UNIQUE ASPECTS OF MODELING IRRIGATION-INDUCED SOIL EROSION

D.L. Bjorneberg[1], D.C. Kincaid[1], R.D. Lentz[1], R.E. Sojka[1] and T.J. Trout[2]

ABSTRACT

The mechanics of soil erosion from irrigated and rainfed lands are similar. Soil particles are detached, transported and deposited. However, there are some systematic differences between irrigation and rainfall erosion. Electrolyte concentrations in irrigation water, for example, are almost always greater than in rain water. Differences between rainfall and irrigation are more prominent for surface irrigation than for sprinkler irrigation. For instance, rainfall wets the soil before runoff begins, but water initially flows onto dry soil in irrigation furrows. Furthermore, furrow flow rate decreases with distance and increases with time, while the opposite tends to occur with rainfall. For sprinkler systems, travel direction and slope aspect interact, so runoff can flow within the irrigated area or from the irrigated area onto dry or wet soil. Thus, a sprinkler-irrigation erosion model must consider both the rainfall-runoff situation and the furrow flow situation. These differences in soil and water interactions must be considered before computer models can accurately simulate irrigation-induced soil erosion.

Key Words: Soil erosion, Irrigation, Electrolyte concentration, Furrow flow, Runoff, Modeling

1 INTRODUCTION

Irrigation is important to food production throughout the world. Irrigation is used on about 15% of the world's cropland (Kendall and Pimentel, 1994) and 5% of the world's food production land, which includes rangeland and permanent cropland (FAO, 1998). However, irrigated land produces more than 30% of the world's food (Tribe, 1994), which is 2 1/2 times as much per unit area compared to non-irrigated production (Kendall and Pimentel, 1994). In the United States, approximately 15% of the harvested cropland is irrigated, but almost 40% of the total crop value is produced on irrigated land (National Research Council, 1996).

Soil erosion can be a serious problem on irrigated land. Erosion rates as great as 145 Mg/ha in one hour (Israelson et al., 1946) and 40 Mg/ha in 30 minutes (Mech, 1949) were reported in some early furrow irrigation erosion studies. Although these loses are extreme, they are one-time measurements and do not represent a sustained seasonal rate. Annual soil losses of 1 to 141 Mg/ha were reported in a more recent southern Idaho study (Berg and Carter, 1980).

Soil erosion impacts both the environment and crop productivity. Eroded soil can pollute streams and fill reservoirs. Within a field or watershed, eroded soil can plug drains and fill ditches, causing drainage problems and localized flooding. Within-field erosion is damaging on furrow irrigated fields where essentially all of the erosion occurs on the upper quarter to third of fields with uniform slope (Trout, 1996). Eroded soil from the upper end of a field is deposited on the lower end of the field or flows from the field with runoff. Losing topsoil from the upper end of the field can decrease crop yields 25% compared to the lower end of the field (Carter et al, 1985).

Soil erosion from irrigated fields has been discussed and summarized in several articles (Carter, 1990; Koluvek et al., 1993; Sojka, 1998; Trout and Neibling, 1993). The purpose of this paper is to discuss some unique differences between soil erosion caused by irrigation and rainfall, and the implications that these differences may have for erosion modeling. The main focus is on surface irrigation because greater differences occur between surface irrigation and rainfall than between sprinkler irrigation and rainfall. Moreover, over 40% of the irrigated land in the U.S. is still surface irrigated (Anonymous, 1998).

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[1] USDA-ARS, Northwest Irrigation and Soils Research Lab, Kimberly, ID

[2] USDA-ARS, Water Management Research Lab, Fresno, CA

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2 RAINFALL AND IRRIGATION EROSION DIFFERENCES

Soil erosion mechanics can be divided into three components: detachment, transport and deposition. Water droplets and flowing water detach soil particles. Flowing water then transports these detached particles downstream. Deposition occurs when flowing water can no longer transport the soil particles. Some particles are deposited within a few meters while others are transported off the field with runoff water. These mechanisms are the same for surface irrigation, sprinkler irrigation and rainfall, but there are some systematic differences between irrigation and rainfall erosion, especially between surface irrigation and rainfall.

Runoff is essential for transporting sediment. Properly designed and managed sprinkler irrigation systems should not have any runoff from the irrigated area. However, economic and water supply constraints often force compromises in sprinkler irrigation design. Water begins to flow once the sprinkler application rate exceeds the infiltration rate and surface storage. Conversely, furrow irrigation is generally managed so a portion of the water runs off the field, unless furrow ends are blocked to eliminate runoff.

2.1 Dry soil

The most apparent difference between soil erosion from rain and from surface irrigation is the lack of water droplets impacting the soil during surface irrigation. This fundamental difference is important. Droplet kinetic energy affects both erosion and infiltration (Bubenzer and Jones, 1971; Kinnell, 1982; Mohammed and Kohl, 1987; Thompson and James, 1985). At the onset of rain, droplets wet the soil surface and detach soil particles. As runoff begins, rills form in wet soil. Water flowing in rills is also often exposed to falling raindrops, which may affect detachment and deposition in the rills.

For furrow irrigation, rills are mechanically formed in dry soil before irrigation begins. Only a small portion of the soil surface is wet during irrigation. As water advances down the field, it flows over dry, loose soil. Irrigation water instantaneously wets the soil, rapidly displacing air adsorbed on internal soil particle surfaces (Kemper et al., 1985). The rapid replacement of air with water can actually break apart soil aggregates (Carter, 1990), likely increasing the erodibility of the soil. This is a possible reason why furrow erosion initiates before a critical shear is exceeded (Kemper et al., 1985).

Preliminary results from a southern Idaho field study with 24-m long furrows showed that soil erosion from dry furrows was significantly greater than from furrows that were prewet by lightly spraying or by drip tape (Bjorneberg et al., unpublished data). For a simulated rain on 0.37 m^2 trays, prewetting soil reduced runoff and erosion rates compared to air-dry soil (Le Bissonnais and Singer, 1992). Erosion rates for subsequent irrigations continued to be greater from air dried soil than from prewet soil. The prewet soil was saturated by capillary action and allowed to drain for about two hours before initiation of simulated rain. A small flume (0.5 m long) study also showed that air dried soil (water content <25 g kg^{-1}) had greater rill erodibility than wet soil (water content >200 g kg^{-1}), and rill erodibility decreased with time after wetting the soil (Shainberg et al., 1996).

In addition to initial soil conditions, crop canopy influences rain drop distribution. Early in the growing season, rainfall distribution is relatively uniform. As the crop grows, more rain is intercepted by the crop canopy before it strikes the soil surface. Crop canopy generally does not affect water application during furrow irrigation, except occasionally when leaves and stems from growing crops interfere with water flowing in furrows.

2.2 Hydraulics

Rill flow rate from rain runoff tends to increase downstream as additional rain water and sheet and rill flow join the rill. Rill flow also decreases with time after rain stops. During furrow irrigation, flow rate decreases with distance down the furrow as water infiltrates and increases with time as infiltration rate decreases. Therefore, sediment detachment and transport capacities change as flow rate and shear gradually change with distance and time due to infiltration. Therefore, sediment discharge from a field is sensitive to correctly predicting infiltration with time and distance in a furrow.

Sprinkler irrigation is defined as distributing discrete water droplets through the air, and thus is similar to rain. However, rain presumably occurs simultaneously over an entire watershed, whereas irrigation may be applied to a small portion of a field. The sprinkler system most similar to rain is the solid-set system, with a grid of stationary sprinklers operating simultaneously over a large area. This system has a nearly uniform, low intensity application rate so runoff is rarely a problem.

At the other end of the spectrum are continuously moving laterals (center-pivot and linear-move systems) and traveling big-gun systems. These systems apply water to smaller areas at greater rates than solid-set systems. Because of the high cost per unit length, traveling laterals must irrigate a large area and thus have high discharge and instantaneous application rates. Therefore, runoff is almost always a potential problem with these systems.

Due to the ease of operation and low labor requirements, center-pivot systems are becoming the system of choice for new installations and conversion from surface irrigation. Approximately 50% of the sprinkler irrigated land in the U.S. is now irrigated with center-pivots. A center-pivot system is a traveling lateral which pivots about one end, irrigating a nearly circular area. Center-pivot laterals are commonly 400-m long and irrigate about 55 ha. The lateral length determines the application rates because the average application rate increases in direct proportion to the distance from the pivot. Thus, the greatest potential runoff occurs near the outer edge of the field.

The most important factor regarding sprinkler irrigation erosion potential is the average application rate within the wetted area. Sprinkler type affects application rate because application rate is inversely proportional to the sprinkler wetted area. Low pressure sprinklers, which are increasing in popularity, have reduced pattern widths and increased application rates. Sprinkler droplet sizes are also affected by the nozzle pressure, discharge rate and nozzle type. Larger drops have larger impact energy on the soil, which in turn affects infiltration, runoff, and soil detachment. The irrigation designer has control over the amount, intensity, area and timing of water application, but these are limited by water supply and economic considerations.

Sprinkler systems, particularly center pivots, operate on variable slopes and topography. Slope direction relative to the lateral affects how runoff accumulates. If the lateral is perpendicular to the slope direction, runoff will tend to move away from the lateral where water is being applied, allowing water to infiltrate before traveling very far. However, if the slope is parallel to the lateral, runoff can accumulate down slope and begin flowing in erosive streams. Crop ridges relative to the slope and lateral also affect runoff flow direction. It is common practice to plant row crops perpendicular to the lateral, which is a circular pattern under center pivots, to help direct any runoff away from the lateral. Irrigation system wheel tracks (commonly 40 to 50 m apart) also provide runoff diversion channels. Furthermore, if the lateral is traveling up slope, runoff will move on to a previously wetted area; whereas with down slope travel, runoff can move onto dry soil. Thus, a sprinkler irrigation erosion model for traveling sprinkler systems must be able to handle both the rainfall-runoff situation and the furrow flow situation, or any combination thereof.

2.3 Duration and Timing

Furrow irrigation tends to last 12 hours or longer while runoff from rain typically occurs for a much shorter time. The longer duration means temporal changes in infiltration, rill size and shape, and soil erodibility parameters may be more important for furrow irrigation than for rain. Changes in erodibility parameters may be insignificant during a one or two hour irrigation or rain but, such changes may significantly affect erosion during a 24 h irrigation. Sediment concentration, for example, tends to decrease with time during furrow irrigation. Flow rate, however, increases with time, which should increase sediment detachment and transport. This indicates that some other phenomena, such as armoring, reduce erodibility during furrow irrigation.

Furrow irrigation erosion also changes during the season. Brown et al. (1995) found that the greatest seasonal soil erosion (Mg ha^{-1}) occurred during irrigations from the end of June to the beginning of July. This phenomenon occurred for various crops during several years. The same seasonal peak erosion occurred during the same time period on an uncultivated, non-cropped field. Therefore, the seasonal peak was not due to crop growth or cultivation but to other unexplained conditions.

The potential influence of water temperature on infiltration and erosion is much greater during furrow irrigation than during rain storms. Cloud cover limits sunlight during rain storms, but irrigation often occurs on sunny days. Solar radiation can significantly increase water temperature with distance and time during furrow irrigation. In theory, infiltration rate increases with increasing water temperature due to decreased water viscosity. Jaynes (1990) measured diurnal infiltration rate changes up to 30% of the mean rate. The infiltration rate changes followed soil surface temperature changes. Duke (1992) measured water temperature increases up to 22° C from inflow to the downstream ends (550 m) of a furrow irrigated onion field in mid-afternoon. Theoretically, this temperature increase would increase hydraulic conductivity 70%. When a crop shaded the furrows however, water temperature increase across a 150-m long field was only 2 to 3° C (Duke, 1992).

Predicting small erosion events is much more important for irrigation than for rainfall. Irrigation-induced erosion occurs during several controlled events rather than one or two large erosion events. In southern Idaho for example, a corn field may be sprinkler irrigated 15 to 20 times or furrow irrigated 6 to 8 times during the growing season. The magnitude of a single irrigation erosion event is usually much smaller than erosion from a single 50-mm thunderstorm occurring on freshly tilled soil without an established crop. In fact, runoff should not occur from a properly designed and managed sprinkler irrigation system. However field conditions, water supply and system management are seldom ideal and compromises are often made that result in runoff and erosion.

2.4 Water Quality

Chemical quality of rainfall varies less from location to location than surface water and groundwater quality. Water quality significantly impacts erosion from furrow and sprinkler irrigated fields. Greater soil erosion occurred on a silt loam when furrow irrigation water had low electrical conductivity and high sodium adsorption ratio (EC = 0.7 dS m^{-1} and SAR = 9.1) compared to low EC (0.5 dS m^{-1}) and low SAR (0.9), high EC (2.1 dS m^{-1}) and low SAR (0.5), and high EC (1.7 dS m^{-1}) and high SAR(9.3) irrigation water. High SAR irrigation water also infiltrated less than low SAR water (Lentz et al., 1996).

Increasing EC from 0 to 0.5 dS m^{-1} decreased runoff, increased final infiltration rate, and decreased soil erosion from sandy loam and clay loam in a laboratory rainfall simulator study (Kim and Miller, 1996). Increasing EC up to 2.0 dS m^{-1} did not affect runoff, infiltration rate or erosion further. However, Flanagan et al. (1997a) found that final infiltration and runoff rates for field simulated rains on a silt loam were not significantly different between deionized water (EC = 0.01 dS m^{-1}) and tap water (EC = 0.6 dS m^{-1}). They also found that steady state sediment discharge rate from 10.7-m long rills with initially dry soil was significantly greater for the lower EC deionized rain water than for tap rain water (Flanagan et al., 1997b). Soil erosion was not different between deionized and tap water from interrill subplots (0.8 m by 0.6 m). The interrill subplots were closer in size to the small trays (0.2 m by 0.4 m) used by Kim and Miller (1996) than were the rill plots. A possible reason for the conflicting results between these two studies is that EC = 0.5 dS m^{-1} was great enough to cause clay flocculation for the soils used by Kim and Miller (1996), but not for the soil used by Flanagan et al. (1997 a and b). There also could have been some interaction with application rate. Kim and Miller applied water at 41 mm h^{-1} for 60 min (41 mm application depth). Flanagan et al. applied water at 64 mm h^{-1} until steady-state runoff occurred (53 to 107 mm application depth). Soil detachment may have been influenced more by application rate than by water quality. Simulated rainfall kinetic energy for both studies was about 20 J m^{-2} mm^{-1}.

3 MODELING FURROW IRRIGATION EROSION

The phenomena of soil erosion by water are easily identified: detachment, transport and deposition. Equations used to predict soil erosion are predominantly empirical. Hence, the conditions used during experiments to develop these equations need to be followed when simulating soil erosion. These experimental conditions, however, may not represent actual erosion conditions. Sediment transport equations, for example, have typically been developed for streams and rivers using particle sizes ranging from sand to cobbles (Vanoni, 1975). Moreover, erosion equations and parameters defined from simulated rain may not be applicable to furrow irrigation conditions due to differences stated in previous sections.

Most erosion caused by rain occurs during a few severe rain storms. If erosion is accurately predicted for these storms, the annual soil loss is also accurately predicted. Irrigation-induced erosion occurs during several scheduled irrigations and therefore each small event must be accurately predicted to achieve satisfactory annual soil loss predictions.

In some ways, modeling soil erosion from sprinkler irrigation is easier than erosion caused by rain because intensity, duration and droplet energy are known before the irrigation occurs. Irrigation is also applied to a known area at a relatively uniform rate. Two complicating factors for sprinkler irrigation are moving irrigation systems (i.e. center-pivot and linear-move systems) and runoff from an irrigated area onto a non-irrigated area.

Modeling furrow irrigation erosion is complex because infiltration, furrow flow rate and soil erosion are all inter-related. As aggregates break down and fine soil particles form a surface seal, infiltration rate decreases. Surface seal can reduce infiltration by almost 50% compared to no surface seal during a five hour irrigation (Segeren and Trout, 1991). Shear and flow velocity also vary greatly along furrows resulting in headcuts, meandering streams and dunes. These irregularities also affect infiltration.

3.1 Modeling History

The goal of early soil loss prediction efforts was to minimize soil loss while adequately irrigating the crop. Researchers attempted to define maximum nonerosive flow rates. Gardner and Lauritzen (1946) proposed the following critical flow–critical slope relationship

$$Q_m = cS^d \tag{1}$$

where Q_m is the maximum nonerosive flow rate, S is slope, c is an empirical soil parameter, and d is an empirical exponent. Using data from irrigation trials on different soils and slopes, Hamad and Stringham (1978) defined c and d coefficients for six different soil groups. They found that c varied from approximately 0.6 to 1.1 and d varied from -0.55 to -0.94, when flow rate was in liters per minute and slope was in percent. Earlier work by Criddle (1956) resulted in a less site-specific form of equation (1) in which c and d were general constants (c = 37.5 and d = -1). For slopes of about 0.5%, Criddle's equation represents the average of the equations defined for the six soil groups by Hamad and Stringham (1978).

Early soil loss prediction equations correlated erosion with factors such as furrow flow rate, furrow length and field slope. Koluvek et al. (1993) noted that the first published equation to predict furrow irrigation erosion was based on research from Utah. Soil mass eroded per unit of time was measured and correlated with slope and flow rate as follows

$$E = k\,S^aQ^b \tag{2}$$

where E is erosion rate, k is a unit-dependent coefficient, S is furrow slope, Q is flow rate at the measurement point, and a and b are empirical coefficients (Israelson et al, 1946). They noted that erosion more than doubled when S or Q was doubled, indicating that both a and b were greater than one.

More recent research, using a regression model based on data from Wyoming, identified that furrow slope, inflow rate, furrow length and mean particle size were the most important parameters for estimating annual soil loss from irrigation furrows (Fornstrom and Borrelli, 1985). The following equation is similar to equation 2, but it also accounts for soil and furrow-length differences

$$E = 30.9S^{1.66}Q^{2.45}D_{50}{}^{-0.47}L^{-1.62} \tag{3}$$

where E is annual soil loss (Mg ha^{-1} yr^{-1}), S is slope (%), Q is inflow rate (L min^{-1}), D_{50} is mean soil particle diameter (μm), and L is furrow length (m). Note that the parameters equivalent to a and b in equation 2 are both greater than one.

These empirical models are helpful for estimating annual soil loss from a field or identifying ways to reduce soil loss from furrow irrigated fields. However, they do not give any information about soil erosion within the field and are difficult to apply to nonuniform field slopes. As we have learned more about soil erosion and computer speed has increased, modeling efforts expanded to predicting detachment, transport and deposition.

3.2 Current Modeling Status

Two soil erosion models currently being tested for use with irrigation are WEPP and SRFR. The Water Erosion Prediction Project (WEPP) was initiated to develop a new generation of erosion prediction technology for soil and water conservation planning. The surface irrigation model (SRFR) was developed at the USDA-Agricultural Research Service's U.S. Water Conservation Laboratory in Phoenix, AZ to simulate water advance, flow and infiltration for surface irrigation.

3.2.1WEPP

The WEPP model (Laflen et al., 1991) allows users to input various tillage, crop rotation and soil conservation scenarios for a field or watershed. Each day the model predicts plant and soil characteristics important to erosion processes. When rainfall occurs, the model calculates the runoff amount, if any, and then computes sediment detachment, transport and deposition.

The WEPP model categorizes soil erosion into interrill and rill processes. Interrill erosion involves soil detachment and transport by raindrops and shallow sheet flow. Rill erosion processes describe soil detachment, transport and deposition in rill channels (Flanagan and Nearing, 1995). Detachment in rills occurs only when hydraulic shear exceeds the critical shear of the soil and the sediment load is less than the rill transport capacity (Nearing et al., 1989). If the sediment load exceeds the transport capacity, sediment deposition occurs. No detachment occurs when shear in the rill is less than critical shear value of the soil.

Baseline rill erodibility and critical shear represent erodibility characteristics of freshly tilled soil. These two parameters were calculated from WEPP rain simulation field studies on several characteristic soils. Based on these field studies, relationships were developed to calculate baseline parameters from soil texture and organic matter. Rill erodibility and critical shear are adjusted daily in the model to account for residue incorporation; temporal changes in roots, sealing and crusting; and freezing and thawing (Flanagan and Nearing, 1995). Since the WEPP model is a steady-state erosion model, erodibility parameters cannot change during an irrigation. The model also does not account for differences in irrigation water quality.

The WEPP model includes irrigation components for calculating runoff and soil loss from stationary sprinklers and from furrow irrigated fields. Hydrology and soil erosion for sprinkler irrigation is managed the same as for rain. The model contains a separate furrow irrigation hydrology component for calculating infiltration. Soil erosion is then calculated with the same procedures as rill erosion under rainfall conditions.

WEPP model performance for irrigated fields has not been thoroughly evaluated. However, a preliminary evaluation showed the model did not predict any soil erosion unless default baseline erosion parameters were reduced (Bjorneberg et al., 1997). Predicted infiltration also correlated poorly with measured infiltration. The WEPP model could be a useful tool for simulating long-term soil erosion from irrigated areas if these problems can be addressed.

3.2.2 SRFR

SRFR (Strelkoff, 1990) is a surface irrigation model that simulates water advance, infiltration and recession. It was designed to predict irrigation performance for one furrow during a single irrigation event. The user inputs furrow geometry, soil infiltration and roughness characteristics, and irrigation management. Some of the model output parameters are runoff, infiltration, irrigation efficiency, distribution uniformity and deep percolation.

Recently, erosion algorithms, similar to those used in WEPP, were added to SRFR (version 4) to predict soil erosion. This model is not a steady-state erosion model like the WEPP model, so the erosion parameters can vary during an irrigation. However, the model only predicts erosion from one furrow during a single irrigation. It also does not calculate the effects of tillage or climate on soil erosion parameters or predict erosion from a field or watershed for several years. The advantage of the SRFR model is the more detailed representation of furrow irrigation hydraulics and non-steady state erosion predictions. It is useful for quantifying irrigation management effects (such as application rate, irrigation time, furrow length and slope changes) on soil erosion and irrigation performance. For example, would erosion be excessive if inflow rate is increased 20% to increase irrigation uniformity? The erosion component of the model is still being developed and is not ready for distribution. However, the model realistically predicted erosion in a few preliminary tests.

SUMMARY

Soil erosion involves similar mechanisms whether it is caused by rain or irrigation. However, irrigation, especially furrow irrigation, has some unique, systematic differences that must be considered when modeling soil erosion. Water and soil interact differently under irrigated conditions. These differences must be considered before computer models can accurately simulate irrigation-induced soil erosion.

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