Irrigation: Erosion

David L. Bjorneberg
Northwest Irrigation and Soils Research, United States Department of Agriculture–Agricultural Research Service, Kimberly, Idaho, U.S.A.

Abstract
Irrigation is essential for global food production. However, irrigation erosion can limit the ability of irrigation systems to reliably produce food and fiber in the future. The factors affecting soil erosion from irrigation are the same as rainfall—water detaches and transports sediment. However, there are some unique differences in how the factors occur during irrigation and in our ability to manage the application of water that causes the erosion. All surface irrigation entails water flowing over soil. Soil type, field slope, and flow rate all affect surface irrigation erosion, with flow rate being the main factor that can be managed. Ideally, sprinkler irrigation will have no runoff, but application rates on moving irrigation systems can exceed the soil infiltration rate, resulting in runoff and erosion. Using tillage practices to increase soil surface storage and selecting sprinklers with lower application rates will reduce sprinkler-irrigation runoff. Irrigation can be managed to minimize erosion and maintain productivity.

INTRODUCTION

Irrigation is vital to food production in the world. However, irrigation-induced soil erosion reduces productivity of irrigated land and can cause off-site water quality problems. Surface irrigation utilizes the soil to distribute water through the field. Water flowing over soil inherently detaches and transports sediment. Sprinkler and drip irrigation distribute water through fields in pipes, eliminating erosion from water distribution, but erosion can still occur if water is applied faster than it can infiltrate into the soil. This entry will briefly discuss the importance of irrigation to global food production and then discuss the important factors affecting soil erosion for surface- and sprinkler-irrigated land. Much of the information will focus on the United States, with international information included when possible.

IMPORTANCE OF IRRIGATION

Irrigated agriculture contributes a disproportionate amount to global food production. The most cited statistics indicate that irrigated cropland produces about one-third of the world's crop production on only 16% of the cropland that is irrigated.[1] In the United States, farms with all cropland irrigated account for only 8% of the total cropland and about half of the total irrigated land.[2] These farms produce 33% of the market value of crops and 12% of the market value of livestock. Over half of the crop value (55%) is produced on farms with some irrigated land, and these farms account for only 26% of the total cropland in the United States.[3] In some areas, irrigation provides essentially all of the water necessary for crop growth. In other areas, irrigation provides only a small portion of the total crop water requirement but reduces the potential for water stress during critical periods.

While irrigation is critical to global food production, applying water to soil can cause erosion. This is especially true with surface irrigation, where the soil conveys and distributes water through a field by gravity. Sprinkler irrigation and microirrigation use pipes to distribute water through the field. Surface irrigation is generally thought to cause more erosion than sprinkler irrigation; however, erosion can occur any time water flows over soil. Water can be applied with sprinkler irrigation so no runoff occurs, and therefore, no erosion will occur. However, there are situations, especially with moving irrigation systems like center pivots, where water is applied faster than it can infiltrate into the soil, resulting in ponding and, possibly, runoff.

UNIQUE ASPECTS OF IRRIGATION EROSION

The factors affecting soil erosion from irrigation are the same as rainfall. Water detaches and transports sediment in both situations. However, there are some unique differences in how the factors occur with irrigation.[4] For example, rainfall occurs relatively uniformly over an entire field, whereas irrigation is seldom applied to an entire field at the same time. Irrigation is a controlled procedure where water is applied to a specific field, or portion of a field, at a specific time. This can affect the hydrology of the erosion processes on surface- and sprinkler-irrigated fields. A center pivot, for example, is essentially a moving storm

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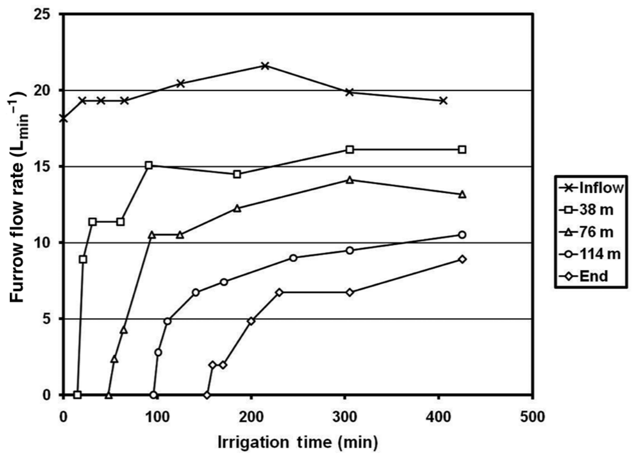

Fig. 1 Furrow flow rate with time at five points in a 150 m–long furrow.

that covers only 1–2% of the field at any given time. This results in unique runoff conditions where water can do the following: 1) flow parallel to the lateral under similar conditions as rainfall; 2) flow from wet soil onto dry soil if the lateral is moving downhill; or 3) flow onto wet soil if the lateral is moving uphill.

In surface irrigation, water flow rate decreases with distance during surface irrigation as water infiltrates. Furrow flow rates also increase with time as infiltration rate decreases (Fig. 1). This creates a condition where sediment can be detached on the upper end of the field and deposited on the lower end. Trout[4] documented erosion rates on the upper end of a field that were 6 to 20 times greater than the field-average erosion rates. Fig. 2 shows eroded furrows on the upper end of a field after one furrow irrigation. During rainfall, raindrops wet the soil surface and detach soil particles. As runoff begins, rills form in wet soil. In contrast, irrigation furrows are formed prior to irrigation, and water flows onto initially dry soil. Furrows with initially dry soil

Fig. 2 Eroded furrows on the upper end of a furrow-irrigated field in Idaho with approximately 1% slope.

have greater soil erosion than furrows that were prewet immediately before furrow irrigation.[5] Irrigation water flowing in furrows is not exposed to falling raindrops that can increase sediment detachment and decrease deposition.

The quality of irrigation water can vary dramatically among water sources, or even within an irrigation tract if drainage water is reused. Conversely, electrolyte concentration of rainfall is quite consistent. Electrolyte concentration in irrigation water affects erosion for both surface and sprinkler irrigation. Furrow-irrigation erosion was greater on a silt loam when irrigation water had low electrical conductivity (EC = 0.7 dS m^{-1}) and high sodium adsorption ratio (SAR = 9.1) compared with 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).[6] Soil erosion was also greater with low-EC water in laboratory and field rainfall simulation studies.[7,8] Lower electrolyte concentrations in water cause greater dispersion of soil particles, which tends to reduce infiltration and increase soil loss.[9]

SURFACE-IRRIGATION EROSION

Surface irrigation continues to be the most common method of irrigation in the world. The four countries with the most irrigated land are India (60.8 Mha), China (57.8 Mha), United States (22.4 Mha), and Pakistan (19.6 Mha).[10] These four countries account for 58% of the irrigated area in the world. All other countries have less than 10 Mha of irrigated land.[10] According to the country fact sheets on the Food and Agriculture Organization's Aquastat Web site,[11] surface irrigation is used on 97% of the irrigated land in India, 94% in China, 44% in the United States, and 100% in Pakistan.

Koluvek et al.[12] provided a good overview of soil erosion from irrigation in the United States. Unfortunately, this information has not been updated, and similar information is not readily available from other countries, so it is difficult to track erosion trends on irrigated lands. Some early studies documented erosion rates as great as 145 Mg ha^{-1} in 1 h[13] and 40 Mg ha^{-1} in 30 min.[14] While these rates represent extreme conditions that can occur, not typical season-long soil loss rates, these studies indicate the potential severity of the problem. One study measured annual soil losses of 1 to 141 Mg ha^{-1} from 33 fields with silt loam soils.[15] The greatest soil loss occurred on a sugar beet (*Beta vulgaris* L.) field with 4% slope. The authors noted that erosion increased sharply when field slope was greater than 1%. Close-growing crops like alfalfa (*Medicago sativa* L.) or wheat (*Triticum aestivum* L.) on fields with 1% slope had annual soil loss of less than 1 Mg ha^{-1}. A recent study in the same area documented that average soil loss from an 80,000 ha irrigated watershed decreased from 450 kg ha^{-1} in 1970 to less than 50 kg ha^{-1} in 2005.[16] This watershed was approximately 90% furrow irrigated

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in 1970 and 60% furrow irrigated in 2005. Another study measured daily sediment loads of 0.4 kg ha^{-1} in a watershed with no furrow irrigation compared to 19 kg ha^{-1} in a watershed with 58% of the cropland furrow irrigated.[17] Irrigation method explained 67% of the variation in soil loss measured in April and May in these nine watersheds.

The main factors affecting surface-irrigation erosion are soil type, field slope and flow rate. Soil erosion is typically not a concern where field slopes are less than 0.5% (Fig. 3). However, erosion tends to increase exponentially for increasing inflow rate and field slope, with an exponent between 1 and 3 for flow rate, and between 2 and 3 for slope.[12,18,19,20] Increasing inflow rate 20% increased erosion 30% and 70% on the upper quarter of two fields.[4] Increasing inflow rate another 20% increased erosion 50% and 100%, which indicates that the exponent between erosion and flow rate was between 2 and 3.[4] Fig. 4 shows soil loss from 10 furrows during a 4 h irrigation at Kimberly, Idaho, with inflow rates randomly set for each furrow.

Reducing field slope by grading the land is a costly practice that is not feasible in most situations compared with alternatives like installing a sprinkler-irrigation system. Reducing inflow rate is a good practice as long as the water advances down the field fast enough to uniformly irrigate the field. Slow water advance rates from low inflow rates cause overirrigation on the inflow end of the field and underirrigation on the lower end of the field due to differences in infiltration opportunity time. This results in poor distribution uniformity but little runoff. Soil loss decreases as distribution uniformity decreases.[20] An excellent practice for reducing irrigation erosion without affecting irrigation uniformity is applying small amounts of polyacrylamide (PAM) with irrigation water.[21,22] Dissolving 10 mg L^{-1} of high-molecular-weight, anionic PAM in furrow-irrigation inflow can reduce soil loss 60–99% compared with untreated furrows. Other technologies like filter strips and sediment ponds on the lower end of the field remove sediment from the water rather than reducing erosion from occurring on the field.

Fig. 3 Level furrow irrigation in Arizona. Photo by Jeff Vanuga, USDA Natural Resources Conservation Service (NRCSAZ02037).

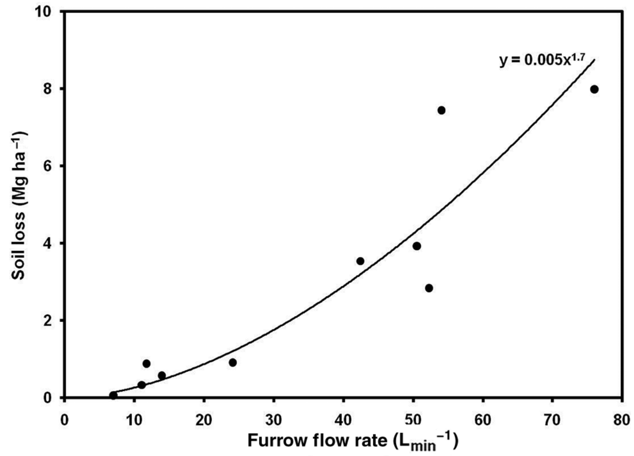

Fig. 4 Relationship between furrow flow rate and soil loss for 10 and 30 m-long furrows with randomly set inflow rates.

SPRINKLER-IRRIGATION EROSION

Ideally, sprinkler-irrigation systems are designed and managed to have all applied water infiltrate into the soil where it was applied. When all water infiltrates, there is no runoff or soil erosion. Solid-set (sprinklers located in the same position for the entire irrigation season) or set-move (sprinklers remaining in a location for 12 to 24 h, then moved to the next set) irrigation systems usually apply water at a low rate (e.g., 3 to 6 mm h^{-1}), so irrigation application rate does not exceed the soil infiltration rate and no soil erosion occurs. Moving irrigation systems, like center pivots, traveling guns, and lateral-move systems, often apply water faster than the infiltration rate. This occurs because the irrigation system must apply enough water as it moves across the field to meet crop water needs until the next time it irrigates that portion of the field. For example, a center pivot operating at 60 h per revolution needs to apply 20 mm per revolution to meet an 8 mm d^{-1} crop water requirement. The irrigation application rate increases with distance from the center pivot because the lateral irrigates more land as the radial distance from the pivot point increases.[23] Near the pivot point, the mean application rate could be about 4 mm h^{-1} (assuming 15 m wetting diameter). Near the end of the pivot, about 400 m, the mean application rate would be about 60 mm h^{-1}. An important fact about moving irrigation systems is that the application rate is a function of irrigation system capacity, or system flow rate. Operating the system faster decreases only the application depth, not the application rate. For example, the same center pivot operating at 48 h per revolution will apply 16 mm of water at the same application rates.

Center-pivot irrigation is the most popular type of irrigation system in the United States. According to the United States Department of Agriculture (USDA) National Agricultural Statistics Service, center-pivot irrigation was used on 47% of the irrigated land and 83% of the sprinkler-irrigated land in 2008, an increase from 25% of the irrigated land in 1988.[2] More land was irrigated by center pivots in the United States in 2008 (10.4 Mha) than all types of gravity irrigation combined (8.9 Mha). As center pivots gained popularity, researchers began to consider runoff potential, mainly to efficiently apply irrigation water. Most sprinkler-irrigation studies were not concerned with soil erosion, probably because the effects of sprinkler-irrigation erosion tend to occur within the field rather than off site.

A 1969 study evaluated center-pivot runoff from a theoretical perspective and showed the importance of modifying infiltration parameters, determined from pond infiltration tests, for the low initial application rate that occurs with moving irrigation systems.[23] Their theoretical evaluation showed that 0–40% of the applied water could run off with typical operating conditions. A 1971 field study documented 11–41% runoff on four center pivots operated by farmers.[24] Runoff with center-pivot irrigation became a more important issue as low-pressure sprinklers began to be used to reduce energy costs. Early types of low-pressure sprinklers applied water to a smaller area, which increased application rates and potential runoff.[25] Low-pressure sprinklers (40 and 100 Pa) averaged 69 or 70 mm of runoff compared with 8 to 10 mm of runoff for high-pressure sprinklers (170 and 345 Pa) during a 4 yr field study.[26] Reducing pressure from 380 to 140 Pa increased irrigation runoff 30% for a center pivot with impact sprinklers.[27] Peak application rate at the outer end of a center pivot would be about 30 mm h^{-1} for a high-pressure impact sprinkler with 20 m wetted radius and more than 100 mm h^{-1} for a low-pressure spray sprinkler with 5 m wetted radius.[25] Fig. 5 shows two sprinkler application rate curves with time and an infiltration rate curve. The volume of water applied when application rate exceeds infiltration is potential runoff. All of this water may not run off if some is ponded or stored on the soil surface.

Many types of sprinklers are now available for center pivots. Some apply water in defined streams with a wetted diameter over 20 m with nozzle pressure of 200 Pa or less. Others distribute water evenly over the wetted area with various combinations of droplet sizes. Various sprinkler designs are the result of manufacturers trying to reduce the kinetic energy applied to the soil during irrigation, so all applied water can infiltrate. Kincaid[28] developed a model in 1996 to estimate kinetic energy per unit drop volume for common sprinkler types. Calculating area-weighted kinetic energies per unit drop volume for individual sprinklers showed that sprinklers with the smallest drop size distributions had the lowest kinetic energy. Sprinklers with smaller sized drops tend to have smaller

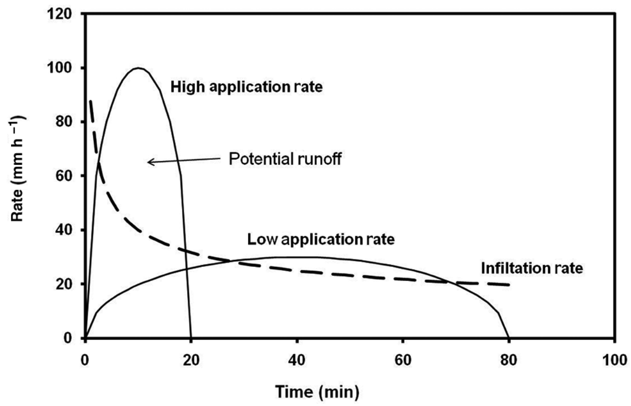

Fig. 5 Example of soil infiltration rate and sprinkler application rates for high- and low-application-rate sprinklers. Runoff potentially occurs when sprinkler application rate exceeds the soil infiltration rate.

wetted diameters because small drops cannot travel as far as large drops. Larger drops travel farther and therefore cover a greater portion of the circular wetted area for an individual sprinkler. A smaller wetted diameter also results in a higher application rate when sprinkler application patterns are overlapped like occurs on a center pivot. An alternative method for characterizing sprinkler kinetic energy is calculating the rate that energy is applied to the soil, or specific power, as a function of radial distance from the sprinkler.[29] The specific power distribution is energy per drop volume multiplied by the application rate and can be overlapped, like water application rate, to develop a composite specific power profile for a sprinkler system. A flat-plate sprinkler with small-sized drops had higher average composite specific power than two other sprinklers with larger drop sizes and larger wetted diameter.[29] Recent field research on small plots showed that soil erosion was significantly greater with the flat-plate spray sprinkler compared with the two other sprinklers with larger drop size distributions.[30] This directly contradicts previous conventional thinking that sprinklers with smaller drops caused less erosion.

The most effective way to control sprinkler-irrigation erosion is to eliminate runoff, which also increases water application efficiency. One way to control runoff is to increase water storage on the soil surface.[25] Reservoir tillage is a practice that forms small pits in the soil to store water. Each pit can hold 5 to 10 L of water.[31] This is especially important on sloping fields. Reservoir tillage reduced runoff 68% and soil erosion 92% during a 50 mm simulated irrigation on a field with 10% slope.[32] Runoff was not different when field slope was only 1%. Increasing surface residue also decreases sprinkler-irrigation runoff similar to rainfall runoff.[27] Disking corn stubble prior to planting, which left approximately 30% of the soil surface covered with crop residue, reduced runoff to 17% of applied irrigation compared with 25% runoff for moldboard plow plots in a 4 yr study.[33] In addition to reducing runoff, disking also reduced soil loss about 50% compared with moldboard plowing.

Applying PAM with sprinkler irrigation can also improve infiltration, which reduces runoff and soil erosion. Field studies have shown that erosion decreased under moving sprinkler systems when 20 kg PAM ha^{-1} was applied to the soil before irrigation.[34,35] Lower PAM application rates can be effective when PAM is applied with irrigation water rather than sprayed directly on the soil surface. In laboratory studies with 2 m^2 soil boxes, applying 2 to 4 kg PAM ha^{-1} at 10 to 20 mg L^{-1} with sprinkler-irrigation water reduced soil erosion 75% compared with untreated soil, but these benefits decreased with subsequent irrigations without PAM.[36] In a similar laboratory study, applying 1 kg PAM ha^{-1} with three consecutive irrigations reduced cumulative runoff 50% compared with untreated soil, while applying 3 kg PAM ha^{-1} with one irrigation only reduced runoff by 35%.[37] Field tests in the United States showed that applying PAM with four irrigations (2 to 3 kg ha^{-1} total applied) significantly reduced soil erosion from 52 and 34 kg ha^{-1} for the control to 21 and 5 kg ha^{-1} for the PAM treatment during the 2 yr of the study.[38] Soil erosion was not significantly different for a similar field study in Portugal with lower PAM application rates (0.3 kg ha^{-1}).[38]

CONCLUSIONS

Irrigation is vital to world food production, but soil erosion during irrigation threatens the long-term productivity of irrigation. Soil erosion is generally greater from surface irrigation because water flows over the soil during irrigation. Surface-irrigation management is often a tradeoff between irrigation uniformity and erosion. High flow rates can cause erosion; low flow rates can cause poor irrigation uniformity. Ideally, sprinkler irrigation should not have any runoff; however, moving irrigation systems, like center pivots, often apply water faster than it can infiltrate into the soil. Current research is attempting to quantify runoff and erosion potential for various types of center-pivot sprinklers so manufacturers can improve sprinkler designs. Irrigation can be managed to minimize erosion and maintain productivity.

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