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# WATER MANAGEMENT PRACTICES
## IRRIGATED CROPLAND

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Irrigation is practiced on about 17 percent of the world's arable land. Irrigated land accounts for 33 percent of the world's food production (FAO, 1988) and contributes greatly to the economy in many agricultural regions. In developing countries, nearly 60 percent of rice and wheat production used for food is grown on irrigated cropland. The United Nation's Food and Agriculture Organization (1988) estimates that about two-thirds of the increase in arable land needed to produce food crops by 2050 will be irrigated. Along with the significant economic impact of irrigated agriculture, however, come significant environmental and natural resource impacts.

U.S. Department of Agriculture (USDA) conservation programs commonly are used to improve irrigation systems and their management in an attempt to reduce the impacts of irrigation on the environment and natural resources.

## Irrigation water management practices

Water management practices applied to irrigated cropland often are placed into one of three categories: (1) water storage, pumping, regulating, and conveyance systems for irrigation water supplies; (2) irrigation water application or distribution systems; and (3) irrigation water management.

The goals of adopting more efficient irrigation systems or better management of irrigation systems generally are to reduce evaporation, reduce overland runoff of water and contaminants, and reduce deep percolation of water and contaminants. These reductions will lead to lower water withdrawals from streams, reservoirs, and ground water and improved water quality. If water is pumped for delivery and/or distribution, there is a concomitant reduction in energy use as well.

## Efficiency and conservation

Before discussing the environmental impacts of improved irrigation, it is important to understand two commonly used terms: "efficiency" and "conservation." The terms "irrigation efficiency," "water application efficiency," and "water conservation" frequently are used in the context of water savings. While it is possible to have a direct relationship between efficiency and conservation (water savings), this linkage depends upon how the savings are accomplished, and one should not assume that higher efficiency always results in water savings (CAST, 1988).

The term "conservation" is used in various contexts. In one context, "hydrological conservation" implies that water is "saved" for subsequent or downstream use. In an agricultural production setting, however, the word "conservation" more likely means that water is saved or captured for enhanced crop production through reduced plant water stress. Water saved through hydrological conservation can be used downstream for all types of uses, including those relating to ecological integrity, such as in-stream flow needs and the needs of riparian zone vegetation. Of course, other downstream uses will include municipal, industrial, and domestic uses, as well as irrigation, to name a few. This chapter strives to distinguish between hydrologic conservation and crop production conservation (behavioral or economic conservation).

Irrigation efficiency is the ratio of water beneficially used to the water delivered or applied (Burt et al., 1997). Application efficiency differs slightly from irrigation efficiency because application efficiency is the water stored in the crop root zone during application divided by the water delivered or applied (Burt et al., 1997). The difference between the water delivered or applied and water beneficially used or stored is a result of water "losses" that occur during application, namely evaporation, drift, runoff, and deep percolation.

Cropland near Phoenix, Arizona, is laser-leveled to manage irrigation water flow across the field.

In addition to "losses" that occur during water application, losses also can occur during conveyance from the water source to the field where it is applied. These conveyance losses usually are confined to seepage and evaporation from open channels. Note, though, that for both application and conveyance "losses," only evaporation results in a loss of "wet" water, that is, a change of phase from liquid to vapor. Runoff, drift, and deep percolating water remains in the liquid state and, hence, available for downstream uses (CAST, 1988) so long as the water's quality continues to meet downstream needs.

Hydrological conservation will result from practices that reduce runoff and deep percolation (return flows) when the runoff and deep percolating waters flow to saline sinks, or when they are used for non-beneficial evapotranspiration, or when water quality is degraded to the point that it is unusable (CAST, 1988). Thus, while improved irrigation practices may increase water use efficiency, those practices do not always result in hydrological water conservation. Upstream water "losses" often are a water source for downstream uses. But water quality degradation often or almost always diminishes as a result of better irrigation practice.

On the other hand, if the term "water conservation" is defined behaviorally or economically, then improved irrigation practices almost always conserve water (CAST, 1988). Howell (2001) presented several definitions of "water use efficiency," all of which relate to the amount of crop yield relative to the water applied or transpired.

In this context, water is conserved when water use efficiency increases as a result of better irrigation practice. Improved water use efficiency, however, does not necessarily lead to conservation in a hydrologic sense.

The following discussion of documented effects accounts for the definitions of "efficiency" and also the connections between efficiency and water quality. There appears to be no obvious link between use of water-management-oriented conservation practices on irrigated cropland and air quality, with the exception of the benefits that might follow from reduced emissions associated with power units that are sometimes necessary to pump water. The documented impacts are discussed in the following order: (1) irrigation water delivery systems; (2) field water application or distribution systems; (3) irrigation water management; and (4) environmental and water quality effects. The linkage between improved irrigation practices and water quality invariably is associated with the reduction of contaminant transport when overland runoff and/or deep percolation are reduced.

## Irrigation water delivery systems

Water must be delivered efficiently to irrigation systems to avoid excess diversions from surface and ground water supplies and to minimize energy for delivery. Also, using reservoirs to regulate water flow allows for more efficient irrigation, especially with labor-intensive systems, because irrigation can then occur at times favorable to the irrigator, for example, during daylight hours.

### Reservoirs and irrigation pumps

Table 1 summarizes the practices that pertain to reservoirs. The benefits of storage reservoirs to economic water conservation are obvious. If water is diverted from a stream for storage and later use, there often is an economic benefit. Regulating reservoirs are intended to make irrigation management more flexible and efficient. This is particularly true for irrigation systems that require a significant amount of labor to operate efficiently, such as certain applications of surface irrigation and hand-moved sprinkler irrigation. For example, surface irrigation efficiencies may be as low as 20 percent (Keller, 1965) with poor management. But with proper labor and management inputs, this efficiency can be increased to as much as 70 percent. Usually, labor is more readily available during daylight hours, so regulating reservoirs can be used to store water for the entire day but only used for water delivery during the daylight hours. Reservoirs, then, must have enough volume to store water for 12 to16 hours.

Losses of water from reservoirs to evaporation can exceed 1,800 mm (70 inches) per year in the southern High Plains of the United States and 2,500 mm (100 inches) per year in the Desert Southwest of the United States (Farnsworth et al., 1982). Reservoirs also experience losses to seepage, either through earthen embankments or directly from the reservoir bottom. Litchtler et al. (1980) measured seepage losses that ranged from 2.5 mm (0.10 inch) to more than 480 mm (19 inches) per day from irrigation runoff recovery reservoirs, with an average loss of about 15 mm (0.6 inch) per day. While an economically effective method of evaporation control has not yet been developed, seepage reduction through soil-treatment liners and membrane liners can effectively reduce seepage losses, especially in smaller reservoirs.

**Table1. National conservation practice standards pertaining to irrigation water storage and regulation (from www.nrcs.usda.gov/technical/Standards/nhcp.html).**

| Code and title | Definition and purpose |
|---|---|
| 436<br>Irrigation storage reservoir | Definition: An irrigation water storage structure made by constructing a dam, embankment, or pit.<br>Purpose: Conserve water by holding it in storage until it is used to meet crop irrigation requirements |
| 552<br>Irrigation regulating reservoir | Definition: A small storage reservoir constructed to regulate an irrigation water supply.<br>Purpose: Collect and store water for a relatively short period of time to:<br>• Improve irrigation water management by regulating fluctuating flows in streams, canals, or from pumping plants.<br>• Provide storage for tailwater recovery and reuse.<br>• Improve offsite water quality. |
| 521<br>Pond sealing or lining | Definition: A liner for a pond or waste impoundment.<br>Purpose: To reduce seepage losses from ponds or waste impoundments for water conservation and environmental protection.<br>There are individual standards for each type of liner or sealing procedure: flexible membrane, 521A; soil dispersant treatment, 521B; bentonite treatment, 521C; and compacted clay treatment, 521D. |
| 533<br>Pumping plant | Definition: A pumping facility installed to transfer water for a conservation need.<br>Purpose: Provide a dependable water source or disposal facility for water management. |

Irrigation pumping plants often are necessary to extract water from wells and surface sources as well as pressurize the water for distribution. As shown by Gilley et al. (1990), energy for irrigation can account for 40 to 60 percent of the total energy used in production agriculture. To minimize energy needs at these pumping plants, it is essential that they be designed and maintained properly. Research shows that, on average, the performance of irrigation pumping plants is less than technically achievable by about 20 to 30 percent (Schroeder and Fischbach, 1983; Miles and Longenbaugh, 1968). In-field adjustments of pumps and engines can save 10 percent or more in energy.

### Open-channel conveyance

Table 2 summarizes the practices that pertain to open-channel conveyance. Irrigation canals and field ditches are one means of delivering water from a source to the point of delivery on the farm. Earthen-lined ditches can have significant seepage losses, in the range of 15 to 45 percent, according to van der Leen et al. (1990). Kraatz (1977) showed that on 46 U.S. Bureau of Reclamation projects seepage losses ranged from 3 to 86 percent, with an average of 40 percent. According to the U.S. Department of the Interior (USDI et al., 1979), losses during conveyance in the United States average 22 percent. Lining can reduce those "losses" significantly, if not entirely.

Typical lining materials include concrete and flexible synthetic membranes. Kraatz (1977) illustrated that flexible plastic lining reduced seepage losses 95 percent. But, like the arguments presented above, lining usually does not save "wet" water because seepage water is potentially available for use downstream. But the amount of diversion can be reduced even if downstream effects are minimal.

### Pipelines

Table 3 summarizes the practices pertaining to irrigation pipelines. Conversion from open channels to pressurized pipelines can essentially eliminate the "losses" of water via evaporation and seepage. As shown in table 3, there are many material options available for these pipelines.

In addition to the use of pipelines for conveyance, they also are used as laterals for water distribution within a field. Included are sprinkler laterals, micro-irrigation laterals, and gated pipelines. For surface irrigation, there are basically two means for delivering water at the head or inlet end to a field: open channels with spiles or siphons and gated pipelines. Gated pipelines can reduce seepage and evaporation losses over losses in open channels (assuming earthen-lined channels) by about 10 percent (Yonts and Klocke, 1997).

**Conversion from open channels to pressurized pipelines can essentially eliminate the "losses" of water via evaporation and seepage.**

## Field water application and distribution systems

### Surface and subsurface systems and tailwater management

Table 4 summarizes the practices that pertain to surface and subsurface systems and tailwater management. Surface irrigation refers to systems

**Table 2. National conservation practice standards pertaining to open channel water conveyance for irrigation (from www.nrcs.usda.gov/technical/Standards/nhcp.html)**

| Code and title | Definition and purpose |
|---|---|
| 320<br>Irrigation canal or lateral | Definition: A permanent channel constructed to convey irrigation water from the source of supply to one or more irrigated areas.<br>Purpose: To convey irrigation water to one or more irrigated areas. |
| 388<br>Irrigation field ditch | Definition: A permanent irrigation ditch constructed in or with earth materials, to convey water from the source of supply to a field or fields in an irrigation system.<br>Purpose: This practice may be applied as part of an irrigation water management system to efficiently convey and distribute irrigation waters. |
| 428<br>Irrigation water conveyance, ditch and canal lining | Definition: A fixed lining of impervious material installed in an existing or newly constructed irrigation field ditch or irrigation canal or lateral.<br>Purpose:<br>• Improve control and management of irrigation water<br>• Prevent water logging of land<br>• Maintain water quality<br>• Prevent erosion<br>• Reduce seepage losses.<br>There are individual standards for each type of fixed liner: plain concrete, 428A; flexible membrane, 428B; and galvanized steel, 428C. |

that rely on overland flow to distribute the water within a field. Examples include basin, furrow, and border irrigation systems. Surface irrigation is practiced on more than 50 percent of the irrigated land in the United States (Howell, 2001), but this percentage is declining. Surface irrigation is practiced on about 90 percent (Kay, 1986) of the irrigated land throughout the world. It is common worldwide because of the lower capital requirements needed for this method compared to the more capital-intensive, pressured systems. In general, surface irrigation methods are less efficient than sprinkler systems and micro-irrigation; typical application efficiencies can be as low as 40 to 50 percent for unimproved systems. Because management of these systems is labor-intensive, their efficiency is inherently lower than for pressurized systems.

Many technologies exist to improve surface irrigation (Musick and Walker, 1987), including controlled land grading (Clemmens, 2000; Agarwal and Goel, 1981), recovery of runoff or tailwater (Eisenhauer and Fekersillasae, 2000), and surge flow (Stringham and Keller, 1979; Eisenhauer and Fekersillasae, 2000). Application efficiencies as high as 90 percent were reported for laser graded level basins (Clemmens, 2000) and nearly 80 percent for surge irrigation systems with runoff recovery (Eisenhauer and Fekersillasae, 2000). Because water applied or withdrawn is inversely proportional to application efficiency, improved irrigation practice can reduce water ap-

**Table 3. National conservation practice standards pertaining to irrigation water conveyance using pipelines (from www.nrcs.usda.gov/technical/Standards/nhcp.html).**

| Code and title | Definition and purpose |
|---|---|
| 430<br>Irrigation pipeline used for conveyance | Definition: A pipeline and appurtenances installed in an irrigation system.<br>Purpose: To prevent soil erosion or loss of water quality or damage to the land, to make possible proper management of irrigation water, and to reduce water conveyance losses.<br>There are individual standards for each pipeline material or type: aluminum tubing, 430AA; asbestos-cement, 430BB; non-reinforced concrete, 430CC; high pressure underground plastic, 430DD; low-pressure underground plastic, 430EE; steel, 430FF; and reinforced plastic mortar, 430GG. |
| 430HH<br>Rigid gated pipeline used for conveyance and distribution | Definition: A rigid pipeline, with closely spaced gates, installed as part of a surface irrigation system.<br>Purpose: To efficiently convey and distribute water to the land surface for better water management, without causing excessive erosion, water losses, or reduction in water. |

**Table 4. National conservation practice standards pertaining to surface and subsurface irrigation systems (from www.nrcs.usda.gov/technical/Standards/nhcp.html).**

| Code and title | Definition and purpose |
|---|---|
| 464<br>Irrigation land leveling | Definition: Reshaping the surface of land to be irrigated to planned grades.<br>Purpose: To permit uniform and efficient application of irrigation water to the leveled land. |
| 443<br>Irrigation system, surface and subsurface | Definition: A system in which all necessary water-control structures have been installed for the efficient distribution of water by surface means, such as furrows, borders, contour levees, or contour ditches, or by subsurface means.<br>Purpose: This practice is applied as part of a conservation management system to achieve one or more of the following:<br>• Efficiently convey and distribute irrigation water to the surface point of application without causing excessive water loss, erosion, or water quality impairment.<br>• Efficiently convey and distribute irrigation water to the subsurface point of application without causing excessive water loss or water quality impairment.<br>• Apply chemicals and/or nutrients as part of an irrigation system. |
| 447<br>Irrigation system, tailwater recovery | Definition: A planned irrigation system in which all facilities utilized for the collection, storage, and transportation of irrigation tailwater for reuse have been installed.<br>Purpose: This practice may be applied as part of a conservation management system to support one or more of the following:<br>• Conserve irrigation water supplies<br>• Improve offsite water quality |
| 450<br>Anionic polyacrylamide (PAM) erosion control | Definition: Erosion control through application of water-soluble anionic polyacrylamide (PAM)<br>Purpose: This practice is applied as part of a conservation management system to minimize or control irrigation-induced soil erosion. |

plications 60 percent or more (see, for example, Spalding et al., 2001).

With surface irrigation, water "losses" are dominated by runoff and deep percolation. As a result, the improved practices do not necessarily result in water being conserved for other uses because the runoff and deep percolation are available for downstream or subsequent use. As discussed earlier, when runoff and deep-percolating water flow to saline sinks, or when they are used for non-beneficial evapotranspiration, or when water quality is degraded to the point that water is unusable (CAST, 1988), downstream uses are no longer plausible and improved irrigation methods can result in more water available for other uses.

Tailwater management or reuse of runoff can significantly affect losses. Tailwater usually accounts for 10 to 30 percent of the water applied, and it is not uncommon for runoff recovery systems to increase efficiency by about 15 percent. For example, Bolen et al. (1989) indicated that in the 1960s about 20 percent of the pumped irrigation water flowed into playa lakes in the southern High Plains. Musick and Walker (1987) showed irrigation runoff losses from farmers' fields to range from 16 to 35 percent of the water applied in the High Plains of Texas. Nearly all this runoff water could be captured and returned for use with a properly designed and maintained runoff recovery system.

Another method of reducing water applications in surface irrigation is through surge irrigation (Stringham and Keller, 1979; Bishop et al., 1981; Yonts et al., 1996; Eisenhauer and Fekersillasae, 2000). The intermittent water application of surging sometimes reduces water infiltration at the upper end of the field, which allows for more uniform water distribution. The efficiencies of surge irrigation can be as high as 90 percent and reduce field-scale water applications 60 percent (Spalding et al., 2001).

In addition to the low water application efficiencies sometimes associated with surface irrigation, soil erosion can be a serious problem with surface irrigation (Trout et al., 1990), especially furrow irrigation (Kemper et al., 1985). Managing the stream to minimize erosion losses largely controls soil erosion in surface irrigation.

## Pressurized irrigation systems

Table 5 summarizes the practices that pertain to pressurized irrigation systems. The greatest change in irrigation application systems in the United States during the 15-year period from 1979 to 1994 involved center-pivot irrigation systems (Howell, 2001). Center-pivot systems require significantly less labor and apply water more efficiently than surface irrigation systems. Water is applied through sprinklers, spray devises, or LEPA. The term LEPA is an acronym for low energy precision application (Lyle and Bordovsky, 1981). With LEPA, water is applied near the soil surface, where it is not as vulnerable to evaporation and drift. Schneider (2000) reviewed the literature on application efficiencies for center-pivot systems with spray and LEPA application devices and found average efficiencies of 85 to 95 percent for spray devices, with some as low as 40 percent. He also found that LEPA

**Table 5. National conservation practice standards pertaining to pressurized irrigation systems (from www.nrcs.usda.gov/technical/Standards/nhcp.html).**

| Code and title | Definition and purpose |
|---|---|
| 442<br>Irrigation system, sprinkler | Definition: An irrigation system in which all necessary equipment and facilities are installed for efficiently applying water by means of nozzles operated under pressure.<br>Purpose: This practice may be applied as part of a conservation management system to achieve one or more of the following:<br>• Efficiently and uniformly apply irrigation water to maintain adequate soil water for the desired level of plant growth and production without causing excessive water loss, erosion, or water quality impairment.<br>• Climate control and/or modification.<br>• Applying chemicals, nutrients, and/or waste water.<br>• Leaching for control or reclamation of saline or sodic soils.<br>• Reduction in particulate matter emissions to improve air quality. |
| 441<br>Irrigation system, micro-irrigation | Definition: An irrigation system for distribution of water directly to the plant root zone by means of surface or subsurface applicators.<br>Purpose: This practice may be applied as part of a conservation management system to support one or more of the following purposes.<br>• To efficiently and uniformly apply irrigation water and maintain soil moisture for optimum plant growth.<br>• To apply chemicals. |

systems have average application efficiencies of 80 to 100 percent, with typical values in the range of 95 to 98 percent. Spalding et al. (2001) found that center-pivot irrigation water applications were more than 70 percent lower than conventional furrow irrigation. Reduced deep percolation can be a key advantage of sprinkler irrigation over surface irrigation. Evaporation losses usually are considered to be higher with sprinkler irrigation, but they typically will be less than commonly perceived. Evaporation losses from sprinkler systems usually are less than 5 percent, but they can be as high as 10 percent (Schneider, 2000). Center-pivot and lateral-move sprinklers probably have efficiencies in the range of 80 to 90 percent (Gilley et al., 1990).

**Reduced deep percolation can be a key advantage of sprinkler irrigation over surface irrigation.**

### Micro-irrigation

Camp (1998) and Ayars et al. (1999) provided excellent reviews of the state-of-the art and research findings on subsurface drip irrigation and micro-irrigation in general. With subsurface drip irrigation, water is applied below the soil surface, typically 30 to 45 cm (12 to 18 inches) below the surface. With relatively uniform application and negligible or zero evaporation losses, the typical efficiencies of these systems reportedly exceed 90 percent. A potential added advantage of these systems is that the soil surface is not wetted during water application, leading to less soil water evaporation. This can be an important factor, particularly in arid areas where the surface is not wetted frequently by rainfall.

As reported by Gilley et al. (1990), the efficiency of micro-irrigation systems can range from 70 to 93 percent. Because runoff and evaporation usually are not a significant part of water losses, the lower end of these efficiency ranges is probably due to poor water distribution. Ayars et al. (1999) reported that uniformity coefficients often exceeded 90 percent for subsurface drip irrigation. Ayars et al. (1999) also stated that the use of high-frequency irrigation resulted in less deep percolation and increased use of water from shallow ground water (via upward flow from the water table) when crops were grown in areas with high water tables. Evett et al. (1995) found that subsurface drip irrigation saved about 10 percent of seasonal precipitation plus irrigation compared to surface-applied drip irrigation.

## Irrigation water management

Table 6 summarizes irrigation water management practices. Irrigation scheduling is a water management practice designed to apply water according to crop and soil evapotranspiration. It can reduce water withdrawals and losses. Ferguson et al. (1990) illustrated reductions in water applications averaging 12 percent due to irrigation scheduling: the proper timing and amount of irrigation. Work by Duke et al. (1978) showed reductions in water applications of 5 to 20 percent on farmers' fields through implementation of irrigation scheduling.

Chemigation, which is the practice of applying chemicals with irrigation systems, has the potential for reducing water quality impairments through better timing of water applications and more precise water applications (Threadgill et al., 1990). There are risks associated with chemigation that must be overcome, as explained by Weihing and Eisenhauer (1991). The key is to have in place the proper safety devices to minimize contamination of water sources through chemigation. The potential for preferential flow of chemigation-applied chemicals is a concern raised by some researchers. Jennings (1990) found that under high-intensity sprinkler application of chemigation-applied bromide, bromide moved more rapidly through a soil with macropores than did a surface-applied chemical. There was little difference in chemical application methods with low-intensity sprinkler application. Likewise, Felsot et al. (1998) found that

**Table 6. National conservation practice standards pertaining to irrigation water management (from www.nrcs.usda. [illegible]).**

| Code and title | Definition and purpose |
| --- | --- |
| 449<br>Irrigation water management | Definition: The process of determining and controlling the volume, frequency and application rate of irrigation water in a planned, efficient manner.<br>Purpose: Manage soil moisture to promote desired crop response:<br>• Optimize use of available water supplies<br>• Minimize irrigation induced soil erosion<br>• Decrease non-point source pollution of surface and groundwater resources<br>• Manage salts in the crop root zone<br>• Manage air, soil, or plant micro-climate<br>• Proper and safe chemigation or fertigation<br>• Improve air quality by managing soil moisture to reduce particulate matter movement |

insecticides applied via sub-surface drip irrigation leached significantly below the emitters. But the researchers stated that this was probably because the irrigation timing did not match the crop evapotranspiration rate. Jaynes et al. (1992) also found that with surface irrigation chemigation can actually increase the risk of leaching of agricultural chemicals.

Crop residue management offers a lot of potential to save "wet" water in irrigated agriculture because 20 to 30 percent of seasonal evapotranspiration is due to soil water evaporation, a loss that has no apparent economic benefit. Crop residue management could reduce those losses significantly, but not completely. Boldt et al. (1999) illustrated that crop residue reduced net depletion of groundwater 50 to 75 mm a year (2 to 3 inches a year). A comprehensive discussion of crop residue effects on soil and water quality can be found in the soil management practices chapter of this book.

## Environmental effects

Irrigated agriculture can potentially impact environmental quality, particularly water quality. Those impacts include depletion of streamflow, mining of ground water, and water quality issues, such as contamination of ground water, salinization of irrigated land and water, and increased sediment delivery to off-site water bodies. In nearly all agricultural production systems, drainage water is necessary to maintain soil salinity and aeration at acceptable levels for crop production. In addition, many surface irrigation systems result in direct field runoff. That water can contain eroded sediments and dissolved chemicals or chemicals associated with the transported sediment. Many of these processes are the same in rain-fed systems. It is not the intent here to provide a comphrensive review of all environmental or water quality impacts of irrigated agriculture, but rather present an overview of the effects and the efforts to minimize the impacts. Environmental issues associated with stream depletion and ground-water mining will not be discussed, even though the effects can be locally significant.

### Salinity and specific ion effects

Salinity and sodic soil management as a conservation practice (practice code 610) is discussed in more detail in the soil management practices chapter of this publication. Salt-affected soils occur in more than 100 countries around the world, with a variety of characteristics. Salinization is the accumulation of water-soluble salts in the soil to such a level that it impacts agricultural production. The level at which deleterious effects occur depends upon plant type, soil-water regime, and climatic condition (Maas, 1986). A requirement for salinity control in irrigated agriculture is that leaching and natural or artificial drainage be adequate to ensure the downward net flux of soluble salts. Methods of water application and soil type are the primary variables affecting the amount of water needed to reclaim saline soils. The amount of water required is referred to as the leaching fraction. Intermittent water applications generally are more effective for leaching soluble salts than ponded water because of water flow path differences between saturated and unsaturated soil conditions. Leaching fractions can vary between 0.1 and 0.6. For more information, read Regasamy (2006), Qadir et al. (2000), Rhoades et al. (1997), Rhoades and Loveday (1990), Rhoades (1974), and Tanji and Hanson (1990).

van Schilfgaarde (1990) emphasized that salts must be removed from irrigated soils if irrigation in the western United States is to be sustainable. Salt loads can be reduced 42 to 48 percent through improved water management, which includes relatively uniform applications of water (van Schilfgaarde et al., 1974). But this will come at a price of reduced water quality, making water management even more imperative.

Rhodes (1985) indicated that there are limits to how much water applications can be reduced without reducing crop yields due to high salinity. Typically, drainage water from irrigated systems is discharged to surface or ground water of better quality, reducing the suitability of that receiving water for use in proportion to the increase in salt concentration.

The magnitude of salt losses is illustrated in a study reported by Carter et al. (1971) of a surface irrigated tract in southern Idaho. Those researchers reported an average of 2.4 metric tons $ha^{-1}$ (about 2,000 pounds per acre) of soluble salt was lost each year from an 82,000-ha (205,000-acre) tract having calcareous silt loam soils that had been irrigated for 65 years. This was with a 50 percent return of input water as subsurface flow, considerably more than necessary to maintain a salt balance. Electrical conductivity increased from 0.46 dS $m^{-1}$ in the input water to 1.04 dS $m^{-1}$ in the return flow. Similarly, 0.66 to 1.3 metric tons $ha^{-1}$ (590 to 1,200 punds per acre) of salt reportedly were lost from an irrigated system in the San Joaquin Valley (Schoups et al., 2005). In both systems, conditions may be at or approaching quasi-equilibrium, given that 70 metric tons $ha^{-1}$ (31 tons per acre) of soluble salt were lost from 5 m (16.5 feet) of soil in the first irrigation season after conversion from native, arid sagebrush land (Carter and Robbins, 1978). The

Drip irrigation is highly efficient because it delivers small amounts of water, here to grape vines, over a long period of time and reduces evaporation.

A moisture meter and electrical resistance blocks placed in the soil profile enable producers to monitor soil moisture in this New Mexico vineyard.

leachate water from that soil profile would have an electrical conductivity of about 32 dS $m^{-1}$, more than sufficient to significantly reduce, if not eliminate, most plant growth (Maas, 1986). Salt in that soil profile probably accumulated with previous weathering over time because the study was in a semiarid environment where annual rainfall was less than potential evaportranspiration.

Specific salts or ions contained in drainage waters can be toxic to some crops or other biological components and systems off-site. Ions causing toxicity problems include boron, chloride, sodium, and heavy metals. Boron and chloride tolerance limits are reported by Maas and Niemann (1978) and Maas (1986). Sodium toxicity effects generally are limited to perennial woody species. Overhead irrigated crops may suffer foliar damage from salt burn caused by drying of the water spray if salt concentrations in the irrigation water are sufficient. Salinity also affects stand establishment, especially under surface irrigation, but usually can be managed with rows and furrows configured to move soluble salts away from the germinating seedling (Bernstein et al., 1955; Bernstein and Francois, 1973).

**Specific salts or ions contained in drainage waters can be toxic to some crops or other biological components and systems off-site.**

Trace elements, such as selenium, molybdenum, and arsenic, in drainage water can have serious impacts. In a large, comprehensive evaluation of water quality as well as biological and geological effects on 600 irrigation projects in the western states, 26 projects showed elevated concentrations of selenium. More than 40 percent of the surface water samples exceeded the U.S. Environmental Protection Agency aquatic-life chronic criterion for selenium (5 µg $L^{-1}$). Irrigation-induced selenium contamination has only been observed in arid and semiarid areas. Those areas were primarily associated with Upper Cretaceous, marine sediments (Nolan and Clark, 1997). Elevated levels of boron, arsenic, mercury, and pesticide residues also were found in some areas (Engberg, 1996; Feltz and Engberg, 1994; Hren and Feltz, 1998; Seiler et al., 2003).

A widely publicized incident at the Kesterson Reservoir in California occurred when elevated selenium concentrations were found in fish and waterfowl in wetlands receiving subsurface drainage from irrigated saline land (Benson et al., 1990; Moore, 1987). That land (Westlands Water District) prior to irrigation contained naturally high concentrations of selenium and other elements. No exact counts of wildlife "lost" were compiled, but visual observations suggested high numbers. Research and other efforts are ongoing to identify and develop suitable remedial solutions to this problem (Letey et al., 2002; Gao et al., 2003).

In contrast, forage selenium concentrations sufficiently low to cause animal disorders exist adjacent to areas having forages with toxic selenium concentrations (Kubota et al., 1967).

## Leaching losses

Nitrate-nitrogen leaching to ground water is considered the major means of nitrogen loss in humid regions and in irrigated agricultural systems. Nitrogen leaching losses from most dryland grain production systems typically range from 10 to 30 percent of the total nitrogen inputs, but those losses can be as high as 60 percent of the applied nitrogen (Meisinger and Delgado, 2002). In one irrigated vegetable system in the north central United States, 61 percent of the total available nitrogen and 77 percent of the applied nitrogen fertilizer was leached from a sandy soil to ground water over a 4-year period (Kraft and Stites, 2003). Major leaching events occur when soil nitrate-nitrogen concentrations are high and water is moving through the soil profile from excess rainfall or irrigation. Leaching also is more significant during non-cropping periods of the year (Peralta and Stockle, 2001).

Improving irrigation systems to reduce deep percolation will leach fewer soluble ions (e.g., nitrate-nitrogen) beneath the crop root zone and generally improve ground water quality (Linderman et al., 1976; Smika et al., 1977; Duke et al., 1978; Ritter and Manger, 1985; Spalding et al., 2001). For example, Smika et al. (1977) and Duke et al. (1978) showed that leaching of nitrate-nitrogen exceeded 10 kg $ha^{-1}$ (9 pounds per acre) for each centimeter (0.4 inch) of deep-percolating water. Linderman et al. (1976) reported similar trends, but leachate concentrations were about four times lower.

Changing irrigation systems also can increase nitrogen fertilizer use efficiency. In citrus, compared with flood irrigation, drip irrigation combined with splitting the applied nitrogen increased nitrogen use efficiency nearly 10 percent while reducing water applications 15 percent, without impairing fruit yield or quality (Quiñones et al., 2005). Scheduling nitrogen fertilizer applications according to crop growth rate increased use efficiency from 60 percent to more than 75 percent in a sprinkler irrigated potato system (Westermann et al., 1987). There also are some indications that nitrogen use efficiencies will be increased by management of soil variability within a field (Power et al., 2001; Khosia et al., 2002; Link et al., 2006).

A primary water management tool to reduce nitrate-nitrogen leaching is irrigation scheduling (Meisinger and Delgado, 2002). Water savings due to scheduling may not be "wet" water, but those savings definitely have potential for reducing leaching and return-flow losses of agricultural chemicals and salts to receiving ground water and surface water (Spalding et al., 2001; van Schilfgaarde et al., 1974; van Schilfgaarde, 1990; Hoffman et al., 1984). Spalding et al. (2001) illustrated that a combination of sprinkler irrigation and nitrogen fertigation reduced nitrogen leaching, with only minor reductions (6 percent) in crop yields. With the surface irrigation systems in their study, the nitrate-nitrogen concentration near the surface of a shallow ground water system was around 30 mg $L^{-1}$, while the concentration was around 13 mg $L^{-1}$ for much of the study under the center pivot sprinkler system. Smika et al. (1977) found that average losses of nitrate-nitrogen to deep percolation were 19, 30, and 60 kg $ha^{-1}$ $year^{-1}$ (17, 27, and 53 pounds per acre per year) when deep percolation was 1.6, 2.9, and 7.3 cm $year^{-1}$ (0.63, 1.1, and 2.9 inches per year), respectively. Watts and Martin (1981) also demonstrated that the mass of nitrate-nitrogen movement below the crop root zone was dependent upon the amount of water flow. Even when there is 11 to 21 percent deficit irrigation, there can be appreciable amounts of nitrate-nitrogen leached if nitrogen is over-applied according to established soil and crop guidelines (Tarkalson et al., 2006). All of these studies illustrate the importance of managing both water and nitrogen applications to improve groundwater quality.

Another management tool that may help deter nitrate-nitrogen leaching is the nitrate leaching index (Shaffer and Delgado, 2002). This index is based on hydrologic soil properties and climate, management practices, crop rotations, and considerations of off-site effects. As proposed, management factors are the dominant variable in determining the potential for leaching (van Es et al., 2002). This concept was applied to irrigated agriculture at the field scale (Wu et al., 2005), where soils, irrigation system, and crops were numerically indexed according to the potential for leaching losses. This approach is similar to that used by the NLEAP (nitrogen leaching and economic assessment package) model (Shaffer et al., 1991), except NLEAP is not a simple screening or assessment tool easily used by field staff, consultants, and farmers. The nitrogen leaching index should be applicable in many irrigated areas when fully implemented in the same way as the phosphorus index (Lemunyon and Gilbert, 1993).

### Irrigation-induced soil erosion

Soil erosion affects 21 percent of the 15 million hectares (37,500,000 million acres) of irrigated land in the United States (Koluvec et al., 1993). Soil erosion as well as low water application efficiencies can be a serious problem with surface irrigation (Trout et al., 1990), especially furrow irrigation (Kemper et al., 1985). High rates of soil erosion from surface-irrigated systems were measured in Washington, Idaho, Wyoming, and Utah. Sediment losses as great as 145 Mg $ha^{-1}$ (65 tons per acre) in 1 hour (Israelson et al., 1946) and 40 Mg $ha^{-1}$ (18 tons per acre) in 30 minutes (Mech, 1949) were reported in two early studies. Eighty years of irrigation-induced soil erosion in southern Idaho reduced crop yield potential between 20 and 50 percent (Carter et al., 1985). In 75 percent of the fields in that study, the highly calcareous subsoil was exposed on the upper or head-end of the field, often comprising more than 25 percent of the field area.

Factors affecting furrow erosion include furrow slope, stream size, crop residue left on the soil surface or in the furrow, surface roughness, tillage, and cropping sequence (Carter, 1990). In many western irrigated areas, extensive land leveling is performed to help distribute water while simultaneously reducing slope. The Natural Resources Conservation Service conservation practice, irrigation land leveling (practice code 464, Table 4), outlines this process. Erosion rates are 6 to 20 times greater in the upper quarter of the field, compared with average rates from the field overall, even when field slopes are uniform (Trout, 1996). Furrow slope also affects the points where detachment, transport, and deposition occur along the furrow length (Trout, 1996).

A related condition that can cause severe soil erosion during surface irrigation is the change in slope between the end of the field and the tailwater ditch. A majority of soil loss from a field can be from this area if the area is convex rather than concave (Carter and Berg, 1983). Field sediment retention basins (Brown et al., 1981), buried pipe systems (Carter and Berg, 1983), and vegetative filter strips (Berg and Carter, 1980) have been proposed to reduce or control irrigation-induced sediment losses at the field end. Adding straw to the bottom of the irrigation furrow also effectively reduces soil erosion (Brown and Kemper, 1987).

Managing stream size to minimize soil erosion losses is an important factor in surface irrigation. The normal practice is to apply a stream large enough to assure that the water reaches the lower end of the field within 25 to 50 percent of the irrigation time. This allows sufficient time for infiltration to provide relatively uniform amounts of water to the crop. Lower soil erosion rates in a field can be achieved if the flow rate is reduced once water reaches the end of the field because erosion is about a 1.5-power function of stream size (Kemper et al., 1985). Modifications of this technique include surge irrigation (Evans et al.,

**Managing stream size to minimize soil erosion losses is an important factor in surface irrigation.**

1995; Miller et al., 1987) and automated cutback systems (Humpherys, 1971; Kemper et al., 1987).

Sediment basins and ponds may be used to remove sediment being transported by irrigation streams (similar to conservation practice code 350, sediment basin). These can be field, farm, or watershed sized. Generally, if properly designed, they can remove 60 to 95 percent of the sediment in the drainage waters as well as 25 to 33 percent of the total phosphorus (Brown et al., 1981; Robbins and Carter, 1975). Clay-sized , suspended particles are not usually trapped without flocculation aids. One limitation to these systems is the requirement for frequent cleaning if efficiency is to be maintained, especially if inflow sediment loads are high. Sediment loads to streams and rivers may not be equivalent to field soil erosion losses because irrigation canals and other internal water transport systems often unintentionally serve as sediment traps (Depeweg and Mendez, 2002). Cleaning these systems substantially adds to a distribution system's operational cost.

Salinity issues pose a challenge to farmers and conservation professionals in the Colorado River Basin and elsewhere in the West.

A relatively new technology developed to reduce irrigation-induced soil erosion losses involves injection of a soil stabilizer, such as polyacrylamide (PAM), into the irrigation water before application. Lentz and Sojka (1994) demonstrated that mixing PAM into irrigation water at a rate of 0.7 kg $ha^{-1}$ (0.62 pound per acre) reduced sediment losses from irrigation furrows by 94 percent. An alternatively effective dry or patch method was later developed (Lentz and Sojka, 1996). Use of PAM in furrow-irrigated fields also reduces transport of phosphorus (Lentz et al., 1998), microorganisms (Sojka and Entry, 2000), weed seeds (Sojka et al., 2003), and pesticides (Singh et al., 1996) off a field. According to Sojka et al. (2000), more than 400,000 ha (100,000 acres) were treated with PAM in the United States in 1999. More information on this conservation practice, anionic polyacrylamide, PAM (practice code 450), can be found in the soil management practices chapter of this book.

In addition to sediment losses, there is increasing concern that phosphorus losses from agricultural land cause accelerated algae and aquatic plant growth in lakes, rivers, and streams (Sharpley et al., 1999). Total phosphorus losses from agricultural fields generally are not large; however, phosphorus concentrations that cause eutrophication can be as low as 0.02 mg $L^{-1}$ (USEPA, 1996). Sediment eroded from irrigated agricultural soils contains 900 to 1,200 mg $kg^{-1}$(1.8 to 2.4 pounds per ton) of total phosphorus (Carter et al., 1974). Typically, the eroded sediment also contains more smaller sized soil particles than in the non-eroded soil, causing nutrient enrichment of the runoff. In a furrow irrigation study, flow-weighed dissolved reactive phosphorus concentrations were found to increase linearly as soil test phosphorus concentrations increased (Westermann et al., 2001). The lowest available soil phosphorus concentration in that study, 10 mg $kg^{-1}$, had a runoff soluble phosphorus concentration of about 0.01 mg $L^{-1}$ and a total phosphorus concentration of more than 1 mg $L^{-1}$. Total phosphorus concentrations were related to sediment concentrations.

In a similar study, except under sprinkler irrigation, Turner et al. (2004) found evidence of a curvilinear relationship between dissolved reactive phosphorus and soil test phosphorus. Again total phosphorus concentrations were one to two orders of magnitude larger than soluble phosphorus. Losses of other nutrients primarily are associated with sediment losses (Bjorneberg et al., 2002). As these studies and others show, soil erosion control is necessary to reduce the loss of phosphorus and other nutrients from irrigated agriculture.

## Soil quality effects

Soil quality effects related to soil physical and chemical changes brought about by irrigation specifically are difficult to document. In general, the chemical properties of soils tend toward the chemical properties of irrigation water applied to those soils. If the irrigation water contains salts or sodium, the soils over time will contain those salts or become sodic. Recent examples include irrigation using wastewater from industrial operations and domestic use (Singh et al., 2003; Qian and Mecham, 2005), dairy factory effluent (Degens et al., 2000), and sewage effluent (Rattan et al., 2005).

A more detailed study by Presley et al. (2004) reported that the pH in an irrigated surface soil was higher than in a non-irrigated soil, as was the exchangeable sodium. In that study, irrigation did not affect the organic carbon or calcium carbonate equivalent of the soil. The data also indicated that irrigation had modified the natural genetic processes by increasing the rate of pedogenic activity relative to natural conditions. The researchers suggested that the irrigation water chemistry was a likely explanation for the lack of calcium carbonate change.

Among various agricultural land use practices, changing from dryland to irrigated agriculture has the potential to increase soil carbon sequestration. Water applications increase biomass productivity and soil carbon inputs through residues and roots, change mineralization rates, and carbonate balances (Watson et al., 2000). Entry et al. (2002) reported that organic soil carbon changes under northern, semiarid irrigated conditions were dependent upon long-term cropping histories. When potential water savings.

- Reduction of soil water evaporation through more effective use of crop residue and other mulch materials.
- Reduction of plant transpiration through limited irrigation management (either deficit irrigation or a reduction of irrigated area) and use of alternative crops that require less water.
- There is increasing emphasis to use a more comprehensive approach to soil, water and crop management practices to lessen off-site impacts (Oster and Wichelns, 2003; Qadir and Oster, 2004). This will be especially important as non-agricultural competition for limited water supplies increases. While this approach should improve agricultural productivity and sustainability, it must also maximize protection of water quality and environmental resources. Present and to-be-developed conservation practices for water, crop, and soil management will have major roles in such approaches.

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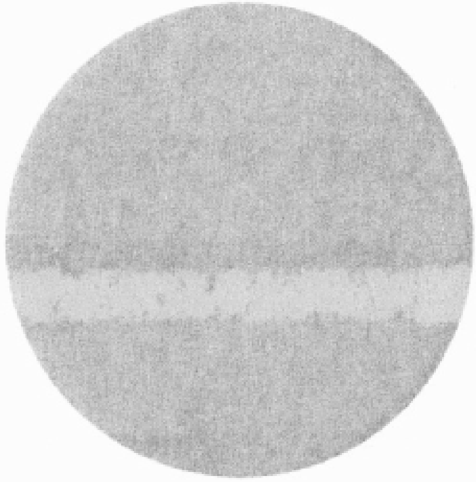

# Environmental Benefits of Conservation on Cropland

## The Status of Our Knowledge

**Max Schnepf** and **Craig Cox,** Editors

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