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Fifty Years of Soil and Water Conservation in the United States

F.J. Pierce and W.W. Fry, eds.

SOIL AND WATER CONSERVATION SOCIETY

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Research contribution to the understanding and management of irrigation-induced erosion

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The importance of irrigated agriculture

Preventing irrigation-induced erosion takes on a special importance because of the indispensable role irrigated agriculture plays in feeding and clothing humanity. Irrigation is one of humanity's most potent weapons in the war against starvation and one of the best strategies for preserving earth's remaining undisturbed environments while meeting human food and fiber needs.

Overall, irrigation is used on about 1/6 of both the U.S. (Fig. 1) and global cropped area, but irrigated cropland produces about 1/3 the annual harvest in both cases (Table 1), and about 1/2 the value of all crops (food, fiber, etc.) harvested (Bucks et al., 1990). A mere 50 million irrigated hectares (125 million acres), or about 4 percent of the world's total cropped land, produces about one third of the world's ***food harvest*** (Tribe, 1994). Irrigated agriculture's predominant association with aridity combines higher photosynthetic efficiency (fewer cloudy days) with the ability to prevent stress and better regulate inputs. These advantages result in higher commodity quality than rainfed agriculture with greater yield assurance, often for crops that cannot be commercially grown otherwise.

Irrigated agriculture also provides substantial environmental dividends. Arid climates generally have lower disease and insect pressures, reducing pesticide requirements. Arid soils have high base saturation and little organic matter, thus they seldom require lime or potassium fertilizers, and have greatly reduced application rate requirements for soil-applied pesticides and herbicides (Stevenson, F.J. 1972; Ross and Lembi, 1985). The two-fold greater efficiency of irrigated agriculture frees almost a half billion hectares (36 times the farmed area of Iowa) from the need for rainfed agricultural development globally (Sojka, 1997). Furthermore, sparsely populated arid lands developed for irrigation have lower speciation densities, resulting in less social and biological displacement and fewer extinctions than occurs for comparable production through development of rainfed lands. In fact, irrigation of arid lands provides habitat that may extend the range of some humid and subhumid wildlife and avian species.

The severity of irrigation-induced erosion

Irrigation-induced erosion is a threat both to the sustainability of irrigated agriculture and to global food security. Yet, relatively little data has been published quantifying the extent of irrigation-induced erosion. Most published data originates from the U.S. Pacific Northwest (PNW), and focuses largely on furrow irrigation. While not entirely representative of all irrigation-induced erosion, the data from this region demonstrates considerations common to nearly all irrigated agriculture.

Arid zone soils are usually low in organic matter and poorly aggregated, with thin, easily eroded A horizons. Carter (1993) demonstrated that, once eroded, yield potentials of PNW soils are severely reduced (Table 2). Furthermore, furrow irrigation, used on much of the world's irrigated land, is an inherently erosive process (Fig. 2).

Furrow irrigation-induced erosion in the PNW commonly removes 5-50 t ha_{-1} of soil per year, with much of the erosion (3-8x the field averaged rate) occurring near the upper end of fields near furrow inlets (Berg and Carter, 1980; Kemper et al., 1985; Fornstrom and Borelli, 1984, Trout, 1996a). Over 50 t ha_{-1} soil loss has been measured for a single 24 hr irrigation (Mech, 1959). The magnitude of this problem is better appreciated when one recognizes that typical soil loss tolerance values for these soils are around 11 t ha_{-1} (5 tons/acre) per year. Thus, in the 90-100 years that PNW furrow irrigation has been practiced, many fields have little or no topsoil remaining on the upper one-third of the field. Furthermore, the topsoil remaining on lower field portions is mixed with subsoil washed off upper field reaches and deposited at the lower end.

The negative impacts of soil loss are numerous (Carter, 1990). The B horizons of most arid zone soils have poor chemical and physical properties. They easily crust, seal, and compact, and often have phosphorous and micronutrient deficiencies, which collectively impair emergence, fertility, rooting, absorption of water and nutrients, and yields. As yield potential decreases, input costs increase, while the probability of response from inputs declines. Thus, production cost increases while yield and profit decline.

Eroded soil deposits in the lower reaches of fields, and in drains, return-flow ditches, lakes, streams or rivers. Even when a significant amount of sediment is captured in the lower reaches of the field or in containment ponds, redistribution onto the field is required. The societal costs of these losses include reduced net on-farm returns and reduced production, with resultant upward pressure on commodity pricing; higher cost of canal maintenance, river dredging, and algal control; riparian habitat degradation and biodiversity reduction; water contamination; impairment of fisheries and recreational resources; reservoir capacity reduction; and accelerated hydro-electric generator wear (Sojka and Lentz, 1995). Many of these expenses and losses are long range costs and are neglected in cost benefit analyses for supporting conservation practices.

Irrigation-induced erosion... A separate case

Despite the importance of irrigated agriculture to world food and fiber supplies, and its role in preserving other threatened natural ecosystems, irrigation-induced erosion has received very little attention in the mainstream erosion research community (Larson et al., 1990). Progress toward raising conservationists' and scientists' collective consciousness about the topic has been slow, but some important papers and reviews have appeared in recent years (Carter, 1990; Carter, 1993; Carter et al., 1993; Koluvek et al., 1993; Trout and Neibling, 1993).

Research on irrigation-induced erosion only began appearing with any frequency in the 1970s, Following establishment of the Kimberly, Idaho, Agricultural Research Service research group in 1964. To date, scientists at the Kimberly location have published over 100 related papers. Because this group had the advantage of drawing conceptually from the extensive body of existing rain-induced research, development of irrigation-induced erosion research has proceeded somewhat holistically. That is to say, description, parameterization, theory and management research all occurred more nearly concurrently than was possible initially for rain and wind-induced erosion.

Irrigation-induced erosion has generally been treated by the unfamiliar as a rudimentary subset of rain-induced erosion systematics. Consequently, irrigation-induced erosion theory has been approached through a series of modifications of rain-induced erosion theory, often using experimental techniques and empirical relationships specifically and exclusively designed to simulate rainfed processes (Trout and Neibling, 1993; Trout, 1996b).

Irrigation water is not rain-water, and it "encounters" soil in a variety of systematically different ways than rainfall, all of which are manageable to varying degrees. While the physical and chemical processes involved in rain-induced erosion and irrigation-induced erosion are the same, the systematics (application, chemistry, energy components, and mass balance) governing irrigation differ vastly from rainfall. For these reasons, both theory and management of irrigation-induced erosion differ significantly from rain-induced erosion theory and rainfed agricultural management. These differences in systematics can be easily identified, although modification of existing rainfed theory, management, and mindset to accommodate these realities has proven somewhat daunting.

Rain-induced erosion theory essentially excludes consideration of water-soil interactive chemistry per se, dealing only with factors that describe stream and/or shower quantity and intensity. Rainwater quality is nearly uniform enough planet-wide (low electrical conductivity--EC and low sodium adsorption ratio--SAR) that variations in these parameters can be largely ignored without consequence in analyzing rain-induced erosion. Nonetheless, miniature laboratory simulations (Levy et al., 1994, Shainberg et al., 1994) and field studies (Le Bissonnais and Singer, 1993; Lentz et al., 1993, 1995) have demonstrated that water quality, especially EC and SAR do significantly impact the erosiveness of a given shower or stream of water.

Other specific physical and chemical components vary in natural and applied waters (e.g. temperature or dissolved organics) and may also have measurable effects. Soil and water temperatures vary systematically during the season and may partially explain some seasonal trends in erosion (Brown et al., 1995). 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).

In existing models, specific soil chemistry-related factors are considered only in as much as they contribute to intrinsic soil erodibility, or are affected through various management-related parameters. The evolution to current process-driven erosion theories and models, e.g. the Water Erosion Prediction Project (WEPP) models (Laflen et al., 1991) have yet to meaningfully embrace interactions of soil and water chemistry, which in arid irrigated soils are very important to soil physical and hydraulic behavior and are temporally variable.

Irrigation water quality varies seasonally and geographically and can even vary on the farm, both between irrigation sets and within an irrigation set, if multiple water sources are involved. High-SAR/low-EC water is more erosive than Low-SAR/high-EC water (Fig. 3). Irrigation water may or may not contain a substantial sediment or suspended biotic load upon entering a furrow. Those loads change systematically as the stream advances. Furrow erosion is affected by the initial sediment load of irrigation water due both to carrying capacity effects and surface sealing (Brown, et al., 1988; Foster and Meyer 1972).

Water advancing down a dry furrow instantaneously hydrates dry soil, destroying soil structure more pervasively than water collecting in wet rills during rainfall (Lentz et al., 1993, 1995). Aggregate stability can be affected by soil water content and gradual water content changes (Bullock, et al., 1988; Kemper and Rosenau, 1984). Furrow stream size, which is exponentially related to detachment (Kemper et al., 1985), decreases down an irrigation furrow (because of cumulative infiltration effects), whereas wetted perimeter generally broadens from accumulated deposition. In rainfed rills, soil is uniformly wet and runoff continuously increases down slope, with comparatively little deposition in the rill. Rill erosion, partitioned from rainfall simulator results, is not analogous to furrow erosion which, in addition to the considerations already mentioned, has no splash or water-drop component nor any intercepted interrill runoff or sediment.

Profile soil water content strongly influences erosion rate (Berg and Carter, 1980; Kemper et al., 1985). In furrow irrigation, it varies progressively along the irrigation path. In contrast, soils in many rainfed agricultural landscapes have similar soil water profiles for all points on the landscape at any time in a rainfall event. Furthermore, irrigation-induced erosion results from a predictable series of nearly uniform and manageable water applications that must be accounted for in whatever conceptual model is used to estimate or predict erosion. Irrigation-induced erosion cannot be assessed by deriving yearly or seasonal relationships based on meteorological inputs averaged from sporadic events of varied intensity, occurring over long time periods across a geographic region. This obstacle is compounded if the amount and kind of irrigation is not accounted for.

Lehrsch and Brown (1995) were unable to correlate furrow irrigation-induced erosion with aggregate stability. Trout (1996b) found that transport relationships used in WEPP did not predict erosion measured in the field, and that sediment transport was more sensitive to shear and flow rate than predicted in the field, possibly because shear did not vary as predicted. These examples represent failures in early tests of correlation between measured furrow erosion and certain modeling parameters currently used in process-based water erosion models derived from rainfed systematics. These failures reinforce doubts that adequate predictive capability can be devised for irrigation-induced erosion without better characterizing the specific phenomena and unique systematics involved in the processes driving irrigation-induced erosion.

Soil conservation practices for irrigated agriculture

Most of the initial impetus for soil conservation in irrigated agriculture was protection of riparian areas receiving irrigation return flows. This led to an early strategy focused mainly on sediment settling basins in return flow systems. Subsequently, efforts concentrated on prevention of soil loss from the farm. A parallel goal of both of these containment strategies was to return captured sediment to eroded sites on farm land. Current research emphasis represents a shift from engineering practices toward development of soil, water and crop management practices aimed at halting all soil movement, thereby retaining soil in place, eliminating subsequent soil handling or transport.

Because each farm is unique, a given sediment containment practice may not be equally suited to all situations. Farmers determine which practice or practices suit their individual situation. 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. These standards may be voluntary standards or may be tied to potent financial incentives or disincentives.

What follows is a brief summary of the more important conservation practices already developed for irrigated agriculture. Practices differ in ease of adoption, effectiveness, and cost of implementation, but offer a range of options to suit most situations. These practices and related factors have been discussed in greater detail in several recent publications (Carter, 1990; Carter et al., 1993; Sojka and Carter, 1994).

Sediment Retention Basins: Sediment ponds can be large, perhaps 1/10th ha (1/4 acre), servicing a 16-24 ha (40-60 acre) field, or small "mini-basins" that temporarily pond runoff for only 6-12 furrows. The basins reduce flow rates and briefly retain water, allowing deposition of suspended particulates and reducing desorption of phosphorous. Retention basin effectiveness depends on sediment load, inflow rates, retention time, and texture of suspended particulates. About 2/3 of solids can be removed from return flows, but only about 1/3 of the suspended clay and total P (Brown et al., 1981). Clay, where most adsorbed P resides, is slow to sink to the pond floor. Thus, the practice is more effective for medium textured soils than for clayey soils.

Buried-pipe Erosion Control Systems: Buried drain pipes with vertical inlet risers allow furrow irrigation tail water to pond at the lower reaches of fields until the water level initiates drainage into the riser. These systems promote sediment retention much as ponds do, and are often an adjunct to mini-basins. The method is best suited to elimination of concave field ends. Effectiveness is near 90 percent while concavities or basins are filling, but drops to pond efficiencies once depressions are filled (Carter and Berg, 1983).

Vegetative Filter Strips: Cereal, grass, or alfalfa (*Medicago sativa*) strips 3-6 m (10-20 feet) wide sown along the lower ends of furrow irrigated row crop fields reduce sediment in runoff 40-60 percent, provided furrows are not cut through the filter strip area (Carter et al., 1992). Harvested filter strips yield 30-50 percent below normal for the strip crop.

Twin row and Close Row Planting: Planting corn (*Zea mays*) as close as possible to both sides of an irrigated furrow to form twin row spacings halved field sediment loss in two years of observation (Sojka et al., 1992). Results for single but narrower row spacings were more variable but showed promise for corn, sugarbeet (*Beta vulgaris*) and field beans (*Phaseolus vulgaris*). Erosion reduction results from a combination of factors including soil binding by roots in close proximity to the flow, introduction of plant litter into the furrow stream, and (with narrow rows only) systematic increase in furrow numbers (and hence wetted perimeter), thus reducing irrigation set duration needed to deliver equivalent quantities of water. This reduces runoff stream size and runoff period relative to total inflow.

Tailwater Reuse: Retention ponds can be inexpensively enhanced to recirculate sediment-laden water into the furrow irrigation water supply. This does not halt or slow erosion per se, but largely automates replacement of sediment onto fields from which they came. Advantages include maximizing water supply efficiency and 100 percent on farm sediment retention (Carter et al, 1993). Capital and energy cost and accelerated pump wear are disadvantages. There is also mingling of disease inoculum, weed seed, and chemicals, although these occur where return flows are reused anyway. On a larger scale, however, many surface irrigation districts have been engineered and are operated with an assumption of return flows making part of the irrigation supply for large portions of the district. Elimination of all return flows could dry up some reaches of existing systems or require modification of primary canal capacity to provide water to farms on lower reaches of the delivery system if some water is not routed through return flow systems.

Improved Water Management: Improved inflow/outflow management, stream size monitoring (post-advance flow reduction), field leveling, alternate furrow irrigation, infiltration measurement (soil water budget monitoring) and irrigation scheduling (furrow or sprinkler), can all improve water use efficiencies. These changes could reduce water application and hence, runoff amounts, reducing erosion as a side benefit (Trout et al., 1994).

Furrow Mulching: Use of plant residue or living mulches in irrigation furrows can be very effective at halting erosion. Permanent furrow sodding halted nearly 100 percent of erosion (Cary, 1986) without adverse yield effects in barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), beans and corn. The technique required a special furrow cutter to maintain established furrows. Straw or other manageable residues can be selectively placed in furrows producing 52-71 percent sediment loss reduction (Miller et al., 1987; Aarstad and Miller, 1981; Brown, 1985; Brown and Kemper, 1987). Drawbacks of these techniques include large increases in advance times and infiltration rates, and the addition of field operations for establishment and/or maintenance of mulches. Mulching can occur at inconvenient times for crop managers, or cause problems during cultivation. Straw also sometimes moves in furrow streams, damming furrows and causing water to flow over rows into adjacent furrows.

Whey Application: Some irrigated areas are near dairy processing plants. For many processors, disposal of acid cottage cheese whey is a problem. Soil-applied acid whey accelerates remediation of exposed lime subsoils and conserves nutrients, using an agricultural byproduct. If combined with straw application, whey can reduce furrow irrigation-induced erosion as much as 98 percent and increase infiltration over 20 percent (Robbins and Lehrsch, 1992; Brown and Robbins, 1995; Lehrsch and Robbins, 1994). The disadvantages of this approach are the cost and inconvenience of bulk hauling and field application of the whey. Usually processors, who often need land application sites, will provide whey at no cost.

Polyacrylamide-Treated Irrigation Water: Treating advancing furrow irrigation water (only) with 10 gm^{-3} polyacrylamide (PAM) has reduced sediment loss in runoff 85-99 percent while increasing infiltration 15 percent (Lentz et al., 1992; Lentz and Sojka, 1994; Sojka and Lentz, 1993, 1994). This translates to about 1 kgha^{-1} of PAM used per treated irrigation. PAM, an industrial flocculent used for food processing and water treatment, is now marketed extensively for erosion control. Results have been highly consistent on a wide range of soils and conditions, showing high effectiveness, low cost, and lack of major effects on other farming practices (Fig. 4). With 10 gm^{-3} PAM, initial water inflows can be more than doubled (then cut back once water has advanced across the field), virtually without erosion. This permits greater field infiltration uniformity. Ongoing PAM research by conservationists and manufacturers is rapidly providing better materials and more effective user protocols. Interest has also arisen for use of PAM with sprinkler irrigation.

Water Quality: In recent field research at Kimberly, ID elevated SAR in furrow irrigation water, especially at low EC, increased the erosivity of the furrow stream (Lentz et al., 1995). Sediment in runoff more than doubled when SAR 12 EC 0.5 dS m^{-1} water was used, compared to SAR 0.7 EC 2.0 dS m^{-1} water. Sediment loss increased 1.5 times, compared to Snake River water (SAR 0.7 EC 0.5 dS m^{-1}). Many farms have multiple water sources (e.g. well and canal water) of varying quality. It behooves farmers to use less erosive water on steeper or more erosive ground, and/or to blend waters, where feasible, to reduce erosion hazard. These results demonstrate that process-driven erosion models must consider water quality effects. They also underscore the need to know the quality of water used in erosion simulators for valid data interpretation.

Conservation Tillage: Field-wide erosion reductions of over 90 percent, reduced production costs, and some yield increases have been noted 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 long range, cost-effective erosion elimination. A disadvantage of conservation tillage is a reluctance by many farmers to adopt such all-encompassing changes to their operations. Furrow irrigation needs reasonably uniform and unobstructed furrows for consistent and timely water advance. This sometimes is a problem in residue-intensive systems. Under sprinkler irrigation, conservation tillage can be implemented much as in rainfed systems.

Zone-subsoiling: Compaction has only recently been recognized as a potential problem in irrigated soils. Compaction deteriorates soil structure and impedes infiltration, impairing crop production and contributing to runoff and erosion. Zone-subsoiling improved yield and grade of furrow irrigated potatoes and increased infiltration up to 14 percent while reducing soil loss in runoff up to 64 percent (Sojka, et al., 1993a, 1993b). Zone-subsoiling can be used with either furrow or sprinkler irrigation.

Reservoir Tillage: Creating small pits between crop rows (called reservoir tillage, dammer diking or basin tillage) helps prevent or reduce runoff. This technique is suitable both to dryland farming and to sprinkler irrigation, but not to furrow irrigation. Sprinklers used on irregular sloping fields, especially the outer reaches of center pivots where application rates are high, can induce excessive runoff and erosion. Reservoir tillage has eliminated about 90 percent of these sprinkler-related runoff and erosion losses (Kincaid et al., 1990).

Low-Pressure Wide-Area Spray Emitters: The geometry of center pivot irrigation systems requires very high instantaneous water application rates in the outermost 1/3 of the pivot. The larger the pivot, the worse the problem. By using spray booms and special emitters, smaller drop sizes are spread over a larger area. Energy is conserved and runoff and erosion are greatly reduced compared to standard impact head systems (Kincaid et al., 1990).

Conclusions

Despite great progress in the past twenty five years 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 is not well appreciated by agriculturists or the general public. Irrigation-induced erosion poses a significant threat to the sustainability of irrigated agriculture.

Most importantly, the uniqueness of irrigation-induced erosion as a phenomenon that is quite different from rainfed erosion, is not well recognized by most of the erosion research community. These perspectives must be fostered in the erosion research community in order for research on irrigation induced erosion and its abatement to be adequately prioritized and financed. The fundamental knowledge needed for development of theory and predictive capability for irrigation-induced erosion must advance and conservation efforts for irrigated land should be strengthened.

The Soil and Water Conservation Society of America and its journal have played key roles in the progress to date, and must continue to do so if these challenges are to be met. Priorities that the Society should consider promoting include: 1) expanded public funding for the development of erosion theory and models that are derived specifically from and for irrigated systematics; 2) encouragement of cost/benefit analysis of government support for soil and water conservation programs and research efforts, based on relative productivity and risk to the land resources being husbanded; and 3) development of permanent efforts within the Society and its Journal to guarantee a balance of focus between rainfed and irrigated agriculture, recognizing the crucial contribution of irrigation to meeting humanity's production needs while protecting the environment.

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.

Anonymous. 1995. 1994 Irrigation survey. Irrig. J. 45:27-42.

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

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 Technology 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., and C.W. Robbins. 1995 (anticipated). Combining cottage cheese whey an straw reduces erosion while increasing infiltration in furrow irrigation. J. Soil Water Conserv. 50:(in press).

Bucks, D.A., T.W. Sammis, and G.L. Dickey. 1990. Irrigation for arid areas. p. 499-548. *In* Management of Farm Irrigation Systems. G.J. Hoffman, T.A. Howell, and K.H. Solomon (eds.). Am. Soc. Ag. 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.

Carter, D.L. 1990. Soil erosion on irrigated lands. In: Irrigation of Agricultural Crops, Ch. 37, Agronomy 30. pages 1143-1171. B.A. Stewart and D.R. Nielson, eds., Am. Soc. Agronomy, Madison, WI.

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

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

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.

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

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

Gleick, P.H. (ed). 1993. Water in Crisis. Oxford University Press, New York. 473 pages.

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

Hoffman, G.J., T.A. Howell and K.H. Solomon (eds.) 1990. Management of Farm Irrigation Systems. 1040 pages. ASAE, St. Joseph, MI.

Hunst, M.A., and B.V. Powers (eds.) 1993. Agricultural Statistics, 1993. U.S. Govt. Printing office.

Kemper, W.D., and R.C. Rosenau. 1984. Soil cohesion as affected by time and water content. Soil Sci. Soc. Am. J. 48:1001-1106.

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

Kincaid, D.C., I. McCann, J.R. Busch and M. Hasheminia. 1990. Low pressure center pivot irrigation and reservoir tillage. pp. 54-60. In: Visions of the Future. Proc. 3rd Natl. Symp., Phoenix, AZ, Oct. 28-Nov. 1, 1990, ASAE. St. Joseph, MI.

Koluvek, P.K., K.K. Tanji and T.J. Trout. 1993. Overview of soil erosion from irrigation. J. Irr. Drain. Eng. ASCE. 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 and Water Conserv. 46:34-38.

Larson, W.E., G.R. Foster, R.R. Allmaras and C.M. Smith (eds.). 1990. Proceedings of Soil Erosion and Productivity Workshop. University of Minnesota, St. Paul. 142 pages.

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

Le Bissonnais, 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 C.W. Robbins. 1994. Cheese whey as an amendment to disturbed lands: effects on soil hydraulic properties. In: Proc. Int. Land Reclamation and Mine Drainage Conf. and Third Int. Conf. on the Abatement of Acidic Drainage, Pittsburgh, PA. Apr. 1994. Vol. 3. USDI Bur. Mines Spec. Publ. SP 06C-94. NTIS, Springfield, VA.

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 Science. 158:274-282.

Lentz, R.D., R.E. Sojka and D.L. Carter. 1993. Influence of irrigation water quality on sediment loss from furrows. Proceedings Vol. II of the SWCS Conference on Agricultural Research to Protect Water Quality, 21-24 Feb. 1993, Minneapolis, MN. pages 274-278.

Lentz, R.D., R.E. Sojka and D.L. Carter. 1995 (anticipated). Furrow irrigation water-quality effects on soil loss and infiltration. Soil Sci. Soc. Am. J. 59:(in press).

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

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

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

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. and Rehab. 6:127-134.

Ross, M.A., and C.A. Lembi. 1985. Applied Weed Science. 340 pages. McMillan and Company. New York.

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.

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 Publishers, Boca Raton.

Sojka, R.E., and R.D. Lentz. 1993. Improving water quality of return flows in furrow-irrigated systems using polymer-amended inflows. Proceedings of the SWCS Conference on Agricultural Research to Protect Water Quality, 21-24 Feb., 1993. Minneapolis, Minn, pp. 395-397.

Sojka, R.E., and R.D. Lentz. 1994. Polyacrylamide (PAM): A new weapon in the fight against Irrigation-induced erosion. USDA-ARS Soil and Water Management Research Unit, Station Note #01-94.

Sojka, R.E., and R.D. Lentz. 1995. Decreasing sedimentation loss from surface irrigation into riparian areas. Proceedings: Northwest Regional Riparian Symposia. Diverse Values: Seeking Common Ground. Idaho Riparian Cooperative. University of Idaho and the Idaho Water Resources Research Institute. 8-9 December, 1994. Boise, ID pages 62-68.

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 & Till. 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. Pot. J. 70:475-484.

Sojka, R.E. 1997. Irrigation. In: Sybil Parker (ed.) 1997 Yearbook of Science and Technology. Mcgraw Hill, New York. (In Press).

Stevenson, F.J. 1972. Organic matter reactions involving herbicides in soils. J. Environ. Qual. 1:333-343.

Tribe, Derek. 1994. Feeding and Greening the World, the Role of Agricultural Research. 274 pages. CAB International. Wallingford, Oxon, United Kingdom.

Trout, Tom, Dave Carter, and Bob Sojka. 1994. Irrigation-induced soil erosion reduces yields and muddies rivers. Irrigation J. 44:8, 11-12.

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

Trout, T.J. 1996a. Furrow irrigation erosion and sedimentation: on-field distribution. Trans. ASAE (In Press).

Trout, T.J. 1996b. Modelling sediment transport in irrigation furrows. Soil Sci. Soc. Am. J. (In Press).

Young, R.A., M.J.M. Romkens, and D.K. McCool. 1990. Temporal variations in soil erodibility. In: R.B. Bryan (ed.) Soil Erosion--Experimental Models. Catena Suppl. 17. Catena Verlag, Lawrence, KS. pp.41-53.

Table 1. A general summary of the extent and importance of irrigated Agriculture compiled from several sources (Anonymous, 1995; Tribe, 1994; G.J. Hoffman et al., 1990; Gleick, 1993; Hunst and Powers, 1993).

Extent of Irrigated Crop Areas

Worldwide Cropped Acres 3.0-3.5 billion

Irrigated Crop Acres 540-600 million (15-18 percent)

U.S. Irr. Crop Acres 59.4 million (14.8 percent)

Surface Flow 32.5 million

Sprinkler 24.5 million

Other 2.5 million

17 Western State Total 46.4 million

Importance of Irrigated Agriculture

Irrigation occurs on 1/6 of global and U.S. cropped area:

*producing 1/3 the annual global and U.S. overall harvest

*producing 1/2 the monetary value of crops harvested

*producing 1/3 the global *food harvest* on the best 50 million ha

*freeing 1.2 billion acres of rainfed land in natural habitat

*providing greatly enhanced food security (yield reliability)

*providing (where surface waters are developed) flood control, transport, recreation, hydropower, community development

Table 2. Percent maximum yield of Portneuf soil having the entire A horizon removed (from Carter, 1993).

Crop	Percent Max. Yield without a horizon
Wheat	51
Sweet corn	52
Alfalfa	67
Dry Bean	60
Barley	68
Sugarbeet	79

FIGURE LEGENDS

Fig. 1. Survey of irrigated land by county in the U.S. (Source, SCS, 1993).

Fig. 2. Sediment deposition in a tail water ditch from a single 12 hour furrow irrigation on Portneuf Silt Loam Soil on a 275 meter long 1.5 percent slope in Kimberly Idaho. Erosional losses at upper furrow ends are typically 3-8 times the measured runoff sediment losses.

Fig. 3. The effect of four water qualities on soil lost in tailwater from irrigation furrows (Lentz et al., 1993).

Fig. 4. The effect of 10 gm$_{-3}$ polyacrylamide in advancing furrow irrigation water (only) on soil lost in tailwater for the entire 12 hr duration of irrigation.