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8 Irrigation-Induced Erosion

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This chapter builds on, updates, and integrates several earlier reviews (Bjorneberg et al., 1999, 2000a, 2000b; Bjorneberg and Sojka, 2002; Carter, 1990, 1993; Carter et al., 1993; Fitzsimmons et al., 1972; Koluvek et al., 1993; Sojka, 1996, 1998; Sojka and Bjorneberg, 2002a, 2002b; Sojka and Carter, 1994; Sojka and Lentz, 1995; Strelkoff and Bjorneberg, 2001; Trout and Neibling, 1993). We cover new information, mitigation research, and modeling efforts with an emphasis on more recent findings and newly developed technologies.

IMPORTANCE OF SUSTAINABLE IRRIGATION

Irrigation-induced erosion is one of the most serious sustainability issues in agriculture, impacting not only the future strategic and commercial viability of irrigation agriculture, but also the survival and comfort of earth's human population. Preventing irrigation-induced erosion to maintain the high crop yield and quality advantages of irrigated agriculture is also a key to the preservation of natural ecosystems. This is because replacement of irrigated production requires two to three times the equivalent rainfed production area to match any lost irrigated production (Sojka, 1998).

Food production and population growth experts agree that meeting the projected food and fiber needs and the increased living standard aspirations of earth's growing human population requires continued improvement in all sectors of agriculture, but especially in irrigated agriculture (FAO, 1988; Rhoades, 1997; English et al., 2002; Plusquellec, 2002). World population reached six billion in 1999 and estimates of population in 2050 vary from 7.3 to 10.7 billion (Howell, 2000), depending primarily on the success of efforts to curb birth rates in underdeveloped nations. Various models show that to meet the needs of a population of 8 billion

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Irrigation of Agricultural Crops, 2nd ed., Agronomy Monograph no 30.

by 2025, irrigated area must expand over 20% and irrigated crop yields must improve by 40% over current yields (Plusquellec, 2002).

About one-sixth of both the USA's and the world's cropped area is irrigated, but irrigated cropland produces about one-third the annual harvest and nearly half the value of all crops (food, fiber, etc.) harvested (Howell, 2000; Bucks et al., 1990; Kendall and Pimentel, 1994; National Research Council, 1996). Tribe (1994) noted that a mere 50 million irrigated ha of earth's most productive irrigated land, accounting for only 4% of the world's total cropped land, produces one-third of the world's harvested food. Because most irrigated agriculture exists in arid and semiarid settings, it tends to have exceptionally high photosynthetic efficiency. This is the result of the low number of cloudy days in dry climates (hence, providing a high quantum of photosynthetically active radiation) coupled with irrigation's ability to prevent stress and closely regulate inputs (e.g., via fertigation and chemigation). Thus, beyond higher crop yields, irrigation also tends to be associated with higher commodity quality and value as well as greater yield assurance than rainfed agriculture. Irrigation is also often the key to successful commercial production of certain crops that cannot tolerate stress or that require very close regulation of inputs.

The significance of irrigated agriculture in meeting the increased demand for food and fiber in the 21st century is disproportionately more important to raising the fortunes of underdeveloped nations and the poor. In addition to the impact of their increased numbers, this sector has expectations for improved per capita supplies of food and fiber to bring its standard of living closer to that of the developed world (Seckler, 2000; Seckler et al., 1998).

The annual growth rate of agricultural production steadily declined from 3% during the heyday of the Green Revolution in the 1960s to an annual rate of 1.8% in 1995 (Alexandratos, 1995). This drop in production growth rate tracked (and is probably explained largely by) a concomitant decline in the worldwide rate of increase of irrigated land area. Irrigated agriculture expansion was >3% per year in the 1960s but fell to a rate of <1% in the late 1980s (Jensen et al., 1990; Howell, 2000).

Currently about 270 million ha of cropland worldwide are irrigated (FAO, 2003), five times the area at the beginning of the 20th century (Rosegrant et al., 2003); about 90% is surface irrigated (FAO, 2003). According to the National Agricultural Statistics Service's "Farm and Ranch Irrigation Survey" results released 15 Nov. 2004, there are 21 288 838 ha of irrigated cropland in the USA, of which 50.5% are sprinkler irrigated, 43.4% are surface irrigated (about half of which is furrow irrigated), 5.6% are drip or microirrigated, and 0.5% are subirrigated (USDA, 2004).

IRRIGATION-INDUCED EROSION EFFECT ON WATER QUALITY

At the same time that agriculture is undergoing unprecedented production demands, there is a new and equally urgent need to preserve and enhance water supplies and quality for the full range of human endeavors. One of the greatest threats to surface water quality is contamination from farm runoff containing eroded sediment, nutrients, organisms, and agrichemicals (Khaeel et al., 1980; Mawdsley et al., 1995; USEPA, 1998, 2000). In the USA, the USEPA (2000) estimated that water quality was impaired in 35% of surface waters (rivers, streams, lakes, reservoirs, and ponds), and that an additional 9 to 10% was threatened.

Nonpoint-source pollution from agriculture was identified as the leading contributor to this broad category of impaired surface water, accounting for a third to nearly half of the pollution. Erosion and runoff of sediment and associated chemical, mineral, and biological contaminants from agricultural lands to these surface waters are the processes responsible for the impairment. Because much of irrigated agriculture systematically delivers contaminated return flows to surface receiving waters, the link between erosion on the land and surface water contamination, while not necessarily different in severity, is more readily observable than for rainfed agriculture. Bjorneberg et al. (2002b) noted that when applying 1000 mm of water as surface irrigation in an average U.S. Pacific Northwest (PNW) cropping season, with a typical 20% runoff and a modest 10 Mg ha^{-1} seasonal soil loss, the water quality impact can be extremely negative in the absence of any downstream sediment collection. In this case, runoff would carry a mean load of 5000 mg kg^{-1} of sediment in the runoff, nearly 100 times the current TMDL (total maximum daily load) mitigation goal of 52 mg kg^{-1} for the middle reach of the Snake River in southern Idaho. It should be noted, however, that the impact of surface irrigation on runoff water quality depends on many conditions, especially management. In a 3-yr study in Idaho, Bondurant (1971) saw paired inflow–outflow sediment loads from fields of 49 and 30, 26 and 46, and 100 and 242 mg kg^{-1}; notably, in 1 of the 3 yr, the runoff water quality from farmed fields actually improved compared with inflow quality. Improved management resulting from research in the last two decades is making this a more common occurrence.

The challenges of meeting projected production needs and environmental protection for irrigated agriculture are difficult enough taken at face value. They are alarmingly daunting when one realizes that the most productive irrigated soils are typically fragile arid soils with thin, easily eroded A horizons. Erosion of these horizons can reduce crop yield potential as much as 50% (Carter, 1986, 1990; Carter et al., 1985). Thus, one of the greatest global threats to sustainable high agricultural productivity and, simultaneously, to clean water is irrigation-induced erosion.

MAGNITUDE OF IRRIGATION-INDUCED EROSION

While recognized as a serious problem in the early 1990s (Larson et al., 1990), there is still relatively little published data that systematically quantifies the extent of irrigation-induced erosion. Most of the organized efforts and public funding for erosion inventorying and for development of technology to understand, predict, and mitigate erosion has been aimed at rainfall-induced erosion. Of the existing irrigation-induced erosion research, much has originated from the Pacific Northwest and, until the last decade, was focused primarily on furrow irrigation. Indeed, a comprehensive survey of the extent and the agricultural, economic, and environmental impacts of irrigation-induced erosion has been identified as an unmet critical need by irrigators and government agencies for more than a decade (Reckendorf, 1995). Given the continued, albeit reduced, growth of irrigation in most sectors of U.S. agriculture and the continually changing mix of irrigated settings and technologies, this need, while more challenging than ever, has never been more urgent. This is particularly true given the elevated national priority of water quality protection, which is strongly linked to erosion, and which in irrigated agriculture is often systematically concomitant.

The published literature gives some documentation of the potential magnitude of the problem. Field sediment losses of 145 Mg ha^{-1} in 1 h (Israelson et al., 1946) and 40 Mg ha^{-1} in 30 min (Mech, 1949) were reported for furrow irrigation. While these were single observations and do not reflect seasonal losses, they still reflect the potential intensity of the problem in ordinary row-crop situations. More than 50 Mg ha^{-1} soil loss was measured for a single 24-h furrow irrigation (Mech, 1959). Berg and Carter (1980) reported annual losses ranging between 1 and 141 Mg ha^{-1} in southern Idaho. In Washington, Koluvek et al. (1993) measured a range of 0.2 to 50 Mg ha^{-1} soil loss per season and 1 to 22 Mg ha^{-1} per irrigation in Wyoming.

Because most furrows are long enough to create all three phases of erosion (detachment, transport, and deposition) along their length, the effects of erosion are not uniform along the furrow. Some soil eroded from the upper end of the field is deposited at the lower end because the transport capacity of the furrow stream is diminished as stream size gradually decreases due to infiltration along the furrow. Soil leaving the field in runoff is permanently lost, unless measures are taken to collect it in sediment basins or other catchment areas. Soil deposited at lower reaches of the furrow is not lost, but may include subsoil washed from the upper end of the field and may have less productive chemical and physical properties. This soil, deposited onto or mixed with the topsoil of lower field reaches, can decrease the productivity of those areas.

Several researchers have reported that three to eight times the field-averaged erosion rate occurs in the upper end of fields near furrow inlets (Berg and Carter, 1980; Kemper et al., 1985b; Fornstrom and Borelli, 1984). In southern Idaho, Trout (1996) estimated this disparity as 10 to 30 times the field-averaged erosion rate for the upper quarter of the furrow on a 1% sloping field of Portneuf silt loam. The impact of this magnitude of erosion is worsened by the fact that typical soil loss tolerance values for these soils are around 11 t ha^{-1} (5 U.S. tons acre^{-1}) yr^{-1}. Thus, in the first century of irrigation in the Pacific Northwest, many fields have little or no topsoil remaining on the upper one-third of the field. Carter et al. (1985) and Carter (1986) noted that 75% of southern Idaho's furrow-irrigated fields have lost all the average 38-cm-thick A horizon (and often some of the B horizon) from the upper ends, whereas "topsoil" thickness of lower ends had increased two- to fourfold due to deposition. Nonetheless, overall productivity was estimated to be only 75% of the pre-eroded level (Carter, 1993), with yield reductions of specific crops varying from 20 to 50% for areas with complete topsoil loss.

The erosion of furrow-irrigated land in the Pacific Northwest reflects the situation throughout most of the world's irrigated lands, which are predominately surface irrigated and in arid or semiarid settings. Arid-zone soils usually have low

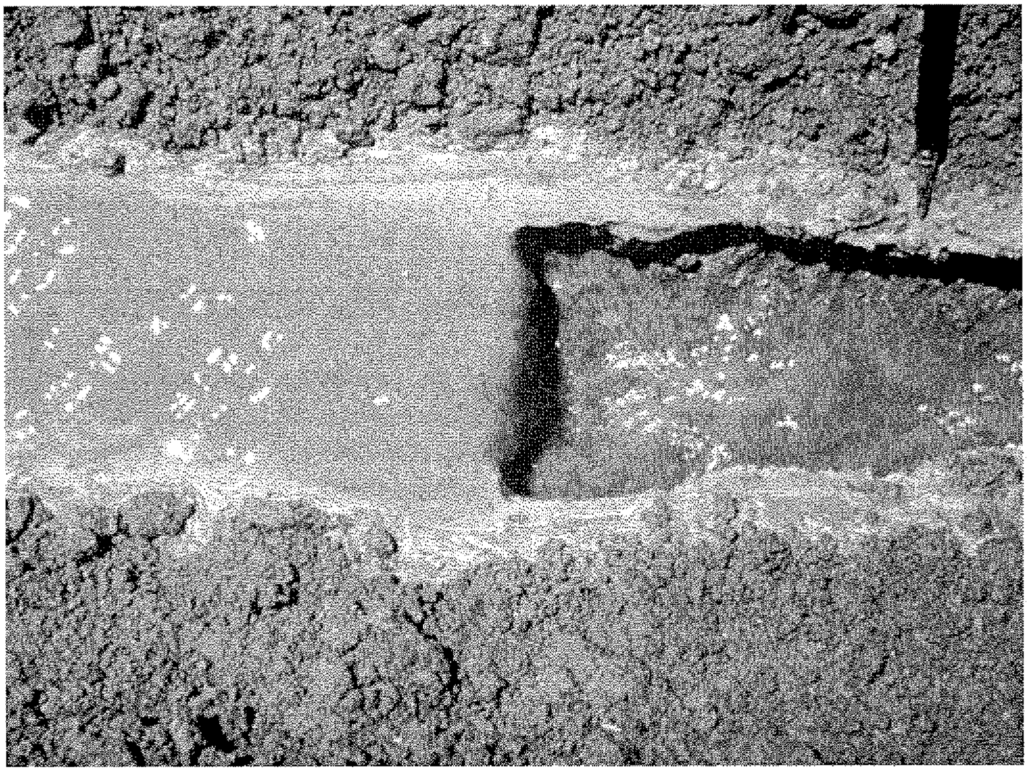

Fig. 8–1. "Head cutting" is shown in a typical irrigation furrow on a Portneuf silt loam soil. This is one of several processes that makes furrow irrigation inherently erosive.

organic matter contents, are poorly aggregated, and have thin, easily eroded A horizons. Furthermore, furrow irrigation, water flowing downslope on bare soil, is inherently erosive (Fig. 8–1).

IMPACTS OF IRRIGATION-INDUCED EROSION

There are many negative agricultural, environmental, and societal impacts of erosion and soil loss from irrigated fields. Exposed subsoil horizons generally have less productive chemical and physical properties. The exposed and transported subsoil contributes to easier crusting, sealing, compaction, and nutrient deficiencies that impair seedling emergence; limit fertility, rooting, and absorption of water and nutrients; and ultimately reduce crop quality and yields. As crop yield potential decreases, input costs increase, while the probability of response from inputs decreases. Thus, erosion causes production costs to increase while resulting in reduced crop yields and profit.

Many of the costs associated with irrigation-induced erosion are long range and are often neglected in cost–benefit analyses used to support conservation practices. Eroded soil migrates to lower field reaches, settles in drains and return-flow ditches, and contaminates lakes, streams, and rivers. Even if sediment is captured in lower field reaches or containment ponds, it must be redistributed onto eroded upper portions of fields at considerable expense. Irrigation-induced erosion reduces production and farm income, which ultimately leads to higher commodity prices for consumers. Off-site costs also arise from canal maintenance, river dredging, and algal control. Additional costs arise from riparian habitat degradation and biodiversity reduction, water contamination, impaired fisheries and recreational resources, reduced reservoir capacity, accelerated hydroelectric generator wear, and the mitigation of these damages.

UNIQUE ASPECTS OF IRRIGATION-INDUCED EROSION

Most research on water erosion before the late 1980s treated irrigation-induced erosion as a nearly undifferentiated subset of rain-induced erosion. Water erosion theory and models based on statistical relationships between meteorological events and soil loss were superficially modified in attempts to apply the relationships to the prediction of irrigation-induced erosion (Trout and Neibling, 1993). Although the physical and chemical processes that cause water erosion of soil are universal, system components vary in their composition and intensity, resulting in differing impact and importance between rainfed and irrigated systems. The degree to which a given process governs erosion from rainfall vs. irrigation can vary appreciably, resulting in substantially different outcomes (Bjorneberg et al., 2000b; Strelkoff and Bjorneberg, 2001; Bjorneberg and Sojka, 2002). Consequently, applying rainfed-erosion models to describe or estimate erosion from irrigation has encountered numerous problems (Bjorneberg et al., 1999, 2000b; Trout, 1996; Bjorneberg and Trout, 2001).

Irrigation water is not rainwater, and it "encounters" soil differently, in ways unique to specific irrigation systems, with considerably more flexibility to manage the soil water interaction than in rainfed agriculture. While the physical and chemical processes that bring about rain-induced erosion and irrigation-induced erosion are the same, the systematics of water application, timing, chemistry, energy components, and mass balance governing irrigation are quite different. Consequently, the theory and management of irrigation-induced erosion differ markedly from rain-induced erosion theory and rainfed agricultural management. Although these differences are relatively easy to identify, it is more difficult to appropriately modify rainfed theory, management, and mindset to deal with the differences.

Water Quality Effects

Rain-induced erosion theory has yet to incorporate water–soil interactive chemistry effects into predictive models. Because rainwater does not vary significantly in chemistry (EC [electrical conductivity], SAR [sodium adsorption ratio], or other organic or mineral constituents), rain-induced erosion theory and models focus narrowly on the physical attributes of relatively pure water as they affect stream and shower quantity and intensity. Similarly, interactions of soil properties with water are largely limited to physical phenomena via slope, slope length, surface roughness, cover, etc.; however, laboratory simulations and rain 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 erosive potential of a given shower or stream of water. Soil chemistry effects, to the extent that they exist in rainfed conditions, are indirectly integrated in rain-induced soil erosion models by affecting soil aggregation and dispersion on wetting. To this extent, their impact on rainfed-based models is indirectly quantified through their contribution to a given soil's erodibility. The degree and mode of water quality effects on irrigation-induced erosion is considered in greater detail with conservation practices, below.

Aggregate Stability Effects

Soil erodibility is affected by both the degree of soil aggregation and the stability of the aggregates in water. These properties affect erosion both by enhancing infiltration in well-aggregated soils and by resisting shear and dispersion of soil in runoff. Changes in aggregate stability have been attributed to small changes in soluble soil organic constituents (Coote et.al., 1988; Harris et al., 1966; Young et al., 1990). Irrigation water can vary in dissolved organic solute composition as a result of variation in watershed characteristics and water collection and storage history; however, we found no recent reports examining the effect of irrigation water dissolved organic solutes on erosion.

In field trials on Portneuf silt loam, Lehrsch and Brown (1995) did not observe a correlation between furrow-irrigation-induced erosion and aggregate stability. There are several possible explanations for this failure. Because the body of literature examining the relationship between erosion and aggregate stability has come predominately from rain studies (or rain simulation studies), it is likely that the absence of water drop impact and splash in furrow irrigation reduced the detachment energy and altered the mode of particle detachment, thereby weakening the correlation.

Suspended Solids Effects

Unlike rainwater, irrigation water can contain a substantial sediment or suspended biotic load. In furrows, those loads change systematically as the stream advances. Furrow erosion is affected by irrigation water sediment load through influences on both carrying capacity and surface sealing (Brown et al., 1988; Foster and Meyer, 1972). Solids in sprinkler-applied water can also contribute to surface sealing and impaired infiltration, resulting in greater runoff and erosion.

Many farms have multiple water sources (e.g., well, pond, process waste, river or canal water) of varying water quality. Future water development schemes may add urban gray waters to the selection of possible water sources. An informed farmer should plan an irrigation strategy to use less erosive water on steeper or more erodible land, or, if feasible, to blend waters to reduce erosion.

Water Application Effects

One of the most obvious differences between rainfed soil erosion and irrigation-induced soil erosion is that, generally, irrigation occurs on very dry bare soil. Furthermore, under irrigation, the transition from dry soil surface to excess water and runoff is often virtually instantaneous, especially in furrow irrigation, but also in traveling gun systems and at the outer reaches of center pivots where the instantaneous water application rate is very high.

For furrow irrigation, "rills" are mechanically created in dry soil before irrigation. As water advances down the furrow during the first irrigation, or following cultivation, it flows over dry, loose soil. The advancing water instantaneously hydrates dry soil, rapidly displacing air in pores and adsorbing on internal soil surfaces (Kemper et al., 1985a). The rapid hydration and displacement of air combine to produce strong disruptive forces that destroy soil structure and exacerbate the erodibility of the soil (Carter, 1990). Kemper et al. (1985a, 1985b) suggested that these combined effects may explain why furrow erosion often initiates before critical shear values have been exceeded. The rapidity and intensity of these processes are more pronounced with furrow irrigation than in most rain events. With rain, the soil surface is hydrated gradually during several minutes, after which excess water that accumulates on the surface begins collecting in and running off the field via rills that have been gradually prewet by rain.

The significance of gradual vs. instantaneous hydration has been verified in field and laboratory studies. Using 24-m furrows, Bjorneberg et al. (2002a) showed that erosion from dry furrows of a Portneuf silt loam soil was significantly greater than from furrows that were prewet by applying a light spraying or by drip tape. Le Bissonais and Singer (1992) showed that simulated rainfall onto small laboratory trays of Capay silty clay loam and Solano silt loam produced less runoff and erosion when the soils were prewet from the bottom by capillarity and drained for 2 h before simulated rain. The effect persisted into subsequent irrigations, presumably because of differences in surface seal conditions that resulted from the initial event. Mamedov et al. (2002) found greater erosion from simulated rain on small soil trays as the wetting rate increased in six Israeli soils, and the effect was more pronounced with increasing clay content. A small flume study by Shainberg et al. (1996) showed that air-dried soil had greater rill erodibility than wet soil, and that rill erodibility decreased with time after wetting the soil. These erosion effects of prewetting are thought to be related to the hydration dynamics that occur within aggregates. Aggregate stability is affected by both the soil water content and the rate of water content changes (Bullock et al., 1988; Kemper and Rosenau, 1984).

Another aspect of water application that differs significantly between rain erosion and furrow irrigation relates to the nature of irrigation furrow streams compared with rain-induced rill streams. Stream size, which is exponentially related to detachment (Kemper et al., 1985b), decreases down the length of an irrigation furrow (due to cumulative infiltration effects), while at the same time the wetted perimeter in the lower third or half of the field generally broadens (due to erosion of the furrow sides and accumulated sediment deposition on the furrow bottom). By contrast, in rainfed rills, soil is gradually and uniformly wet and interrill runoff and erosion accumulates in rills downslope, increasing the stream size, with comparatively little deposition in the rill. Furthermore, in furrow irrigation there is no water drop impact or splash component affecting or contributing to the erosion process between or within rills. For all these reasons, temporal and spacial components of infiltration, runoff, shear, detachment, transport, and deposition are vastly different for furrow-irrigation-induced erosion than for any component or the sum of components of rain-induced erosion. Consequently, rill erosion relationships partitioned from rain simulator results do not relate well to erosion outcomes in furrow irrigation.

Sprinkler irrigation is similar to rain in many respects, but there are some important differences. Water quality effects remain a factor, as described above. There are also spatial and temporal considerations. Rain events occur across the landscape at a watershed scale, whereas most sprinkler irrigation methods in production agriculture involve water application to only portions of fields at a given time. Runoff may, depending on slope direction and field configuration, flow onto dry or wet soil.

Solid set sprinkler systems have the greatest similarity to rain. Using a grid of stationary sprinklers operating simultaneously across an entire irrigated field, these systems can provide uniform, low-intensity water application to avoid runoff and erosion. These systems are often expensive, however, or are not feasible because of water supply restrictions that preclude irrigating an entire field at one time at a reasonable application rate.

In contrast, perhaps the fastest growing sprinkler strategy in the USA is the center pivot. More than half the sprinkler-irrigated land in the USA uses center-pivot systems. Center pivots are typically 400 m long, allowing irrigation of ~55 ha. Lengths can vary to meet specific needs; however, the lateral length dictates system application rates along the pivot. The average application rate increases in direct proportion to the distance from the center of the circle. Therefore, the greatest potential application rate and greatest potential runoff occurs at field edges, along the outer reaches of the pivot arm, where instantaneous application rates are their highest.

Another high-application-rate sprinkler irrigation system is the traveling gun, which is moved from position to position in the field. The traveling gun applies a high rate of water application from a single rotating nozzle or "gun" that laterally arcs a high-volume stream of water 10 to 20 m, irrigating a circular section of the field during the course of several hours at each stationary position.

A key factor that governs erosion potential from any sprinkler irrigation system is the average application rate at a given point within the wetted area. Center pivots are being adapted with wide area application booms and the use of low-pressure heads to spread water application across a larger area or reduce water drop energy. These strategies aim to reduce surface soil disruption and sealing, thereby maintaining a higher infiltration rate, and to restrict instantaneous application rates at any point along the pivot to values that do not exceed the saturated hydraulic conductivity or steady-state infiltration rate of the soil. Doing this eliminates runoff, which in turn eliminates erosion; however, because sprinkler systems are often used to overcome terrain limitations (steep slopes, rolling hills, etc.), and because soil properties often vary within fields, runoff and erosion still often occur under center pivots (Fig. 8–2) since water application strategies tend to be designed to meet *average* field needs. New programmable, variable-rate application systems can overcome these problems to prevent erosion; however, limiting water application to prevent erosion may come at the cost of crop yield re-

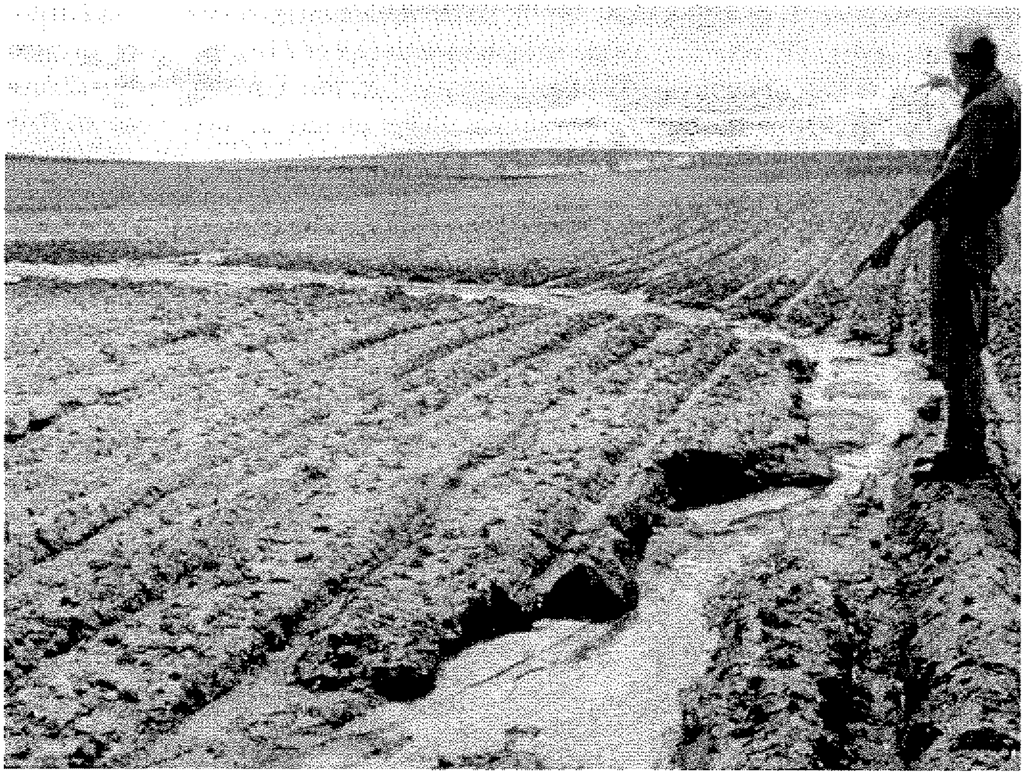

Fig. 8–2. The erosion in the foreground is the result of runoff from the sprinkler irrigation in an adjacent field. Ideally sprinklers can eliminate erosion; however, poor design or use on steep or variable slopes and in situations where field infiltration is not uniform often leads to erosion problems.

ductions due to inadequate water application or storage in portions of the field. The farmer must make decisions prioritizing yield and environmental concerns.

As alluded to above, sprinkler systems operate on variable topography with slopes that are not uniform. This is especially a factor for center-pivot systems. If laterals are perpendicular to the slope, runoff moves away from the lateral applying the water, allowing water to infiltrate before flowing any great distance. If the slope is parallel to the lateral, however, runoff accumulates downslope, initiating erosive runoff streams. Crop ridges, relative to the slope and lateral, can also affect runoff flow direction. Often crops are planted in circular patterns under center pivots to keep all rows and ridges perpendicular to the lateral spray arm. Another erosion factor with center-pivot systems is wheel tracks, which form under each support tower as the pivot lateral moves through the field. These wheel tracks are typically 40 to 50 m apart and tend to channel runoff in portions of the field, often resulting in considerable erosion. If the pivot lateral is moving upslope, runoff on the field and in wheel tracks will be onto wet areas behind the advancing lateral. When the lateral arm is moving downslope, runoff is onto dry areas of the field and wheel track ahead of the advancing lateral arm. Thus any attempt to conceptualize or model erosion from center pivots or other traveling irrigation systems must account for both the rain-like runoff aspects, as well as water quality and site factors that influence both interrill runoff and erosion, as well as these special and unusual cases of rill or furrow runoff and erosion (Bjorneberg et al., 2000b). Various other lateral-move systems, such as linear traveling systems, wheel lines, and hand-moved laterals have characteristics that draw from and are somewhat intermediate to the various systems described above, further complicating the task of conceptualizing and predicting erosion.

Regardless of the kind of irrigation system, the effect of applied water on infiltration, runoff, and erosion is also influenced by the soil profile water content and distribution. Profile soil water content strongly influences the erosion rate (Berg and Carter, 1980; Kemper et al., 1985a, 1985b). In furrow irrigation, it varies progressively along the irrigation path. In contrast, soils in rainfed agricultural landscapes generally have similar soil water profiles for most points in a field at any time during a rain event.

Water Temperature and Temporal Effects

Soil and water temperature, as well as dissolved organic constituents, probably also have measurable effects on soil erosion. Soil and water temperatures vary systematically during a season, among various 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. Again, to the extent they are incorporated, they are dealt with indirectly via statistical correlations of storm events and erosion observations. In irrigation, temperature variations are sufficiently systematic that a few studies have been able to estimate the magnitude of their effects on irrigation-induced erosion. Brown et al. (1995) used several years of data to estimate the effect of irrigation date on furrow-irrigation-induced erosion. They noted that soil erodibility in southern Idaho appeared to peak each year around the end of June or beginning of July. They concluded that soil or water temperatures, or both, were probably being affected by the annual solar cycle, with the peak erodibility coinciding with the summer solstice, which they speculated was sufficiently affecting soil and water temperatures to cause measurable changes in furrow erodibility. Lentz and Bjorneberg (2002) directly correlated changes in furrow stream water temperature through the diurnal cycle with fluctuations in furrow infiltration rates. Infiltration rates increased 2% with each 1°C increase in water temperature. They speculated that these changes were the result of temperature influences on water viscosity and the solubility of soil constituents. The magnitude of water infiltration change would be enough to sufficiently affect stream flow, shear, and deposition variation along a typical furrow length to impact measured sediment loss.

Furrow irrigation events are typically 12 or 24 h in duration, and runoff typically occurs for 9 to 18 h, whereas runoff from rain events typically occurs for much briefer times. The longer duration of irrigation runoff means that temporal changes in infiltration, furrow size and shape, and soil erodibility parameters tend to be more important for furrow irrigation than for rain. For example, sediment concentration generally decreases with time during furrow irrigation. This occurs despite the fact that even with a constant inflow stream, furrow runoff usually increases with time during a furrow irrigation event. Increasing runoff should result in greater shear, detachment, and transport; that it doesn't indicates that, during these prolonged events, other phenomena are occurring that reduce the erodibility of the soil or erosiveness of the water. These could include armoring of the furrow, temperature-related water viscosity shifts, or other as yet unrecognized phenomena (Bjorneberg et al., 2000b; Lentz and Bjorneberg, 2002).

Furrow-irrigation-induced erosion changes during the season. Brown et al. (1995) found that erosion from irrigations conducted from late June to early July were considerably greater than for comparable irrigation events before or after that period. The data were consistent across several crops and several years. The erosion peak was also consistent for cropped and uncropped fields. All this suggests that some factor other than cropping culture or tillage practices was causing the effect. Because late June to early July coincides with the summer solstice, it is plausible that soil and water temperature could be influencing erodibility.

Soil and water temperatures are more likely a factor for furrow-irrigation-induced erosion than for rain-induced erosion. Rain is usually preceded by and accompanied by reduced solar irradiance and thus soil cooling, and the temperature of rainwater tends to be nearly constant during the rain event and is usually at or near the dew point for the time period. Droplets reaching the ground from sprinkler irrigation systems also tend to match the dew point temperature. By contrast, irrigation, especially in arid settings, often occurs on sunny days that heat the soil surface and, in the case of furrow irrigation, results in temporal and spatial variation in the temperature of the furrow irrigation stream (Lentz and Bjorneberg, 2002). Infiltration rate increases with rising water temperature due to an accompanying drop in viscosity. Infiltration rate varied up to 30% of the mean value diurnally in a study by Jaynes (1990), who noted that the infiltration changes corresponded with changes in soil temperature. Water temperature increased by 22°C in midafternoon along a 550-m furrow in a study by Duke (1992), who estimated that the accompanying change in viscosity could increase hydraulic conductivity up to 70%. Where the field was shaded by trees, the temperature of the furrow irrigation water only rose 3°C.

The temporal pattern of irrigation events is also much different than the random occurrence of rain events. Irrigation-induced erosion tends to occur in a series of several relatively small (in terms of water amount) runoff events, while rain-induced erosion typically is generated in only a few relatively large storms each growing season. Irrigation-induced erosion cannot be conceptualized or predicted by deriving yearly or seasonal hydraulic or erosion relationships based on meteorological inputs averaged from sporadic events of varied intensity, occurring during long time periods across a geographic region. This obstacle is compounded if one does not also account for the amount and kind of irrigation, water quality, and spatial and temporal variability.

MODELING IRRIGATION-INDUCED EROSION

As discussed above, irrigation erosion is systematically different from rain-induced erosion. Models developed for rain-induced erosion cannot be used on irrigated fields without some (often substantial) modification. Three erosion models have been or are being developed for estimating soil loss from irrigated fields: the SISL (Surface Irrigation Soil Loss) model, the WEPP (Water Erosion Prediction Project) model, and the SRFR model. These models vary in degree of complexity and application[1].

Surface Irrigation Soil Loss Model

The Idaho NRCS developed the SISL model for estimating soil loss from furrow-irrigated fields (NRCS, 2000). This empirical model uses a formula similar to the USLE (Universal Soil Loss Equation) where 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

$$\text{SISL} = \text{BSL} \times \text{KA} \times \text{PC} \times \text{CP} \times \text{IP} \qquad [1]$$

where SISL is surface irrigation soil loss from a field (Mg ha^{-1} yr^{-1}; as deployed by NRCS, U.S. conventional units are used with output expressed as U.S. tons acre^{-1} yr^{-1}), BSL is the base soil loss rate, KA is the soil erodibility adjustment factor, PC is the prior crop adjustment factor, CP is the conservation practice adjustment factor, and IP is the irrigation management adjustment factor. The BSL was established after measuring soil loss from >200 furrow-irrigated fields in southern Idaho. The BSL is affected by crop type, 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 varies from 0 Mg ha^{-1} for permanent crops on fields with <1% slope to >135 Mg ha^{-1} for intensive row crops (e.g., sugarbeet [*Beta vulgaris* L. subsp. *vulgaris*] or onion [*Allium cepa* L.]) with >3% slope. The value of KA varies from 0.45 to 1.12 based on the soil erosion factor *K* found in the NRCS soil survey. The PC accounts for crop residue from the previous crop, varying from 0.65 for pasture to 1.0 for low-residue crops like bean (*Phaseolus vulgaris* L.) and onion. The conservation practice factor (CP) varies from 1.0 for conventional moldboard plow tillage to 0.10 for no-till and 0.05 for PAM (polyacrylamide) use. The IP factor accounts for the level of irrigation management combined with practices such as cutback and surge irrigation. Although the SISL model has not been thoroughly evaluated, it is used by the Idaho NRCS for ranking the need for conservation practices on furrow-irrigated fields and is being used as the basis for conservation practice compensation in a P pollution trading scheme being developed for the lower reaches of the Snake River in Idaho.

Water Erosion Prediction Project Model

The WEPP model is a process-based model that simulates a daily water balance, plant growth, residue decomposition, soil consolidation, and erosion mechanics (Nearing et al., 1989; Laflen et al., 1991). The WEPP model categorizes

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[1] Two additional irrigation erosion models have been developed and have had some local use, but on a more limited basis: SPER/ERO, a sprinkler erosion model for center pivots, was deployed for limited field-scale assessment in the state of Washington (Spofford and Koluvek, 1987); FUSED was developed by Koluvek in 1988 as a single furrow or seasonal field-scale erosion assessment model, using Idaho and Montana field data, and has had limited use in the state of Washington but was never published (T.L. Spofford, personal communication).

soil erosion into rill and interrill processes. Interrill erosion involves soil detachment and transport by raindrops and sheet flow. Interrill erosion delivers sediment to concentrated flow channels or 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 net sediment detachment and deposition:

$$dG/dx = D_f + D_i \qquad [2]$$

where G is sediment load in the rill (kg $m^{-1}s^{-1}$), x is downslope distance (m), and D_f and D_i are rill and interrill erosion rates (kg s^{-1} m^{-2}), respectively. Interrill erosion is a function of rainfall intensity, interrill runoff rate, and interrill erodibility (Flanagan and Nearing, 1995). Rill detachment is a linear function of hydraulic shear and is calculated according to the following equation:

$$D_c = K_r(\tau - \tau_c) \qquad [3]$$

where D_c is the detachment rate for clear water (kg $s^{-1}m^{-2}$), K_r is rill erodibility (s m^{-1}), τ is hydraulic shear of flowing water (Pa), and τ_c is soil critical shear (Pa) (Elliot and Laflen, 1993; Flanagan and Nearing, 1995). *Rill erodibility* is the rate at which sediment is detached and *critical shear* is the shear force that must be exceeded before detachment can occur. Baseline values of erodibility and critical shear are soil-specific parameters defined during rain simulations or by empirical equations. These baseline values are adjusted daily by the model to account for temporal changes in surface residue, root growth, sealing and crusting, and freezing and thawing.

The WEPP model includes the concept that sediment detachment is limited by the amount of sediment that the flowing water can transport—the *transport capacity*. Net soil detachment is calculated by:

$$D_f = D_c(1 - G/T_c) \qquad [4]$$

where D_f is the net detachment rate (kg $s^{-1}m^{-2}$) and T_c is the transport capacity of the rill flow (kg $m^{-1}s^{-1}$). Thus, detachment in rills only occurs when hydraulic shear exceeds the soil critical shear (Eq. [3]) and when sediment load in the rill is less than the transport capacity (Eq. [4]). 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:

$$T_c = k_t\tau^{3/2} \qquad [5]$$

where k_t is 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

$$D_f = (T_c - G)\beta V_f/q \qquad [6]$$

where V_f is the effective fall velocity for the sediment (m s^{-1}), q is the flow rate per unit rill width (m^2 s^{-1}), and β is a raindrop-induced turbulence coefficient that equals 0.5 when raindrops are impacting rill flow and 1.0 for snowmelt and furrow irrigation. The WEPP model only calculates deposition when the rill sediment load is greater than the transport capacity.

The WEPP model includes irrigation components for simulating erosion from sprinkler and furrow irrigation. Sprinkler irrigation from solid set or set-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. The WEPP model can predict sprinkler irrigation runoff reasonably well if the effective soil hydraulic conductivity can be estimated for soils in the field so that runoff is accurately predicted (Kincaid, 2002). Since the WEPP model is a steady-state model, it cannot directly simulate erosion from moving sprinkler systems such as center pivots or traveling guns. A moving irrigation system would be similar to a very small storm moving through a field. The model can, however, be used with some reservations to evaluate erosion potential on small areas of center-pivot-irrigated fields (Kincaid and Lehrsch, 2001).

The WEPP model contains a separate component for calculating infiltration and runoff from furrow-irrigated fields. Furrow-irrigation erosion is then calculated using the same rill erosion algorithms that are used for rainfall. Interrill erosion processes are not considered because water is only flowing in furrows (i.e., rills). The WEPP model cannot be used on furrow-irrigated fields without adjusting the baseline critical shear and rill erodibility parameters that were defined for rainfall erosion (Bjorneberg et al., 1999). Both critical shear and rill erodibility had to be decreased for silt loam soils in southern Idaho. Kemper et al. (1985b) noted that critical shear for furrow irrigation is essentially zero. The WEPP model also overcalculated transport capacity, so sediment deposition was not accurately predicted (Bjorneberg et al., 1999).

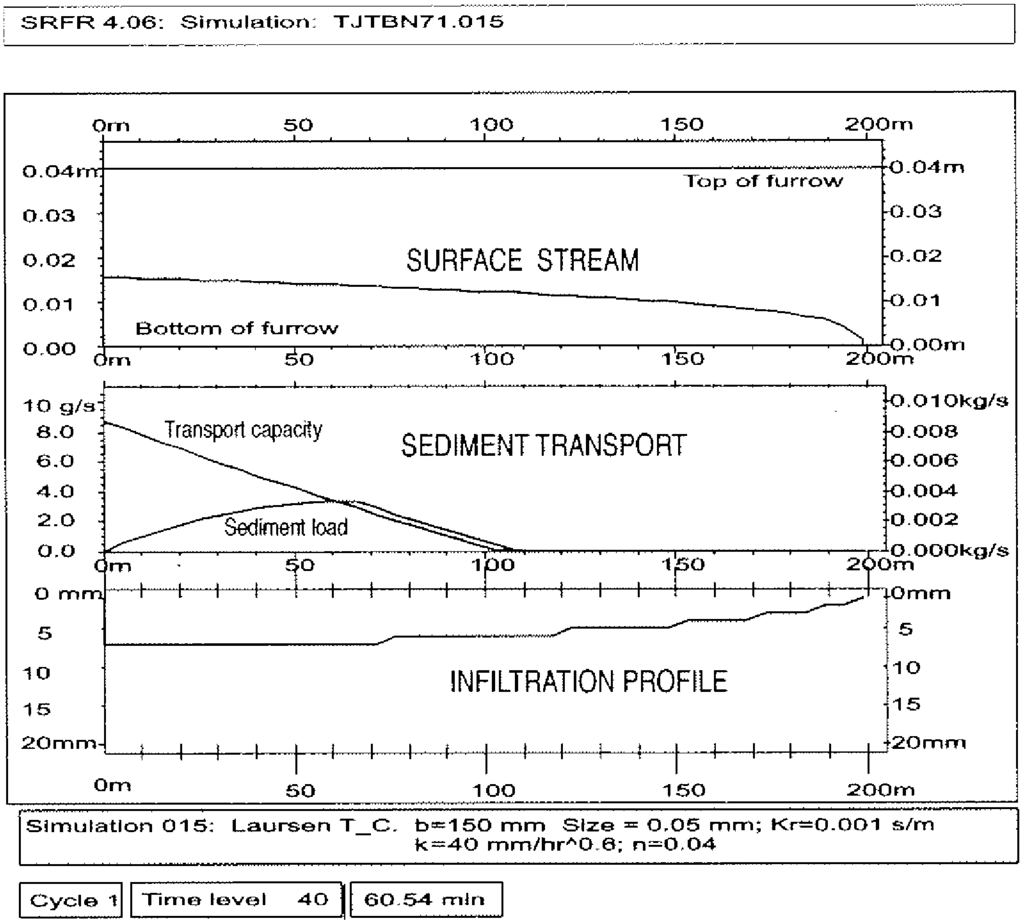
SRFR Model

The model SRFR Version 3 (Strelkoff et al., 1998) is a comprehensive surface irrigation simulation model developed at the USDA-ARS U.S. Water Conservation Laboratory in Phoenix, AZ, for simulating the hydraulics of water flow in an individual furrow during an irrigation. 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 on the flowing water. Version 4 is being developed to simulate sediment transport. Following Fernandez Gomez (1997), the SRFR model uses many of the same fundamental erosion equations as the WEPP model, but these equations are applied to the flow hydraulics calculated by the SRFR model for each time and distance point in the furrow. Input to the SRFR model includes site-specific soil erodibility K_r and critical shear τ_c. Measured decreases in erodibility with time during an irrigation can be accommodated, reflecting decreases in sediment concentration that are often observed during irrigation. Decreasing sediment concentration while flow rate remains constant suggests supply-limited erosion. In other words, the same shear force detaches less sediment. One possible explanation for this phenomenon 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 the WEPP model overpredicting transport capacity in furrows (Bjorneberg et al., 1999), a different transport capacity equation was sought. The Laursen (1958) formula was chosen because (i) it deals with total sediment load, both suspended and bed load, (ii) it includes silts in its experimental database, and (iii) it is a classical exercise in dimensional analysis, with appropriate contributions from physical reasoning and even a little intuition—with the final results both confirmed and defined empirically. It was judged second overall from among a large group of transport formulas in the literature on rivers by Chang et al. (1982), and first for long straight channels in agricultural soils (Alonzo et al., 1981). The Yalin formula was selected for WEPP because it best predicted erosion in very shallow rainfed overland flow on concave hillsides (see, e.g., Foster, 1982). Furthermore, rather than making any assumptions regarding the variation of transport capacity along the length of a furrow (Eq. [5]), local transport capacity at points in the furrow were calculated 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 on the basis of local values of the hydraulic variables—in contrast to Laursen, who employed several constant dimensionless values in analyzing his database.

Figure 8–3, drawn from a frame of the animation displayed by SRFR during the simulation, illustrates typical behavior of the transport-capacity function and resultant sediment loads at one instant of time (60 min into the irrigation). There is a region behind the stream front in which the transport capacity and detachment are zero. The flow rate there is so small that the boundary shear lies below the threshold for entrainment (discharge continually decreases with distance down the field because of infiltration). Far upstream, the sediment load grows the fastest at the clear-water inflow, where the transport capacity is a maximum and the existing sediment load zero. With distance downstream, the transport capacity decreases due to infiltration, and the sediment load increases due to upstream entrainment; both factors lead to reductions in further growth in the load. Eventually, though, transport capacity *is* exceeded, and some of the load starts to be deposited back onto the bed. In accord with the deposition equation, some excess of load over transport capacity persists for a short distance.

In its initial version, the SRFR erosion component was based on one representative aggregate size for the mix of sediment transported in the furrow flow. Figure 8–4 compares calculated sediment-load hydrographs with average values at the quarter points in the furrow, gleaned from irrigated bean data (Trout, 1996). The input value of $K_r = 0.001$ s m^{-1} for the simulation was calibrated from the comparison between measured and calculated hydrographs at the first quarter point, before transport capacity plays 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 capacities predicted by the Yang (1973, selected as first choice in the ASCE 1982 study) and Yalin (1963, used in WEPP) for-



SRFR 4.06: Simulation: TJTBN71.015

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

Cycle 1 | Time level 40 | 60.54 min

Fig. 8–3. Frame of output animation of SRFR simulation—profiles of surface stream depth, sediment load, and transport capacity, and infiltrated depths; time = 61 min (Strelkoff and Bjorneberg, 2001).

mulas precluded deposition, and indicated continual growth of the sediment load with distance.

Despite the qualitative agreement shown in Fig. 8–4, it should be noted that the data points used in the development of transport-capacity formulas, in general, exhibit a scatter around the formulas of almost an order of magnitude (see, e.g., Laursen, 1958). Absolute accuracy cannot be expected from simulations based on these formulas. At the same time, predicted relative changes in sediment transport resulting from changes in design or management of surface irrigation systems should nonetheless prove useful in a decision-making process.

In addition, as noted in Strelkoff and Bjorneberg (2001), treatment of erosion–transport–deposition phenomena in terms of a single representative particle size leads to results overly sensitive to the selected size. While it is possible to match field-measured hydrographs of total load with a reasonable single size in the range of measured values, selection of equally reasonable values, greater and lesser, can lead to significant changes in simulated loads. For example, increasing somewhat the representative particle size can lead to loss of all sediment in calculated tailwater loads. A postulated mix of particle sizes circumvents this problem and leads to gradual changes in total sediment load as the fractions of each

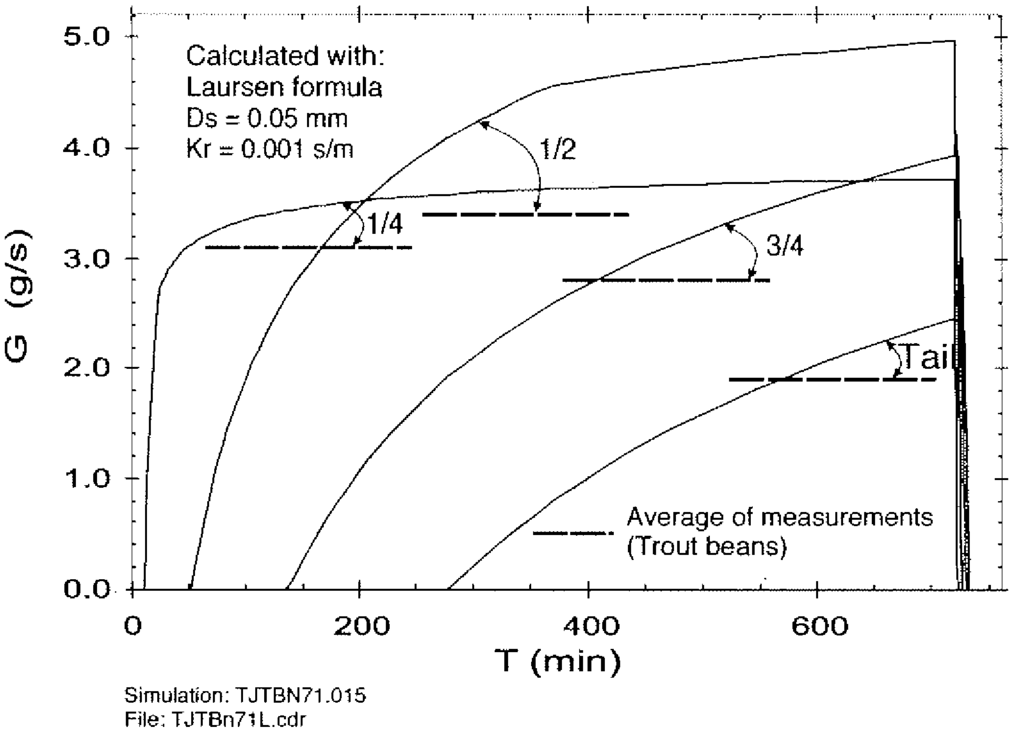


Fig. 8–4. Comparison of simulated sediment transport hydrographs at furrow quarter points with averages from measured Trout (1996) field bean data of 1 July 1994—site-specific rill erodibility (K_r) = 0.001 s m^{-1}, soil critical shear (τ_c) = 1.2 Pa; Laursen (1958) transport-capacity formula in effect; trends correct (Strelkoff and Bjorneberg, 2001).

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

The importance of developing a robust, reliable, relatively accurate transient-state erosion model for surface irrigation can hardly be overstated. As noted above, the "lion's share" of irrigation worldwide is furrow irrigation, an inherently erosive process. Even in the USA, 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. 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.

SOIL CONSERVATION PRACTICES FOR IRRIGATED AGRICULTURE

A variety of soil conservation practices have been developed for irrigated agriculture. They differ in ease of adoption, effectiveness, cost of implementation, and offer a range of options for a variety of situations. These practices and related factors have been discussed in several previous publications (Carter, 1990; Carter et al., 1993; Sojka and Carter, 1994; Sojka, 1998). The evolution of practices has reflected both changes in the motivation for conservation and improvements in available conservation technologies.

Initially, the motivation for irrigation-induced erosion prevention was tied most closely to crop yield and productivity considerations. Because these effects could be masked by relatively inexpensive or cost-free management or input adjustments, it was often difficult to convince farmers of the existence of an erosion problem or the need to mitigate it. By the late 1970s and early 1980s, the impact of erosion on yield potential was thoroughly documented. At the same time, concerns about the link between erosion and surface water pollution created a greater urgency for conservation in all sectors of agriculture. Because irrigation return flows are conspicuous contributors to surface water bodies, new attention was focused on the environmental impacts of irrigation-induced erosion. Environmental protection is now the dominant driver in irrigation-induced erosion research.

Along with this evolution in motivation, there has also been an evolution in conservation strategy. Early conservation efforts sought to capture soil leaving the field with an eye toward physically replacing the captured soil on the eroded areas. Eventually greater emphasis was placed on developing strategies for soil loss prevention and erosion on the field, i.e., holding soil in place rather than capturing and replacing it. This strategy shift places less emphasis on engineering-oriented practices and more on the development of soil, water, and crop management practices. This approach is better suited to halting soil movement, thereby retaining soil in place and eliminating subsequent soil handling or transport and the attendant inconvenience and expense.

Because each farm is unique, a given conservation practice is not equally suited to all situations. Farmers, alone or with help from public conservation advisors and or paid consultants, determine which practice or practices best suit their particular needs. Ultimately, erosion abatement practices that are used are more valuable than practices that are not used, regardless of the relative *potential* effectiveness of a given practice. Enforcement of clean water standards may eventually demand that return flows leaving a farm meet specified water quality standards or, alternatively, that runoff contaminants be contained on farm by not allowing return flows at all.

Return-flow water quality standards may be voluntary or may be tied to fines or other monetary incentives. In 1997, the Idaho courts required establishment of TMDL limits for 962 water-quality-impaired stream segments. A compliance target date of 2007 was mandated. Since then, the two largest canal companies managing irrigation water diversion along the middle reaches of the Snake River have enacted measures to allow withholding of water delivery to farms that seriously impair water quality of return flows. These events reflect similar activity throughout the western USA. As a result, water districts, who often are the legal water right holders or are identified as legally most responsible for water quality improvements, have become proactive in identifying, promoting, and in some instances supporting research for development of on-farm management practices to protect return-flow water quality. What follows below is a summary of some of the more important practices available for the prevention of irrigation-induced erosion and the protection of return-flow water quality.

Water Management

Irrigation-induced erosion cannot occur without water application; furthermore, there must be runoff. The first line of defense against erosion, therefore, is management of applied water to optimize crop production in the absence of erosive runoff. This approach involves several considerations: crop water use, application efficiency and timing considerations based on crop needs and soil water storage capacity, timing considerations based on water availability within the macroscale irrigation system infrastructure, and water application method and intensity as determined by the limitations of the on-site delivery system.

With furrow irrigation, improved inflow–outflow management, stream size monitoring (checking siphon tubes or gated pipe for proper flow rates), post-advance flow reduction (sometimes called *cutback irrigation*), field leveling, alternate furrow irrigation, infiltration measurement (soil water budget monitoring), and irrigation scheduling can all improve water use efficiencies and uniformities, and minimize shear forces leading to detachment, transport, and deposition. These improvements can reduce water application and runoff amounts, thereby reducing erosion, generally in proportion to runoff reduction or better (Trout et al., 1994).

Tailwater Elimination or Reuse

In many irrigation schemes, attention to water management and application efficiency, as described above, results in elimination of all runoff or tailwater. Where this is the case, no soil will move off the site; there may be some movement of soil from one part of the irrigated field to another, but there are no offsite impacts. If on-field erosion occurs, there may still be some yield or sediment, nutrient, or agrichemical uniformity issues that could require intervention, and hence incur some management expense. However, offsite water quality would not be impaired.

Some irrigation schemes are designed for constant water flow to a user, particularly where the irrigation scheme was initially designed for furrow irrigation. In these cases, fields often also have sufficient slope to require a constant runoff during the irrigation event to adequately provide infiltration opportunity to the entire field (i.e., furrows cannot simply be diked and filled for even water application across the field). These systems also usually depend on a substantial return-flow component (typically 20%) to provide adequate water supplies to downstream users. Where these considerations exist, it may not always be practical or possible to reduce or eliminate runoff.

Where runoff reduction or elimination is possible, that result can either be achieved by inflow management, as described above, or by use of runoff collection ponds. These ponds can be managed to maximize sediment retention as well as to supply an extended water supply to the farm.

Retention ponds can be inexpensively enhanced to recirculate sediment-laden water into the furrow irrigation water supply (Trout, 1994, 1995; American Society of Agricultural Engineers, 2003). This does not prevent erosion, but it au-

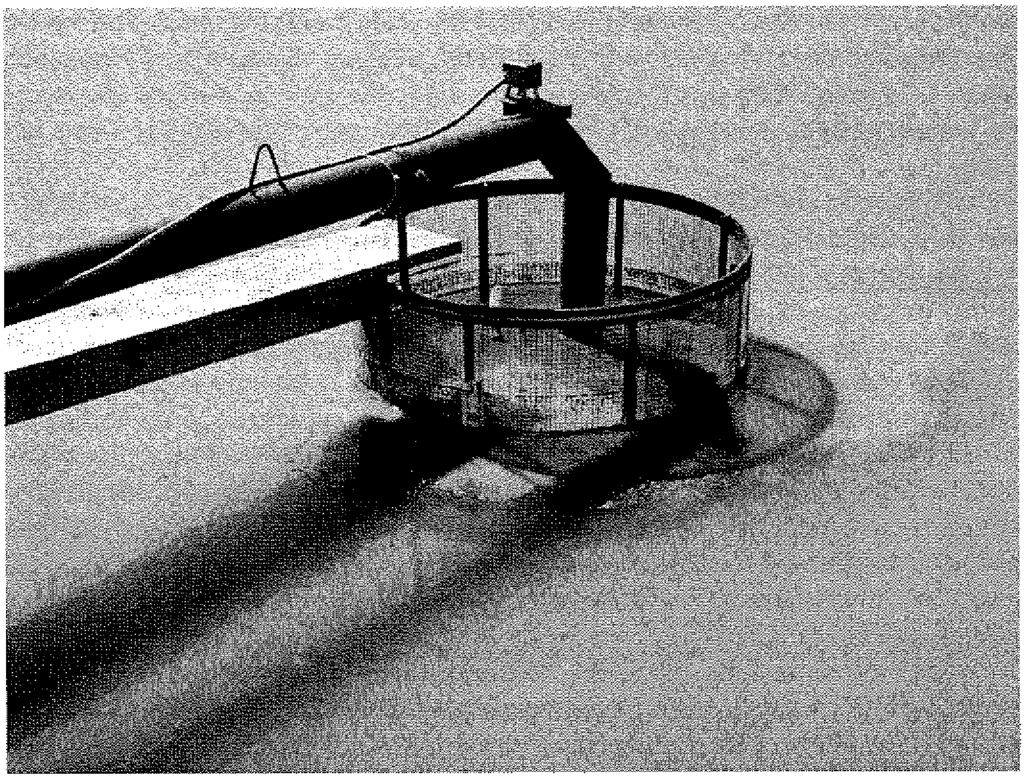


Fig. 8–5. Sediment-laden runoff, collected in a settling pond, can be efficiently transported back onto the eroding field if the pump-back intake pipe is located immediately adjacent to the runoff delivery pipe (courtesy Dr. Tom Trout).

tomates replacement of sediment back onto the fields from which it came (Fig. 8–5). Advantages include maximizing water supply efficiency and 100% on-farm sediment retention (Carter et al., 1993). There are capital and energy costs associated with this approach; furthermore, pump wear in a system designed to carry suspended sediment is accelerated, but this has been determined to be a minor expense (Trout, 1995). The sum of these costs is relatively small for a significant enhancement in water supply that includes the elimination of most of the sediment redistribution inconvenience and expense. One drawback is the collection, mingling, and delivery of disease inoculum, weed seeds, nematodes, and chemicals onto fields receiving pump-back water; however, this vectoring already occurs to varying degrees in any irrigation scheme where return flows are reused. Perhaps the greatest disadvantage of this approach is that elimination of all return flows within an established irrigation scheme could reduce downslope farm allocations dependent on them. Substantial return flow reduction could also require modification of primary canal capacity or individual farm allocations of water to provide water to farms on lower reaches of the delivery system to compensate for water not routed through return flows.

Sediment Retention Ponds

Sediment ponds or basins vary from about 0.1 ha (0.25 acre), typically servicing a 16- to 24-ha (40–60-acre) field, to "minibasins" that pond runoff in the final 4 to 5 m for 6 to 12 furrows at their lower end. Ponds or minibasins reduce flow rates and hold water, even if only briefly, to allow deposition of suspended particulates larger than clay. Minibasins also help prevent concave-end erosion at the bottom of fields where furrow runoff would otherwise flow directly into a tail ditch.

Retention pond effectiveness depends on sediment load, inflow rate, retention time, and texture of suspended particulates. Brown et al. (1981) estimated that, for Portneuf silt loam, about two-thirds of the total solids were removed from furrow irrigation return flows, but only about one-third of the suspended clay and total P. Clay is slow to sink to the pond floor. Since the greatest fraction of surface-adsorbed P resides on clay minerals, loss of these fines (the clay fraction) carries a disproportionate fraction of P per kilogram of sediment. Thus, ponds are generally less effective for clayey soils than coarser textured soils for both sediment and P retention. In addition, if pond overflow is not retained on farm, the sediment returned to eroded portions of fields via pond excavation and field spreading will be coarser than the soil eroded. This compounds problems of nutrient management since the soil clay fraction is the dynamic mineral fraction of the soil involved in nutrient exchange.

Recent research has demonstrated better sediment retention pond performance with the addition of precipitating agents, coagulants, and flocculents to enhance removal of soluble P and fine clays, along with their adsorbed nutrients and agrichemicals (Leytem and Bjorneberg, 2005). This approach is a straightforward adaptation for the agricultural setting of municipal and industrial water treatment approaches. Preliminary results suggest, however, that these approaches may be less suited for an on-farm strategy than for large-scale treatment of tailwater by an irrigation district. Treatment of consolidated return flows before release into riparian waters appears both more efficient and more cost effective.

Buried Return-Flow Pipes

Concave-end erosion can be prevented by replacing return-flow ditches at the bottom of fields with buried drain pipes having short vertical inlet risers. In these systems, furrow irrigation tailwater ponds to a shallow depth at the ends of fields until the water drains into the collection riser. These systems achieve sediment retention like ponds or minibasins, and are often an adjunct to minibasins. Effectiveness is ~90% while concavities or minibasins are filling in with sediment, but falls to ~60% once depressions are filled (Carter and Berg, 1983). At 60% efficiency, these systems match large pond efficiency, but with less seasonal maintenance. When combined with other on-field practices, buried pipe systems can remove most of the risk of serious sediment loss in return flows.

Vegetative Filter Strips

Vegetative filter strips are effective for the removal of a wide range of sediments, nutrients, and microorganisms from runoff water (Omernik et al., 1981; Schlosser and Karr, 1981; Griffiths et al., 1997; Entry et al., 2000a, 2000b; Hubbard et al., 1998; Snyder et al., 1998; Jordan et al., 1993; Spackman et al., 2003).

Coyne et al. (1995, 1998), Walker et al. (1990), and Young et al. (1980) concluded that 10-m-wide grass filter strips can reduce fecal coliform bacteria by as much as 70% in runoff leaving areas where poultry or dairy waste had been applied. Spackman et al. (2003) found that runoff from coliform-laden furrow irrigation water reached nearly undetectable coliform levels when the water flowed across 100 m of grassed furrows in the absence of stocking. Carter et al. (1993) found that cereal, grass, or alfalfa (*Medicago sativa* L.) strips 3 to 6 m (10–20 ft) wide, sown along the lower ends of furrow-irrigated row crop fields, reduced sediment in runoff by 40 to 60%. Filter strip plantings needed to be perpendicular to the irrigated furrows to be effective, and furrows should not be cut all the way through the filter strip area to the tail ditch. Harvested filter strips yielded 30 to 50% below normal for the strip crop.

Narrow or Twin-Row Planting

Irrigating broadcast or drilled crops, like small grains, pea (*Pisum sativum* L.), or alfalfa seldom results in serious runoff or erosion problems because the crop performs much like a vegetative filter strip. Narrow or twin-row planting configurations of standard row crops are a compromise that create canopy and soil conditions that respond to water application and runoff more nearly like filter strips. Planting corn (*Zea mays* L.) as close as possible to both sides of the irrigated furrow to form twin-row spacings reduced field sediment loss by half in a 2-yr study (Sojka et al., 1992). Results for single but narrower row spacings were more variable but also showed erosion reductions for corn, sugarbeet and field bean (*Phaseolus vulgaris* L.). The reduced erosion resulted from a combination of factors including soil binding by roots close to the wetted furrow, introduction of plant litter into the furrow stream, and (with single narrow rows only) more furrows per unit area. The latter also meant an effective increase in wetted perimeter, which reduced the duration of irrigation set needed to deliver equivalent quantities of water. Runoff stream size and runoff period were also reduced relative to total inflow with narrow row plantings.

Furrow Mulching

Use of plant residue or living mulches in irrigation furrows can be very effective at halting erosion. Where establishment of a vegetative mulch is not feasible, it is sometimes possible to manage residues from a preceding crop, or mechanically introduce residue from off site. Permanent furrow sodding eliminated nearly 100% of erosion (Cary, 1986) without reducing the yield of barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), field bean, or corn. Furrow sodding requires a special furrow cutter to maintain established furrows. Straw or other manageable residues can be mechanically placed in furrows, reducing sediment loss 52 to 71% (Miller et al., 1987; Aarstad and Miller, 1981; Brown, 1985; Brown and Kemper, 1987; Evans et al., 1987).

A drawback of these techniques is significant slowing of water advance down furrows caused by greatly increased infiltration rates. Farmers are also often reluctant to add the field operations needed to establish and maintain mulched furrows. Mulching can occur at inconvenient times for crop managers, or cause problems during cultivation. Straw also tends to migrate down-furrow with the advancing water stream and can dam furrows, causing water levels to rise in the dammed furrow and wash into adjacent furrows. Lentz and Bjorneberg (2001) reported that straw damming was less of a problem when PAM was added to the advancing water; the PAM greatly reduced soil migration, which prevented it from interacting with the straw to dam the furrow. Instead, even when straw gathered in clumps along the furrow, water flowed freely under the straw because soil did not collect in the straw. They also speculated that the straw was eventually glued in place by the PAM, which helped preserve erosion-reducing properties in subsequent irrigations.

Synthetic and Biopolymers

The 1990s saw realization of a completely new approach to reducing irrigation-induced erosion, involving delivery of minute quantities of highly surface-active polymers in the irrigation water (Paganyas, 1975; Mitchell, 1986; Ben Hur et al., 1989, 1990; Smith et al., 1990; Lentz et al., 1992; Gal et al., 1992; Levy et al., 1991, 1992, 1995; Ben Hur, 1994; Lentz and Sojka, 1994; McCutchan et al., 1994; Bernas et al., 1995; Levy and Agassi, 1995; Trout et al., 1995; Bjorneberg et al., 2000a; Sojka and Lentz, 1997; Robbins and Lehrsch, 1997; Aase et al., 1998; Brown et al., 1998; Sojka et al., 1998; Flanagan et al., 1997a, 1997b; Orts et al., 1999, 2000, 2001, 2002; Waters et al., 1999). Several classes of polymers have shown varying degrees of success; all are very large molecules capable of increasing cohesion between primary mineral particles, thereby raising the critical shear necessary for detachment. To date, the most efficacious class of polymers has been anionic PAMs.

Treating advancing furrow irrigation water (only) with 10 g m^{-3} PAM reduced sediment loss in runoff 85 to 99% while increasing infiltration 15% (Lentz et al., 1992; Lentz and Sojka, 1994; Sojka and Lentz, 1993, 1994). This translates to ~1 kg ha^{-1} of PAM used per treated irrigation. Polyacrylamide, an industrial flocculent used for food processing and water treatment, is now marketed extensively for controlling erosion and improving return-flow water quality. The extent of irrigated area in 2003 using PAM for irrigation erosion prevention in the USA was estimated at nearly 800 000 ha (Henri Asbell, personal communication, 2003). The efficacy of PAM has proven consistent for a wide range of soils and conditions at low cost and without major impacts on other farming practices. With 10 g m^{-3} PAM, initial water inflows can be more than doubled (then cut back once water has advanced across the field) and most of the erosion is still prevented (Sojka et al., 1998). This permits greater field infiltration uniformity by reducing the difference in infiltration opportunity time between the upper and lower field.

Several studies have verified that application of PAM as a powder patch placed directly on the soil in the first 1 to 2 m of the furrow before inflow is as effective at reducing sediment loss in the runoff in most circumstances as dissolving PAM in the advancing inflow (Sojka and Entry, 2000; Sojka et al., 2003a, 2003b; Entry and Sojka, 2003). The patch application method is easier for most furrow ir-

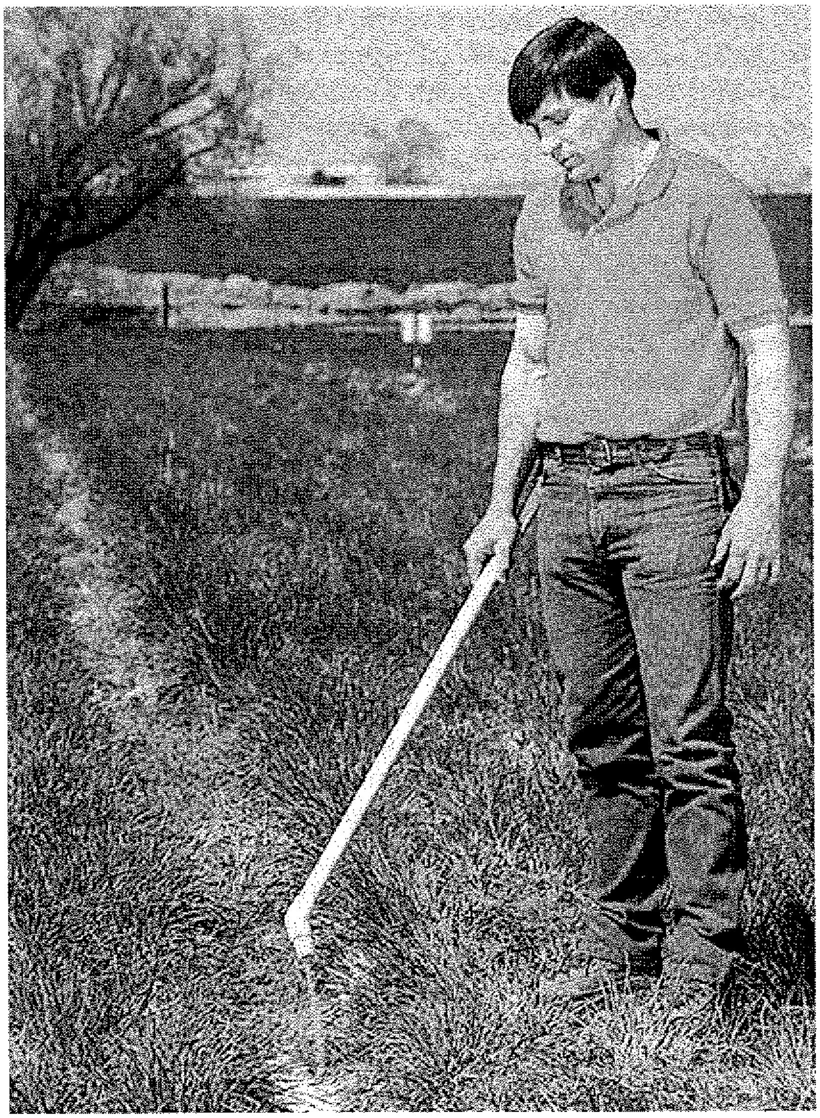


Fig. 8–6. A simple hand-held granular PAM (polyacrylamide) dispenser is used to apply PAM granules to the first 1 to 2 m of dry furrow below the water inflow point immediately before irrigation, allowing highly effective and inexpensive furrow erosion control.

rigators and has become the most widely adopted PAM application method (Fig. 8–6).

A significant ancillary benefit of PAM use to prevent erosion is its effectiveness in reducing several classes of contaminants in the runoff. These contaminants are homogenously mixed with soil and become entrained in the runoff with the eroding soil. Some contaminants are sorbed onto soil surfaces and their desorption is greatly enhanced by the turbulent mixing and washing of solids in the runoff stream. These additional contaminants in runoff include nutrients (Entry and Sojka, 2003; Entry et al., 2003; Lentz et al., 1998, 2001; Sojka et al., 2003a; Waters et al., 1999), agrichemicals (Agassi et al., 1995; Bahr and Steiber, 1996; Lu et al., 2002a, 2000b; Singh et al., 1996; Waters et al., 1999), organic substrates

(Lentz and Sojka, 1994), and biotic material (Sojka and Entry, 2000; Entry and Sojka, 2000, 2001; Entry et al., 2003; Sojka et al., 2003b) in runoff. Some contaminant reduction comes about through the reduction in sediment, which serves as a carrier or desorbing surface for these materials. Some of the reduction is the result of direct sequestration on PAM molecule adsorption sites, with the PAM itself immobilized on the surface of structurally stabilized and immobile soil particles.

Since the late 1990s, there has been growing interest in the use of PAM with sprinkler irrigation, especially in center pivots. Ideally, sprinklers eliminate erosion; however, as noted above, complete elimination is rarely the case. Studies in large soil boxes showed that a PAM application rate of 2 to 4 kg ha^{-1} in the first simulated sprinkler irrigation on bare soil reduced >70% of runoff and erosion from the first three irrigations (Aase et al., 1998; Bjorneberg et al., 2000a, 2003). If very dilute applications of PAM were added to each subsequent irrigation, erosion control and infiltration improved. Testimonials from farmers using PAM with sprinklers suggest that preventing ponding and crusting are important side benefits to PAM use with sprinklers, with savings in seed costs from reduced seeding rates or prevention of stand failures necessitating reseeding often enough to pay for the PAM. Tests of polymer anticrusting agents have usually had highly variable results; however, prevention of ponding could prove very effective for flooding- or disease-sensitive seedlings. As might be expected, PAM in sprinkler irrigation greatly improves infiltration uniformity by reducing runoff and run-on problems, especially in bedded or ridged crops and on sloping land (Horne et al., unpublished data, 2000).

Although to date anionic PAMs have consistently been the most efficacious polymers for irrigation-induced erosion control and irrigation enhancement, there is growing interest in identifying biopolymer surrogates for PAM. Various natural or "organically based" compounds have shown promise. These include polymer derivatives of starch, chitin, polysaccharides, cellulose microfibril suspensions, cheese whey, and other potential protein-based polymers (Robbins and Lehrsch, 1992; Lehrsch and Robbins, 1994; Brown et al., 1998; Orts et al., 1999, 2000, 2001, 2002). Currently the best of these polymers remain about one-fifth as effective per unit mass as PAM and are typically more expensive, although costs are expected to fall to compete with PAM when organic-based polymer production achieves economies of scale.

Water Quality

While there is little information about irrigation water organic content effects on erosion, several important studies have documented the effects of EC and SAR. These vary seasonally and geographically and even on the farm, either within or between irrigation sets, if multiple water sources are involved (conjunctive water use). Thus, they offer potential for erosion and infiltration management if understood. For example gypsum is commonly added to irrigation waters in Australia to raise the water EC and lower its SAR. The result is to improve infiltration, reduce soil detachment and erosion, and lower soil exchangeable Na percentage.

High-SAR and low-EC water is more erosive than low-SAR and high-EC water. Lentz et al. (1996) found that sediment in runoff more than doubled when furrow irrigating with 12 SAR, 0.5 dS m^{-1} EC water, compared with 0.7 SAR, 2.0 dS m^{-1} EC water, and was 1.5 times that from Snake River water (0.7 SAR, 0.5 dS m^{-1} EC). Because the high SAR waters increased aggregate disruption and seal formation on furrow bottoms, infiltration was also reduced, increasing runoff and hence stream velocity and shear (Fig. 8–7).

Similar results were seen in sprinkler studies or rain simulators where water electrolyte quality was varied. Final infiltration rate decreased, while runoff and erosion increased when Kim and Miller (1996) used deionized water rather than 0.5 dS m^{-1} water during a 20 J m^{-2} mm^{-1} rain. In their laboratory study, however, using small soil trays, there was no erosion difference between 0.5 and 2.0 dS m^{-1} water. In a field rain simulator study, Flanagan et al. (1997a, 1997b) saw greater erosion once infiltration plateaued when sprinkling deionized water than when sprinkling water containing electrolytes if the event was initiated on dry soil; however, they did not see electrolyte-related differences in final infiltration rate, runoff, or the erosion measured in small interrill subplots. While the rain energy for the simulated storm event was the same as the Kim and Miller (1996) study, the rain application protocol and plot size were different, suggesting again that

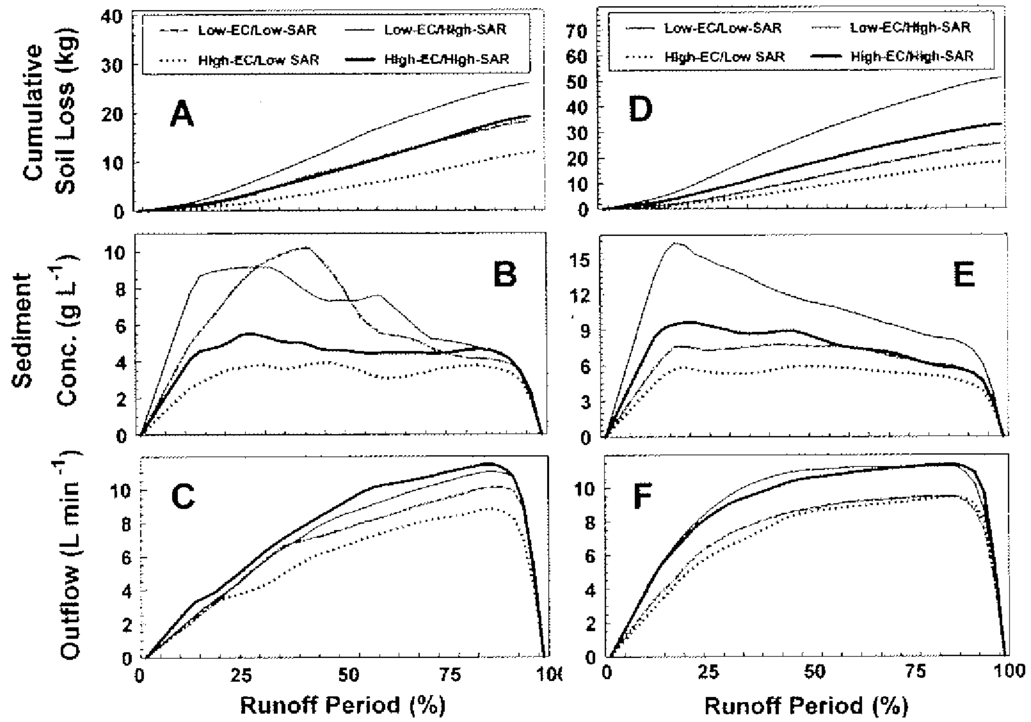


Fig. 8–7. The effect of EC (electrical conductivity) and SAR (sodium adsorption ratio) on sediment concentration, accumulated sediment loss, and runoff during a furrow irrigation event for Portneuf silt loam soil: (A–C) first irrigation following furrow formation, where soil is loose; (D–F) second irrigation, where soil is consolidated following the preceding irrigation event 2 wk earlier. Data are adapted from Lentz et al. (1996).

water application mode affects detachment and shear in ways that interact with water quality and soil properties. Le Bissonais and Singer (1993) noted that soil extract EC significantly affected infiltration, runoff, and erosion rates when comparing 17 diverse California soils; Mamedov et al. (2002) saw similar results across soil exchangeable Na percentages for six Israeli soils.

Numerous studies have explored the ways in which irrigation (or rain) water quality influences erosion through effects on the interrelationships of particle cohesion, dispersion, flocculation, and critical shear (Quirk and Schofield, 1955; Oster and Schroer, 1979). Where detachment, aggregate disruption, and dispersion of soil particles is affected by the quality of flowing water (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), the result is usually expressed in effects on seal formation. Since seals are favored by detachment and dispersion, they are usually more pronounced at higher SAR and lower EC (Shainberg and Singer, 1985; Brown et al., 1988).

The magnitude of the water quality effect on sealing and infiltration has been linked to several soil properties including the presence of flocculating or aggregate-stabilizing agents such as organic matter, and 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 K (Robbins, 1984). Arora and Coleman (1979) demonstrated that raising the EC of irrigation water improved flocculation of suspended fines and Robbins and Brockway (1978) showed that this effect could be used to improve the performance of return-flow sediment removal basins. By contrast, Gregory (1989) showed that, as water velocity increased shear forces, flocculated fines were partially broken, resulting in a grading of entrained flocs to a narrow size range, suggesting the existence of complex interactions between water quality effects and erodible minerals in irrigation-induced erosion processes.

Tillage Practices

Erosion reductions of >90% coupled with improved production costs and yields are achievable for a range of conservation tillage and no-till cropping systems under furrow irrigation (Carter and Berg, 1991; Sojka and Carter, 1994). Once established, these systems can provide cost-effective erosion elimination. A disadvantage of conservation tillage under furrow irrigation is reluctance by farmers to adopt the practice because of difficulties of integrating no-till practices with the requirements of furrow irrigation. Another problem with no-till in furrow irrigation is rotating among crops using different row spacing.

Furrow irrigation requires uniform and unobstructed furrows for even and timely water advance. This can be a problem in residue-intensive systems. Residues can migrate and lead to damming of furrows, causing water to fill furrows and wash over planted beds or ridges. This then results in portions of some furrows failing to receive water, while generating erosion in other furrows because of excess flow. Because the damming often occurs in midfield, obscured by the crop canopy, it can be difficult to cope with even when irrigators are alert to the problem.

Lentz and Bjorneberg (2001) found that using PAM with straw residue enhanced straw effectiveness, "gluing" both the straw and soil in place, and preventing sediment migration, which, in the absence of PAM, deposited amidst clumps of transported straw and caused furrow blockage. Since PAM nearly halts sediment migration, even if transported straw clumps in the furrow, the water runs underneath the straw unobstructed if no soil is washed along to fill the interstices between residue strands.

Because many crops in a rotation have different row spacing requirements, the permanent location of furrows that occurs when using no-till prevents many cropping options. This has discouraged adoption of no-till by many conservation-minded farmers.

Under sprinkler irrigation, conservation tillage can be implemented much as in rainfed systems. Wheel tracks and tower positioning must be considered to accommodate the system, but otherwise the approach is reasonably flexible. Since ridge and row patterns are often laid out in circles to take best advantage of center-pivot geometry, cropping patterns and traffic-related operations must be able to operate within this consideration.

Compaction has only begun to receive widespread attention in irrigated soils in recent years. In the past, great reliance was placed on irrigation's ability to overcome soil-related water and nutrient supply limitations. With many irrigated areas in the world approaching significant longevities, fuller appreciation is developing for the need to retain soil structure to ensure infiltration and root penetration. Compaction deteriorates soil structure and impedes infiltration, impairing crop production and contributing to runoff and erosion. A variety of approaches have been used across agriculture to reduce compaction potential and mitigate its effects.

Zone subsoiling to alleviate compaction improved crop yield and grade of furrow-irrigated potato (*Solanum tuberosum* L.) and increased infiltration up to 14% while reducing soil loss in runoff up to 64% (Sojka et al., 1993a, 1993b). Zone subsoiling can be used with either furrow or sprinkler irrigation, although with furrow irrigation greater care must be taken to retain the integrity of the trafficked furrows. This is to assure that disruption is directed to the zone of greatest root development (under the crop row) without creating excessive infiltration in the irrigated furrow, or preventing subsequent tractor or implement trafficability problems.

Tilling small pits between crop rows (*reservoir tillage*, *dammer diking*, or *basin tillage*) helps prevent or reduce runoff. This approach is suitable both to dryland farming and to sprinkler irrigation, but not to irrigated furrows. Sprinklers used on irregular sloping fields, especially the outer reaches of center pivots where application rates are high, can induce high rates of localized runoff and erosion. Kincaid et al. (1990) found that reservoir tillage eliminated 90% of these runoff and erosion losses. In some areas, such as the Texas High Plains, unirrigated furrows are dammer diked to retain rainfall when it occurs, but not the irrigation furrow itself. Thus this approach is used in conjunction with an alternate-furrow irrigation strategy.

Low-Pressure Wide-Area Sprays

The geometry of center-pivot irrigation systems requires very high instantaneous water application rates in the outermost third of the pivot. The larger the pivot, the worse the problem. A number of researchers have found that droplet kinetic energy from sprinklers or rain are directly related to particle detachment and transport, seal formation, runoff, and erosion (Bubenzer and Jones, 1971; Kinnell, 1982; Thompson and James, 1985; Moldenhauer and Kemper, 1969; Mohammed and Kohl, 1987; Moldenhauer and Long, 1964; Kincaid, 1996). By using spray booms and special emitters, smaller drop sizes are spread across a larger area (Fig. 8–8). This approach conserves energy (for pressurization), decreases droplet energy, and reduces runoff and erosion compared with standard impact-head systems (Kincaid et al., 1990, 2000). Another approach useful in some situations is LEPA (low-energy precision application) technology, which combines aspects of center-pivot water distribution and surface application (Schneider et al., 2000).

Micro- and Subirrigation

Yet another approach to reducing erosion is to use systems that provide ultra-low water application rates or that deliver water to the crop root system below ground instead of via infiltration from the surface. Drip irrigation, from ei-

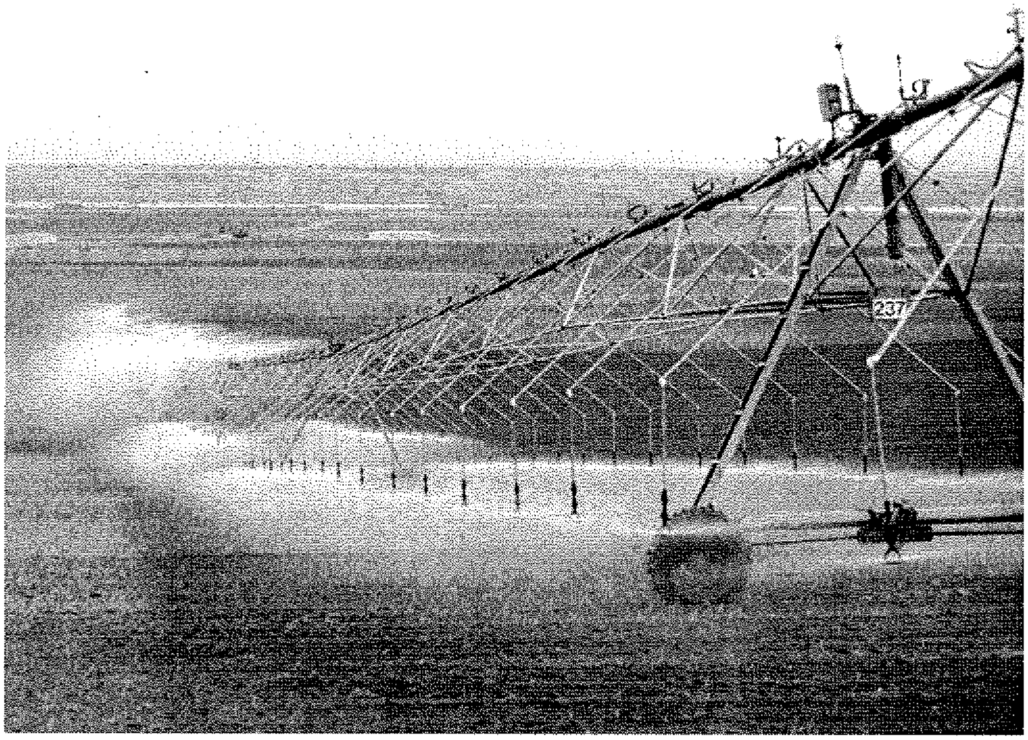


Fig. 8–8. A center pivot in south-central Idaho adapted with low-pressure nozzles and wide-area drop booms in the outer reaches of the pivot (foreground) to reduce water drop size and energy. Note that the interior reaches of the pivot, where the instantaneous water application rate is lower, use standard overhead impact heads.

ther surface or buried tubing, is usually among the most efficient and least erosion prone of irrigation systems. This is true provided water application at any given point on the landscape or in time does not combine with external effects (rain, slope, etc.) to allow water to well up to the surface and initiate runoff. The literature on drip irrigation is extensive, but as might be expected, there is no literature on erosion associated with drip irrigation.

Subirrigation systems are often combined with surface and subsurface drainage strategies (Busscher et al., 1992; Evans et al., 1992; Shirmohammadi et al., 1992; Stone et al., 1992; Thomas et al., 1992). In wet periods, water is collected in ditches or reservoirs via surface and subsurface drainage. In dry periods, water is pumped via shallow lifts from the ditches or reservoirs to the shallow tile drains that now act as subsurface irrigation distribution pipes. Again, as long as systems are managed to prevent overfilling the profile before rainfall and without significant landscape slope interactions, surface runoff is eliminated and erosion does not occur.

Drip irrigation and subsurface irrigation systems have distinct advantages and disadvantages over more conventional irrigation. They can greatly reduce or even eliminate the evaporation component of water use, greatly increasing water use efficiency. System installation and maintenance can be challenging technologically and expensive, however. In the case of drip irrigation, water quality must meet specific standards to prevent drip line plugging, and tubing longevity is typically only 2 to 5 yr. When buried drip line or tile line failures occur, it can be a significant challenge to locate and repair the problem. As a result of these costs and challenges, to date only a small percentage of the U.S. and world total irrigated area have used these technologies, despite their erosion prevention and energy and water use efficiency advantages.

CONCLUSIONS

While there has been great progress in the past 30 yr, much work remains to achieve the needed understanding and control of irrigation-induced erosion. The importance of irrigation to feeding and clothing the world's growing population and protecting unspoiled habitats continues to be poorly appreciated by both agriculturalists and the general public. Irrigation-induced erosion poses a significant threat to the sustainability of irrigated agriculture and is a major concern worldwide for the safeguarding of surface water quality.

The uniqueness of irrigation-induced erosion, as a phenomenon quite different from rainfed erosion, is better recognized by the erosion research community today than a decade ago; however, the need for improved understanding and for proper simulation models to estimate, predict, and inventory irrigation-induced erosion remains largely unsatisfied. These needs must be championed vigorously by the erosion research community if research on irrigation-induced erosion and its abatement are to be adequately prioritized and financed. The fundamental knowledge needed for the development of theory and predictive capability for irrigation-induced erosion must advance and conservation efforts for irrigated land should be strengthened.

Sojka (1998) noted three priorities deserving greater promotion in this area of endeavor. They remain largely unchanged: (i) expanded public funding for the development of erosion theory and models that are derived specifically from and for irrigated systematics; (ii) encouragement of cost–benefit analysis of government support for soil and water conservation programs and research efforts, based on relative productivity of and risk to the land resources being husbanded; and (iii) development of permanent efforts within the soil science community, its journals, and public policymakers to guarantee a balanced focus between rainfed and irrigated agriculture, recognizing the crucial contribution of irrigation to meeting humanity's production needs while protecting the environment.

A fourth priority should probably be added: for the USA and other key irrigation-intensive nations to undertake a systematic and comprehensive inventory of the extent, severity, and nature of their irrigation-induced erosion problems. Such an inventory is crucial to preserving the huge production and global environmental advantage offered by irrigation, which, despite its vast success, remains precariously balanced by the fragility of the resource base and the need for high quality management of the soil and water resources that enable its productivity.

REFERENCES

Aarstad, J.S., and D.E. Miller. 1981. Effects of small amounts of residue on furrow erosion. Soil Sci. Soc. Am. J. 45:116–118.

Aase, J.K., D.L. Bjorneberg, and R.E. Sojka. 1998. Sprinkler irrigation runoff and erosion control with polyacrylamide—Laboratory tests. Soil Sci. Soc. Am. J. 62:1681–1687.

Agassi, M., J. Letey, W.J. Farmer, and P. Clark. 1995. Soil erosion contribution to pesticide transport by furrow irrigation. J. Environ. Qual. 24:892–895.

Alexandratos, N. (ed.) 1988. World agriculture toward 2000: An FAO study. Bellhaven Press, London.

Alexandratos, N. (ed.). 1995. World agriculture: Towards 2010. An FAO Study. FAO, Rome.

Alonso, C.V., W.H. Neibling, and G.R. Foster. 1981. Estimating sediment transport capacity in watershed modeling. Trans. ASAE 24:1211–1226.

American Society of Agricultural Engineers. 2003. Surface irrigation runoff reuse systems (EP 408.2). p. 912–915. *In* ASAE standards 2003: Standards, engineering practices, data. ASAE, St. Joseph, MI.

Arora, H.S., and N.T. Coleman. 1979. The influence of electrolyte concentration on flocculation of clay suspensions. Soil Sci. 127:134–139.

Bahr, G.L., and T.D. Steiber. 1996. Reduction of nutrient and pesticide losses through the application of polyacrylamide in surface irrigated crops. p. 41–48. *In* R.E. Sojka and R.D. Lentz (ed.) Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide, Proc., Twin Falls, ID. 6–8 May 1996. Misc. Publ. 101–96. Univ. of Idaho, Moscow.

Berg, R.D., and D.L. Carter. 1980. Furrow erosion and sediment losses on irrigated cropland. J. Soil Water Conserv. 35:367–370.

Bernas, S.M., J.M. Oades, and G.J. Churchman. 1995. Effects of latex and poly-DADMAC on erosion, hydrophobicity and water retention. Aust. J. Soil Res. 33:805–816.

Ben-Hur, M. 1994. Runoff, erosion, and polymer application in moving-sprinkler irrigation. Soil Sci. 158:283–290.

Ben-Hur, M., J. Faris, M. Malik, and J. Letey. 1989. Polymers as soil conditioners under consecutive irrigation and rainfall. Soil Sci. Soc. Am. J. 53:1173–1177.

Ben-Hur, M., J. Letey, and I. Shainberg. 1990. Polymer effects on erosion under laboratory rainfall simulator conditions. Soil Sci. Soc. Am. J. 54:1092–1095.

Bjorneberg, D.L., J.K. Aase, and R.E. Sojka. 2000a. Sprinkler irrigation runoff and erosion control with polyacrylamide. p. 513–522. *In* R.G. Evans et al. (ed.) Decennial Natl. Irrig. Symp., 4th, Phoenix, AZ. 14–16 Nov. 2000. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

Bjorneberg, D.L., D.C. Kincaid, R.D. Lentz, R.E. Sojka, and T.J. Trout. 2000b. Unique aspects of modeling irrigation-induced soil erosion. Int. J. Sediment Res. 15:245–252.

Bjorneberg, D.L., F.L. Santos, N.S. Castanheira, O.C. Martins, J.L. Reis, J.K. Aase, and R.E. Sojka. 2003. Using polyacrylamide with sprinkler irrigation to improve infiltration. J. Soil Water Conserv. 58:283–289.

Bjorneberg, D.L., and R.E. Sojka. 2002. Irrigation erosion. p. 742–744. *In* R. Lal (ed.) Encyclopedia of soil science. Marcel Dekker, New York.

Bjorneberg, D.L., R.E. Sojka, and J.K. Aase. 2002a. Pre-wetting effect on furrow irrigation erosion: A field study. Trans. ASAE 45:717–722.

Bjorneberg, D.L., and T.J. Trout. 2001. Evaluating WEPP predicted on-field furrow irrigation erosion. p. 693–698. *In* D.E. Stott et al. (ed.) Sustaining the global farm. Proc. Int. Soil Conserv. Organiz. Meet., 10th, West Lafayette, IN. 24–29 May 1999 [CD-ROM]. Natl. Soil Erosion Res. Lab., West Lafayette, IN.

Bjorneberg, D.L., T.J. Trout, R.E. Sojka, and J.K. Aase. 1999. Evaluating WEPP-predicted infiltration, runoff, and soil erosion for furrow irrigation. Trans. ASAE 42:1733–1741.

Bjorneberg, D.L., D.T. Westermann, and J.K. Aase. 2002b. Nutrient losses in surface irrigation runoff. J. Soil Water Conserv. 57:524–529.

Bondurant, J.A. 1971. Quality of surface irrigation runoff water. Trans. ASAE 14:1001–1003.

Brown, M.J. 1985. Effect of grain straw and furrow irrigation stream size on soil erosion and infiltration. J. Soil Water Conserv. 40:389–391.

Brown, M.J., J.A. Bondurant, and C.E. Brockway. 1981. Ponding surface drainage water for sediment and phosphorous removal. Trans. ASAE 24:1478–1481.

Brown, M.J., D.L. Carter, G.A. Lehrsch, and R.E. Sojka. 1995. Seasonal trends in furrow irrigation erosion in southern Idaho. Soil Technol. 8:119–126.

Brown, M.J., and W.D. Kemper. 1987. Using straw in steep furrows to reduce soil erosion and increase dry bean yields. J. Soil Water Conserv. 42:187–191.

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

Brown, M.J., C.W. Robbins, and L.L. Freeborn. 1998. Combining cottage cheese whey and straw reduces erosion while increasing infiltration in furrow irrigation. J. Soil Water Conserv. 53:152–156.

Bubenzer, G.D., and B.A. Jones. 1971. Drop size and impact velocity effects on the detachment of soils under simulated rainfall. Trans. ASAE 14:625–628.

Bucks, D.A., T.W. Sammis, and G.L. Dickey. 1990. Irrigation for arid areas. p. 499–548. *In* G.J. Hoffman et al. (ed.) Management of farm irrigation systems. Am. Soc. Agric. Eng., St. Joseph, MI.

Bullock, M.S., W.D. Kemper, and S.D. Nelson. 1988. Soil cohesion as affected by freezing, water content, time and tillage. Soil Sci. Soc. Am. J. 52:770–776.

Busscher, W.J., E.J. Sadler, and F.S. Wright. 1992. Soil and crop management aspects of water table control practices. J. Soil Water Conserv. 47(1):71–74.

Carter, D.L. 1986. Effects of erosion on soil productivity. p. 1131–1138. *In* Proc. Water Forum '86, Long Beach CA. 4–6 Aug. 1986. Vol.2. Am. Soc. Civ. Eng., New York.

Carter, D.L. 1990. Soil erosion on irrigated lands. p. 1143–1171. *In* B.A. Stewart and D.R. Nielson (ed.) Irrigation of agricultural crops. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, WI.

Carter, D.L. 1993. Furrow erosion lowers soil productivity. J. Irrig. Drain. Eng. 119:964–974.

Carter, D.L., and R.D. Berg. 1983. A buried pipe system for controlling erosion and sediment loss on irrigated land. Soil Sci. Soc. Am. J. 47:749–752.

Carter, D.L., and R.D. Berg. 1991. Crop sequences and conservation tillage to control irrigation furrow erosion and increase farmer income. J. Soil Water Conserv. 46:139–142.

Carter, D.L., R.D. Berg, and B.J. Sanders. 1985. The effect of furrow irrigation erosion on crop productivity. Soil Sci. Soc. Am. J. 49:207–211.

Carter, D.L., C.E. Brockway, and K.K. Tanji. 1993. Controlling erosion and sediment loss from furrow-irrigated cropland. J. Irrig. Drain. Eng. 119:975–988.

Cary, J.W. 1986. Irrigating row crops from sod furrows to reduce erosion. Soil Sci. Soc. Am. J. 50: 1299–1302.

Chang, H.H., W.L. Graf, E.H. Grissinger, H.P. Guy, W.R. Osterkamp, G. Parker, S.W. Trimble, and L.J. Lane. 1982. Relationship between morphology of small streams and sediment yield. J. Hydraul. Div. ASCE 108:1328–1365.

Coote, D.R., C.A. Malcolm-McGovern, G.J. Wall, W.T. Dickinson, and R.P. Rudra. 1988. Seasonal variation of erodibility indices based on shear strength and aggregate stability in some Ontario soils. Can. J. Soil Sci. 68:405–416.

Coyne, M.S., R.A. Gilifillen, R.W. Rhodes, and R.L. Blevins. 1995. Soil and fecal coliform trapping by grass filter strips during simulated rain. J. Soil Water Conserv. 50:405–408.

Coyne, M.S., R.A. Gilifillen, A. Villalba, Z. Shang, R.W. Rhodes, L. Dunn, and R.L. Blevins. 1998. Fecal coliform trapping by grass filter strips during simulated rain. J. Soil Water Conserv. 52: 140–145.

Duke, H. 1992. Water temperature fluctuations and effect on irrigation infiltration. Trans. ASAE 35:193–199.

Elliot, W.J., and J.M. Laflen. 1993. A process-based rill erosion model. Trans. ASAE 36:65–72.

English, M.J., K.H. Solomon, and G.J. Hoffman. 2002. A paradigm shift in irrigation management. J. Irrig. Drain. Eng. 128:267–277.

Entry, J.A., R.K. Hubbard, J.E. Thies, and J.J. Fuhrmann. 2000a. The influence of vegetation in riparian filterstrips on coliform bacteria: I. Movement and survival in water. J. Environ. Qual. 29: 1206–1214.

Entry, J.A., R.K. Hubbard, J.E. Thies, and J.J. Fuhrmann. 2000b. The influence of vegetation in riparian filterstrips on coliform bacteria: II. Survival in soils. J. Environ. Qual. 29:1215–1224.

Entry, J.A., I. Phillips, H. Stratton, and R.E. Sojka. 2003. Polyacrylamide+$Al(SO_4)_3$ and polyacrylamide+CaO remove coliform bacteria and nutrients from swine wastewater. Environ. Pollut. 121:453–462.

Entry, J.A., and R.E. Sojka. 2000. The efficacy of polyacrylamide and related compounds to remove microorganisms and nutrients from animal wastewater. J. Environ. Qual. 29:1905–1914.

Entry, J.A., and R.E. Sojka. 2001. Polyacrylamide compounds remove coliform bacteria from animal wastewater. p. 277–280. *In* Preferential flow—Water movement and chemical transport in the environment. Proc. Int. Symp., 2nd, Honolulu, HI. 3–5 Jan. 2001. Am. Soc. Agric. Eng., St. Joseph, MI.

Entry, J.A., and R.E. Sojka. 2003. The efficacy of polyacrylamide to reduce nutrient movement from an irrigated field. Trans. ASAE 46:75–83.

Evans, R.E., J.S. Aarstad, D.E. Miller, and M.W. Kroeger. 1987. Crop residue effects on surface furrow irrigation hydraulics. Trans. ASAE 30:424–429.

Evans, R.O., J.E. Parsons, K.C. Stone, and W.B. Wells. 1992. Water table management on a watershed scale. J. Soil Water Conserv. 47:58–64.

FAO. 2003. Aquastat. Available at www.fao.org/ag/agl/aglw/aquastat/main/index.stm (accessed 29 Apr. 2003; verified 20 May 2006) Land and Water Dev. Div., FAO, Rome.

Fernandez Gomez, R. 1997. La erosion del suelo en el riego por surcos. Ph.D. diss. Univ. de Cordoba, Cordoba, Spain.

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

Fitzsimmons, D.W., G.C. Lewis, D.V. Naylor, and J.R. Busch. 1972. Nitrogen, phosphorus and other inorganic materials in waters in a gravity-irrigated area. Trans. ASAE 15:292–295.

Flanagan, D.C., and M.A. Nearing (ed.). 1995. USDA Water Erosion Prediction Project: Technical documentation. NSERL Rep. no. 10. Natl. Soil Erosion Res. Lab., West Lafayette, IN.

Flanagan, D.C., L.D. Norton, and I. Shainberg. 1997a. Effect of water chemistry and soil amendments on a silt loam soil—Part I: Infiltration and runoff. Trans. ASAE 40:1549–1554.

Flanagan, D.C., L.D. Norton, and I. Shainberg. 1997b. Effect of water chemistry and soil amendments on silt loam soil—Part II: Soil erosion. Trans. ASAE 40:1555–1561.

Fornstrom, K.J., and J. Borelli. 1984. Design and Management procedures for minimizing erosion from furrow irrigated cropland. ASAE Pap. 84-2595. Am. Soc. Agric., Eng., St. Joseph, MI.

Foster, G.R. 1982. Modeling the erosion process. Ch. 8. *In* C.T. Haan et al. (ed.) Hydrologic modeling of small watersheds. ASAE Monogr. Am. Soc. Agric. Eng., St. Joseph, MI.

Foster, G.R., and L.D. Meyer. 1972. A closed-form soil erosion equation for upland areas. p. 12-1–12-19. *In* H.W. Shen (ed.) Sedimentation (Einstein). Colorado State Univ., Fort Collins.

Frenkel, H., J.O. Goertzen, and J.D. Rhoades. 1978. Effects of clay type and content, exchangeable sodium percentage, and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Sci. Soc. Am. J. 42:32–39.

Gal, M., R. Stern, J. Levin, and M. Ben-Hur. 1992. Polymer effect on water infiltration and erosion of sodic soils. S. Afr. J. Plant Soil 9:108–112.

Goldberg, S., and H.S. Forster. 1990. Flocculation of reference clays and arid-zone soil clays. Soil Sci. Soc. Am. J. 54:714–718.

Goldberg, S., and R.A. Glaubig. 1987. Effect of saturating cation, pH, and aluminum and iron oxide on the flocculation of kaolinite and montmorillonite. Clays Clay Miner. 35:220–227.

Goldberg, S., D.L. Suarez, and R.A. Glaubig. 1988. Factors affecting clay dispersion and aggregate stability of arid-zone soils. Soil Sci. 146:317–325.

Gregory, J. 1989. Fundamentals of flocculation. Crit. Rev. Environ. Control 19:185–230.

Griffiths, R.P., J.A. Entry, E.R. Ingham, and H. Emmingham. 1997. Chemistry and microbial activity of forest and pasture riparian-zone soils along three Pacific Northwest streams. Plant Soil 190: 169–178.

Harris, R.F., G. Chesters, and O.N. Allen. 1966. Dynamics of soil aggregation. Adv. Agron. 18:107–169.

Howell, T.A. 2000. Irrigation's role in enhancing water use efficiency. p. 66–80. *In* R.G. Evans et al. (ed.) Decennial Natl. Irrig. Symp., 4th, Phoenix, AZ. 14–16 Nov. 2000. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

Hubbard, R.K., G.L. Newton, J.G. Davis, R. Lowrance, G. Vellidis, and C.R. Dove. 1998. Nitrogen assimilation by riparian buffer systems receiving swine lagoon wastewater. Trans. ASAE 41: 1295–1304.

Israelson, O.W., G.D. Clyde, and C.W. Lauritzen. 1946. Soil erosion in small irrigation furrows. Bull. 320. Utah Agric. Exp. Stn., Logan.

Jaynes, D.B. 1990. Temperature variations effect on field-measured infiltration. Soil Sci. Soc. Am. J. 54:305–312.

Jensen, M.E., W.R. Rangeley, and P.J. Dieleman. 1990. Irrigation trends in world agriculture. p. 31–67. *In* B.A. Stewart and D.R. Nielsen (ed.) Irrigation of agricultural crops. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, WI.

Jordan, T.E., D.T. Correll, and D.E. Weller. 1993. Nutrient interception by a riparian forest receiving inputs from adjacent cropland. J. Environ. Qual. 14:467–472.

Kemper, W.D., and R.C. Rosenau. 1984. Soil cohesion as affected by time and water content. Soil Sci. Soc. Am. J. 48:1001–1006.

Kemper, W.D., R. Rosenau, and S. Nelson. 1985a. Gas displacement and aggregate stability of soils. Soil Sci. Soc. Am. J. 49:25–28.

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

Kendall, H.W., and D. Pimentel. 1994. Constraints on the expansion of the global food supply. Ambio 23:198–205.

Khaeel, R., K.R. Reddy, and M.R. Overcash. 1980. Transport of potential pollutants in runoff water from land areas receiving animal wastes: A review. Water Res. 14:421–436.

Kim, K.-H., and W.P. Miller. 1996. Effect of rainfall electrolyte concentration and slope on infiltration and erosion. Soil Technol. 9:173–185.

Kincaid, D.C. 1996. Spraydrop kinetic energy from irrigation sprinnklers. Trans. ASAE 39:847–853.

Kincaid, D.C. 2002. The WEPP model for runoff and erosion prediction under sprinkler irrigation. Trans. ASAE 45:67–72.

Kincaid, D.C., B.A. King, and D.W. DeBoer. 2000. Sprinkler packages and their configuration for center pivot irrigation. p. 109–114. *In* R.G. Evans et al. (ed.) Decennial Natl. Irrig. Symp., 4th, Phoenix, AZ. 14–16 Nov. 2000. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

Kincaid, D.C., and G.A. Lehrsch. 2001. The WEPP model for runoff and erosion prediction under center pivot irrigation. p. 115–118. *In* J.C. Ascough II and D.C. Flanagan (ed.) Soil erosion research for the 21st century. Proc., Honolulu, HI. 3–5 Jan. 2001. Am. Soc. Agric. Eng., St. Joseph, MI.

Kincaid, D.C., I. McCann, J.R. Busch, and M. Hasheminia. 1990. Low pressure center pivot irrigation and reservoir tillage. p. 54–60. *In* Visions of the future. Proc. Natl. Symp., 3rd, Phoenix, AZ. 28 Oct.–1 Nov. 1990. Am. Soc. Agric. Eng., St. Joseph, MI.

Kinnell, P.I.A. 1982. Laboratory studies on the effect of drop size on splash erosion. J. Agric. Eng. Res. 27:431–439.

Koluvek, P.K., K.K. Tanji, and T.J. Trout. 1993. Overview of soil erosion from irrigation. J. Irr. Drain. Eng. 119:929–946.

Laflen, J.M., J. Lane, and G.R. Foster. 1991. The Water Erosion Prediction Project—A new generation of erosion prediction technology. J. Soil Water Conserv. 46:34–38.

Larson, W.E., G.R. Foster, R.R. Allmaras, and C.M. Smith (ed.). 1990. Proc. Soil Erosion and Productivity Worksh., Bloomington, MN. 13–15 Mar. 1989. Univ. of Minnesota, St. Paul.

Laursen, E.M. 1958. The total sediment load of streams. J. Hydraul. Div. ASCE 84:1530-1–1530-36.

Le Bissonais, Y., and M.J. Singer. 1992. Crusting, runoff, and erosion response to soil water content and successive rainfall. Soil Sci. Soc. Am. J. 56:1898–1903.

Le Bissonais, Y., and M.J. Singer. 1993. Seal formation, runoff, and interrill erosion from seventeen California soils. Soil Sci. Soc. Am. J. 57:224–229.

Lehrsch, G.A., and M.J. Brown. 1995. Furrow erosion and aggregate stability variation in a Portneuf silt loam. Soil Technol. 7:327–341.

Lehrsch, G.A., and C.W. Robbins. 1994. Cheese whey as an amendment to disturbed lands: Effects on soil hydraulic properties. p. 330–336. *In* Proc. Int. Land Reclamation and Mine Drainage Conf. and Int. Conf. on the Abatement of Acidic Drainage, 3rd, Pittsburgh, PA. Apr. 1994. Vol. 3. USDI Bur. Mines Spec. Publ. SP 06C–94. Natl. Tech. Inf. Serv., Springfield, VA.

Lentz, R.D., and D.L. Bjorneberg. 2002. Influence of irrigation water properties on furrow infiltration: Temperature effects. p. 705–709. *In* D.E. Stott et al. (ed.) Sustaining the global farm. Proc. Int. Soil Conserv. Organiz. Meet., 10th, West Lafayette, IN. 24–29 May 1999 [CD-ROM]. Natl. Soil Erosion Res. Lab., West Lafayette, IN.

Lentz, R.D., and D.L. Bjorneberg. 2001. PAM and straw residue effects on irrigation furrow erosion and infiltration. p. 175–178. *In* J.C. Ascough II and D. C. Flanagan (ed.) Soil erosion research for the 21st century. Proc. Int. Symp., Honolulu, HI. 3–5 Jan. 2001. Am. Soc. Agric. Eng., St. Joseph, MI.

Lentz, R.D., I. Shainberg, R.E. Sojka, and D.L. Carter. 1992. Preventing irrigation furrow erosion with small applications of polymers. Soil Sci. Soc. Am. J. 56:1926–1932.

Lentz, R.D., and R.E. Sojka. 1994. Field results using polyacrylamide to manage furrow erosion and infiltration. Soil Sci. 158:274–282.

Lentz, R.D., R.E. Sojka, and D.L. Carter. 1993. Influence of irrigation water quality on sediment loss from furrows. p. 274–278. *In* Agricultural Research to Protect Water Quality, Proc. Conf., Minneapolis, MN. 21–24 Feb. 1993. Soil Water Conserv. Soc., Ankeny, IA.

Lentz, R.D., R.E. Sojka, and D.L. Carter. 1996. Furrow irrigation water-quality effects on soil loss and infiltration. Soil Sci. Soc. Am. J. 60:238–245.

Lentz, R.D., R.E. Sojka, and C.W. Robbins. 1998. Reducing phosphorus losses from surface-irrigated fields: Emerging polyacrylamide technology. J. Environ. Qual. 27:305–312.

Lentz, R.D., R.E. Sojka, C.W. Robbins, D.C. Kincaid, and D.T. Westermann. 2001. Polyacrylamide for surface irrigation to increase nutrient-use efficiency and protect water quality. Commun. Soil Sci. Plant Anal. 32:1203–1220.

Levy, G.J., and M. Agassi. 1995. Polymer molecular weight and degree of drying effects on infiltration and erosion of three different soils. Aust. J. Soil Res. 33:1007–1018.

Levy, G.J., M. Ben-Hur, and M. Agassi. 1991. The effect of polyacrylamide on runoff, erosion, and cotton yield from fields irrigated with moving sprinkler systems. Irrig. Sci. 12:55–60.

Levy, G.J., J. Levin, M. Gal, and M. Ben-Hur. 1992. Polymers' effects on infiltration and soil erosion during consecutive simulated sprinkler irrigations. Soil Sci. Soc. Am. J. 56:902–907.

Levy, G.J., J. Levin, and I. Shainberg. 1994. Seal formation and interill soil formation. Soil Sci. Soc. Am. J. 58:203–209.

Levy, G.J., J. Levin, and I. Shainberg. 1995. Polymer effects on runoff and soil erosion from sodic soils. Irrig. Sci. 16:9–14.

Leytem, A.B., and D.L. Bjorneberg. 2005. Removing soluble phosphorus in irrigation return flows with alum additions. J. Soil Water Conserv. 60:200–208.

Lu, J., L. Wu, J. Letey, and W.J. Farmer. 2002a. Anionic polyacrylamide effects on soil sorption and desorption of metolachlor, atrazine, 2,4-D, and picloram. J. Environ. Qual. 31:1226–1233.

Lu, J., L. Wu, J. Letey, and W.J. Farmer. 2002b. Picloram and napropamide sorption as affected by polymer addition and salt concentration. J. Environ. Qual. 31:1234–1239.

Malik, M., M.A. Mustafa, and J. Letey. 1992. Effect of mixed Na/Ca solutions on swelling, dispersion and transient water flow in unsaturated montmorillonitic soils. Geoderma 52:17–28.

Mamedov, A.I., I. Shainberg, and G.J. Levy. 2002. Wetting rate and sodicity effects on interill erosion from semi-arid Israeli soils. Soil Tillage Res. 68:121–132.

Mawdsley, J.L., R.D. Bardgett, R.D. Merry, B.F. Pain, and M.K. Theodorou. 1995. Pathogens in livestock waste, their potential for movement through soil and environmental pollution. Appl. Soil Ecol. 2:1–15.

McCutchan, H., P. Osterli, and J. Letey. 1994. Polymers check furrow erosion, help river life. Calif. Agric. 47:10–11.

McNeal, B.L., and N.T. Coleman. 1966. Effect of solution composition on soil hydraulic conductivity. Soil Sci. Soc. Am. Proc. 30:308–312.

Mech, S.J. 1949. Effect of slope and length of run on erosion under irrigation. Agric. Eng. 30:379–383, 389.

Mech, S.J. 1959. Soil erosion and its control under furrow irrigation in arid West. Inf. Bull. 184. U.S. Gov. Print. Office, Washington, DC.

Miller, D.E., J.S. Aarstad, and R.G. Evans. 1987. Control of furrow erosion with crop residues and surge flow irrigation. Agron. J. 51:421–425.

Mitchell, A.R. 1986. Polyacrylamide application in irrigation water to increase infiltration. Soil Sci. 141:353–358.

Mohammed, D., and R.A. Kohl. 1987. Infiltration response to kinetic energy. Trans. ASAE 30:108–111.

Moldenhauer, W.C., and D.C. Long. 1964. Influence of rainfall energy on soil loss and infiltration rates: I. Effects over a range of texture. Soil Sci. Soc. Am. Proc. 28:813–817.

Moldenhauer, W.C., and W.D. Kemper. 1969. Interdependence of water drop energy and clod size on infiltration and clod stability. Soil Sci. Soc. Am. Proc. 33:297–301.

National Research Council. 1996. A new era for irrigation. Natl. Acad. Press, Washington, DC.

Nearing, M.A., G.R. Foster, L.J. Lane, and S.C. Finkner. 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. Trans. ASAE 32:1587–1593.

NRCS. 2000. Idaho NRCS Agron. Tech. Note no. 32. Rev. 2. Univ. of Idaho, Moscow.

Omernik, J.M., A.R. Abernathy, and L.M. Male. 1981. Stream nutrient levels and proximity of agricultural and forest land to streams: Some relationships. J. Soil Water Conserv. 36:227–231.

Orts, W.J., R.E. Sojka, and G.M. Glenn. 2000. Biopolymer additives to reduce erosion-induced soil losses during irrigation. Ind. Crops Products 11:19–29.

Orts, W.J., R.E. Sojka, and G.M. Glenn. 2002. Polymer additives in irrigation water to reduce erosion and better manage water infiltration. Agro Food Ind. Hi-Tech 13(4):37–41.

Orts, W.J., R.E. Sojka, G.M. Glenn, and R.A. Gross. 1999. Preventing soil erosion with polymer additives. Polymer News 24:406–413.

Orts, W.J., R.E. Sojka, G.M. Glenn, and R.A. Gross. 2001. Biopolymer additives for the reduction of soil erosion losses during irrigation. p. 102–116. *In* R.A. Gross and C. Scholz (ed.) Biopolymers from polysaccharides and agroproteins. ACS Symp. 786. Am. Chem. Soc., Washington, DC.

Oster, J.D., and F.W. Schroer. 1979. Infiltration as influenced by irrigation water quality. Soil Sci. Soc. Am. J. 43:444–447.

Paganyas, K.P. 1975. Results of the use of Series "K" compounds for the control of irrigational soil erosion. Sov. Soil Sci. 5:591–598.

Peele, T.C. 1936. The effect of calcium on the erodibility of soils. Soil Sci. Soc. Am. Proc. 1:47–58.

Plusquellec, H. 2002. Is the daunting challenge of irrigation achievable? Irrig. Drain. 51:185–198.

Quirk, J.P., and R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. J. Soil Sci. 6:163–178.

Reckendorf, F. 1995. RCA III: Sedimentation in irrigation water bodies, reservoirs, canals, and ditches. Working Paper no. 5. Available at www.nrcs.usda.gov/technical/land/pubs/wp05text.html (verified 20 May 2006). NRCS, Washington, DC.

Rhoades, J.D. 1997. Sustainability of irrigation: An overview of salinity problems and control strategies. p. 1–42. *In* Footprints of Humanity: Reflections on Fifty Years of Water Resource Developments, CWRA 1997 Annual Conf., Lethbridge, AB, Canada. 3–6 June 1997. Can. Water Resour. Assoc., Ottawa, ON.

Robbins, C.W. 1984. Sodium adsorption ratio–exchangeable sodium percentage relationships in a high potassium saline-sodic soil. Irrig. Sci. 5:173–179.

Robbins, C.W., and C.E. Brockway. 1978. Irrigation water salt concentration influences on sediment removal by ponds. Soil Sci. Soc. Am. J. 42:478–481.

Robbins, C.W., and G.A. Lehrsch. 1992. Effects of acidic cottage cheese whey on chemical and physical properties of a sodic soil. Arid Soil Res. Rehabil. 6:127–134.

Robbins, C.W., and G.A. Lehrsch. 1997. Cheese whey as a soil conditioner. p. 167–186. *In* A. Wallace and R.E. Terry (ed.) Handbook of soil conditioners, substances that enhance the physical properties of soil. Marcel Dekker, New York.

Rosegrant, M.W., X. Cai, and S.A. Cline. 2003. Will the world run dry? Global water and food security. Environment 45:24–36.

Schlosser, I.J., and J.R. Karr. 1981. Water quality in agricultural watersheds: Impact of riparian vegetation during base flow. Water Resour. Bull. 17:233–240.

Schneider, A.D., G. Buchleiter, and D.C. Kincaid. 2000. LEPA irrigation developments. p. 89–96. *In* R.G. Evans et al. (ed.) Decennial Natl. Irrig. Symp., 4th, Phoenix, AZ. 14–16 Nov. 2000. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

Seckler, D. 2000. IWMI draft strategy. Int. Water Manage. Inst., Colombo, Sri Lanka.

Seckler, D., U. Amarasinghe, D. Molden, R. de Silva, and R. Barker. 1998. World water demand and supply, 1990 to 2025: Scenarios and issues. Res. Rep. 19. Int. Water Manage. Inst., Colombo, Sri Lanka.

Shainberg, I., D. Goldstein, and G.J. Levy. 1996. Rill erosion dependence on soil water content, aging, and temperature. Soil Sci. Soc. Am. J. 60:916–922.

Shainberg, I., J.M. Laflen, J.M. Bradford, and L.D. Norton. 1994. Hydraulic flow and water quality characteristics in rill erosion. Soil Sci. Soc. Am. J. 58:1007–1012.

Shainberg, I., J.D. Rhoades, and R.J. Prather. 1981. Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil. Soil Sci. Soc. Am. J. 45:273–277.

Shainberg, I., and M.J. Singer. 1985. Effect of electrolyte concentration on the hydraulic properties of depositional crusts. Soil Sci. Soc. Am. J. 49:1260–1263.

Shainberg, I., D. Warrington, and J.M. Laflen. 1992. Soil dispersibility, rain properties, and slope interaction in rill formation and erosion. Soil Sci. Soc. Am. J. 56:278–283.

Shirmohammadi, A., C.R. Camp, and D.L. Thomas. 1992. Water table management for field-sized areas in the Atlantic Coastal Plain. J. Soil Water Conserv. 47(1):52–57.

Singh, G., J. Letey, P. Hanson, P. Osterli, and W.F. Spencer. 1996. Soil erosion and pesticide transport from an irrigated field. J. Environ. Sci. Health B 31(1):25–41.

Smith, G.G., J.L. Foley, and R.J. Loch. 1992. Effects of electrical conductivity of water used in wetting and in wet sieving on measured aggregate water stability. Soil Technol. 5:177–184.

Smith, H.J.C., G.J. Levy, and I. Shainberg. 1990. Water-droplet energy and soil amendments: Effect on infiltration and erosion. Soil Sci. Soc. Am. J. 54:1084–1087.

Snyder, N.J., S. Mostaghimi, D.F. Berry, R.B. Reneau, S. Hong, P.W. McClellan, and E.P. Smith. 1998. Impact of riparian buffers on agricultural nonpoint source pollution. J. Am. Water Res. Assoc. 34:385–395.

Sojka, R.E. 1996. Management options for control of irrigation-induced erosion. p. 95–103. *In* Proc. Winter Commodity Schools. Vol. 28. Univ. of Idaho Coop. Ext. System, Moscow.

Sojka, R.E. 1998. Understanding and managing irrigation-induced erosion. p. 21–37. *In* F.J. Pierce and W.W. Frye (ed.) Advances in soil and water conservation. Ann Arbor Press, Chelsea, MI.

Sojka, R.E., and D.L. Bjorneberg. 2002a. Erosion, controlling irrigation-induced. p. 411–414. *In* R. Lal (ed.) Encyclopedia of soil science. Marcel Dekker, New York.

Sojka, R.E., and D.L. Bjorneberg. 2002b. Soil erosion reduction. p. 310–312. *In* E. Geller et al. (ed.). Yearbook of science and technology. McGraw-Hill, New York.

Sojka, R.E., M.J. Brown, and E.C. Kennedy-Ketcheson. 1992. Reducing erosion from surface irrigation by furrow spacing and plant position. Agron. J. 84:668–675.

Sojka, R.E., and D.L. Carter. 1994. Constraints on conservation tillage under dryland and irrigated agriculture in the United States Pacific Northwest. Ch. 12. *In* M.R. Carter (ed.) Conservation tillage in temperate agroecosystems. Lewis Publ., Boca Raton, FL.

Sojka, R.E., and J.A. Entry. 2000. Influence of polyacrylamide application to soil on movement of microorganisms in runoff water. Environ. Pollut. 108:405–412.

Sojka, R.E., J.A. Entry, W.J. Orts, D.W. Morishita, C.W. Ross, and D.J. Horne. 2003a. Synthetic- and bio-polymer use for runoff water quality management in irrigated agriculture. p. 3-130–3-136. *In* Proc. Int. Water Assoc. Int. Conf. on Diffuse Pollution and Basin Management, 7th, Dublin, Ireland. 17–22 Aug. 2003. Vol.1. IWA Publ., London.

Sojka, R.E., and R.D. Lentz. 1993. Improving water quality of return flows in furrow-irrigated systems using polymer-amended inflows. p. 395–397. *In* Agricultural Research to Protect Water Quality, Proc. Conf., Minneapolis, MN. 21–24 Feb. 1993. Soil Water Conserv. Soc., Ankeny, IA.

Sojka, R.E., and R.D. Lentz. 1994. Polyacrylamide (PAM): A new weapon in the fight against irrigation-induced erosion. Stn. Note no. 01–94. USDA-ARS Soil and Water Manage. Res. Unit, St. Paul, MN.

Sojka, R.E., and R.D. Lentz. 1995. Decreasing sedimentation loss from surface irrigation into riparian areas. p. 62–68. *In* Diverse Values: Seeking Common Ground. Proc. Northw. Regional Riparian Symp., Boise, ID. 8–9 Dec. 1994. Univ. of Idaho, Moscow.

Sojka, R.E., and R.D. Lentz. 1997. Reducing furrow irrigation erosion with polyacrylamide (PAM). J. Prod. Agric. 10:47–52.

Sojka, R.E., R.D. Lentz, and D.T. Westermann. 1998. Water and erosion management with multiple applications of polyacrylamide in furrow irrigation. Soil Sci. Soc. Am. J. 62:1672–1680.

Sojka, R.E., D. Morishita, J. Foerster, and M. Wille. 2003b. Weed seed transport and weed establishment as affected by PAM in furrow-irrigated corn. J. Soil Water Conserv. 58(5):319–326.

Sojka, R.E., D.T. Westermann, M.J. Brown, and B.D. Meek. 1993a. Zone-subsoiling effects on infiltration, runoff, erosion, and yields of furrow-irrigated potatoes. Soil Tillage Res. 25:351–368.

Sojka, R.E., D.T. Westermann, D.C. Kincaid, I.R. McCann, J.L. Halderson, and M. Thornton. 1993b. Zone-subsoiling effects on potato yield and grade. Am. Potato J. 70:475–484.

Spackman, R., J.A. Entry, R.E. Sojka, and J.W. Ellsworth. 2003. Polyacrylamide for coliform bacteria removal from agricultural waste water. J. Soil Water Conserv. 58(5):7–14.

Spofford, T.L., and P.K. Koluvek. 1987. Sprinkler erosion model. p. 108–115. *In* L.G. James and M.J. English (ed.) Irrigation Systems for the 21st Century, Proc. Conf. 28–30 July 1987. Am. Soc. Civ. Eng., Reston, VA.

Stone, K.C., R.C. Sommers, G.H. Williams, and D.E. Hawkins. 1992. Water table management in the eastern Coastal Plain. J. Soil Water Conserv. 47(1):47–51.

Strelkoff, T.S., and D.L. Bjorneberg. 2001. Hydraulic modeling of irrigation-induced furrow erosion. p. 699– 705. *In* D.E. Stott et al. (ed.) Sustaining the global farm. Proc. Int. Soil Conserv. Organiz. Meet., 10th. West Lafayette, IN. 24–29 May 1999 [CD-ROM]. Natl. Soil Erosion Res. Lab., West Lafayette, IN.

Strelkoff, T.S., A.J. Clemmens, and B.V. Schmidt. 1998. SRFR, Version 3.21—A model for simulating surface irrigation in borders, basins, and furrows. U.S. Water Conserv. Lab., Phoenix, AZ.

Thomas, D.L., P.G. Hunt, and J.W. Gilliam. 1992. Water table management for water quality improvement. J. Soil Water Conserv. 47(1):65–70.

Thompson, A.L., and L.G. James. 1985. Water droplet impact and its effect on infiltration. Trans. ASAE 28:1506–1510, 1520.

Tribe, D. 1994. Feeding and greening the world—The role of agricultural research. CAB Int., Wallingford, UK.

Trout, T., D. Carter, and R.E. Sojka. 1994. Irrigation-induced soil erosion reduces yields and muddies rivers. Irrig. J. 44:8, 11–12.

Trout, T.J. 1994. Irrigation tailwater reuse in southern Idaho. ASAE Pap. no. 942138. Am. Soc. Agric. Eng., St. Joseph, MI.

Trout, T.J. 1995. The case for irrigation tailwater reuse in southern Idaho. Proc. Univ. Idaho Winter Commodity Schools 27:93–94.

Trout, T.J. 1996. Furrow irrigation erosion and sedimentation: On-field distribution. Trans. ASAE 39:1717–17-23.</bok>

Trout, T.J., and W.H. Neibling. 1993. Erosion and sedimentation processes on irrigated fields. J. Irrig. Drain. Eng. 119:947–963.

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

USDA. 2004. Farm and ranch irrigation survey 2003. Vol. 3. Special Studies, Part 1. AC-02-SS-1. USDA, Washington, DC.

USEPA. 1998. Environmental impacts of animal feeding operations. Preliminary data summary. Feedlots point source category study. USEPA, Washington, DC.

USEPA. 2000. The quality of our nation's waters. A summary of the national quality inventory: 1998 report to Congress. EPA841-S-00–001. USEPA Office of Water, Washington, DC.

Velasco-Molina, H.A., A.R. Swoboda, and C.L. Godfrey. 1971. Dispersion of soils of different mineralogy in relation to sodium adsorption ratio and electrolyte concentration. Soil Sci. 111:282–287.

Walker, S.E., S. Mostaghimi, T.A. Dillaha, and F.E. Woeste. 1990. Modeling animal waste management practices: Impacts on bacteria levels in runoff from agricultural land. Trans. ASAE 33:807–817.

Waters, D., R. Drysdale, and S. Kimber. 1999. Benefits of planting into wheat stubble. Aust. Cotton Grower Mag. 20(4):8–13.

Yalin, M.S. 1963. An expression for bed-load transportation. J. Hydraul. Div. ASCE 89:221–250.

Yang, C.T. 1973. Incipient motion and sediment transport. J. Hydraul. Div. ASCE 99:1679–1704.

Young, R.A., T. Hundtrods, and W. Anderson. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. J. Environ. Qual. 9:483–487.

Young, R.A., M.J.M. Römkens, and D.K. McCool. 1990. Temporal variations in soil erodibility. p. 41–53. *In* R.B. Bryan (ed.) Soil erosion–Experimental models. Catena Suppl. 17. Catena Verlag, Lawrence, KS.