more widely than inflow rates. Fornstrom



(a)



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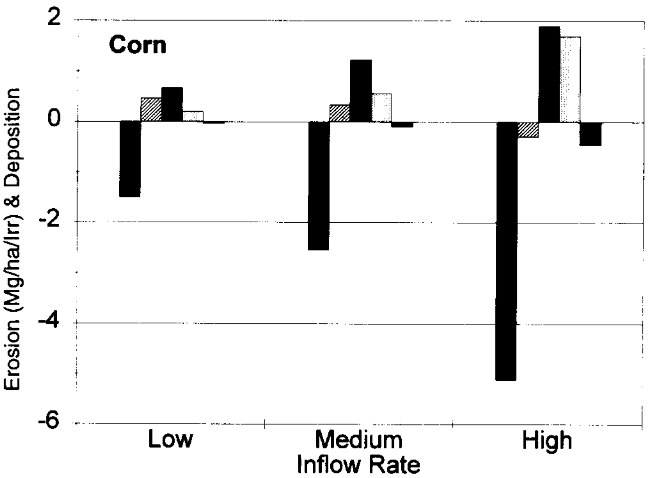

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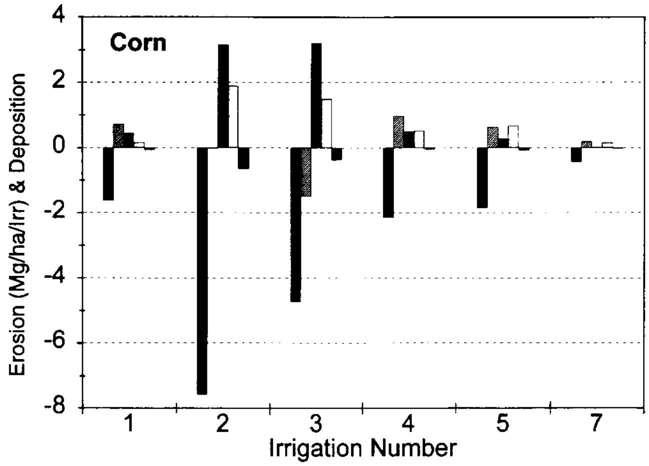

(d)

Figure 4–Calculated erosion (negative) and deposition in each furrow section and for the whole field [average for four replications and all irrigations (a and b) or treatments (c and d)].

Table 2. Average flow rate and erosion summary

Crop Irrig No.	Inflow Rate (L/min)			Runoff Percentage (%)			1/4 Erosion (Mg/ha)			Avg Field Erosion (Mg/ha)			Erosion Ratio*		
Flow	*Low*	*Med*	*High*	*Low*	*Med*	*High*	*Low*	*Med*	*High*	*Low*	*Med*	*High*	*Low*	*Med*	*High*
Bean															
1	15	18	20	33	40	51	9.1	9.6	14.6	0.6	1.5	1.9	16	7	8
2	17	21	25	45	51	58	12.4	13.7	25.9	0.9	1.9	3.3	14	7	8
3	15	18	21	44	49	56	14.6	18.5	25.4	1.5	3.4	5.2	10	5	5
4	14	16	19	25	36	44	7.0	15.2	18.2	0.3	1.0	2.9	22	15	6
6	14	16	19	14	29	38	2.5	3.0	7.2	0.1	0.3	0.7	24	9	10
Avg.	15	18	21	32	41	49	9.1	12.0	18.3	0.7	1.6	2.8	13	7	7
Total							45.6	60.0	91.2	3.4	8.2	13.9			
Corn															
1	39	46	55	4	21	33	0.7	1.0	3.3	0.0	0.0	0.2	35	24	20
2	32	38	45	25	34	48	2.6	7.0	13.2	0.1	0.4	1.5	21	20	9
3	27	32	42	32	38	49	2.8	3.5	7.9	0.1	0.2	0.9	36	21	9
4	25	28	33	17	22	31	1.5	2.2	2.8	0.0	0.0	0.1	81	69	49
5	24	28	33	24	33	46	1.2	1.3	3.0	0.0	0.0	0.1	69	42	22
7	24	28	36	20	25	38	0.3	0.3	0.7	0.0	0.0	0.0	45	30	19
Avg.	28	33	41	20	29	41	1.5	2.5	5.1	0.0	0.1	0.5	34	25	11
Total							9.1	15.3	30.7	0.3	0.6	2.7			

*Erosion Ratio = 1/4 Erosion / Field Average Erosion Rate.

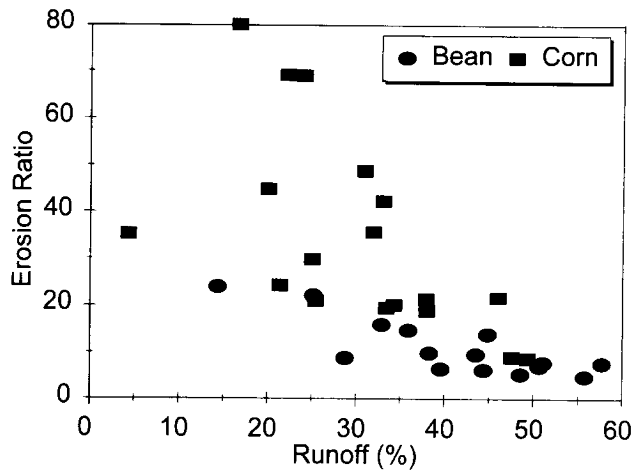

Figure 5–Measured variation in the first quarter-to-field average erosion (erosion ratio) with tailwater runoff.

and Borrelli (1984) found furrow inflow rate to the 2.5 power best fit their Wyoming sediment outflow data.

In spite of using inflow rates on the bean field about half those on the corn field, upper 1/4 erosion was 3 1/2 times higher. Although field preparation and crop differences might have caused some of the difference, the primary factor was the steeper slope. Sediment discharge from the tail end from the bean field was five times that from the corn, with a 35% smaller average outflow rate. These results indicate a high sensitivity of erosion to slope. Kemper et al. (1985) estimated the erosion:slope relationship exponent in the range of 1.4 to 2.7. The Fornstrom and Borrelli (1984) regression erosion model derived a 1.7 exponent on the slope term.

On both fields, the highest erosion and sediment discharge rates occurred during the second and third irrigations, and the lowest rate for each was for the final measured irrigation (figs. 4c and 4d). Low erosion at the end of the season results from consolidation and stabilization of the furrow soils and is commonly observed. The high rates are difficult to explain. They were not consistently related to preceding tillage (irrigations following tillage were no. 1 and 3 for the beans and no. 1, 2 and 4 for the corn). Higher than average tailwater runoff rates during irrigations 2 and 3 on both fields could explain the high sediment discharge rates and thus field average erosion rates. However, upper 1/4 erosion should be more closely related to inflow rate, which was highest for the first three irrigations. I have no explanation for the relatively low erosion during the first irrigation.

Sediment concentration in the flows varied widely with time during the irrigations (fig. 6). In most cases, sediment concentration peaked within a few minutes after flow reached a location and then decreased continuously until the end of the irrigation. Flow rates usually approached a steady-state value within an hour after flow reached a measurement location. Decrease in furrow sediment transport with time, even though flows are steady, has been measured previously (Trout and Neibling, 1993; Brown et al., 1988; Kabir and King, 1981). Possible explanations for the decreasing erosion rate with time include the initial flushing of loose aggregates created by tillage or rapid wetting, the stabilization of the furrow perimeter soil, and erosion to a more resistant soil layer. The depicted irrigation (fig. 6) was on previously irrigated furrows and there was no evidence of eroding to a resistant layer. I have no explanation for the decrease in transport with time at the tail end where sediment transport should be controlled by transport capacity rather than upstream erosion.

Furrow Erosion Measurement and Prediction

The measured sediment transport trends along furrows are similar to those predicted by the theory depicted in figure 1. The erosion rate was highest at the upper end of the furrows where flow erosiveness was highest (highest flow rate) and where the transport was much less than transport capacity. As flow rate decreased along the furrows and sediment concentration in the water increased, erosion decreased until the transport capacity of the flow was reached and net deposition began.

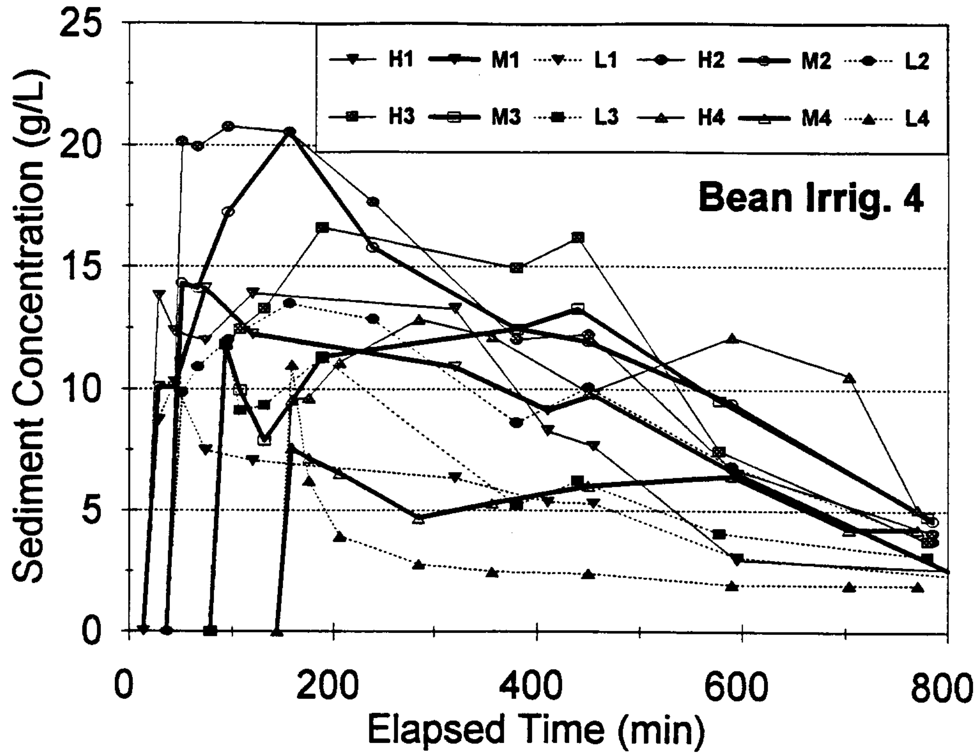

Figure 6–Variation in sediment concentration with elapsed time during bean irrigation no. 4. [Label letter represents inflow rate (L = low, etc.) and label number represents field location (1 = first quarter, etc.).]

The allowable annual erosion from these fields (the T value from the soil survey) is 11 Mg/ha (5 tons/acre). Tail-end sediment discharge measurements indicated that neither field irrigated with moderate flow rates exceeded the T value. These field-average measurements are in the range of those reported by Berg and Carter (1980) for row crops on fields with Portneuf soil and slopes of 1%. Based on numerous furrow erosion studies that used sediment discharge measurements, Koluvec et al. (1993) predicted that erosion should not be excessive on slopes less than 1%. However, in this study, the T value was exceeded in the upper quarter of both fields. In the bean field with medium flow rates, the seasonal erosion in the upper quarter was 5 times the T value. This is equivalent to about 5 mm of top soil lost in one year and 400 mm lost in 80 years of irrigation — sufficient to expose the white subsoils evident in figure 2. Figure 1 predicts much higher erosion at the upper end of the furrows than average erosion for the upper quarter of the field. The commonly made tail-end sediment yield measurement quantifies sediment discharge and potential downstream damages, but greatly underestimates the extent of erosion damage to furrow-irrigated fields.

A relationship among the erosion ratio, runoff percentage, and the portion of the furrow that is eroding (or, more precisely, the portion where there is no deposition) is shown in figure 7. The relationship is based on the assumptions that (1) infiltration rate is uniform along the furrow so that flow rate decreases linearly, (2) slope is uniform, (3) transport is equal to transport capacity where deposition is occurring, (4) sediment transport capacity is proportional to shear squared (from Trout, 1997, based on this data), and (5) shear is proportional to flow rate to the 3/8 power (Trout, 1991). With these assumptions, if the location where deposition begins is known (i.e., sediment transport capacity is reached), the amount of deposition in the rest of the furrow can be calculated. Factoring in the relative field area that is eroding results in the erosion ratio relationship shown in figure 7. The collected data support these trends. This relationship is not dependent on soil, furrow length or slope as long as the five assumptions are met. Even when the assumptions are not met, the relationship provides a reasonable estimate for the erosion ratio.

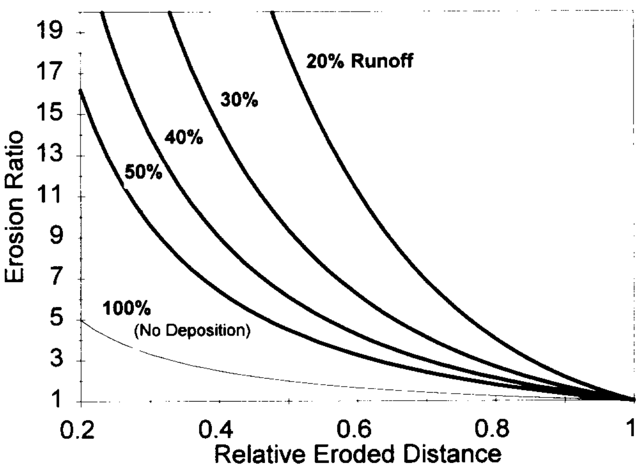

Figure 7–Predicted variation in erosion ratio with relative eroded distance and percent runoff.

Determining the location where deposition begins is difficult, so measurements to assess furrow-induced erosion must include in-field measurements. The in-field location where sediment transport is maximum (net erosion ceases) will vary with the soil and field conditions, but even sediment transport measurement at a single location about 1/3 of the furrow length from the head end will provide valuable information about head-end erosion damage.

The measured within-furrow sediment movement trends follow erosion and transport theory. The widely varying upper 1/4 erosion rates from irrigation to irrigation could be caused by variation in the soil stability and erodibility with time. However, the widely varying sediment transport over time and between irrigations in the lower half of the field where net deposition is occurring (i.e., transport capacity is reached) cannot be explained by present theory. Sediment transport is related to the flow hydraulics (shear) and the transported sediment particle sizes and densities. Sediment particle sizes and densities (and thus transportability) should not change much throughout an irrigation or from irrigation to irrigation on a field. Thus, theory would predict that, for a given slope and flow rate, if the soil erodibility increases, the transport capacity would be reached in a shorter distance, but the transport capacity itself would not change. Further analysis of these data in Trout (1997) supports the need for a new theory to describe sediment transport in furrows.

Conclusions

Furrow-induced erosion rates from the upper ends of fields in southern Idaho are at least six times greater than the field average. Commonly made tail-end sediment yield measurements, although useful to evaluate potential sediment-related damage to downstream water bodies, greatly underestimate erosion damage at the field head end. In-field measurements at about 1/3 furrow length are recommended to assess erosion damage. The measured erosion and deposition trends along furrows can be explained by theory, but the apparent variation in transport capacity cannot.

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