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The importance and challenge of modeling irrigation-induced erosion

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Abstract: Irrigation-induced erosion and rain-induced erosion result from very different systematics. Therefore, both cannot be predicted effectively using the same models. The average two-fold yield and three-fold economic advantage of irrigation over rain-fed agriculture, coupled with the fragility of irrigated land and the strategic importance of irrigation development to meet world agricultural production needs, has raised the urgency for the development of robust, accurate, and precise irrigation-induced erosion models. This paper details the rationale for separate irrigation-induced erosion models, presents essential aspects unique to irrigation that must be accounted for in the models, and summarizes the progress (to date) toward the goal of irrigation-induced erosion model development.

Key words: infiltration—runoff—RUSLE—SISL—SRFR—USLE—water quality—WEPP

Soil erosion models are indispensable tools for conservation planning, erosion inventory, risk assessment, and policy development. The most successful rain-fed soil erosion models have been the statistically-based Universal Soil Loss Equation (USLE), its successor the Revised Universal Soil Loss Equation (RUSLE), and more recently the process-based Water Erosion Prediction Project (WEPP). No comparable, widely validated model exists for irrigation-induced erosion. In September of 2005, letters to the Agricultural Research Service (ARS) Acting Deputy Administrator for Natural Resources and Sustainable Agricultural Systems D.R. Upchurch from Natural Resources Conservation Service (NRCS) Deputy Chief of Science and Technology Lawrence Clark and Acting Director for Conservation Engineering Barry Kintzer exhorted the ARS to raise the priority of developing and validating a reliable model for wide use by the NRCS and other public entities to help predict and inventory irrigation-induced erosion.

The importance of developing erosion models for irrigated agriculture cannot be overemphasized. Only one-sixth of the United States and world's cropland is irrigated, but irrigated cropland produces one-third of the annual harvest and one-half of the value of all crops (food, fiber, etc.) harvested (Howell 2000; Bucks et al. 1990; Kendall and Pimentel 1994; National Research Council 1996). A mere 5×10^7 ha (1.25×10^8 ac) of Earth's most productive irrigated land, only 4% of the world's total cropped land, produces one-third of the world's harvested food (Tribe 1994). Over 80% of the fresh fruit and vegetables produced in the United States are grown with irrigation (Trout 1998). Still, to meet the needs of 8×10^9 people by 2025, Plusquellec (2002) estimated that irrigated area must expand over 20% and irrigated crop yields must rise 40%. However, irrigated production is largely on shallow, fragile soils vulnerable to irrigation-induced erosion (Sojka et al. 2007b), making it one of the most serious sustainability issues in agriculture.

Approximately 2.70×10^8 ha (6.75×10^8 ac) of cropland worldwide is irrigated; about 90% is surface irrigated (Food and Agriculture Organization 2003). According to the 2004 NASS "Farm and Ranch Irrigation Survey," 21,288,838 ha (53,222,095 ac) of US cropland are irrigated: 50.5% are sprinkler irrigated, 43.4% are surface irrigated (about half in furrows), 5.6% are drip or micro-irrigated, and 0.5% are sub-irrigated (USDA 2004).

Attempts to apply rain-induced erosion models to irrigated fields have had only limited success. Our understanding of the unique systematics of irrigation-induced erosion systematic and the difficulties of adapting rain-induced erosion models continues to improve (Sojka 1998; Bjorneberg et al. 1999, 2000; Bjorneberg and Trout 2001; Bjorneberg and Sojka 2002; Kincaid and Lehrsch 2001; Kincaid 2002; Strelkoff and Bjorneberg 2001). Our paper examines the importance and current state of irrigation-induced erosion modeling, our understanding of the differences between irrigation-induced and rain-induced erosion, and the needs and knowledge gaps that must be filled for further advances to occur.

Magnitude of Irrigation-Induced Erosion

There is only limited published data on irrigation-induced erosion. A survey of the extent of irrigation induced erosion and its agricultural, economic, and environmental impacts has been cited as a critical need by irrigators and government (Reckendorf 1995). This need affects our ability to protect water quality, which is strongly linked to erosion, especially in irrigated agriculture.

In furrow irrigation, sediment losses of 145 Mg ha^{-1} (65 ton ac^{-1}) in 1 hour (Israelson et al. 1946) and 40 Mg ha^{-1} (18 ton ac^{-1}) in 30 minutes (Mech 1949) have been reported. Over 50 Mg ha^{-1} (22 ton ac^{-1}) of soil loss was measured for a single 24-hour furrow irrigation (Mech 1959). Berg and Carter (1980) reported annual losses ranging from 1 to 141 Mg ha^{-1} (0.4 to 63 ton ac^{-1}) in southern Idaho. In Washington, Koluvek et al. (1993) measured from 0.2 to 50 (0.1 to 22 ton ac^{-1}) Mg ha^{-1} of soil loss per season and 1 to 22 Mg ha^{-1} (0.4 to 12 ton ac^{-1}) per irrigation in Wyoming.

Berg and Carter (1980), Kemper et al. (1985b), and Fornstrom and Borelli (1984) reported that 3 to 8 times the field-averaged erosion occurs in the upper ends of fields. Trout (1996) estimated the disparity as 10 to 30 times

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the field-averaged erosion for the upper fourth of furrows on a 1% sloping field of Portneuf silt loam, which has a "soil loss tolerance" around 11 Mg ha^{-1} (5 ton ac^{-1}) per year.

Erosion effects are not uniform along furrows. As water infiltrates along a furrow, stream size decreases, reducing detachment and carrying capacity. Thus, some soil eroded from the upper field is deposited at the lower end. Soil leaving a field in runoff is permanently lost unless it is collected in catchments. Soil deposited at lower reaches of furrows is not lost but may include subsoil eroded from the upper reaches that have chemical and physical problems that decrease productivity in deposition areas.

Carter et al. (1985) and Carter (1986) noted that 75% of the furrow irrigated fields in Idaho had lost the entire 38 cm (15 in) A-horizon in the upper reaches, while deposition had increased "topsoil" thickness of the lower ends two to fourfold. Net productivity was reduced to 75% of pre-eroded values (Carter 1993) with yield reductions of 20% to 50% on areas denuded of topsoil.

Effects on Water Quality

Even as production demands are increasing, there is an urgent need to improve the water quality of farm runoff (Khaeel et al. 1980; Mawdsley et al. 1995; USEPA 1998, 2000; Trout 2000; van Schilfgaarde and Trout 1997). Erosion of agricultural land is the leading cause of surface water quality impairment, accounting for one-third to nearly one-half of surface water pollution across the United States (USEPA 2000). Because much of irrigated agriculture systematically returns runoff to surface receiving waters, the link between soil erosion and surface water contamination is stronger than for rain-fed agriculture.

Bjorneberg et al. (2002b) noted that 1,000 mm (40 in) of surface irrigation in a US Pacific Northwest cropping season, with a modest 10 Mg ha^{-1} (4.4 ton ac^{-1}) seasonal soil loss and a typical 20% runoff, would carry a mean 5,000 mg kg^{-1} (5,000 ppm) of sediment load. This is nearly 100 times more than the 52 mg kg^{-1} (52 ppm) allowable Total Maximum Daily Load for the Snake River. However, the impact of surface irrigation on runoff water quality depends on many factors, especially management. Bondurant (1971) concluded that an irrigated Idaho watershed was a sink for soluble nutrients because inflow and return flow concentrations were similar and 85% of the diverted water infiltrated within the watershed. Carter et al. (1974) found that a primarily sprinkler irrigated watershed retained 0.7 Mg ha^{-1} (0.3 ton ac^{-1}) of sediment, while a surface irrigated watershed lost 0.5 Mg ha^{-1} (0.2 ton ac^{-1}).

Less Recognized Impacts of Irrigation-Induced Erosion

Exposed and transported subsoil contributes to crusting, sealing, compaction, and nutrient deficiencies that impair seedling emergence, rooting, absorption of water and nutrients, and ultimately reduces crop quality and yields. Thus, erosion raises production costs, while reducing potential yields and profit.

Many long-term costs associated with irrigation-induced erosion are neglected in economic analyses. Irrigation-induced erosion lowers production and farm income, which ultimately leads to higher commodity prices. Costs accumulate for ditch and canal maintenance, river dredging, algal control, habitat restoration, biodiversity protection, water quality remediation, fishery restoration, as well as for mitigation of recreational resource losses, reduced reservoir capacity, and accelerated hydro-electric generator wear.

Unique Aspects of Irrigation-Induced Erosion

The chemical and physical processes that induce water erosion of soil are universal, but the order, duration, spatial relationships, energy, chemistry, mass balance and intensity of system components vary between rain-fed and irrigated systems, resulting in different erosion outcomes (Bjorneberg et al. 2000; Strelkoff and Bjorneberg 2001; Bjorneberg and Sojka 2002). In other words, irrigation water is not rain water, and irrigation water "encounters" soil differently and in ways unique to specific irrigation systems. The differences are easily identified, but it is a challenge to appropriately modify theory, management, and mindset to deal with the differences. Applying superficially modified rain-fed erosion models to estimate erosion from irrigation has not produced acceptable results (Bjorneberg et al. 1999, 2000; Trout 1996; Bjorneberg and Trout 2001; Trout and Neibling 1993).

Irrigation Water Quality Effects

Irrigation water often contains a substantial sediment or suspended biotic load. In furrows, the loads change systematically as the stream advances, influencing carrying capacity and surface sealing (Brown et al. 1988; Foster and Meyer 1972). Solids in sprinkler-applied water can also contribute to surface sealing, reducing infiltration, and thus increasing runoff and erosion.

Rain is nearly pure water and does not vary significantly in chemistry (electrical conductivity [EC], sodium adsorption ratio [SAR], or other organic or mineral constituents). Rain-induced erosion theories and models concentrate on the physical properties of relatively pure raindrops and/or water streams and how they affect erosion. Laboratory simulations and rainfall simulator studies (Levy et al. 1994; Shainberg et al. 1994; Kim and Miller 1996; Flanagan et al. 1997a, 1997b), as well as furrow irrigation studies (Lentz et al. 1993, 1996), have demonstrated that EC and SAR significantly influence the erosivity of water. Soil and water chemistry effects, to the extent that they exist in rain-fed conditions, are indirectly integrated into rain-induced soil erosion models via a given soil's erodibility. The degree and mode of water quality effects on irrigation-induced erosion are far more pronounced.

High SAR/low EC water is more erosive than low SAR/high EC water. Lentz et al. (1996) found that sediment in furrow irrigation runoff more than doubled with SAR 12, EC 0.5 dS m^{-1} water, compared to SAR 0.7, EC 2.0 dS m^{-1} water and was 1.5 times greater when compared with Snake River water (SAR 0.7 EC 0.5 dS m^{-1}). Because the high SAR waters increased aggregate disruption and seal formation in furrows, infiltration was reduced, which increased runoff, stream velocity, and shear.

Sprinkler- and rain-simulator studies had similar results when water electrolyte quality was varied. Final infiltration rates decreased, while runoff and erosion increased when Kim and Miller (1996) used deionized water compared to 0.5 dS m^{-1} water. However, when sprinkling on small soil trays, there was no erosion difference between 0.5 and 2.0 dS m^{-1} water. When sprinkling deionized water in a field rain simulator, Flanagan et al. (1997a, 1997b) observed that erosion increased when compared to sprinkling with water containing electrolytes. However, they did not see electrolyte related differences in final infiltration rates, in runoff, or in the erosion measured in small inter-rill subplots. While the rain energy for the simulated storm event was the same as in the Kim and Miller (1996) study, the rain application protocol and plot size were different. This suggests that mode of water application affects detachment and shear in ways that interact with water quality and soil properties.

Studies have explored how irrigation (or rain) water quality influences erosion via effects on particle cohesion, dispersion, flocculation, and critical shear (Quirk and Schofield 1955; Oster and Schroer 1979). Where detachment, aggregate disruption, and particle dispersion are affected by water quality, the end result is usually seal formation (Arora and Coleman 1979; Velasco-Molina et al. 1971; Frenkel et al. 1978; Malik et al. 1992; Shainberg et al. 1981, 1992; Smith et al. 1992; Peele 1936; Oster and Schroer 1979). Since detachment and dispersion promote seal formation, they are more evident at higher SAR and lower EC (Shainberg and Singer 1985; Brown et al. 1988).

The degree of water quality effect on sealing and infiltration is tied to several soil and water properties including presence of flocculating or aggregate-stabilizing agents, such as organic matter, Fe and Al oxides (Le Bissonais and Singer 1993; Goldberg et al. 1988; Goldberg and Forster 1990; Goldberg and Glaubig 1987; Shainberg et al. 1981), soil texture (Frenkel et al. 1978), clay mineralogy (McNeal and Coleman 1966), and specific cation effects involving potassium (Robbins 1984). Arora and Coleman (1979) demonstrated that raising the EC of irrigation water improves flocculation of suspended fines. Robbins and Brockway (1978) showed that this effect could be used to improve performance of sediment removal basins. Gregory (1989) showed that as increases in water velocity increased shear forces, the flocculated fines were partially broken, resulting in a grading of entrained flocs to a narrow size-range. This demonstrated a complex interaction between water quality and erodible minerals in irrigation-induced erosion processes.

Water Application Effects

Unlike rainfall, irrigation usually occurs on dry and bare soil, where the transition from dry soil to excess water and runoff is often virtually instantaneous. This is true in furrow irrigation but also with traveling guns and at the outer ends of center pivots, where the sprinkler movement and water application rates are high.

For furrow irrigation, "rills" are tilled into dry soil prior to irrigation. As water advances along the furrow during the first irrigation or following cultivation, it flows over loose, dry soil. The advancing water instantly hydrates dry soil, displacing the air that is in pores and adsorbed on internal soil surfaces (Kemper et al. 1985a). This produces strong, disruptive forces that destroy soil structure and increase soil erodibility (Carter 1990). Kemper et al. (1985a,b) suggested that these effects explain how furrow erosion often initiates before critical shear is exceeded. The speed and intensity of these irrigation processes are greater than in rain events, where the soil surface is hydrated gradually over several minutes after excess water begins collecting on and running off field surfaces that were gradually pre-wet by rain. Using 24 m (80 ft) furrows, Bjorneberg et al. (2002a) showed that erosion from dry furrows in a Portneuf silt loam soil was greater than from gradually pre-wet furrows. Le Bissonais and Singer (1992) showed that simulated rainfall onto trays of Capay silty clay loam and Solano silt loam produced less runoff and erosion when soils were pre-wet from the bottom by capillarity and drained prior to simulated rain. The effect persisted into later irrigations. Mamedov et al. (2002) found greater erosion in six Israeli soils from simulated rain on soil trays as wetting rate and clay content increased. A small flume study by Shainberg et al. (1996) showed that air-dried soil exhibited greater rill erodibility than wet soil and that erodibility decreased with time after wetting. Pre-wetting effects on erosion are related to aggregate hydration dynamics. Aggregate stability is affected both by soil water content and rate of water content change (Bullock et al. 1988; Kemper and Rosenau 1984).

Furrow stream dynamics differ greatly from rill streams. Stream size, which is exponentially related to detachment (Kemper et al. 1985b), decreases along irrigation furrows (due to cumulative infiltration effects). At the same time, the wetted perimeter in the lower third or half of the field broadens (via sloughing of the furrow sides and sediment deposition on the furrow bottom). By contrast, in rain-fed rills, soil is gradually and uniformly wetted, and flow rate, carrying capacity, and erosion increase down the slope as cumulative inter-rill inflow increases. There is little deposition in rills unless field slope substantially decreases. In furrow irrigation, there is no water drop impact or splash component affecting or contributing to the erosion process between or within rills. Thus, the temporal and spatial components of infiltration, runoff, shear, detachment, transport, and deposition differ vastly for furrow irrigation erosion and rain-induced erosion. Hence, rill erosion relationships and parameters extracted from rain simulated results do not relate well to furrow irrigation erosion. Calibrated rill erodibility was almost two orders of magnitude less and calibrated critical shear was one-third lower for irrigation furrows than values calculated from rain simulator tests on the same soil (Bjorneberg et al. 1999).

Sprinkler irrigation is similar to rain in many ways, but there are important differences. Water quality effects are as described above. There are also spatial and temporal differences. Rain events occur across landscapes at watershed scale, whereas sprinkler irrigation involves water application to only portions of fields at a given time. Runoff may flow onto dry or wet soil, which depends upon slope direction and field configuration.

Solid-set and periodic-move sprinkler systems bear the greatest similarity to rain. A grid of stationary sprinklers operating simultaneously over an irrigated field provides uniform, low intensity water application. These systems seldom produce runoff and erosion.

Almost 80% of the sprinkler irrigated land in the United States uses center pivots (USDA 2004). Lateral lengths vary to meet specific needs; however, the lateral length dictates system application rates along the pivot. Average application rate increases in direct proportion to distance from the center. The greatest potential application rate and potential runoff occur at field edges along the outer reaches of the pivot arm, where instantaneous application rates are highest.

Another high application rate sprinkler irrigation system is the traveling gun, which applies a high water application rate from a single rotating nozzle or "gun" that laterally arcs a high volume (and large droplet size) stream of water a distance of 30 to 60 m (100 to 200 ft), irrigating a gradually advancing circular section of the field.

The application rate at a given point within the wetted area is a key factor governing erosion potential from sprinkler systems. Sprinkler systems operate on variable topography with non-uniform slopes, especially center pivot systems. If laterals are aligned across the slope, a dispersed area of runoff moves away from the lateral, which allows water to infiltrate in a short distance on a non-irrigated area. However, if the lateral is aligned with the slope, the applied water concentrates down slope, initiating erosive runoff streams. Orientation of crop ridges relative to the slope and lateral also affect runoff flow direction. Crops are sometimes planted in circular patterns under center pivots to keep rows and ridges perpendicular to the lateral spray arm. The wheel tracks that form under support towers as the pivot lateral moves through a field collect and channel runoff, initiating erosion. If the pivot lateral is moving up slope, runoff on the field and in wheel tracks will flow onto wet areas behind the advancing lateral. When the lateral is moving downslope, runoff enters dry areas of the field and wheel tracks ahead of the advancing lateral arm. Modeling erosion from center pivots or other traveling irrigation systems must account for the rain-like aspects, as well as water quality and site factors that influence both inter-rill runoff and erosion and these special cases of rill or furrow runoff and erosion (Bjorneberg et al. 2000). Other lateral move systems, such as linear traveling systems, wheel lines, and hand moved laterals, exhibit characteristics intermediate to the systems described above, which further complicates the conceptualization and modeling of erosion.

Water Temperature and Temporal Effects

Soil and water temperatures vary systematically over the course of a season, both among storm events and diurnally. In models of rain-induced erosion, temperature effects on water viscosity and solubility relationships of soil chemical components have not been considered directly. To the extent they are incorporated into models, they are dealt with indirectly via statistical correlations of storm events and erosion observations. Soil and water temperatures are more likely a factor in irrigation-induced erosion than for rain-induced erosion. Rain is usually preceded by and accompanied by reduced solar irradiance and thus soil cooling. Temperature of rainwater is nearly constant at or near the dew point during a rain event. Droplets reaching the ground from sprinkler irrigation also tend to match the dew point temperature. In contrast with rain, irrigation usually occurs on sunny days when soil surfaces are hot, especially in arid settings. In furrow irrigation, this causes large temporal and spatial variation of irrigation stream temperature (Lentz and Bjorneberg 2002).

In irrigation, temperature variations are quite systematic, and the magnitude of their effects on irrigation-induced erosion has been measured. Brown et al. (1995) estimated the effect of the irrigation date on furrow irrigation-induced erosion, finding that soil erodibility in southern Idaho peaked annually near the end of June or the beginning of July. They concluded that soil and/or water temperatures were linked to the solar cycle, with the peak erodibility coinciding with the summer solstice, which they speculated was affecting soil and water temperatures to cause changes in furrow erodibility. Lentz and Bjorneberg (2002) correlated diurnal changes in furrow stream water temperature with fluctuations in furrow infiltration rates. Infiltration rates increased 2% per °C (approximately 1% per °F) of water temperature rise. They speculated that higher temperatures influenced water viscosity and solubility of soil constituents. The magnitude of infiltration change was enough to affect stream flow and potentially impact sediment loss. Infiltration rates varied diurnally, up to 30% of the mean in a study by Jaynes (1990), who noted that infiltration changes tracked changes in soil temperature. Water temperature rose 22°C (72°F) in mid-afternoon along a 550 m furrow in a study by Duke (1992), who calculated that the resulting change in viscosity could increase hydraulic conductivity by 70%.

The controlled temporal patterns of irrigation events are also very different from the more random nature of rain events. Irrigation-induced erosion tends to occur in a series of several relatively small runoff events, whereas rain-induced erosion is typically generated in a few relatively large storms each season. Rainfall-induced erosion is predicted by deriving yearly or seasonal hydraulic or erosion relationships based on meteorological inputs averaged from sporadic events of varied intensity occurring over long time periods across a geographic region. Irrigation hydrology is much more controlled and predictable and much more sensitive to small variations in conditions. This obstacle is compounded if one also fails to account for the amount and kind of irrigation, water quality, spatial and temporal variability, etc.

Furrow irrigation events are typically 12 or 24 hours in duration, with runoff occurring for about 9 to 18 hours, whereas most runoff from rain events typically occurs for briefer periods. Because the duration of irrigation runoff is longer, temporal changes in infiltration, furrow size and shape, and soil erodibility parameters are more important for furrow irrigation than for rain. For example, sediment concentration in furrow irrigation runoff usually decreases with time, even though there is a constant inflow stream, and runoff usually increases over time. Greater runoff should cause increased shear, detachment, and transport. In fact it does not, which indicates that during prolonged irrigation events, other phenomena are reducing the erodibility of the soil or erosivity of the water. Such phenomena could include armoring of the furrow, temperature-related water viscosity shifts, or other unknown factors (Bjorneberg et al. 2000; Lentz and Bjorneberg 2002). Long runoff times also allow relatively low erosion rates to result in substantial cumulative erosion, so it is important to be able to predict these low erosion rates.

Modeling Irrigation-Induced Erosion

Models developed for rain-induced erosion cannot be used for irrigation without substantial modification. (Units in this section of the paper are given as the actual input units required for the models to function.) The USLE and its successor, RUSLE, are the most commonly used models for estimating erosion rates associated with rain-fed cropland agriculture (Wischmeier and Smith 1965 and 1978; Renard et al. 1997). The USLE was developed in the United States during the 1950s and 1960s (Laflen and Moldenhauer 2003) and has been adapted, modified, expanded, and used for conservation purposes throughout the world (e.g., Schwertmann et al. 1990; Larionov 1993).

The USLE was originally based on statistical analyses of more than 10,000 plot-years of data collected from natural runoff plots located at 49 erosion research stations in the United States; the final version published in 1978 (Wischmeier and Smith 1978) included data from additional runoff plots and experimental rainfall simulator studies. No data from irrigation-induced erosion was used in the development of either the USLE or RUSLE, and documented methods for applying the technology to irrigated agriculture are virtually nonexistent.

The basic form of the USLE and RUSLE equations is as follows:

$$A = R \times K \times L \times S \times C \times P\ , \tag{1}$$

where

A = average annual soil loss over the part of the field that experiences net loss (Mg ha^{-1} yr^{-1}),

R = rainfall erosivity (MJ mm hr^{-1} ha^{-1} yr^{-1}),

K = soil erodibility (Mg hr MJ^{-1} mm^{-1}),

L = the slope length factor (unitless ratio),

S = the slope steepness factor (unitless ratio),

C = the cropping factor (unitless ratio), and

P = the conservation practices factor (unitless ratio).

In addition to the lack of irrigation data analyzed within the framework of the USLE and RUSLE, the erosivity term (R) constitutes an inherent problem with regards to the application of these equations to irrigation induced erosion. Wischmeier (1959) found for the plot data that the erosive power of the rain was statistically related to the total storm energy multiplied with the maximum 30-minute storm intensity. It is unknown if the same type of energy intensity term would be applicable for erosion caused by sprinkler irrigation, and of course, such an erosivity term would not be relevant to furrow irrigation.

Three models have been or are being developed to estimate soil loss from irrigated fields: the Surface Irrigation Soil Loss model (SISL), the WEPP model, and the surface-irrigation simulation model (SRFR) (Strelkoff et al. 1998). Each model differs in complexity and the mode of application. Two additional irrigation erosion models have been developed and have had some local use (albeit on a limited basis). The sprinkler erosion and runoff model (SPER/ERO) for center pivots, was deployed for limited field scale assessment in Washington State (Spofford and Koluvek 1987). The furrow soil erosion model (FUSED) was developed as a single furrow or seasonal field scale erosion assessment model (Fornstrom et al. 1985). It uses Wyoming field data and has had limited use in Washington state.

The Idaho NRCS developed the SISL model to estimate soil loss from furrow irrigated fields (NRCS 2000). This simple empirical model uses a formula similar to the USLE. A base soil loss value is multiplied by several factors to account for variations in soil erodibility, previous crop, conservation practices, and irrigation management. The SISL equation is as follows:

$$SISL = BSL \times KA \times PC \times CP \times IP\ , \tag{2}$$

where

SISL = surface irrigation soil loss from a field (Mg ha^{-1} yr^{-1}; as deployed by NRCS, English units are used with output expressed in tons ac^{-1} yr^{-1}),

BSL = the base soil loss rate, and

KA, PC, CP, and IP= dimensionless adjustment factors for soil erodibility, prior crop, conservation practice, and irrigation practice, respectively.

The BSL was established from soil loss measured on over 200 furrow irrigated fields in southern Idaho. The BSL is affected by crop, field slope, field length, end-of-field slope-shape (i.e., convex end), and type of inflow (siphon tube, gated pipe or feed ditch). The BSL values, provided in tabular format, vary from 0 Mg ha^{-1} for permanent crops on fields with <1% slope to >173 Mg ha^{-1} for intensive row crops (e.g. sugarbeet or onion) with >3% slope. KA varies from 0.45 to 1.12, based on the soil erosion factor K, as defined by NRCS and provided in soil surveys. PC accounts for crop residue from the previous crop, ranging from 0.65 for pasture to 1.0 for low residue row crops. CP varies from 1.0 for conventional moldboard plow tillage to 0.10 for no-till and 0.05 for polyacrylamide use (Sojka et al. 2007a). IP accounts for the choice and intensity of irrigation management practices (e.g., cutback or surge irrigation).

An evaluation of SISL using data from six production fields near Kimberly, Idaho, along with previously published furrow irrigation erosion data from Kimberly, Idaho, and Prosser, Washington, 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). One major limitation of SISL is that the number of irrigations and amount of runoff are embedded within the BSL. This limits application of this model to areas with furrow irrigation practices similar to southern Idaho.

The process-based WEPP model (Nearing et al. 1989; Laflen et al. 1991) categorizes soil erosion into rill and inter-rill processes. Inter-rill erosion involves soil detachment and transport by raindrops and shallow sheet flow. Inter-rill erosion delivers sediment to rills. Rill erosion processes describe soil detachment, transport, and deposition in rill channels (Flanagan and Nearing 1995).

The WEPP model uses the following steady state sediment continuity equation to calculate change in sediment load along the rill:

$$\frac{dG}{dx} = D_f + D_i\ , \tag{3}$$

where

G = sediment load in the rill per unit width (kg m^{-1} s^{-1}),

X = down-slope distance (m), and

D_f and D_i = rill erosion rate and inter-rill (lateral) sediment delivery rate to the rill, respectively, each per unit length and width of rill (kg s^{-1} m^{-2}).

Inter-rill erosion is a function of rainfall intensity, inter-rill runoff rate, and inter-rill erodibility (Flanagan and Nearing 1995). Rill detachment is a linear function of hydraulic shear and is calculated for clear water via the following equation:

$$D_c = K_r\,(\tau - \tau_c)\ , \tag{4}$$

where

D_c = the detachment rate (kg s^{-1} m^{-2}), the rate at which sediment is entrained into the flow,

K_r = rill erodibility (s m^{-1}),

τ = hydraulic shear of flowing water (Pa), and

τ_c = soil critical shear (Pa) (Elliot and Laflen 1993; Flanagan and Nearing 1995).

Rill erodibility is the rate at which sediment is detached by clear water (per unit shear over the critical), and critical shear is the shear stress that must be exceeded before detachment can occur. Erodibility and critical shear baseline values are site-specific parameters defined during rainfall simulations or by empirical equations based on soil properties. These (baseline) values are adjusted by the model to account for temporal changes in surface residue, root growth, sealing, crusting, freezing, and thawing.

WEPP assumes that detachment is limited to the amount of sediment the flowing water can transport (transport capacity) and is inhibited at lesser concentrations in accordance with the following relation:

$$D_f = D_c\left(1 - \frac{G}{T_c}\right), \qquad (5)$$

where

D_f = rill erosion rate (kg s^{-1} m^{-2}),

D_c = the detachment rate (kg s^{-1} m^{-2}),

G = sediment load in the rill per unit width (kg m^{-1} s^{-1}), and

T_c = the transport capacity of the rill flow (kg m^{-1} s^{-1}).

It is generally an empirical relationship based on data collected in rivers, streams, and laboratory flumes. Thus, detachment in rills occurs only when hydraulic shear exceeds the soil critical shear (equation 4) and when sediment load in the rill is less than the transport capacity (equation 5). Rill detachment is zero when hydraulic shear is less than the critical shear stress of the soil. Detachment is also zero when the sediment load is equal to or greater than the transport capacity of the rill flow. Transport capacity in the WEPP model is calculated by the following simplified transport equation:

$$T_c = k_t \tau^{3/2}, \qquad (6)$$

where

T_c = the transport capacity of the rill flow (kg m^{-1} s^{-1}) and

k_t = a transport coefficient ($m^{1/2}$ s^2 $kg^{-1/2}$) based on transport capacity calculated by the Yalin (1963) equation at the end of a uniform slope as described by Finkner et al. (1989).

Net deposition in a rill occurs when sediment load exceeds sediment transport capacity. Deposition is calculated by the following equation:

$$D_f = (T_c - G)\frac{\beta V_f}{q}, \qquad (7)$$

where

D_f = rill erosion rate (kg s^{-1} m^{-2}),

T_c = the transport capacity of the rill flow (kg m^{-1} s^{-1}),

G = sediment load in the rill per unit width (kg m^{-1} s^{-1}),

β = a raindrop-induced coefficient reflecting the effect of increased turbulence in keeping sediment in suspension (set to 0.5 when raindrops are impacting rill flow and to 1.0 for snowmelt and furrow irrigation),

V_f = effective fall velocity for the sediment (m s^{-1}), and

q = flow rate per unit rill width (m^2 s^{-1}).

WEPP only calculates deposition when the rill sediment load is greater than the transport capacity.

WEPP includes irrigation components for simulating erosion from sprinkler and furrow irrigation. Sprinkler irrigation from solid-set or periodic-move systems is simulated similarly to rain, with the field size defined as the area being irrigated. The operator inputs irrigation rate, depth, and droplet energy. WEPP predicts sprinkler irrigation runoff fairly well if the effective soil hydraulic conductivity can be estimated (Kincaid 2002). Since WEPP is a steady state model, it cannot directly simulate erosion from moving systems, such as center pivots or traveling guns. A moving irrigation system would be similar to a very small storm crossing a field. WEPP can, with some reservations, evaluate erosion potential on small areas of center pivot irrigated fields (Kincaid and Lehrsch 2001).

WEPP contains a separate component for calculating infiltration and runoff from furrow irrigated fields. Furrow irrigation erosion is then calculated using the same steady state rill erosion algorithms that are used for rainfall. Inter-rill erosion processes are not considered (D_i = 0 in equation 3) because water is only flowing in furrows (i.e., rills). WEPP was unable to predict furrow-induced erosion without substantially altering the baseline critical shear and rill erodibility parameters that were defined for rainfall erosion for the same soil (Bjorneberg et al. 1999). Kemper et al. (1985b) noted that critical shear for furrow irrigation is essentially zero. WEPP also over-calculated transport capacity, so sediment deposition was not accurately predicted (Bjorneberg et al. 1999).

SRFR version 3 (Strelkoff et al. 1998) is a comprehensive surface irrigation model developed to simulate the hydraulics of water flow in an individual furrow. It solves the equations of mass and momentum conservation of general physics, coupled to empirical formulas for time-dependent infiltration and the hydraulic drag of bed roughness and vegetation upon the flowing water. Version 4 is being developed as a component of the integrated Windows program (WinSRFR) at the USDA ARS United States Arid Land Agricultural Research Center, Maricopa, Arizona, to simulate sediment transport. Following Fernandez Gomez (1997), SRFR uses many of the same fundamental erosion equations as WEPP, but they are applied to the flow hydraulics calculated by SRFR for each distance point and time step in the furrow. Input to SRFR includes site-specific soil erodibility (K_r) and critical shear (τ_c). Measured decreases in erodibility with time during irrigation can be accommodated for, reflecting sediment concentration decreases often observed during irrigation. Decreasing sediment concentration while flow rate remains constant suggests supply-limited erosion (i.e., the same shear force detaches less sediment). One possible explanation for this is that the remaining soil particles on the furrow bed are too large or heavy to be eroded and these particles protect smaller particles below.

With WEPP over-predicting transport capacity in furrows, a different transport capacity equation was sought. The Yalin formula had been selected for WEPP because it most effectively predicted erosion for very shallow rain-fed overland flow on concave hillsides (see, e.g., Foster 1982). The Laursen (1958) formula was chosen (Strelkoff and Bjorneberg 2001) because (1) it predicts both suspended and bed load, (2) it includes silts in its experimental database, and (3) it is a classic exercise in dimensional analysis with contributions from physical reasoning and intuition and with final results confirmed empirically. It was judged second overall from amongst a large group of transport formulas in the literature on rivers by a Task Committee of the Hydraulics Division Committee on Sedimentation (ASCE 1982) and first for long straight channels in agricultural soils (Alonso et al. 1981). Also, rather than making assumptions regarding the variation of transport capacity along the length of a furrow (equation 6), local transport capacities were calculated at points in the furrow by applying Laursen's formula to shear and other hydraulic variables as calculated by SRFR. Critical shear at incipient motion is also calculated in SRFR based on local values of the hydraulic variables—in contrast to Laursen, who employed several constant dimensionless values to analyze his database.

Figure 1, drawn from an animation frame displayed by SRFR during simulation, illustrates typical transport capacity behavior and resultant sediment loads at one point in time (61 minutes into the irrigation). There is a region behind the streamfront in which transport capacity and detachment are zero. The flow rate in that region is so small that the boundary shear lies below the threshold for entrainment (recall that discharge decreases with distance along the furrow because of infiltration). At the upstream end of the furrow, the rate of erosion is highest and sediment load increases the fastest at the clear water inflow, where transport capacity is maximum and sediment load is zero. Transport capacity decreases with distance downstream (with the decreasing flow velocity), and the sediment load increases due to upstream entrainment; both factors inhibit further growth in the load. Eventually transport capacity is exceeded and deposition begins. In accordance with the deposition equation, some excess of load over transport capacity persists over a short distance.

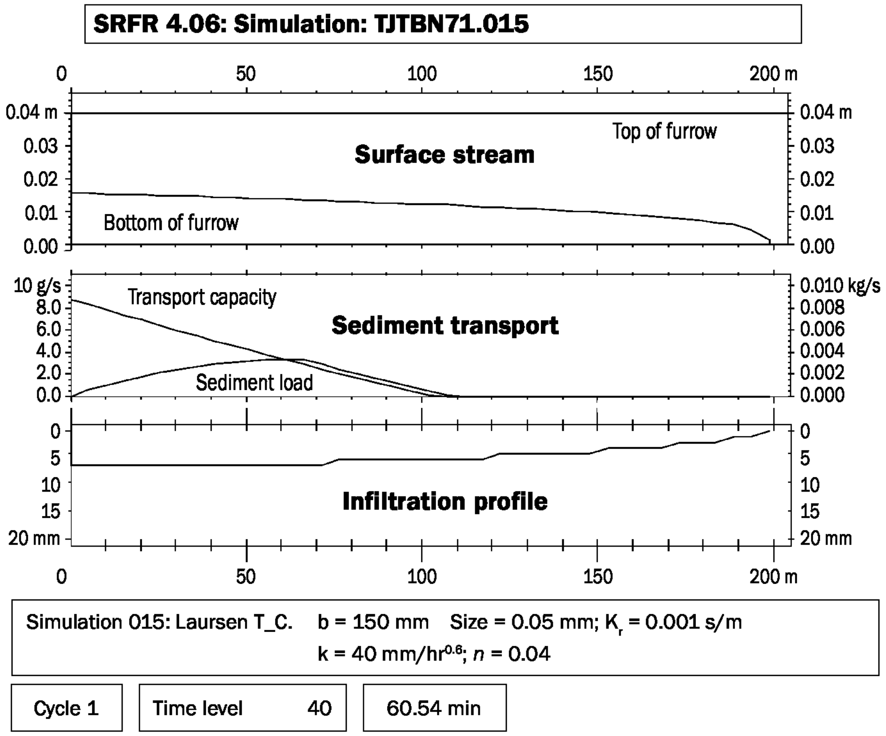
Initially, the SRFR erosion component used one representative aggregate size for the mix of sediment transported in the furrow flow. Figure 2 compares calculated sediment load hydrographs with average values at the quarter points in the furrow in an irrigated dry bean field (Trout 1996). The value of $K_r = 0.001$ s m^{-1} input for the simulation was calibrated from the comparison between measured and calculated hydrographs at the first quarter point, before transport capacity is able to play much of a role in limiting sediment loads. These limitations are clearly evident at subsequent quarter points in both measured and simulated data, the latter obtained with the Laursen transport capacity formula. The overly large transport capacity predicted by the formula of Yalin (1963) used in WEPP precluded deposition, indicating a continual increase of the sediment load with distance.

Despite qualitative agreement, it should be noted that the data points used to develop transport capacity formulas commonly exhibit an order of magnitude scatter (e.g., Laursen 1958). Absolute accuracy is not possible from simulations based on these formulas. Nonetheless, predicted relative changes in sediment transport resulting from changes in design or management of surface irrigation systems would be useful for decision making.

In addition, as noted by Strelkoff and Bjorneberg (2001), the use of a single representative particle size to characterize erosion/transport/deposition phenomena renders results highly sensitive to the selected size. For example, modest increases in representative particle size can lead to prediction of zero sediment in tailwater. A postulated mix of particle sizes would circumvent this problem and lead to gradual changes in total sediment load as the fractions of each size are

Figure 1

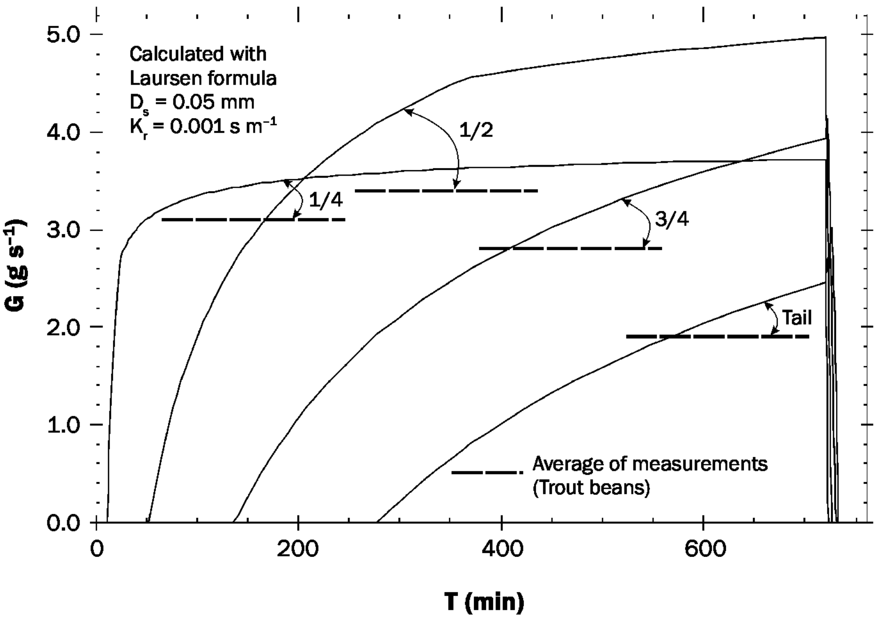
Frame of output animation of SRFR simulation: profiles of surface stream depth, sediment load and transport capacity, and infiltrated depths (time = 61 minutes) (Strelkoff and Bjorneberg 2001).



Simulation 015: Laursen T_C. b = 150 mm Size = 0.05 mm; K_r = 0.001 s/m
k = 40 mm/hr$^{0.6}$; n = 0.04

Figure 2

Comparison of simulated sediment transport hydrographs at furrow quarter points with averages from measured Trout bean data (July 1, 1994) (Strelkoff and Bjorneberg 2001).



Notes: Site-specific K_r = 0.001 s m^{-1}, τ_c = 1.2 Pa. Laursen (1958) transport-capacity formula is in effect. Trends are correct.

varied. The erosion component of SRFR is still being developed and tested to predict detachment, transport, and deposition of each size class of aggregates.

Summary and Conclusions

The importance of developing a robust, reliable, accurate, transient state erosion model for irrigation can hardly be overstated. The deficiency of predictive capability for furrow irrigation is especially troubling. As noted in the introduction, 90% of irrigation worldwide is surface irrigation, an inherently erosive process. Even in the United States, much of our most productive and profitable agriculture is furrow-irrigated. Regional and national assessments of erosion and water quality impairment from irrigated land runoff have been hampered for decades by the lack of appropriate simulation models. This inadequacy adversely affects management choices, resource conservation strategies and policy, as well as conservation practice compensation. We have demonstrated the potential of process-based models for predicting the effects of changes in design and management of furrow irrigation. Given the high productivity of irrigated lands and their fragility, development and validation of appropriate irrigation-induced erosion models should be among the highest priorities for agricultural research in general and for natural resource management in particular.

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