4F: Irrigation Water Management

Management Measure for Irrigation Water

To reduce nonpoint source pollution of ground and surface waters caused by irrigation:

(1) Operate the irrigation system so that the timing and amount of irrigation water applied match crop water needs. This will require, as a minimum: (a) the accurate measurement of soil-water depletion volume and the volume of irrigation water applied, and (b) uniform application of water.

(2) When chemigation is used, include backflow preventers for wells, minimize the harmful amounts of chemigated waters that discharge from the edge of the field, and control deep percolation. In cases where chemigation is performed with furrow irrigation systems, a tailwater management system may be needed.

The following limitations and special conditions apply:

(1) In some locations, irrigation return flows are subject to other water rights or are required to maintain stream flow. In these special cases, on-site reuse could be precluded and would not be considered part of the management measure for such locations. In these locations, improvements to irrigation systems and their management should still occur.

(2) By increasing the water use efficiency, the discharge volume from the system will usually be reduced. While the total pollutant load may be reduced somewhat, there is the potential for an increase in the concentration of pollutants in the discharge. In these special cases, where living resources or human health may be adversely affected and where other management measures (nutrients and pesticides) do not reduce concentrations in the discharge, increasing water use efficiency would not be considered part of the management measure.

(3) In some irrigation districts, the time interval between the order for and the delivery of irrigation water to the farm may limit the irrigator's ability to achieve the maximum on-farm application efficiencies that are otherwise possible.

(4) In some locations, leaching is necessary to control salt in the soil profile. Leaching for salt control should be limited to the leaching requirement for the root zone.

(5) Where leakage from delivery systems or return flows supports wetlands or wildlife refuges, it may be preferable to modify the system to achieve a high level of efficiency and then divert the "saved water" to the wetland or wildlife refuge. This will improve the quality of water delivered to wetlands or wildlife refuges by preventing the introduction of pollutants from irrigated lands to such diverted water.

(6) In some locations, sprinkler irrigation is used for frost or freeze protection, or for crop cooling. In these special cases, applications should be limited to the amount necessary for crop protection, and applied water should remain on-site.

A primary concern for irrigation water management is the discharge of salts, pesticides, and nutrients to ground water and discharge of these pollutants plus sediment to surface water.

Management Measure for Irrigation Water: Description

The goal of this management measure is to reduce movement of pollutants from land into ground or surface water from the practice of irrigation. This goal is accomplished through consideration of the following aspects of an irrigation system, which will be discussed in this chapter:

1. Irrigation scheduling
2. Efficient application of irrigation water
3. Efficient transport of irrigation water
4. Use of runoff or tailwater
5. Management of drainage water

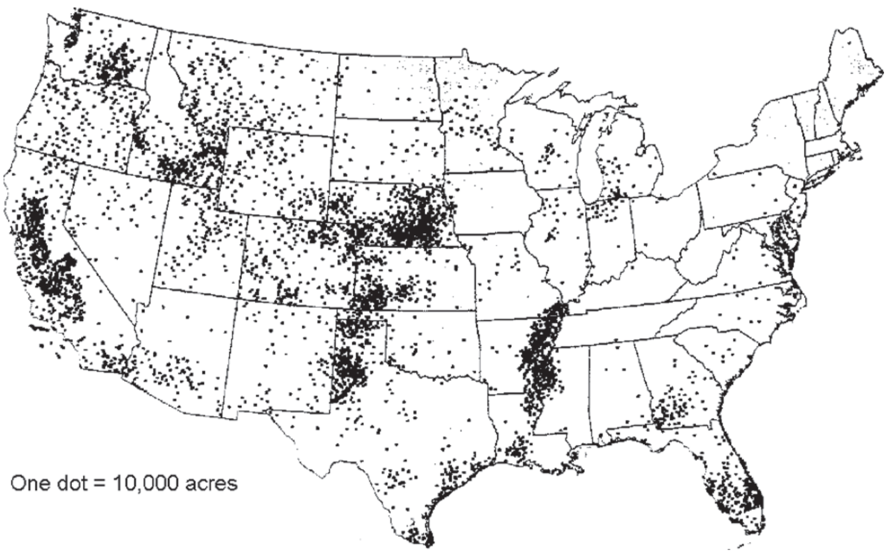
Effective irrigation management reduces runoff and leachate losses, controls deep percolation and, along with cropland sediment control, reduces erosion and sediment delivery to waterways.

A well designed and managed irrigation system reduces water loss to evaporation, deep percolation, and runoff and minimizes erosion from applied water. Application of this management measure will reduce the waste of irrigation water, improve water use efficiency, and reduce the total pollutant discharge from an irrigation system. It focuses on components to manage the timing, amount and location of water applied to match crop water needs, and special precautions (i.e., backflow preventers, prevent runoff, and control deep percolation) when chemigation is used.

Irrigation and Irrigation Systems: An Overview

Irrigation, the addition of water to lands via artificial means, is essential to profitable crop production in arid climates. Irrigation is also practiced in humid and sub-humid climates to protect crops during periods of drought. Irrigation is practiced in all environments to maximize production and, therefore, profit by applying water when the plant needs it. Figure 4f-1 shows the distribution of irrigated farmland in the U.S. (USDA-ERS, 1997).

Figure 4f-1. Irrigated land in farms, 1992. Source: USDA-ERS, 1997, based on USDC 1992 Census of Agriculture data.



Soil-Water-Plant Relationships

Effective and efficient irrigation begins with a basic understanding of the relationships among soil, water, and plants. Figure 4f-2 illustrates the on-farm hydrologic cycle for irrigated lands, and Table 4f-1 provides definitions of several terms associated with irrigation. Water can be supplied to the soil through precipitation, irrigation, or from groundwater (e.g., rising water table due to drainage management). Plants take up water that is stored in the soil (soil water), and use this for growth (e.g., nutrient uptake, photosynthesis) and cooling. Transpiration is the most important component of the on-farm hydrologic cycle (Duke, 1987), with the greatest share of transpiration devoted to cooling. Water is also lost via evaporation from leaf surfaces and the soil. The combination of transpiration and evaporation is evapotranspiration, or ET. ET is influenced by several factors, including plant temperature, air temperature, solar radiation, wind speed, relative humidity, and soil water availability (USDA-NRCS, 1997a). The amount of water the plant needs, its consumptive use, is equal to the quantity of water lost through ET. Due to inefficiencies in the delivery of irrigated water (e.g., evaporation, runoff, wind drift, and deep percolation losses), the amount of water needed for irrigation is greater than the consumptive use. In arid and semi-arid regions, salinity control may be a consideration, and additional water or "leaching requirement" may be needed.

Figure 4f-2. On-farm hydrologic cycle for irrigated lands.

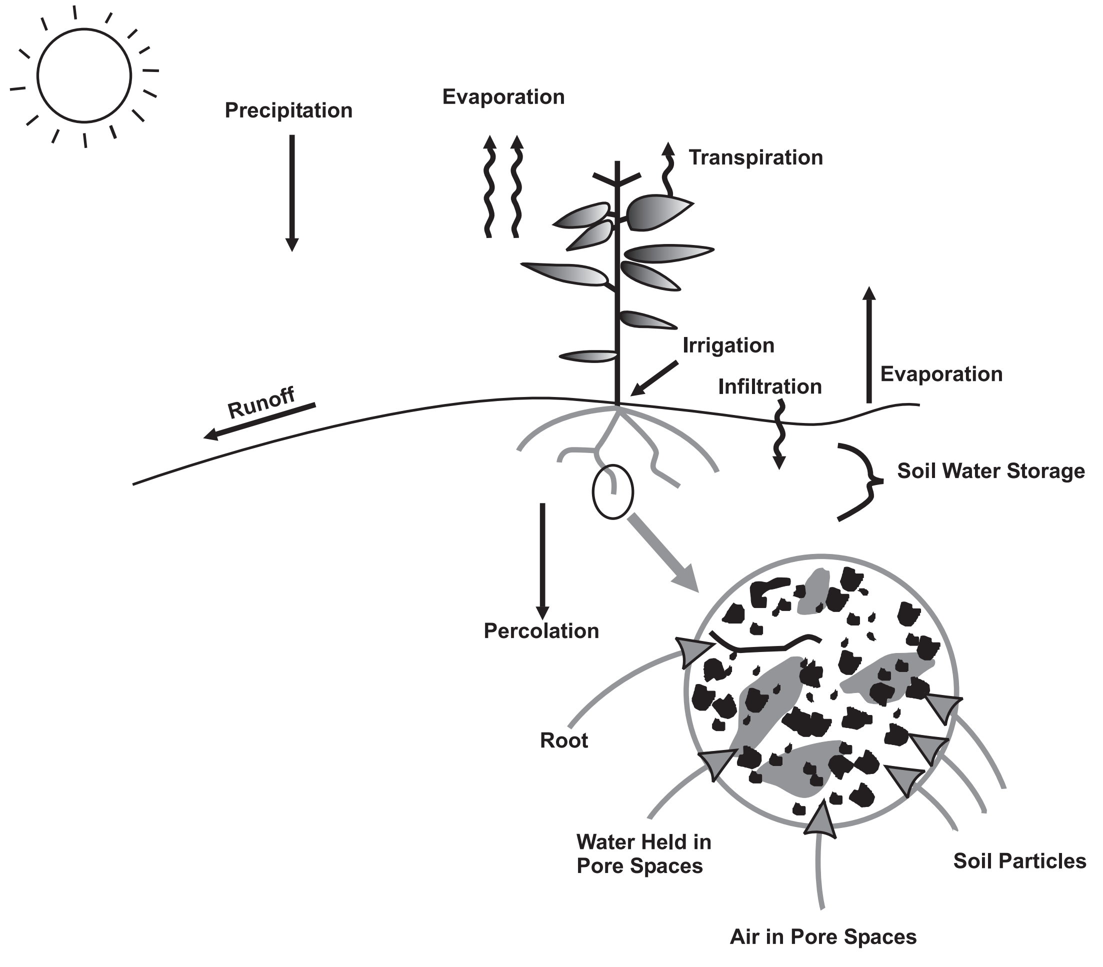


Table 4f-1. Soil-water-plant relationship terms.

Term	Definition
Evaporation	The transformation of water to vapor without passing through the plant.
Transpiration	The movement of water into plant roots, through the plant, and out the stomata as water vapor.
Evapotranspiration (ET)	Evaporation + Transpiration
Soil water	Water stored in the soil.
Soil-water potential Soil-water tension Soil moisture tension	A measure of the strength with which the soil holds the water. Soil water potential is the amount of work required per unit quantity of water to transport water in soil, and is measured in units of bars and atmospheres or cm. A tension is a negative potential. Water moves from high to low potential.
Gravitational water Free water	Water that moves downward freely in soils under the force of gravity.
Capillary water	Water that moves slowly through smaller pores in soils, due to surface tension forces in unsaturated conditions.
Field capacity	The amount of soil water stored in the soil after free water (gravitational water) passes through the soil profile. Sometimes referred to as 2-3 day drainage or a soil water potential of about -1/3 bar. For a sandy soil, this might occur in less than one day.
Available water capacity	The amount of stored soil water that is available to the plant.
Water holding capacity	The amount of water that can be stored in the soil at field capacity.
Permanent wilting point	The soil-water content at which most plants cannot obtain sufficient water to prevent permanent tissue damage, about -15 bars.
Management allowable depletion (MAD)	The greatest amount of water that can be removed by plants before irrigation is needed to avoid undesirable crop water stress.
Consumptive use	The amount of water that is used by the plant. Is equal to ET.
Soil texture	The proportion of the various sizes of soil particles (sand, silt, and clay). Defines coarseness or fineness of soil, along with structure, and controls the hydraulic characteristics of the soil.
Soil structure	The arrangement and organization of soil particles into natural units of aggregation.
Bulk density	The weight of a unit volume of dry soil.

Build up of salts typically occurs in regions where evapotranspiration exceeds precipitation. Salts contained in precipitation or dissolved in the soil are left behind as evaporation and capillary action transports and deposits these salts near the surface. Salinity is not normally a problem in humid regions, where natural leaching of salts from rainfall occurs.

Excess salts in the soil have an adverse impact on plant growth. The total concentration of salts in the soil solution exerts an osmotic force, and therefore makes it more difficult for plants to uptake water. In addition, specific ions, such as chloride, sodium, boron and others may have a toxic effect on plants at certain levels. Crops respond differently to both total and specific salts, some being more sensitive than others.

Plant growth depends upon a renewable supply of soil water, which is governed by the movement of water in the soil, the soil-water holding capacity, the amount of soil water that is readily available to plants, and the rate at which soil water can be replenished (Duke, 1987). Efficient irrigation provides plants with this renewable supply of soil water with a minimum of wasted time, energy, and water. Knowledge and understanding of the factors that affect water movement in the soil, storage of water in the soil, and the availability of water to plants are essential to achieving maximum irrigation efficiencies.

Movement of soil water

When water is applied to soils it moves via such pathways as infiltration, runoff, and evaporation (Figure 4f-2). The ultimate fate and transport of applied water is determined by various forces, including gravity and capillary force. Gravity pulls water downward freely in soils with large pores, causing it to move through the root zone quickly if not taken up by the crop (Duke, 1987). As the water passes through the soil, the pores are filled again with air, preventing crop damage that could arise due to excess water. In soils with smaller pores, water moves via capillary forces. This "capillary water" moves more slowly than gravitational water, and tends to move from wetter areas to drier areas. The lateral distribution of capillary water makes it more important to the irrigated crop since it provides greater wetting of the soil (Duke, 1987). In saturated conditions, gravity is the primary force causing downward water movement (Watson, et al. 1995), while capillary action is the primary force in unsaturated soil.

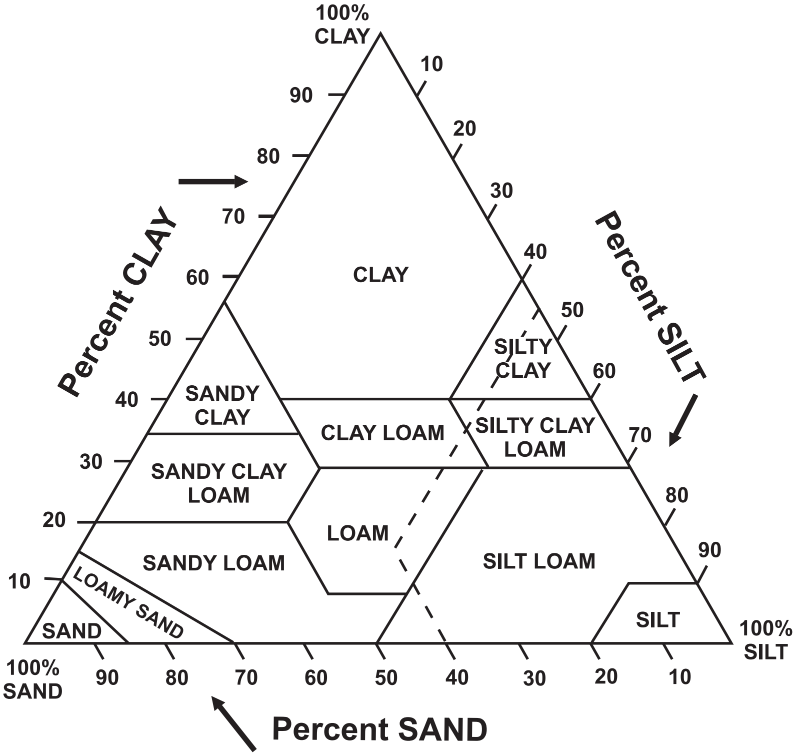
The above discussion uses subjective terms such as "capillary water" and "gravitational water" (see Table 4f-1) to simplify the description of how water moves in soils. USDA describes this movement in the more technically correct terms of soil-water potential, measured in units of bars and atmospheres (USDA-NRCS, 1997a). Soil-water potential is the sum of matric, solute, gravitational, and pressure potential, detailed discussions of which are beyond the scope of this document. In simple terms, however, water in the soil moves toward decreasing potential energy, or commonly from higher water content to lower water content (USDA-NRCS, 1997a).

Storage and availability of soil water

The amount of water that soil can hold, its water holding capacity, is a key factor in irrigation planning and management since the soil provides the reservoir of water that the plant draws upon for growth. Water is stored in the soil as a film around each soil particle, and in the pore spaces between soil particles (Risinger and Carver, 1987). The magnified area in Figure 4f-2 illustrates how soil water and air are held in the pore spaces of soils.

All soil water is not equally available for extraction and use by plants. The ability of plants to take water from the soil depends upon a number of factors, including soil texture, soil structure, and the layering of soils (Duke, 1987). Texture is classified based upon the proportion of sand, silt, and clay particles in the soil (Figure 4f-3). Structure refers to how the soil particles are arranged in groups or

Figure 4f-3. Soil textural triangle for determining textural class (Duke, 1987).



aggregates, while layering refers to the vertical distribution of soils in the soil profile (e.g., clay soils underlying a sandy loam layer). The type and extent of layering can influence the percolation and lateral distribution of applied water.

Soil texture and structure affect the size, shape, and quantity of pores in the soil, and therefore the space available to hold air or water. For example, the available water capacity of coarse sand ranges from 0.1 to 0.4 inches of water per foot of soil depth (in/ft), while silt holds 1.9–2.2 in/ft, and clay holds 1.7–1.9 in/ft (USDA-NRCS, 1997a). The structure of some volcanic ash soils allows them to carry very high water content at field capacity levels, but pumice and cinder fragments may contain some trapped water that is not available to plants (USDA-NRCS, 1997a). In fine-textured soils and soils affected by salinity, sodicity, or other chemicals, a considerable volume of soil water may not be available for plant use due to greater soil water tension (USDA-NRCS, 1997a).

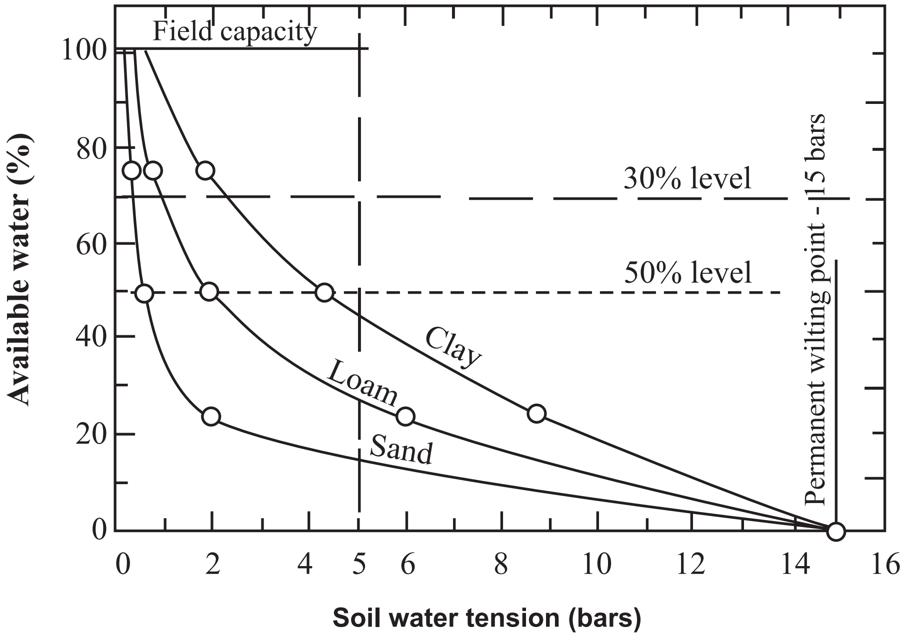
Field capacity is the amount of water a soil holds after "free" water has drained because of gravity (USDA-NRCS, 1997a). "Free" water, which is conceptually similar to "gravitational" water, can drain from coarse-textured (e.g., sandy) soils in a few hours from the time of rainfall or irrigation, from medium-textured (e.g., loamy) soils in about 24 hours, and from fine-textured (e.g., clay) soils in several days. Soil properties that affect field capacity are texture, structure, bulk density, and strata within the soil profile that restrict water movement. Available water capacity is the difference between the amount of water held at field capacity and the amount held at the permanent wilting point (Burt, 1995).

Uptake of soil water by plants

Water stored in soil pore spaces is the easiest for the plant to extract, while water stored in the film around soil particles is much more difficult for the plant to withdraw (Risinger and Carver, 1987). As evapotranspiration draws water from the soil, the remaining water is held more closely and tightly by the soil. Soil moisture tension increases as soils become drier, making it more difficult for the plant to extract the soil water. Figure 4f-4 is a soil moisture release curve that shows how greater energy (tension measured in bars, or potential measured in negative (-) bars) is needed to extract water from the soil as soil-water content decreases (USDA-NRCS, 1997a). This figure also illustrates the greater soil-water tension (or lesser soil-water potential) in clays versus loam and sand for any given soil-water content. Because clay holds water at greater tension than medium-textured soils (e.g., loam) at similar water contents, it has less *available* water capacity despite its greater water holding capacity (USDA-NRCS, 1997a).

Wilting occurs when the plant cannot overcome the forces holding the water to the soil particles (i.e., the soil-water tension). Irrigation is needed at this point to save the plant. The permanent wilting point (represented as -15 bars in Figure 4f-4) is the soil-water content at which most plants cannot obtain sufficient water to prevent permanent tissue damage (USDA-NRCS, 1997a). Based upon yield and

Figure 4f-4. Typical water release curves for sand, loam, and clay (USDA-NRCS, 1997a).



Texture	**Tension level (atmospheres or bars)** @field capacity	 @Perm. wilting point
Course	0.1	15.0
Medium & fine	0.33	15.0

product quality objectives, growers decide how much water to allow plants to remove from the soil before irrigation. This amount, the Management Allowable Depletion (MAD), is expressed as a percentage of the available water-holding capacity and varies for different crops and irrigation methods. As a general rule of thumb, MAD is 50%. Smaller MAD values, which result in more frequent irrigations, may be desirable where micro-irrigation is practiced, when saline water is used, for shallow root zones, and in cases where the water supply is uncertain (Burt, 1995). Large MAD values might be desirable when hand-move and hose-pull sprinklers are used, where furrows are long and soils are sandy, or for crops such as some varieties of cotton that need to be stressed on heavy soil to develop a sufficient number of cotton bolls (Burt, 1995).

Irrigation Methods and System Designs

Irrigation systems consist of two basic elements: (1) the transport of water from its source to the field, and (2) the distribution of transported water to the crops in the field. A number of soil properties and qualities are important to the design, operation, and management of irrigation systems, including water holding capacity, soil intake characteristics, permeability, soil condition, organic matter, slope, water table depth, soil erodibility, chemical properties, salinity, sodicity, and pH (USDA-NRCS, 1997a). Some soils cannot be irrigated due to various physical problems, such as low infiltration rates and poor internal drainage which may cause salt buildup. The chemical characteristics of the soil and the quantity and quality of the irrigation water will determine whether irrigation is a suitable management practice that can be sustained without degrading the soil or water resources (Franzen et al., 1996; Scherer et al., 1996; and Seelig and Richardson, 1991).

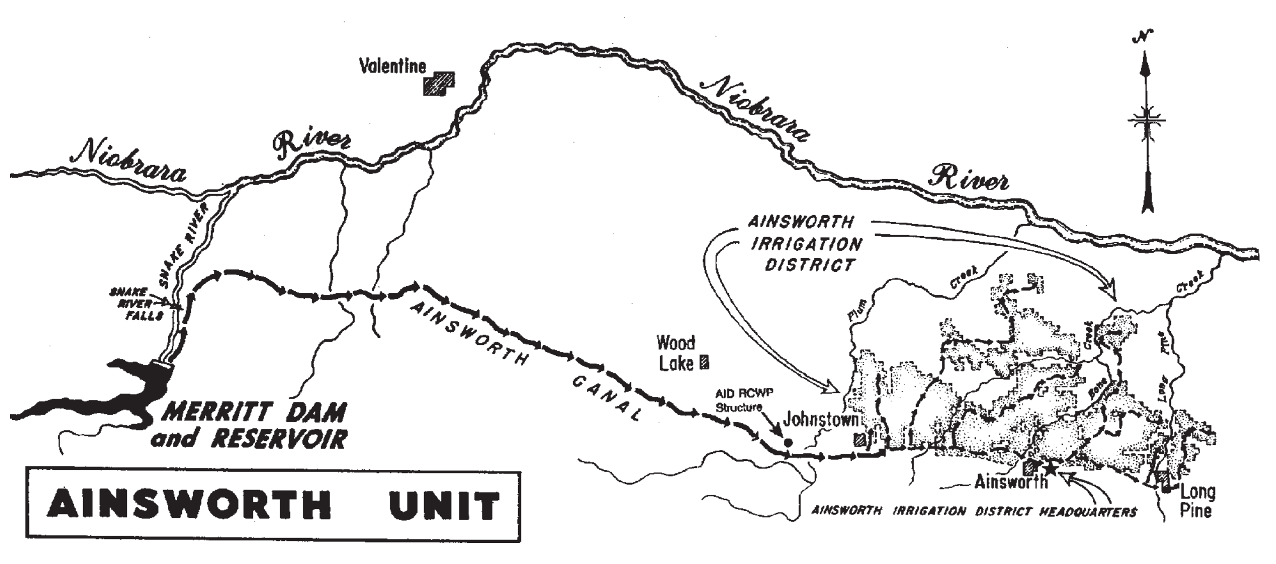
Water supply and demand

Producers need to factor the availability of good quality water (in terms of amount, timing, and rate) into their irrigation management decisions. Both surface water and ground water can be used to supply irrigation water. An assessment of the total amount of water available during an irrigation season is essential to determining the types and amounts of irrigated crops that can be grown on the farm.

The quality of some water is not suitable for irrigating crops. Irrigation water must be compatible with both the crops and soils to which it will be applied (Scherer and Weigel, 1993; Seelig and Richardson, 1991). The quality of water for irrigation purposes is generally determined by its salt content, bicarbonate concentration, and the presence of potentially toxic elements. Irrigation water can also contain appreciable amounts of nutrients that should be factored into the overall nutrient management plan.

Efficient irrigation scheduling depends upon knowledge of when water will be available to the producer. In some areas, particularly west of the Mississippi River, irrigation districts or some other outside entities may manage the distribution of water to farms, while farmers in other areas have direct access to and control over their water supplies. An irrigation district is defined as blocks of irrigated land within a defined boundary, developed or administered by a group or agency (USDA-NRCS, 1997a). Water is delivered from a source to individual turnouts via a system of canals, laterals, or pipelines. Figure 4f-5 depicts the Ainsworth Unit in northern Nebraska within which water from the Merritt Reservoir is distributed to the Ainsworth Irrigation District via the 53-mile long, concrete-lined Ainsworth Canal (Hermsmeyer, 1991). A system of laterals and drains serves approximately 35,000 acres of cropland in the irrigation district. Irrigation districts that deliver water to farms on a rotational basis control when the farmer can irrigate, leaving the farmer to choose only the rate and methods of irrigation. In cases where farmers are able to control the availability of irrigation water it is possible, however, to develop a predetermined irrigation schedule.

Figure 4f-5. Ainsworth Unit in northern Nebraska.



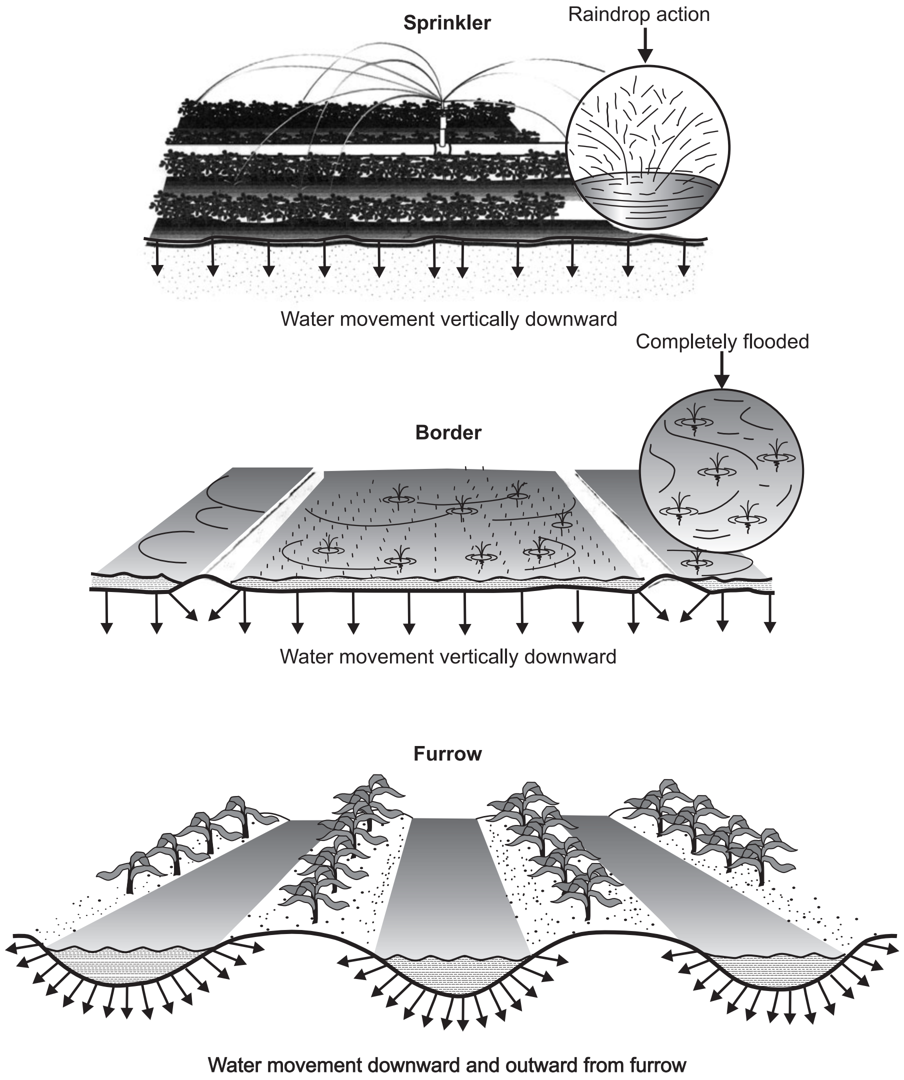
The amount of water that is needed for adequate irrigation depends upon climate and crop growth stage. Different crops require different amounts of water, and the water demand for any particular crop varies throughout the growing season. Producers need to factor the peak-use rates, the amount of water used by a crop during its period of greatest water demand (usually during period of peak growth), into both the initial design of an irrigation system and annual irrigation planning.

Irrigation methods

There are four basic *methods* of applying irrigation water: (1) surface (or flood), (2) sprinkler, (3) trickle, and (4) subsurface. Types of surface irrigation are furrow, basin, border, contour levee or contour ditch. Factors that are typically considered in selecting the appropriate irrigation method include land slope, water intake rate of the soil (i.e., how fast the soil can absorb applied water), water tolerance of the crops, and wind. For example, sprinkler, surface, or trickle methods may be used on soils (e.g., fine soils) with low water intake rates, but surface irrigation may not be appropriate for soils (e.g., coarse soils) with high water intake rates. Key factors that determine water intake rates are soil texture, surface sealing due to compaction and sodium content of the soil and/or irrigation water, and electrical conductivity of the irrigation water.

Water available to the farm from either on-site or off-site sources can be transported to fields via gravity (e.g. canals and ditches) or under pressure (pipeline). Pressure for sprinkler systems is usually provided by pumping, but gravity can be used to create pressure where sufficient elevation drops are available.

Figure 4f-6. Water infiltration characteristics for sprinkler, border, and furrow irrigation systems

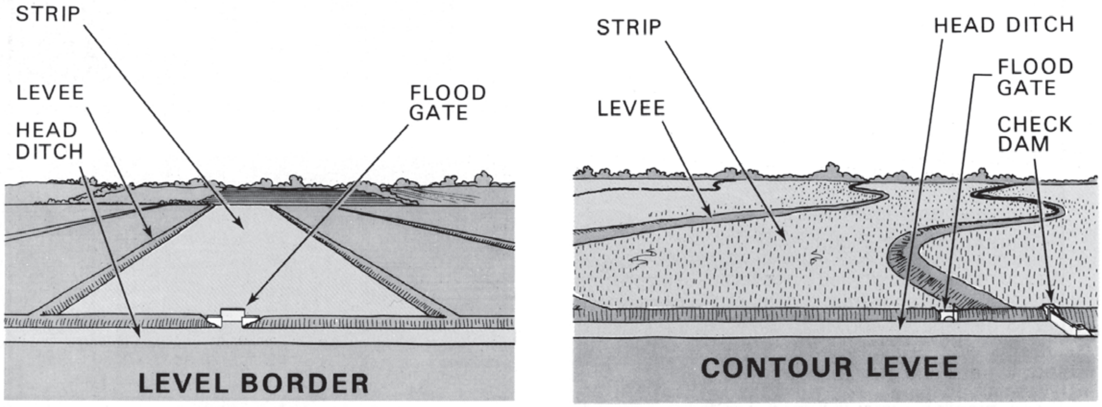


Gravity-based, or surface irrigation systems, rely on the ponding of water on the surface for delivery through the soil profile (Figure 4f-6), whereas pressure-based sprinkler systems are generally operated to avoid ponding for all but very short time periods (USDA-NRCS, 1997a).

Irrigation systems

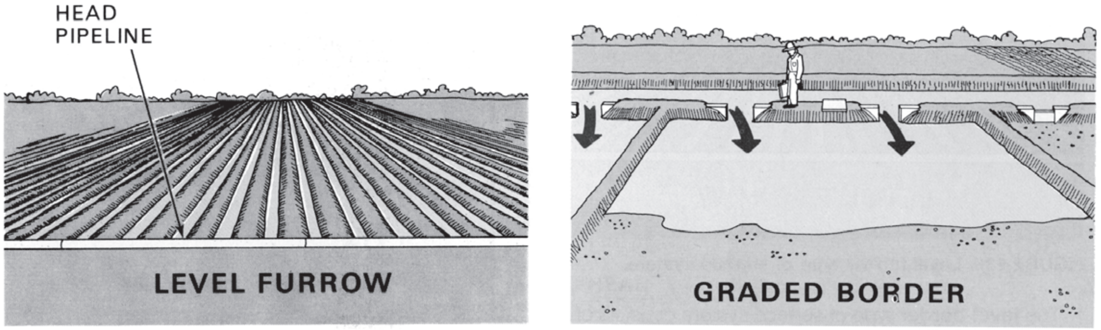
There are several irrigation *system* options for each irrigation *method* selected for the farm. The options for irrigation by gravity include level basins or borders, contour levees, level furrows, graded borders, graded furrows, and contour ditches (Figure 4f-7) (USDA-NRCS, 1997a). Pressure-based irrigation systems include periodic move, fixed or solid-set, continuous (self) move, traveling gun, and traveling boom sprinkler systems, as well as micro-irrigation and subirrigation systems. Operational modifications to center pivot and linear move systems, including Low Energy Precision Application (LEPA) and Low Pressure In Canopy (LPIC), increase the range of pressure-based options to select from (USDA-

Figure 4f-7. Irrigation system options for irrigation by gravity (Turner, 1980).



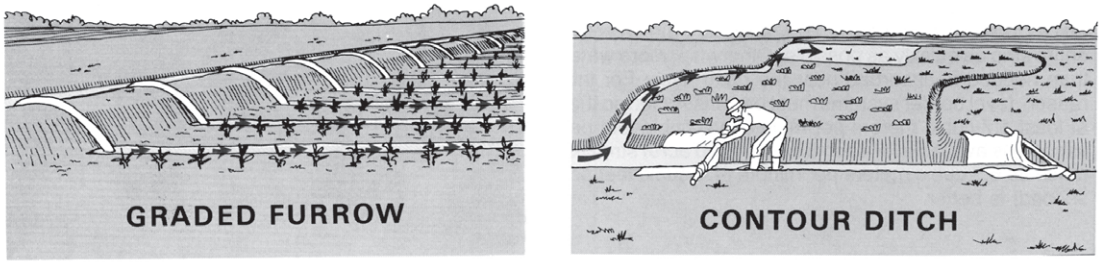
Level border type of surface system.

Contour levee type of surface system.



Level furrow type of surface system.

Graded border type of graded surface system.



Graded furrow type of graded surface system.

Contour ditch type of graded surface system.

NRCS, 1997a). Figure 4f-8 illustrates a range of sprinkler systems. Micro-irrigation systems (Figure 4f-9) include point-source emitters (drip, trickle, or bubbler emitters), surface or subsurface line-source emitters (e.g., porous tubing), basin bubblers (Figure 4f-10), and spray or mini-sprinklers. Table 4f-2 summarizes the basic features of each type of irrigation system (USDA-NRCS, 1997a), and Figure 4f-11 shows typical layouts of graded-furrow with tailwater recovery and reuse, solid-set, center pivot, traveling gun, and micro-irrigation systems (USDA-NRCS, 1997a; Turner, 1980).

Figure 4f-8. Typical types of sprinkler irrigation systems (Turner, 1980).

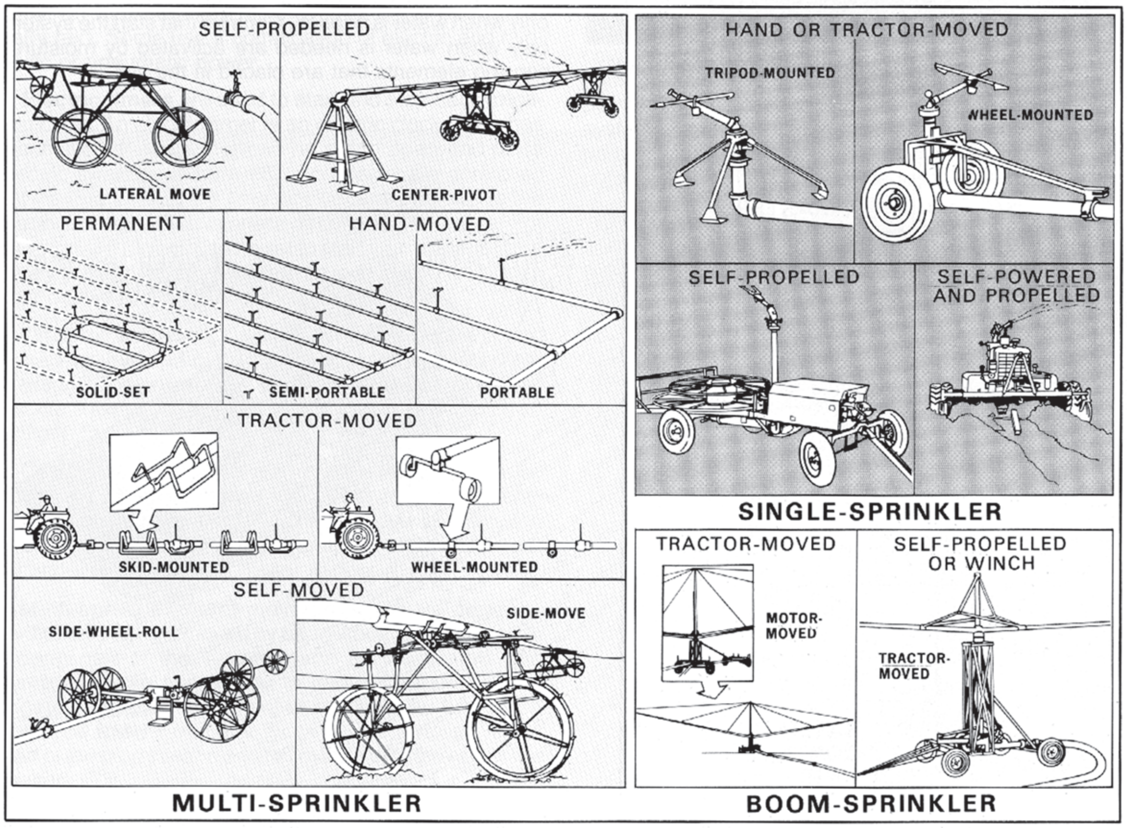
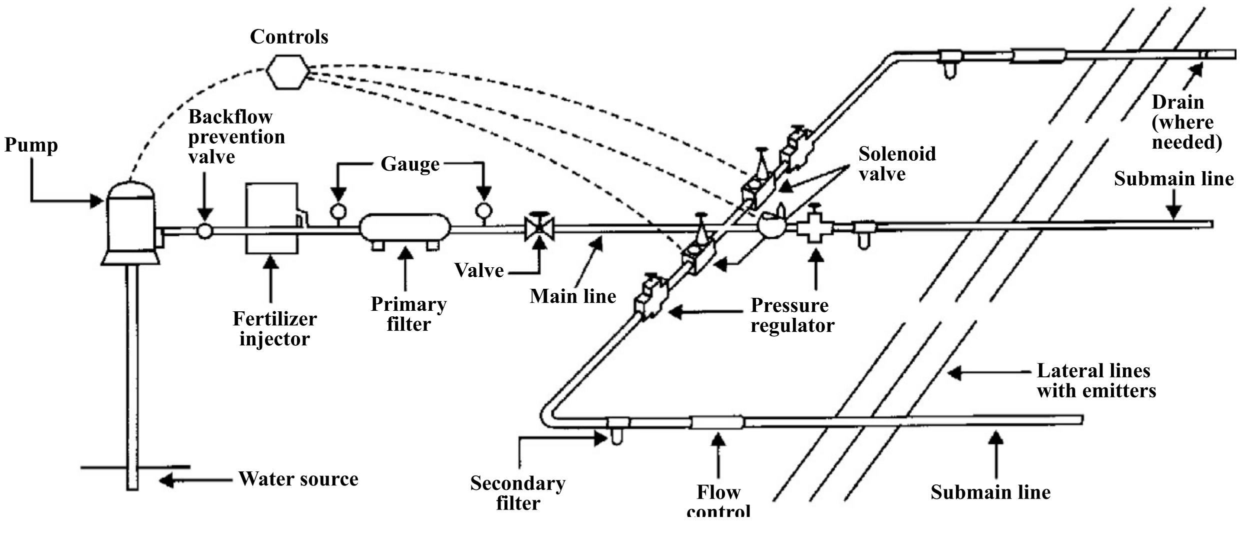


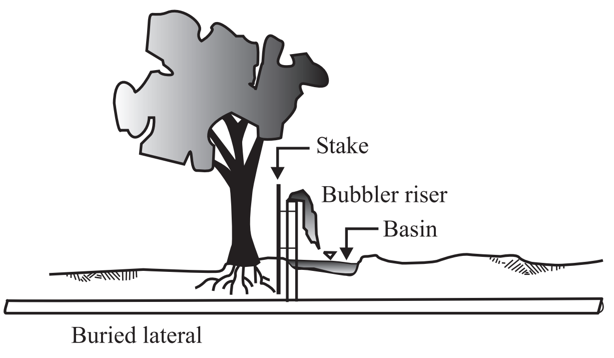
Figure 4f-9. Micro-irrigation system components (USDA-NRCS, 1997a).



The advantages and disadvantages of the various types of irrigation systems are described in a number of existing documents and manuals (USDA-NRCS, 1997a; EduSelf Multimedia Publishers Ltd., 1994).

A comprehensive set of publications, videos, interactive software, and slides on irrigation has been assembled by the U.S. Department of Agriculture to train its employees (USDA-NRCS, 1996a). This irrigation "toolbox" covers soil-water-plant relationships, irrigation systems planning and design, water measurement, irrigation scheduling, soil moisture measurement, irrigation water management planning, and irrigation system evaluation. Updated material is provided periodically as it becomes available. Other sources of material may be found in USDA-NRCS, 1997a, Sec. 652-1502.

Figure 4f-10. Basin bubbler system (USDA-NRCS, 1997a).



Pollutant Transport from Irrigated Lands

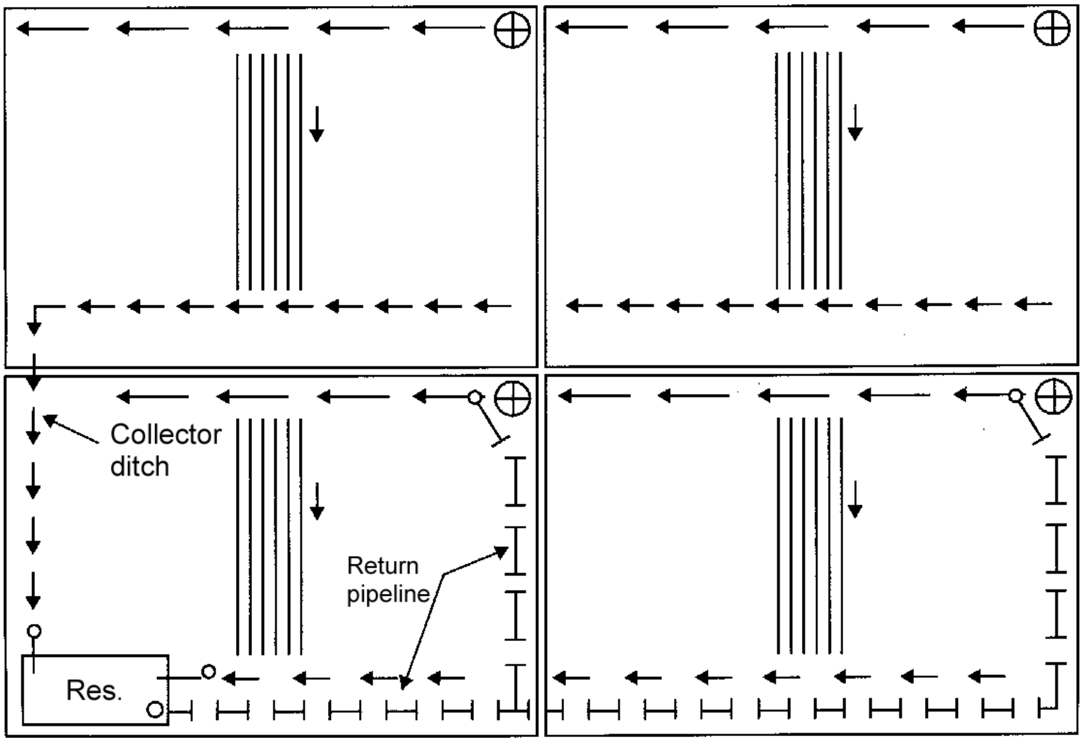
Return flows, runoff, and leachate from irrigated lands may transport the following types of pollutants to surface or ground waters:

- ☐ Sediment and particulate organic solids;
- ☐ Particulate-bound nutrients, chemicals, and metals, such as phosphorus, organic nitrogen, a portion of applied pesticides, and a portion of the metals applied with some organic wastes;
- ☐ Soluble nutrients, such as nitrogen, soluble phosphorus, a portion of the applied pesticides, soluble metals, salts, and many other major and minor nutrients; and
- ☐ Bacteria, viruses, and other pathogens.
- ☐ If soils or drainage in the irrigated area contain toxic substances that may concentrate in the drainage or reuse system, this factor must be considered in any decisions about use of the water and design of the reuse system. Discharge of drainage water containing selenium into wetlands is an example of where this type of problem can occur.

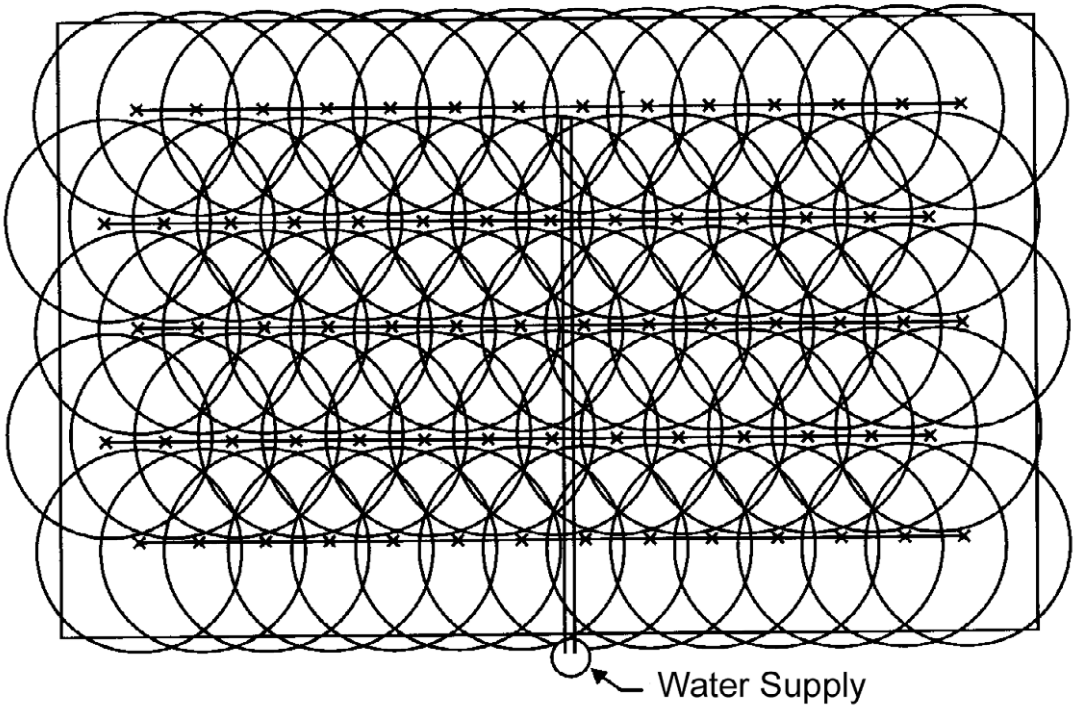
The movement of pollutants from irrigated lands is affected by the timing and amount of applied water and precipitation; the physical, chemical, and biological characteristics of the irrigated land; the type and efficiency of the irrigation system used; crop type; the degree to which erosion and sediment control, nutrient management, and pesticide management are employed; and the management of the irrigation system.

Transport of irrigation water from the source of supply to the irrigated field via open canals and laterals can be a source of water loss if the canals and laterals are not lined. Water is also transported through the lower ends of canals and laterals as part of flow-through requirements to maintain water levels. In many soils, unlined canals and laterals lose water via evaporation and seepage in bottom and side walls. Seepage water either moves into the ground water through percolation or forms wet areas near the canal or lateral. This water will carry with it any soluble pollutants in the soil, thereby creating the potential for pollution of ground or surface water (Figure 4f-12).

Figure 4f-11. Typical irrigation system layouts (USDA-NRCS, 1997a; Turner, 1980).

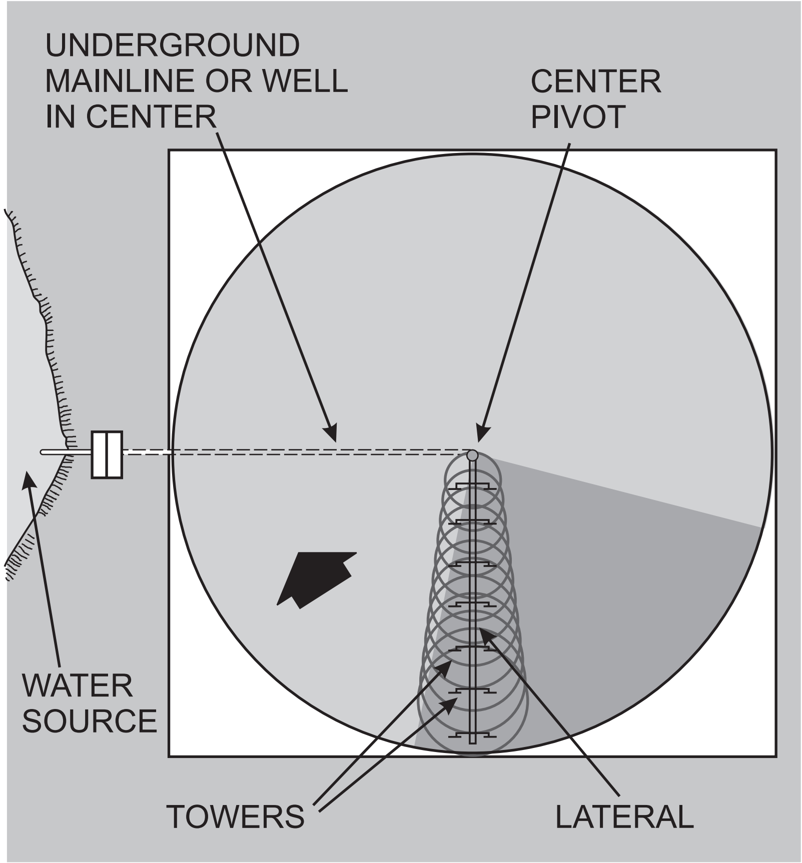


Typical layout for a tailwater recovery and reuse facility.

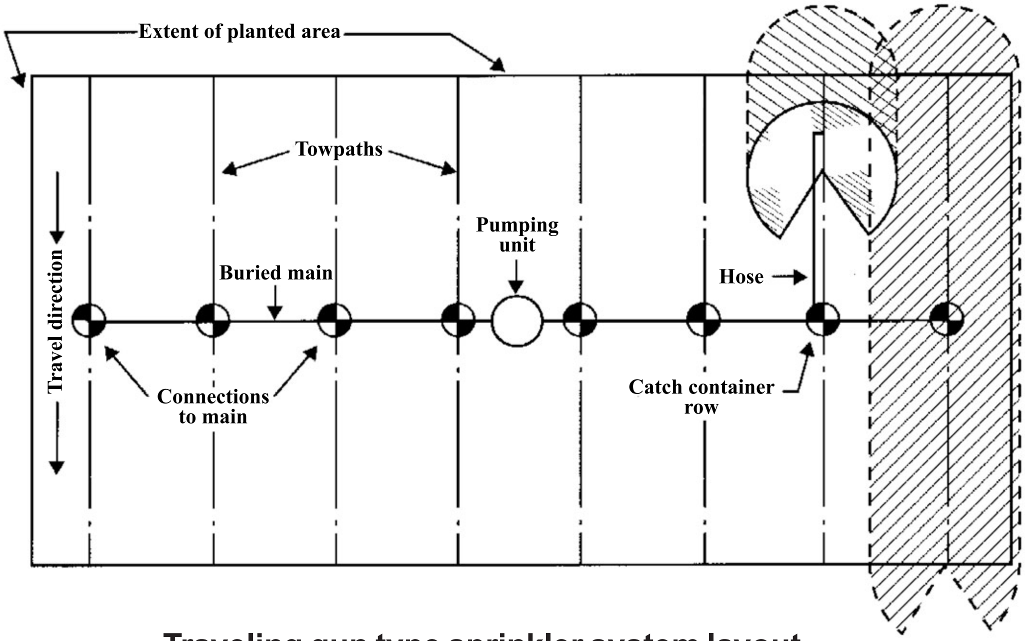


Solid set sprinkler system layout.

Figure 4f-11. Typical irrigation system layouts (USDA-NRCS, 1997a; Turner, 1980). Continued

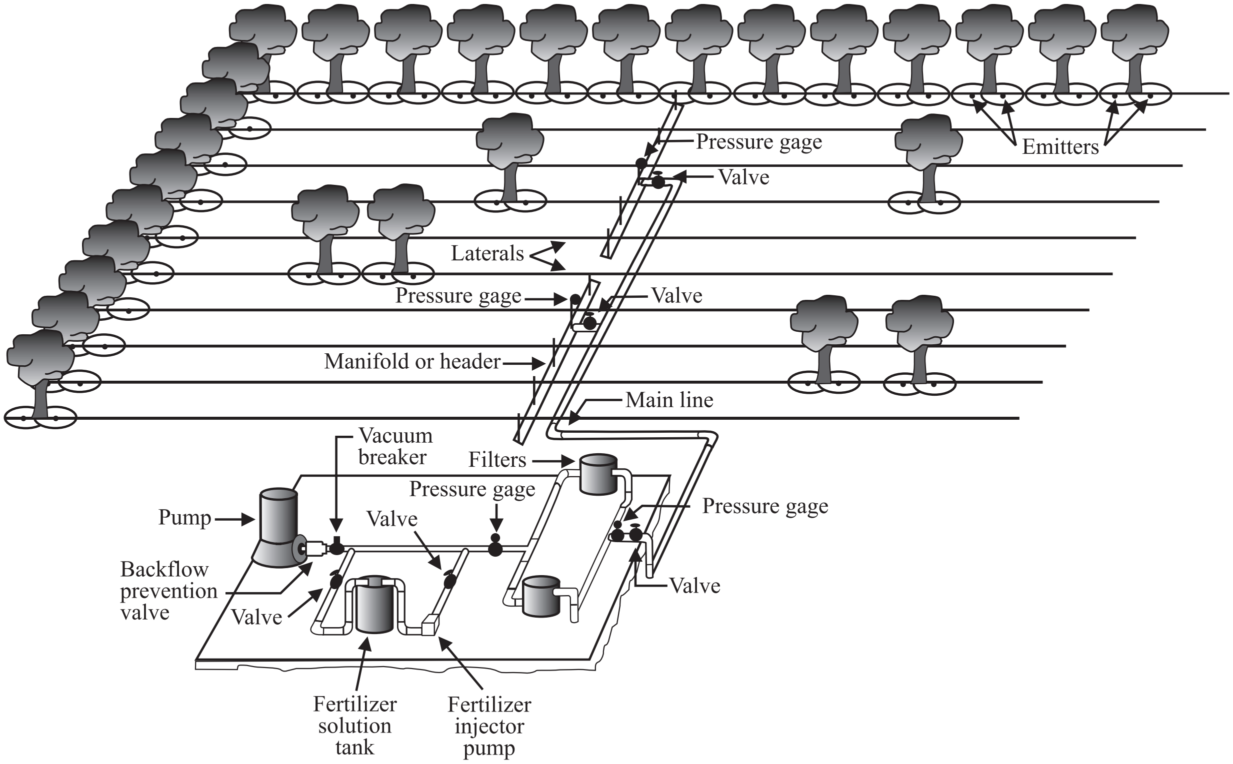


Field layout for self-propelled, center-pivot system.



Traveling gun type sprinkler system layout.

Figure 4f-11. Typical irrigation system layouts (USDA-NRCS, 1997a; Turner, 1980). Continued

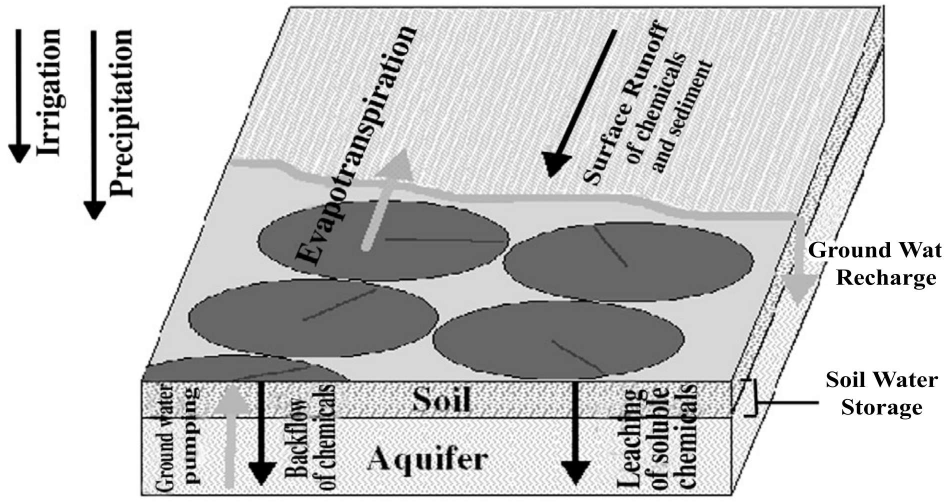


Typical orchard micro-system layout.

Table 4f-2. Types of Irrigation Systems.

Irrigation System Type	Major Features of System
Gravity-Level Basins	Large flow rates over short periods to flood entire field or basin. Level fields surrounded by low dike or levee. Best for soils with low to medium water intake rate.
Gravity-Contour Levees	Similar to level basins except for rice. Small dikes or levees constructed on contour. For rice, ponding is maintained. Best for soils with very low intake rate.
Gravity-Level Furrows	Large flow rates over short periods. Level fields. End of furrow or field is blocked to contain water. Best for soils with moderate to low water intake rate and moderate to high available water capacity.
Gravity-Graded Borders	Controlled surface flooding. Field divided into strips bordered by parallel dikes or border ridges. Water introduced at upper end.
Gravity-Graded Furrows	Like graded borders, but only furrows are covered with water. Water distribution via vertical and lateral infiltration. Water application amount is a function of intake rate of soil, spacing of furrows, and length of field. Heavy soils (small pores sizes) provide slower infiltration and greater lateral movement.
Gravity-Contour Ditches	Controlled surface flooding. Water discharged with siphon tubes, over ditch banks, or from gated pipes located upgradient and positioned across the slope on contour. Sheet flow is goal.
Pressure-Periodic Move Sprinkler	Sprinkler is operated in a fixed location for a specified period of time, then moved to the next location. Many design options including hand-moved laterals, side-roll laterals, end-tow laterals, hose-fed (pull) laterals, guns, booms, and perforated pipe.
Pressure- Fixed or Solid-Set Sprinkler	Laterals are not moved, but one or more sections of sprinklers are cycled on and off to provide coverage of entire field over time.
Pressure-Continous Move Sprinkler	Center pivot (irrigates in circular patterns, or rectangular with end guns or swing lines) or linear (straight lateral irrigates in rectangular patterns) move continuously to irrigated field. Multiple sprinklers located along the laterals.
Pressure-Traveling Gun Sprinkler	High-capacity, single-nozzle sprinkler fed by flexible hose. Hose is dragged or on a reel. Gun is guided by cable, and moved from field to field. Best for soils with high water intake rates.
Pressure-Traveling Boom Sprinkler	Similar to traveling gun, except a boom with several nozzles is used.
Micro/Pressure-Point Source Emitters	Frequent, low-volume, low-pressure applications through small tubes and drop, trickle, or bubbler emitters. Water must be filtered. Used for orchards, vineyards, ornamental landscaping. Emitters discharge from 0.5 to 30 gallons per hour.
Micro/Pressure-Line Source Emitters	Frequent, low-volume, low-pressure applications through surface or buried tubing that is porous or has uniformly spaced emitter points. For permanent crops, but also vegetables, cotton, melons.
Micro/Pressure-Basin Bubblers	Water applied via risers into small basins adjacent to plant. Bubblers discharge less than 60 gallons per hour. Water filtration not required. Orchards and vineyards. Best for medium to fine textured soils.
Micro/Pressure-Spray or Mini-Sprinklers	Water applied as spray droplets from small, low-pressure heads. Wets a greater area (2 to 7 feet in diameter) than drop emitters. Discharges less than 30 gallons per hour.
Subirrigation	Manage water table by providing subsurface drainage, providing controlled drainage, and irrigating via buried laterals.

Figure 4f-12. Fate of water and pollutants in an irrigated hydrologic system.



Since irrigation is a consumptive use of water, any pollutants in the source waters that are not consumed by the crop (e.g., salts, pesticides, nutrients) can be concentrated in the soil, concentrated in the leachate or seepage, or concentrated in the runoff or return flow from the system. Salts that concentrate in the soil profile must be managed in order to sustain crop production. In such cases, a carefully calculated additional amount of water may be applied to leach the salts below the root zone. The application of this “leaching requirement” should be timed to prevent the leaching of other potential pollutants when possible (e.g., after the growing season when nutrients are low, or after a cover crop that has used excess nutrients).

Irrigation Scheduling

Both long-term and short-term irrigation decisions must be made by the producer. Long-term decisions, which are associated with system design and the allocation of limited seasonal water supplies among crops, rely on average water use determined from historical data (Duke, 1987) and average water availability. Particularly in arid areas, long-term irrigation decisions are needed to determine seasonal water requirements of different possible crops, determine which crops to grow based upon crop adaptability and water availability, and in some cases to determine when and how much to stress the various crops to maximize economic return. Short-term decisions determine when and how much to irrigate, and are based upon daily water use. In areas where rainfall is either insignificant or falls predictably during the growing season, long-term decisions can be used to construct an irrigation schedule at the beginning of the growing season (Duke, 1987), although better water management is obtained by constant updating of information. In semi-arid and humid areas where weather varies significantly on a daily basis, short-term irrigation decisions are used in lieu of pre-determined irrigation schedules. The emphasis of this guidance is placed on short-term irrigation decisions.

Irrigation scheduling is the use of water management strategies to prevent over-application of water while minimizing yield loss from water shortage or drought stress (Evans et al., 1991c). Irrigation scheduling will ensure that water is applied to the crop when needed and in the amount needed (USDA-NRCS, 1997a). Effective scheduling requires knowledge of the following factors (Evans et al., 1991b; Evans et al., 1991c):

- ❐ Soil properties
- ❐ Soil variability within the field
- ❐ Soil-water relationships and status
- ❐ Type of crop and its sensitivity to drought stress
- ❐ The stage of crop development and associated water use
- ❐ The status of crop stress
- ❐ The potential yield reduction if the crop remains in a stressed condition
- ❐ Availability of a water supply
- ❐ Climatic factors such as rainfall and temperature

Much of the above information can be found in Natural Resources Conservation Service soil surveys and Extension literature. However, all information should be site-specific and verified in the field.

In environments where salts tend to concentrate in the soil profile, additional information is needed to sustain crop production, including:

- ❐ Salt tolerance of the crop
- ❐ Salinity of the soil
- ❐ Salinity of the irrigation water
- ❐ Leaching requirement of the soil

Deciding when to irrigate

There are three ways to determine when irrigation is needed (Evans et al., 1991c):

- ❐ Measuring soil water
- ❐ Estimating soil water using an accounting approach
- ❐ Measuring crop stress

Research in irrigation scheduling indicates the need for specific site-dependent data for plan development.

Soil water can be measured directly by sampling the soil and determining the water content through gravimetric analysis. The distribution of plant roots and their pattern of development during the growing season are very important considerations in deciding where and at what depth to take soil samples to determine soil water content (USDA-NRCS, 1997a). For example, all plants have very shallow roots early in their development, and the concentration of moisture-absorbing roots of most plants is usually greatest in the upper quarter of the root zone. Further, since roots will not grow into a dry soil, it may be important to measure soil moisture beyond the current root zone to determine irrigation needs associated with full root development. Figure 4f-13 illustrates the typical water extraction pattern in a uniform soil, again pointing out the need to relate soil sampling decisions to crop development.

Soil moisture can also be determined indirectly using a range of devices (Evans et al., 1991a; Werner, 1992), including tensiometers (Figure 4f-14), electrical resistance blocks (Figure 4f-14), neutron probes, heat dissipation sensors, time domain reflectometers, and carbide soil moisture testers (USDA-NRCS, 1997a). Table 4f-3

Figure 4f-13. Typical water extraction pattern in uniform soil profile (USDA-NRCS, 1997a).

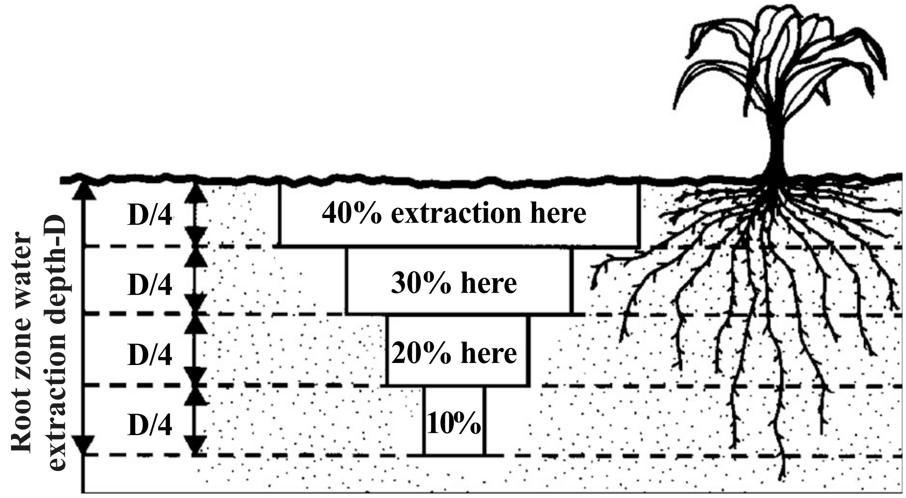


Figure 4f-14. Soil moisture measurement devices: (a) tensiometer and (b) electrical resistance block.

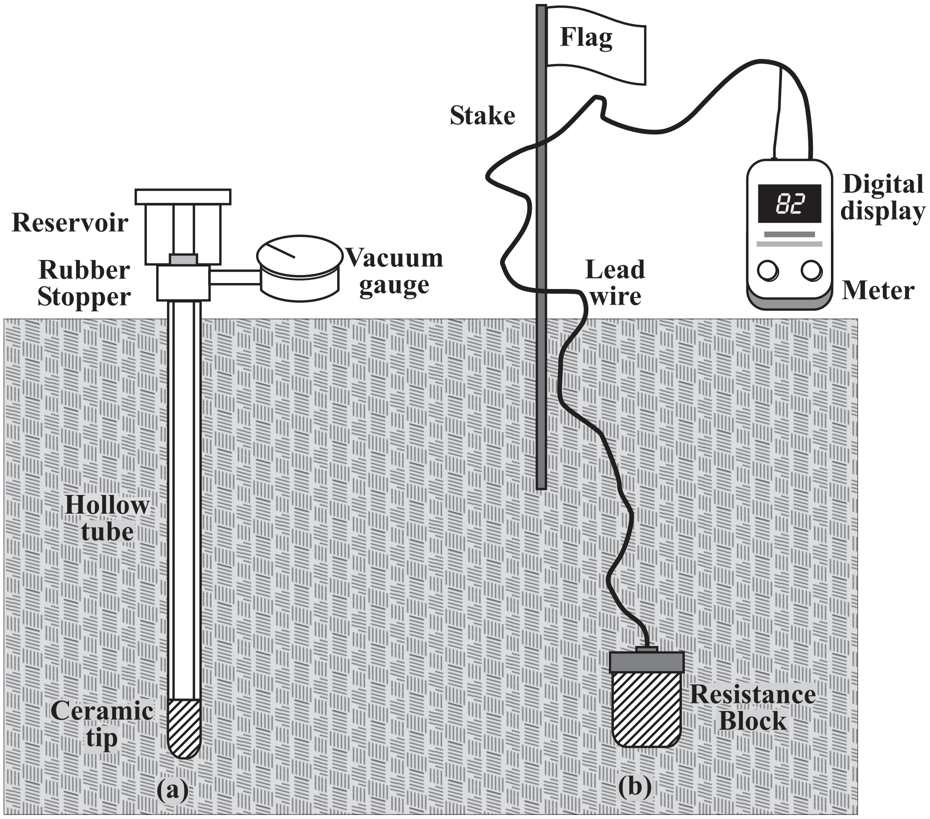


Table 4f-3. Devices and methods to measure soil moisture.

Device (Other Names)	How It Works	Comments
Tensiometer	Measures soil suction which is related to soil water content.	Available in lengths from 6 to 72 inches. Requires careful installation and field maintenance. Most applicable when soil moisture is between 50-75 percent of field capacity, and on medium to fine-textured soils with frequent irrigation.
Electrical Resistance Block (Gypsum or Moisture or Porous Block)	Measures electrical resistance which is related to soil water content via a calibration curve.	Inexpensive. Simple to use. Gives accurate readings over wider moisture range than tensiometers, but limited to medium to coarse-textured soils. Most accurate when soil moisture is below field capacity. Sodic soils problematic. Gypsum blocks need replacement each growing season; nylon, plastic, fiberglass more durable.
Neutron Probe (Neutron Scattering)	Measures thermalized neutrons (fast neutrons that are slowed by collisions with hydrogen molecules in water) which are related to volumetric soil water content by a calibration curve.	Can be most accurate and precise method. Requires calibration using gravimetric procedures, especially if used for top 6 inches of soil profile, in clay soils, soils with high organic matter content, and soils with boron ions. Requires licensed operator since radioactive. Expensive.
Thermal Dissipation Block (Heat Dissipation Sensor)	Estimates soil water based upon the relationship between heat conductance and soil water content.	Requires calibration. Work across wide range of soil-water content.
Time Domain Reflectometer (TDR) & Frequency Domain Reflectometer (FDR) (Dialectric Constant Method)	Senses the dielectric property of soil which is related to water content.	Requires careful installation. TDR works across wide range of soil texture, bulk density, and salinity. FDR results may be skewed as salinity increases.
Carbide Soil Moisture Tester (Speedy Moisture Tester)	Measures gas pressure from reaction of calcium carbide with water in soil sample.	Provides percent water content of soil. Works in field. Practice necessary for reliable results.
Feel and Appearance Method	Soil samples are compared to tables or pictures that give moisture characteristics of different soil textures.	Experienced individuals can estimate soil moisture within 10 percent of true value, but tables and pictures use ranges of 25 percent.
Gravimetric Method (Oven Dry)	Soil samples from field are weighed, dried, and weighed again in the lab.	Accurate measure of water content. Requires sensitive scales, drying method, and known or estimated bulk density value to calculate % volume of water.

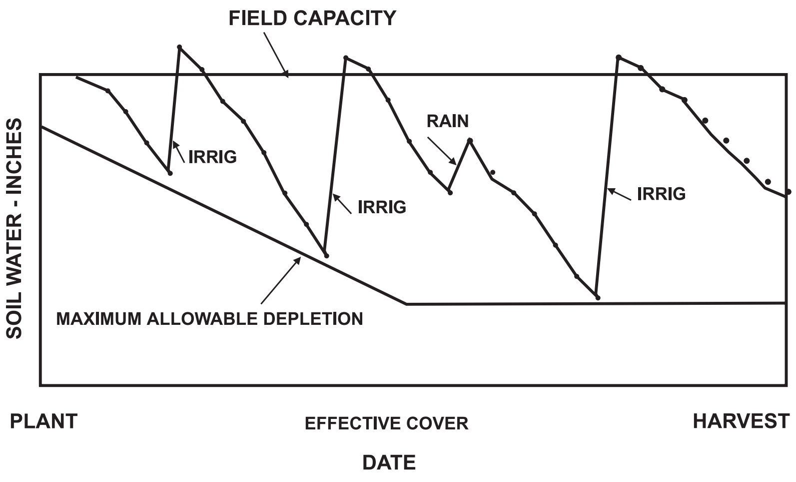
provides an overview of these devices. The appropriate device for any given situation is a function of the acreage of irrigated land, soils, cost, available trained labor, and other site-specific factors.

Direct measurement of soil water status or crop status is always more accurate than estimating its magnitude, but because of the cost associated with obtaining representative samples in some situations, it may be more appropriate to use estimation techniques (Duke, 1987). Accounting approaches estimate the quantity of plant-available water remaining in the effective root zone. A variety of methods can be used to estimate and predict the root zone water balance, including a simple checkbook method (USDA-NRCS, 1997a), computer-assisted methods (Hill, 1997 and Allen, 1991), graphical methods (Figure 4f-15), and tabular methods. In essence, these methods begin with an estimate of initial soil-water depletion and use measurements or estimates of daily water inputs (rain, irrigation) and outputs (evapotranspiration) to determine the current soil-water depletion volume (Equation 4f-1).

Net irrigation depth is the depth of water applied multiplied by the irrigation efficiency, which ranges from 75-100% for drip systems to 20-60% for furrow irrigation on sandy soils (Duke, 1987). Effective precipitation is the amount of precipitation minus losses due to runoff or unnecessary deep percolation. At some pre-determined moisture deficit (e.g., the MAD value), irrigation must be started (Figure 4f-15). The water balance must be updated at least weekly, including field checks on estimated parameters, to be useful for scheduling irrigations (Duke, 1987).

Potential sources of data for Equation 4f-1 include field measurements to determine the initial soil-water content, field measurements to determine effective rooting depth as the plant matures, ET measurements or estimates based upon data from weather stations, irrigation depth measurements, measured precipitation,

Figure 4f-15. Graphical format for irrigation scheduling (Duke, 1987).



Equation 4f-1. Soil-water depletion volume (Duke, 1987).

$$D = D_0 + ET - IR - R - WT$$

where D = soil-water depletion at end of day (D=0 at field capacity)

D_0 = soil-water depletion for previous day

ET = ET for the day

IR = net irrigation depth (depth of applied water which is stored in soil root zone) for the day

R = effective precipitation during the day

WT = upward movement of water during the day from water table close to bottom of root zone

If the water table is not near the root zone, the last term (WT) may be dropped.

and estimates of water table contributions. Clearly, good estimates or measurements of ET are essential to successful accounting approaches since crop water use can vary considerably with crop type, stage of growth, temperature, sunshine, wind speed, relative humidity, and soil moisture content (Figure 4f-16). Direct measurement of ET with lysimeters may not be practical for most farms, but evaporation pans and atmometers can be used effectively. There is also, however, a wide range of computational techniques for estimating ET from weather data (Doorenbos and Pruitt, 1975; Jensen et al., 1990; USDA-SCS, 1993). Crop ET data are often available in newspapers, through telephone dial-up service, or on television, and some farms have on-site weather stations that provide the necessary ET data (USDA-NRCS, 1997a). There is also a growing number of computer programs that aid the irrigation decisionmaker, including the NRCS Scheduler (Figure 4f-17) and others (Smith, 1992; Allen, 1991; and Hill, 1991).

Figure 4f-16. Crop water use for corn, wheat, soybean, and potato based on average climatic conditions for North Dakota (Lundstrom and Stegman, 1991).

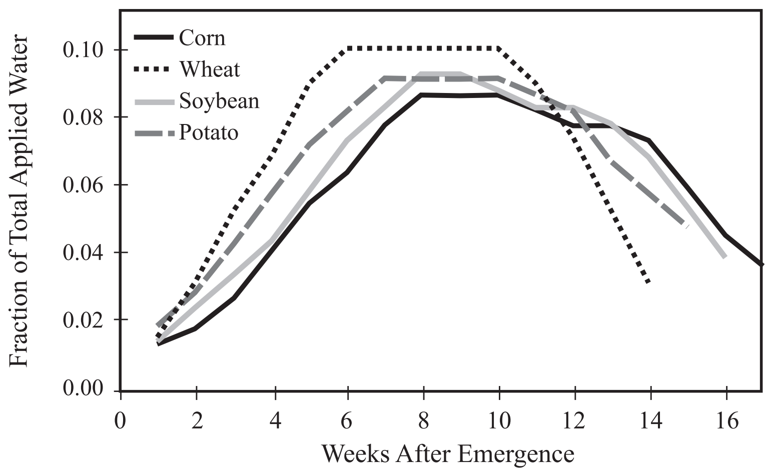
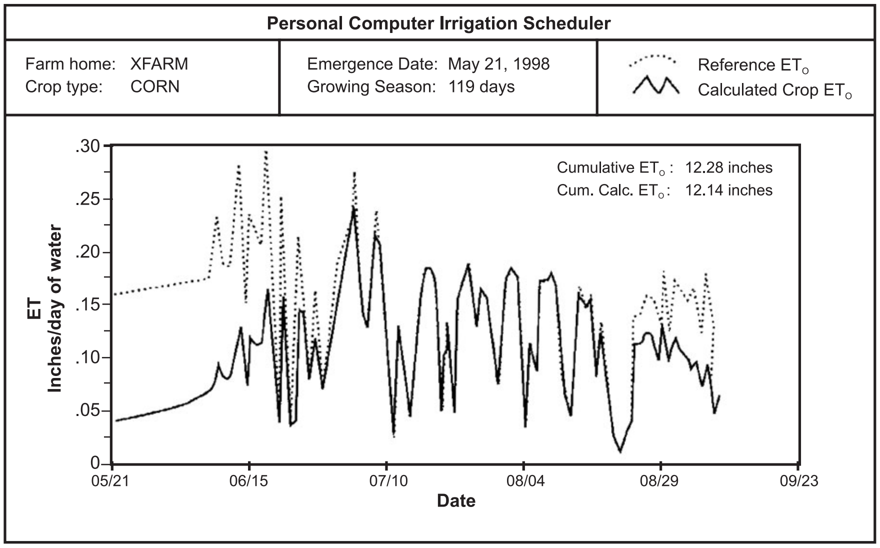


Figure 4f-17. NRCS (SCS) Scheduler – seasonal crop ET (USDA-NRCS, 1997a).



Personal Computer Irrigation Scheduler

Farm home: XFARM
Crop type: CORN

Emergence Date: May 21, 1998
Growing Season: 119 days

Cumulative ET$_o$: 12.28 inches
Cum. Calc. ET$_o$: 12.14 inches

Measuring crop stress is another way to determine when irrigation is needed. Unavailability of water during crop stress periods could result in crop failure or reduced yields that leave unused nutrients vulnerable to runoff and deep percolation. Devices and methods used to measure crop stress include the crop water stress gun, leaf moisture stress as measured in a pressure chamber, and infrared photography (USDA-NRCS, 1997a). However, infrared photography is typically not an option for "real time" water management due to slow turnaround times. The crop water stress gun calculates plant water stress and expresses it as an index value based on measurements of plant canopy temperature, ambient air temperature, relative humidity, and a range of solar radiation. Using a crop water stress index, irrigation can be scheduled depending on the severity of moisture stress. Threshold values must be developed for each crop.

Deciding how much water to apply

Once the decision to irrigate has been made, the amount of water to apply must be determined. A decision rule should be established to determine how much water to apply, with the basic choices being full irrigation to replenish the root zone to field capacity or partial irrigation. Partial irrigation, which is more easily achieved via sprinkler systems, may be preferred if there is opportunity for rainfall to provide some of the water needed to reach field capacity.

Factors in determining the amount of irrigation water to apply include the soil-water depletion volume in the effective root zone and local weather forecasts for rain. The application rate should not exceed the water intake rate of the soil when using sprinkler systems, and the application depth should not exceed the soil-water depletion volume, except as necessary for leaching of salts (Duke, 1987). Local weather forecasts for rain should be considered before irrigating to avoid over-application.

The relationship between irrigation system capacity, irrigated area, and time of irrigation may be expressed as

$$Q = \frac{453\,Ad}{fT}$$

where *Q* is system discharge capacity (gpm), *A* is irrigated area (acres), *d* is gross application depth (in), *f* is time allowed for completion of one irrigation (days), and *T* is actual operating time (hr/day) (USDA, 1983). Normally *A*, *T*, and *d* are fixed in a design process. The time allowed for completion of one irrigation should be set to insure that the area initially irrigated does not become stressed before the next irrigation is applied. Note that a system design that just meets the peak crop water demand may be determined as illustrated in Table 4f-4. Partial irrigations may facilitate covering a larger area to prevent immediate crop damage, but they increase the frequency of irrigation necessary, and could impede root growth or harm a crop that will be stressed if the soil is not adequately saturated.

Deep percolation of irrigation water can be greatly reduced by limiting the amount of applied water to the amount that can be stored in the plant root zone. The deep percolation that is necessary for salt management can be accomplished with a sprinkler system by using longer sets or very slow pivot speeds or by applying water during the non-growing season. Salt management by surface irrigation methods is much less efficient than other irrigation methods, and water used to leach salts should be applied when nutrients or pesticides are least vulnerable to

Table 4f-4. System capacity needed in gal/min-acre for different soil textures and crops to supply sufficient water in 9 out of 10 years (Scherer, 1994).

Crop	Root Zone Depth (ft)	Coarse Sand and Gravel	Sand	Loamy Sand	Sandy Loam	Fine Sandy Loam	Loam and Silt Loam
Potatoes[a]	2.0[b]	8.2	7.5	7.0	6.4	6.1	5.7
Dry beans	2.0	7.9	7.1	6.4	6.1	5.7	5.4
Soybeans	2.0	7.9	7.1	6.4	6.1	5.7	5.4
Corn	3.0	7.3	6.6	5.9	5.5	5.3	4.9
Sugarbeets	3.0	7.3	6.6	5.9	5.5	5.3	4.9
Small grains	3.0	7.3	6.6	5.9	5.5	5.3	4.9
Alfalfa	4.0	6.8	5.9	5.6	5.1	5.0	4.5

[a] Adjusted for 40% depletion of available water.

[b] An application efficiency of 80% and a 50% depletion of available soil water were used for calculations.

leaching, such as when maximum uptake or dissipation of the chemical has occurred.

Accurate measurements of the amount of water applied are essential to maximizing irrigation efficiency. A wide range of water measurement devices is available (USDA-NRCS, 1997a). For example, the quantity of water applied can be measured by such devices as a totalizing flow meter that is installed in the delivery pipe or calibrated canal gates. If water is supplied by ditch or canal, weirs or flumes in the ditch can be used to measure the rate of flow. Rain gauges should also be used in the field to determine the quantity of water added through rainfall. Such gauges are also a valuable tool for checking uniformity of application of sprinkler systems.

Efficient Transport and Application of Irrigation Water

There are several measures of irrigation efficiency, including conveyance efficiency (Table 4f-5), irrigation efficiency, application efficiency, project application efficiency, potential or design application efficiency, uniformity of application, distribution uniformity, and Christiansen's uniformity (USDA-NRCS, 1997a). Project water conveyance and control facility losses can be as high as 50% or more in long, unlined, open channels in alluvial soils (USDA-NRCS, 1997a). Seepage losses associated with canals and laterals can be reduced by lining them, or can be eliminated by conversion from open canals and laterals to pipelines. Flow-through losses or spill, however, will not be changed by lining canals and laterals, but can be eliminated or greatly reduced by conversion to pipelines or through changes in operation and management. Flow-through water constitutes over 30% of canal capacity in some water districts, but simple automatic gate/valve control devices can limit flow-through water to less than 5% (USDA-NRCS, 1997a). Conversion to pipelines may in some cases cause impacts to wildlife due to loss of beneficial wet areas, and an environmental assessment or environmental impact statement may be needed before the conversion is made (USDA-NRCS, 1997a).

Table 4f-5. Measures of irrigation efficiency.

Measure of Irrigation Efficiency	Definition
Conveyance Efficiency (to farm)	$\frac{W_{Delivered}}{W_{Diverted}} * 100$
Irrigation Efficiency (on farm)	$\frac{W_{Beneficial}}{W_{Applied}} * 100$
Application Efficiency (on farm)	$\frac{W_{Stored}}{W_{Applied}} * 100$
Project Application Efficiency (to and on farm)	$\frac{W_{Stored}}{W_{Diverted}} * 100$

Where
$W_{delivered}$ = Water delivered
$W_{diverted}$ = Total water diverted or pumped into an open channel or pipeline at upstream end
$W_{beneficial}$ = Avg. depth of water beneficially used
$W_{applied}$ = Avg. depth of applied water
W_{stored} = Avg. depth of water infiltrated and stored in the plant root zone

Water application efficiency can vary considerably by method of application. Increased application efficiency reduces erosion, deep percolation, and return flows. In general, trickle and sprinkler application methods are more efficient than surface and subsurface methods. Two major hydraulic distinctions between surface irrigation methods and sprinkler and micro irrigation are key to this difference in efficiencies (Burt, 1995):

1. The soil surface conveys the water along border strips or furrows in surface irrigation, whereas the water infiltrates into the soil very near to the point of delivery from sprinkler and micro irrigation systems.
2. Water application rate exceeds soil water infiltration rate in surface irrigation, and the soil controls the amount of water that will infiltrate. In properly designed and managed sprinkler and micro irrigation systems, the application rate is equal to the soil water infiltration rate.

The type of irrigation system used will dictate which practices can be employed to improve water use efficiency and to obtain the most benefit from scheduling. Flood systems will generally infiltrate more water at the upper end of the field than at the lower end because water is applied to the upper end of the field first and remains on that portion of the field longer. This will cause the upper end of the field to have greater deep percolation losses than the lower end. This situation can sometimes be improved by changing slope throughout the length of the field or shortening the length of run. For example, furrow length can be reduced by cutting the field in half and applying water in the middle of the field. This will require more pipe or ditches to distribute the water across the middle of the field. Other methods used to improve application efficiency in surface systems are surge and cut-back irrigation. In surge irrigation, flow is pulsed into the furrow allowing for wet and dry cycles, while in cut-back irrigation, the furrow inflow rate is reduced after a period of time. Both of these methods improve irrigation efficiency by allowing for a more uniform time of infiltration. A wide range of options exist for manipulating field lengths, slopes, flow rate, irrigation time, and other management variables to increase surface irrigation efficiency (Burt, 1995; USDA-NRCS, 1997a).

A properly designed, operated, and maintained sprinkler irrigation system should have a uniform distribution pattern. The volume of water applied can be changed by altering the total time the sprinkler runs; by altering the pressure at which the sprinkler operates; or, in the case of a center pivot, by adjusting the speed of travel of the system. There should be no irrigation runoff or tailwater from most well-designed and well-operated sprinkler systems (USDA-NRCS, 1997a). Operating outside of design pressures and using worn equipment can greatly affect irrigation uniformity.

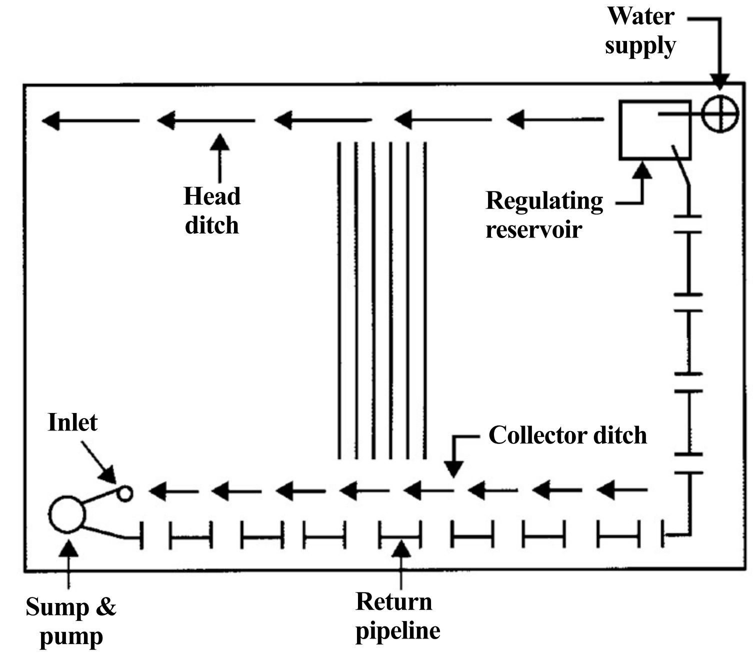
Use of Runoff or Tailwater

Surface irrigation systems are usually designed to have a percentage (up to 30%) of the applied water lost as tailwater. The volume and peak runoff rate of tailwater will depend upon both the irrigation method and its management. Tailwater recovery and reuse facilities collect irrigation runoff and return it to the same, adjacent, or lower fields for irrigation use (USDA-NRCS, 1997a). If the water is pumped to a field at higher elevation, the facility is a return-flow or pumpback facility. Sequence-use facilities deliver the water to adjacent or lower-elevation fields. Those facilities that store runoff and precipitation for later use are reservoir systems, while cycling-sump facilities have limited storage and pump the water automatically to irrigate fields.

The components of a tailwater reuse or pumpback facility include tailwater collection ditches to collect the runoff; drainageways, waterways, or pipelines to convey the water to a central collection area; a sump (cycling-sump facilities) or reservoir (reservoir systems); a pump and power unit for pumpback facilities; and pipelines or ditches to deliver the recovered water (USDA-NRCS, 1997a). A typical pumpback facility plan is illustrated in Figure 4f-18. For new facilities, runoff flows must be measured or estimated to properly size tailwater reuse sumps, reservoirs, and pumping facilities. Capacity should be provided to handle concurrent peak runoff events from both precipitation and tailwater, unexpected interruption of power, and other uncertainties.

Tailwater management is needed to reduce the discharge of pollutants such as suspended sediment and farm chemicals which can be found in the runoff. In reservoir systems, tailwater is typically stored until it can be either pumped back to the head of the field and reused or delivered to additional irrigated land. The quality of tailwater, including nutrient concentrations, should be considered in reuse systems. Water quality testing may be necessary. In some locations, there may be downstream water rights that are dependent upon tailwater, or tailwater

Figure 4f-18. Typical tailwater collection and reuse facility for quick-cycling pump and reservoir (USDA-NRCS 1997a).



may be used to maintain flow in streams. These requirements may take legal precedence over the reuse of tailwater.

If a tailwater recovery system is used, it should be designed to allow storm runoff to flow through the system without damage. Where reservoir systems are used, storm runoff containing a large sediment volume should bypass or be trapped before entering the storage reservoir to prevent rapid loss of storage capacity (USDA-NRCS, 1997a). Additional surface drainage structures such as filter strips, field drainage ditches, subsurface drains, and water table control may also be used to control runoff and leachate if site conditions warrant their use.

Management of Drainage Water

Drainage of agricultural lands is intended to control and manage soil moisture in the crop root zone, provide for improved soil conditions, and improve plant root development (USDA-NRCS, 1997a). In cases where the water table impinges upon the root zone, water table control is an essential element of irrigation water management. However, installation of subsurface drainage should only be considered when good irrigation water management, good nutrient management, and good pesticide management are being conducted. Further, impacts to wetlands, wildlife habitat, and water quality must be thoroughly investigated, and relevant federal, state, and local laws fully considered prior to installation of drainage practices.

Drainage increases water infiltration, which reduces soil erosion and also allows application of excess water to keep salts leached below the root zone. Drainage also provides more available soil moisture and plant food by increasing the depth of the root zone. Subsurface drainage may concentrate soluble nutrients in irrigation return flows. Properly installed subsurface drainage systems can be used successfully as a supplemental source of irrigation water if the water is of good quality (USDA-NRCS, 1997a).

Irrigation Water Management Practices and Their Effectiveness

The practices that can be used to implement this management measure on a given site are commonly used and are recommended by NRCS for general use on irrigated lands. Many of the practices that can be used to implement this measure (e.g., water-measuring devices, tailwater recovery systems, and backflow preventers) may already be required by State or local rules or may otherwise be in use on irrigated fields.

The NRCS practice number and definition are provided for each management practice, where available. Additional information about the purpose and function of individual practices is presented in Appendix A. Another useful reference is “Irrigation Management Practices to Protect Ground Water and Surface Water Quality–State of Washington” (WSU Cooperative Extension, 1995).

Irrigation Scheduling Practices

Proper irrigation scheduling is a key element in irrigation water management. Irrigation scheduling should be based on knowing the daily water use of the crop, the water-holding capacity of the soil, and the lower limit of soil moisture for each crop and soil, and measuring the amount of water applied to the field. Also, natural precipitation should be considered and adjustments made in the scheduled irrigations.

Daily accounting for the cropland field water budget helps determine irrigation scheduling.

Whether the irrigation source is surface or ground water, water availability during the growing season should be adequate to support the most water sensitive crop in the rotation. The design capacity of the irrigation system depends on regional climate, irrigation efficiency, crop, and soil (USDA-SCS, 1993; USDA-SCS, 1970). See Table 4f-4 for typical required system capacities for various crops and soils.

A practice that may be used to accomplish proper irrigation scheduling is:

- ❒ **Irrigation Water Management (449)**: Determining and controlling the rate, amount, and timing of irrigation water in a planned and efficient manner.

Tools to assist in achieving proper irrigation scheduling include:

- ❒ **Water-Measuring Device**: An irrigation water meter, flume, weir, or other water-measuring device installed in a pipeline or ditch.
- ❒ **Soil and Crop Water Use Data**: From soils information the available water-holding capacity of the soil can be determined along with the amount of water that the plant can extract from the soil before additional irrigation is needed (MAD). Water use information for various crops can be obtained from various United States Department of Agriculture (USDA) publications. Crop water use for some selected irrigated crops is shown in Figure 4f-16.

Drainage Systems: An Overview

Drainage is as old as agriculture and dates back to the Roman Empire and probably earlier. Modern drainage practices began in the 1800s. The purpose of drainage is to provide a root environment suitable for plant growth, thereby increasing production and yield of crops. Artificial drainage is essential on poorly drained agricultural fields to provide optimum air and salt environments in the root zone (Ritzema, 1996). Artificial drainage provides for more management control in areas where the water table is in or near the root zone (USDA-NRCS, 1997a). By controlling soil moisture, drainage can also provide for easier farm operations and lessen compaction by animal and equipment traffic (Luthin, 1973).

In 1985, about 107 million acres of land had been drained in the U.S., of which 72 percent was crop land (Zucker and Brown, 1998). Illinois, Iowa, Indiana, and Ohio are the states with the highest total acreage of drained crop land. Together, these states account for 28.6 million acres of drained crop land. In Ohio and Indiana approximately 50 percent of all crop land is drained. In Illinois and Iowa respectively about 35 and 25 percent of all crop land is drained (USDA, 1987).

Arid Lands

In arid lands, drainage may be required to prevent salts from accumulating in the root zone, and to prevent a water table from building up. Drainage has also been used to bring saline soils into production by leaching salts through the soil profile. In many arid regions, it is not uncommon to apply water via irrigation in excess of crop water requirements to keep salts from building up in the soil profile. The amount of water applied in excess of crop water needs is called a “leaching requirement.”

Humid Lands

Drainage in humid lands is required for reasons different from those in arid lands. High water tables are caused by water that builds up over impermeable soil layers due either to clay or compaction. Land may also be subjected to periodic inundation due to topography. Drainage systems are installed to allow for cultural operations (seedbed preparation, planting, harvesting, tillage) and to prevent extended periods of saturated soil conditions (Zucker and Brown, 1998).

Drainage Systems

Subsurface drainage can be achieved through the use of either open ditches or by buried pipe.

Open Ditches

Open ditches are used for collector drains which receive drainage from the buried drains in the field or are sometimes used as field drains. Controlled drainage is oftentimes used with open field drains. Typically, field drains are 3-5 feet deep and spaced between 500 and 600 feet. In a controlled drainage system, the water level is controlled by a water control structure and is used also to irrigate. Irrigation with this method is called “sub-irrigation” or “seepage irrigation.” This method is practiced in humid regions on drought-prone soils in order to reduce drought stress on high value crops.

Buried drainage systems

Historically, buried pipe was made of clay, but today drain pipe is made of plastic. In some cases, mole drains are used. Mole drains are open channels formed beneath the ground by pulling a cylindrical bullet shaped object through the soil. Drain depth and spacing are designed to keep the water table below the root zone. Drain depths may range from 2.5 – 8 feet and drain spacing can range from 50 to over 1,000 feet. The downstream end of the drains are connected to a collector drain. (Figure 1 depicts a buried field drainage system.)

Outlets

There are generally two types of outlets for a drainage system: gravity outlets and pump outlets. As the name implies, in a gravity outlet water flows by gravity into an open ditch or natural channel. If the topography is limiting, pumped outlets may be required. With pumped outlets, a sump normally collects the drainage water from the field drains, and the pump lifts the water to a gravity outlet.

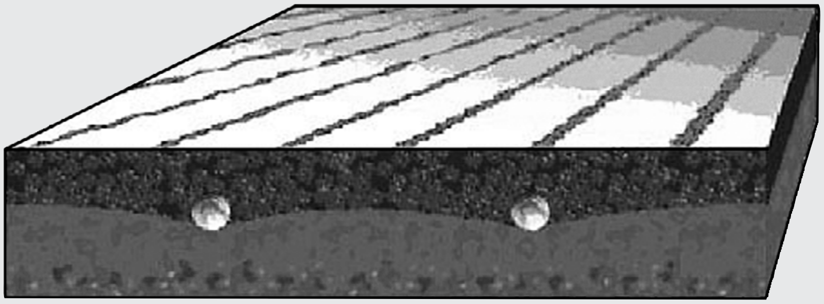


Figure 1. Subsurface field drains showing water table (Zucker and Brown, 1998)

Water quality issues of drainage systems

The installation of drainage systems can result in changes to the ecosystem. These changes can be positive or negative. When compared to agricultural land without subsurface drainage, drained agricultural land can actually have a positive impact on some nonpoint source pollution problems (Zucker and Brown, 1998). The NRCS has listed the subsurface drain as a conservation practice with purposes of reducing erosion and improving water quality (USDA-NRCS, 1997c). However, subsurface drainage water from irrigated agriculture is normally degraded compared with the quality of the original water supply (FAO, 1997). Loss of habitat is also an issue as more than half of the original wetlands in the United States have been lost to drainage practices. Approximately 80 percent of this loss is due to agricultural production (NRC, 1992).

Some of the potential adverse impacts of subsurface drainage systems are:

- **Increased nutrient discharge**
  The two major nutrients in subsurface drainage water are nitrogen and phosphorus. At elevated levels these nutrients contribute to the eutrophication of surface waters which can result in depressed levels of oxygen in receiving waters. The form of nitrogen most prevalent in subsurface drainage is nitrate. Due to strong sorption in the soil, little phosphorus is normally found in subsurface drainage water (Johnson et al., 1965; Mackenzie and Viets, 1974; Madramootoo et al., 1992). The exception to this may be in soils with a highly developed macropore systems (Simard et al., 2000).
- **Pesticide discharge**
  Pesticides may also be of concern, although they are more typically transported with soil particles in surface water drainage (Munster et al., 1995). Although typically low in export loads, pesticide transport may be increased by preferential flow paths resulting in concentrations exceeding drinking water standards (Gentry et al., 2000). Kladivko et al. (1999) found that closer drain tile spacing resulted in more pesticide transport although the total amounts leached were small.
- **Trace elements in effluent**
  Trace elements are commonly present in low levels in nature and may be concentrated in drainage water. Trace elements will depend on geology and, therefore, be different in arid and humid regions. Many of these elements can become toxic a low levels. Mercury (Hg) and selenium (Se) are of particular concern for aquatic life, but arsenic (As), boron (B), molybdenum (Mo), and uranium (U) are also potentially harmful.
- **Sediment**
  Sediment is not normally a problem in subsurface drainage systems since the effluent is primarily ground water. If the system is poorly constructed, sediment can become an issue. More likely, the sediment free water discharging from the subsurface drains might erode the banks of unlined surface drains, thereby increasing the sediment load of the drainage water.

- **Bacteria**

Contamination from bacteria is normally assessed by the presence of coliform and fecal coliform. Irrigated crop land would not be expected to produce adverse bacteriological levels in surface or subsurface drainage water. The presence of coliform or fecal coliform would indicate that wastewater or animal manure has been applied. Since soil is a biological filter, it is not normally expected that micro-organisms will move through the soil from surface water to a subsurface drainage system (FAO, 1997). However, some researchers have implicated subsurface drainage systems in bacteria transport. Geohring, et al. (1998) found that manure applied at nominal rates and followed by a precipitation event can result in bacterial contamination of subsurface drainage in soils exhibiting preferential flow.

- **Salinity**

Salinity of agricultural drainage water is a problem in arid regions. Salts are concentrated in the drainage water. The major cations are sodium (Na), calcium (Ca_2), and potassium (K). Major anions are chloride (Cl), sulfate (SO_4), bicarbonate (HCO_3), nitrate (NO_3), and carbonate (CO_3). Salinity is generally a problem in agricultural reuse of water, as salinity in general can be detrimental to yield and some crops are sensitive to specific ions such as chloride, boron and sodium.

Management Practices for Drainage Water

There are several management practices which may used for effective drainage water management. A few of them are described below. The applicability of drainage practices to a particular site should be determined on a case-by-case basis. When planning to implement a drainage water management program, a producer should contact state and local authorities regarding any specific requirements or limitations. The assistance of NRCS, Cooperative Extension, or another entity familiar with the design and operation of drainage systems should also be sought.

Water Table Management

Water table management or controlled drainage has the potential to significantly reduce NO_3-N. Nitrogen reduction is accomplished by reducing drainage outflow and by providing a denitrifying environment via a higher field water table level. Controlled drainage has been shown to reduce the annual transport of total nitrogen at the field edge by 9 lbs/ac/yr or 45% on the average (Gilliam et al., 1997). Phosphorus transport has also been documented to be reduced by controlled drainage (Gilliam et al., 1997). Water table management has been practiced in the humid environments of the mid-western and eastern parts of the United States in relatively flat landscapes.

Treatment of Drainage Water

Constructed wetlands may be used to treat drainage water. Wetlands are effective in removing sediment, nitrogen and phosphorus. Other physical and chemical treatment processes may be used to treat drainage water (e.g., flocculation, chemical precipitation, or membrane microfiltration), but these are normally only applied where the value of the crop justifies the treatment costs or regulatory requirements exist.

Re-Use of Drainage Water

Drainage water reuse may be appropriate in regions where water is in short supply. The benefit of drainage water reuse is to reduce chemical and nutrient loads to receiving waters. Water quality of re-use water may be of concern, especially in arid regions where salt content of drainage water may be high. Where soils, geologic and hydrologic conditions do not permit constructed wetlands, agricultural drainage water may be re-used on successively salt tolerant crops. Drainage water may also be applied to forested systems. The reduced volume of final drainage water can be discharge to an evaporation pond. With such reuse, care must be taken to insure that concentrations of chemicals do not exceed toxic levels.

The purpose of collecting these data is to allow the manager to estimate the amount of available water remaining in the root zone at any time, thereby indicating when the next irrigation should be scheduled and the amount of water needed. Methods to measure or estimate the soil moisture should be employed, especially for high-value crops or where the water-holding capacity of the soil is low.

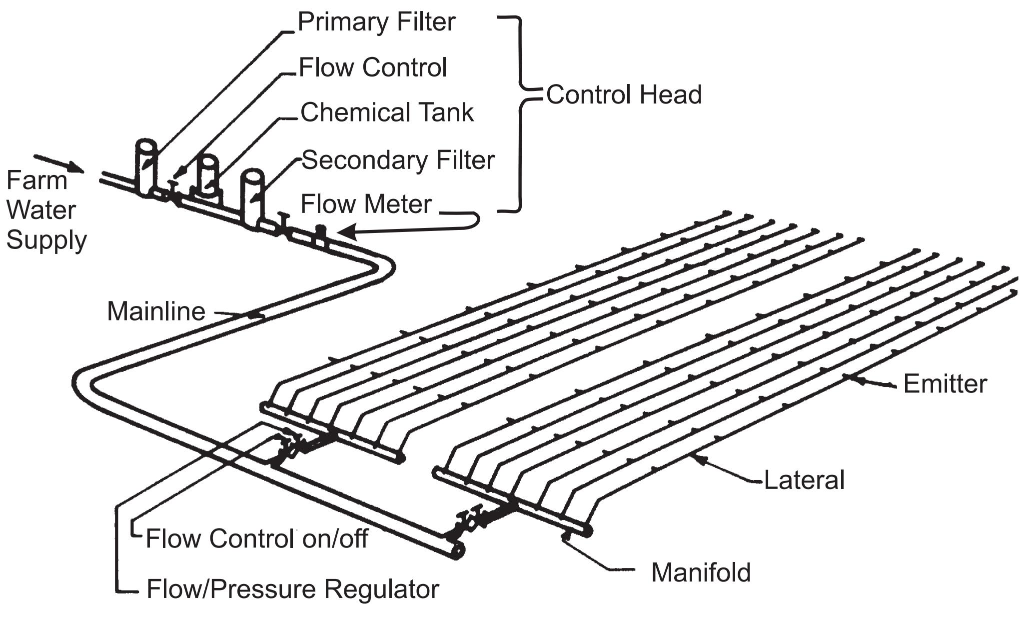
Practices for Efficient Irrigation Water Application

Irrigation water should be applied in a manner that ensures efficient use and distribution, minimizes runoff or deep percolation, and minimizes soil erosion.

The method of irrigation employed will vary with the type of crop grown, the topography, and soils. There are several systems that, when properly designed and operated, can be used as follows:

- ☐ **Irrigation System, Drip or Trickle (441)**: A planned irrigation system in which all necessary facilities are installed for efficiently applying water directly to the root zone of plants by means of applicators (orifices, emitters, porous tubing, or perforated pipe) operated under low pressure (Figure 4f-19).
- ☐ **Irrigation System, Sprinkler (442):** A planned irrigation system in which all necessary facilities are installed for efficiently applying water by means of perforated pipes or nozzles operated under pressure.
- ☐ **Irrigation System, Surface and Subsurface (443)**: A planned irrigation system in which all necessary water control structures have been installed for efficient distribution of irrigation water by surface means, such as furrows, borders, contour levees, or contour ditches, or by subsurface means.

Figure 4f-19. Basic components of a trickle irrigation system (USDA-SCS, 1984).



- ☐ **Irrigation Field Ditch (388)**: A permanent irrigation ditch constructed to convey water from the source of supply to a field or fields in a farm distribution system.
- ☐ **Irrigation Land Leveling (464)**: Reshaping the surface of land to be irrigated to planned grades.

Practices for Efficient Irrigation Water Transport

Irrigation water transportation systems that move water from the source of supply to the irrigation system should be designed and managed in a manner that minimizes evaporation, seepage, flow-through water losses from canals and ditches, and leakage from pipes. Delivery and timing need to be flexible enough to meet varying plant water needs throughout the growing season.

Transporting irrigation water from the source of supply to the field irrigation system can be a significant source of water loss and cause of degradation of both surface water and ground water. Losses during transmission include seepage and evaporation from canals and ditches. The primary water quality concern is the development of saline seeps below the canals and ditches and the discharge of saline waters. Another water quality concern is the potential for erosion within canals and at their turnouts. Practices that are used to ensure proper transportation of irrigation water from the source of supply to the field irrigation system can be found in the USDA-NRCS *Handbook of Practices* (USDA-NRCS, 1977) and include:

- ☐ **Irrigation Water Conveyance, Ditch and Canal Lining (428)**;
- ☐ **Irrigation Water Conveyance, Pipeline (430);** and
- ☐ **Structure for Water Control (587).**

Practices for Irrigation Erosion Control

The design of farm irrigation systems must provide for conveying and distributing irrigation water without causing damaging soil erosion. All unlined ditches should be located on nonerosive gradients. If water must be conveyed down slopes that are steep enough to cause excessive flow velocities, the irrigation system design should provide for the installation of such erosion-control structures as drops, chutes, buried pipelines, or erosion-resistant ditch linings. Conservation treatments such as land leveling, irrigation water management, reduced tillage, and crop rotations should be used to control irrigation-induced erosion.

On surface irrigated lands susceptible to irrigation-induced erosion, the addition of polyacrylamide (PAM) to surface irrigation water may be appropriate to minimize or control soil erosion. However, PAM cannot make up for failure to implement effective overall conservation practices, or replace environmentally responsible farm management. PAM can provide erosion protection in situations where other solutions have proven uneconomical or ineffective. Further description of the use of PAM in irrigation water is found on page 194. This summary reports that application by irrigators is relatively new and requires current information on effective application rates. Research and associated outreach should continue to provide this type of information. Research on the environmental fate and potential ecological effects of PAM use should continue as well.

On sprinkler irrigated land, the design rate of application should be within a range established by the minimum practical application rate under local climatic conditions and the maximum rate consistent with the intake rate of the soil and the conservation practices used on the land. Sprinkler systems should be designed for zero runoff so no water leaves the point of application. The effects on erosion and the movement of sediment, and soluble and sediment-attached substances carried by runoff should be considered whether surface or sprinkler irrigation systems are employed.

Practices for Use of Runoff Water or Tailwater

The use of runoff water to provide additional irrigation or to reduce the amount of water diverted increases the efficiency of use of irrigation water. For surface irrigation systems that require runoff or tailwater as part of the design and operation, a tailwater management practice is needed. The practice is described as follows:

- ☐ **Irrigation System, Tailwater Recovery (447)**: A facility to collect, store, and transport irrigation tailwater for reuse in the farm irrigation distribution system.

Practices for Drainage Water Management

Drainage water from an irrigation system should be managed to reduce deep percolation, move tailwater to the reuse system, reduce erosion, and help control adverse impacts on surface water and ground water. A total drainage system should be an integral part of the planning and design of an efficient irrigation system.

There are several practices to accomplish this:

- ☐ **Filter Strip (393)**: A strip or area of vegetation for removing sediment, organic matter, and other pollutants from runoff and waste water.
- ☐ **Surface Drainage Field Ditch (607)**: A graded ditch for collecting excess water in a field.
- ☐ **Subsurface Drain (606)**: A conduit, such as corrugated plastic tile, or pipe, installed beneath the ground surface to collect and/or convey drainage water.
- ☐ **Water Table Control (641)**: Water table control through proper use of subsurface drains, water control structures, and water conveyance facilities for the efficient removal of drainage water and distribution of irrigation water.
- ☐ **Controlled Drainage (335)**: Control of surface and subsurface water through use of drainage facilities and water control structures.

Practices for Backflow Prevention

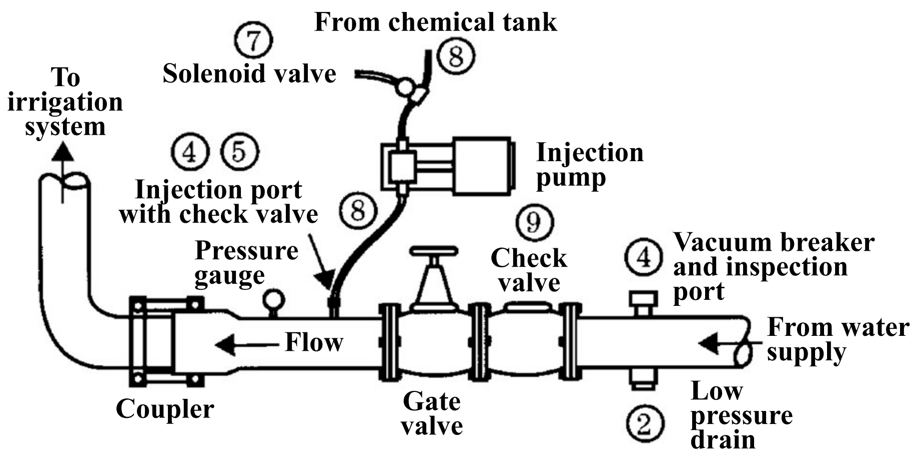
The American Society of Agricultural Engineers recommends, in standard EP409, safety devices to prevent backflow when injecting liquid chemicals into pressurized irrigation systems (ASAE, 1989).

The process of supplying fertilizers, herbicides, insecticides, fungicides, nematicides, and other chemicals through irrigation systems is known as chemigation. A backflow prevention system will “prevent chemical backflow to the water source” in cases when the irrigation pump shuts down (ASAE, 1989).

Three factors an operator must take into account when selecting a backflow prevention system are the characteristics of the chemical that can backflow, the water source, and the geometry of the irrigation system. Areas of concern include whether injected material is toxic and whether there can be backpressure or backsiphonage (ASAE, 1989; EPA, 1991b). Several different systems used as backflow preventers are:

- ☐ **Air gap.** A physical separation in the pipeline resulting in a loss of water pressure. Effective at end of line service where reservoirs or storage tanks are desired.
- ☐ **Check valve with vacuum relief and low pressure drain.** Primarily used as an antisiphon device (Figure 4f-20).
- ☐ **Double check valve.** Consists of two single check valves coupled within one body and can handle both backsiphonage and backpressure.
- ☐ **Reduced pressure principle backflow preventer.** This device can be used for both backsiphonage and backpressure. It consists of a pressure differential relief valve located between two independently acting check valves.
- ☐ **Atmospheric vacuum breaker.** Used mainly in lawn and turf irrigation systems that are connected to potable water supplies. This system cannot be installed where backpressure persists and can be used only to prevent backsiphonage.
- ☐ **Pump interlocking**. Application of chemicals in sprinkler systems require an injection pump. By interlocking the injection pump with the water pump, the injection pump is only powered when the water pump is operating.

Figure 4f-20. Backflow prevention device using check valve with vacuum relief and low pressure drain (USDA-NRCS, 1997a).



Practice Effectiveness

The following is information on pollution reductions that can be expected from installation of the management practices outlined within this management measure. However, it should be noted that practice effectiveness is determined through experience and evaluations based on system limitations, topography, climate, etc., and cannot merely be selected from a chart. The efficiency and effectiveness figures given below are for illustrative purposes.

In a review of a wide range of agricultural control practices, EPA (1982a) determined that increased use of call periods, on-demand water ordering, irrigation scheduling, and flow measurement and control would all result in decreased losses of salts, sediment, and nutrients. Various alterations to existing furrow irrigation systems were also determined to be beneficial to water quality, as were tailwater management and seepage control.

Logan (1990) reported that chemical backsiphon devices are highly effective at preventing the introduction of pesticides and nitrogen to ground water. The American Society of Agricultural Engineers (ASAE) specifies safety devices for chemigation that will prevent the pollution of a water supply used solely for irrigation (ASAE, 1989).

Irrigation management practice systems can reduce suspended sediment loading to streams.

Properly designed sprinkler irrigation systems will have little runoff (Boyle Engineering Corp., 1986). Furrow irrigation and border check or border strip irrigation systems typically produce tailwater, and tailwater recovery systems may be needed to manage tailwater losses (Boyle Engineering Corp., 1986). Tailwater can be managed by applying the water to additional fields, by treating and releasing the tailwater, or by reapplying the tailwater to upslope cropland.

The Rock Creek Rural Clean Water Program (RCWP) project in Idaho is the source of much information regarding the benefits of irrigation water management (USDA, 1991). Crops in the Rock Creek watershed are irrigated with water diverted from the Snake River and delivered through a network of canals and laterals. The combined implementation of irrigation management practices, sediment control practices, and conservation tillage resulted in measured reductions in suspended sediment loadings ranging from 61% to 95% at six stations in Rock Creek (1981-1988). Similarly, 8 of 10 sub-basins showed reductions in suspended sediment loadings over the same time period. The sediment removal efficiencies of selected practices used in the project are given in Table 4f-6.

Normally, drip irrigation will have the greatest irrigation efficiency and contour ditch irrigation will have the lowest irrigation efficiency. See Table 4f-7 for application efficiencies of various systems and Table 4f-8 for a range of deep percolation and runoff losses from surface and sprinkler methods. Tailwater recovery irrigation systems are expected to have the greatest percolation rate. USDA projects significant increases in overall irrigation efficiencies when tailwater recovery facilities are used (Table 4f-9).

Plot studies in California have shown that in-season irrigation efficiencies for drip irrigation and Low Energy Precision Application (LEPA) are greater than those for improved furrow and conventional furrow systems (Table 4f-10). LEPA is a linear move sprinkler system in which the sprinkler heads have been removed and replaced with tubes that supply water to individual furrows (Univ. Calif., 1988). Dikes are placed in the furrows to prevent water flow and reduce soil effects on infiltrated water uniformity.

Mielke and Leavitt (1981) studied the effects of tillage practice and type of center pivot irrigation on herbicide (atrazine and alachlor) losses in runoff and sediment. Study results clearly show that, for each of three tillage practices studied, low-pressure spray nozzles result in much greater herbicide loss in runoff than either high-pressure or low-pressure impact heads.

Table 4f-6. Sediment removal efficiencies and comments on BMPs evaluated (USDA, 1991).

Practice	Sediment Removal Efficiency (%) Average	Sediment Removal Efficiency (%) Range	Comment
Sediment basins: field, farm, subbasin	87	75-95	Cleaning costly.
Mini-basins	86[a]	0-95	Controlled outlets essential. Many failed. Careful management required.
Buried pipe systems (incorporating mini-basins with individual outlets into a buried drain)	83	75-95	High installation cost. Potential for increased production to offset costs. Eliminates tailwater ditch. Good control of tailwater.
Vegetative filters	50[a]	35-70	Simple. Proper installation and management needed.
Placing straw in furrows	50	40-80	Labor-intensive without special equipment. Careful management required.

[a] Mean of those that did not fail.

Table 4f-7. Ranges of irrigation application efficiencies from various sources.

Irrigation System	Application Efficiency, % Duke, 1987[1]	Application Efficiency, % USDA-NRCS, 1997a	Application Efficiency, % Hill, 1994[2]
Center Pivot	70-90	75-85	80
Linear Move		80-87	80
LEPA		90-95	
Solid Set Sprinklers		60-75	70-80
Periodic Move Lateral		60-75	70-80
Drip	75-100		80-90
Level Basin	70-90		80
Border			60-75
Furrow			60-70
Furrow – sandy soil	20-60		40-50
Furrow – clay soil	50-90		65
Contour Ditch		35-60	45-55

[1] Typical single event efficiencies

[2] Possible values for various systems with good design and above average management practices

Table 4f-8. Ranges of Application Efficiency E_a and runoff, deep percolation, and evaporation losses (Hill, 1994).[1]

Method	% Hi	% Low	% Typical
Surface Irrigation			
E_a	72	24	50
Runoff Losses	55	5	20
Deep Percolation Losses	65	20	30
Sprinkler Irrigation			
E_a	84	52	70
Evaporation Losses	45	8	12
Deep Percolation Losses	37	8	18

[1] determined from field evaluations in Utah

Table 4f-9. Overall efficiencies obtainable by using tailwater recovery and reuse facility (USDA-NRCS, 1997a).

		-----First reuse-----			-----Second reuse-----			-----Third reuse-----			----- Fourth reuse-----		
Original applic effic %	**% of water reused**	**% of orig water used**	**Effect use - % of orig**	**Accum effect %**	**% of orig water used**	**Effect use - % of orig**	**Accum effect %**	**% of orig water used**	**Effect use - % of orig**	**Accum effect %**	**% of orig water used**	**Effect use - % of orig**	**Accum effect %**
60	40	16	9.6	69.6	2.6	1.5	71.1	1.1	0.7	71.8	0.2	0.1	71.9
	60	24	14.4	74.4	5.8	3.5	77.9	1.4	0.8	78.7	0.4	0.2	78.9
	80	32	19.2	79.2	10.2	6.1	85.3	3.3	2.0	87.3	1.0	0.6	87.9
50	40	20	10.0	60.0	4.0	2.0	62.0	0.8	0.4	62.4	0.2	0.1	62.5
	60	30	15.0	65.0	9.0	4.5	69.5	2.7	1.4	70.9	0.8	0.4	71.3
	80	40	20.0	70.0	16.0	8.0	78.0	6.4	3.2	81.2	2.6	1.3	82.5
40	40	24	9.6	49.6	5.8	2.3	52.9	1.4	0.6	53.5	0.3	0.1	53.6
	60	36	14.4	54.4	13.0	5.2	59.6	4.7	1.9	61.5	1.7	0.7	62.2
	80	48	19.2	59.2	23.0	9.2	68.4	11.0	4.4	72.8	5.3	2.1	74.9
30	40	28	8.4	38.4	7.8	2.4	40.8	2.2	0.7	41.5	0.6	0.2	41.7
	60	42	12.6	42.6	17.8	5.3	49.9	7.5	2.3	52.2	3.1	0.9	53.1
	80	56	16.8	46.8	31.4	9.4	56.2	17.6	5.3	61.5	9.8	3.0	64.5
20	40	32	6.4	26.4	10.2	2.1	28.5	3.2	0.7	29.2	1.0	0.2	29.4
	60	48	9.6	29.6	23.0	4.6	34.2	11.0	2.2	36.4	5.3	1.1	37.5
	80	64	12.8	32.8	41.0	8.2	41.0	26.2	5.3	46.3	17.5	3.5	49.8

Table 4f-10. Irrigation efficiencies of selected irrigation systems for cotton (California SWRCB, 1992).

System	Year	Seasonal Irrigation (in.)	Distribution Uniformity (%)	Irrigation Efficiency (%)	Deep Percolation (in.)
Subsurface Drip Irrigation	1989[1]	23.54	79	86	2.43
	1990[1]	24.04	76	81	3.98
LEPA (Low Energy Precision Application)	1989	19.89	80	82	2.88
	1990	26.55	92	74	6.13
Improved Furrow	1988	29.77	60	35	18.9
	1990	20.19	82	66	6.06
Conventional Furrow	1989	30.75	61	35	19.39
	1990	28.76	72	62	9.85

[1] includes one preirrigation with hand move sprinklers

Factors in Selection of Management Practices

Irrigation Scheduling

Selecting a water scheduling method will depend on the availability of climatic data. Crop water use depends on the type of crop, stage of growth, temperature, sunshine, wind speed, relative humidity and soil moisture content. Water use can be estimated based on maximum daily temperatures and the growth stage of the crop. If climatic data cannot be measured on site or is not available nearby, it may be more appropriate to schedule irrigation from representative field soil water measurements.

Determining water holding capacity for the field is critical in water scheduling. Where large differences in soil texture are found in an irrigated field, particular attention should be paid to the coarsest textures. Coarse textures will hold less available water than finer textured soils and will reach depletion sooner. Knowledge of soil texture and soil moisture status will help determine the appropriate application rate and depth, so runoff and deep percolation are minimized. Variable rate application of water should be considered if water holding capacities range significantly.

Efficient Irrigation Water Application

The selection of an appropriate irrigation system should be based on having sufficient capacity to adequately meet peak crop water demands for the crop with the highest peak water demand in the rotation. The system capacity is dependent on the peak period evapotranspiration rate, crop rooting depth, available water holding capacity of the soil, and irrigation efficiency. Other potentially limiting factors are water delivery capacity and permitted water allocation (Table 4f-4).

Other factors that should be considered when selecting an irrigation system are the shape and size (acres) of the field and the topography. Field slope and steepness will determine whether surface or sprinkler irrigation can be used. If surface application of water is chosen, land leveling may be required to more efficiently spread water over the field.

A sprinkler system can and should be designed to apply water uniformly without runoff or erosion. The application rate of the sprinkler system should be matched to the intake rate of the most restrictive soil in the field. If the application rate exceeds the soil intake rate, the water will run off the field or relocate within the field resulting in areas of over application that could percolate soluble chemicals to ground water. Care should be taken in a pivot system to match endguns with soil water intake rates.

If secondary salinization from irrigation is a problem, an application method must be chosen to keep salts leached below the root zone.

The selected water application method will also depend on whether chemigation is to be used. Coverage, timing, and type of chemical application will determine which application method will be most efficient. Chemigation with surface irrigation should be avoided when alternative methods are available for the application of fertilizers and pesticides. Additional costs for pollution prevention may be incurred when chemigating.

Tailwater recovery may be required if surface chemigation is practiced, and backflow prevention is needed if sprinkler chemigation is used.

Cost and Savings of Practices

Costs

Costs to install, operate and maintain an irrigation system will depend on the type of irrigation system used. In order to efficiently irrigate and prevent pollution of surface and ground waters, the irrigation system must be properly maintained and water measuring devices used to estimate water use.

A cost of $10 per irrigated acre is estimated to cover investments in flow meters, tensiometers, and soil moisture probes (EPA, 1992a; Evans, 1992). The cost of devices to measure soil water ranges from $3 to $4,900 (Table 4f-11). Gypsum blocks and tensiometers are the two most commonly used devices. A more expensive and instantaneous device is a neutron probe. It uses a radioactive source of neutrons and a probe to measure the amount of moisture in the soil. The probe is inserted into the soil through a tube and the energy, produced by neutons colliding with hydrogen and oxygen atoms that make up water, is measured in the probe indicating the soil moisture content.

For quarter-section center pivot systems, backflow prevention devices cost about $416 per well (Stolzenburg, 1992). This cost (1992 dollars) is for: (1) an 8-inch, 2-foot-long unit with a check valve inside ($386); and (2) a one-way injection point valve ($30). Assuming that each well will provide about 800-1,000 gallons per minute, approximately 130 acres will be served by each well. The cost for backflow prevention for center pivot systems then becomes approximately $3.20 per acre. In South Dakota, the cost for an 8-inch standard check valve is about $300, while an 8-inch check valve with inspection points and vacuum release costs about $800 (Goodman, 1992). The latter are required by State law. For quarter-section center pivot systems, the cost for standard check valves ranges from about $1.88 per acre (corners irrigated, covering 160 acres) to $2.31 per acre (circular pattern, covering about 130 acres). To maintain existing equipment so that water delivery is efficient, annual maintenance costs can be figured at 1.5% of the new equipment cost (Scherer, 1994).

Table 4f-11. Cost of soil water measuring devices.

Device	Approximate Cost
Tensiometers[a]	$50 and up, depending on size
Gypsum blocks[b]	$3-4, $200-400 for meter
Neutron Probe[c]	$4,900
Phene Cell[a]	$4,000-4,500
Tensiometers and soil moisture probes[d]	$10 per irrigated acre

[a] Hydratec, 1998.
[b] Sneed, 1992.
[c] Cambell Pacific Nuclear, 1998.
[d] Evans, 1992.

Polyacrylamide Application for Erosion and Infiltration Management

Polyacrylamide (PAM) is a water soluble polymer produced for agricultural use to control erosion and promote infiltration on irrigated lands. When applied to soils, erosion-prevention PAM binds fine-grained soil particles within the top 1/16 inch (1-2 mm) of soil. It is not only used for erosion control, but it is also employed in municipal water treatment, paper manufacturing, food and animal feed processing, cosmetics, friction reduction, mineral and coal processing, and textile production.

PAM comes in many formulations which should not be confused. The super water-absorbent PAM used to increase soil water holding capacity is not the PAM used for erosion control. Most states require environmental, safety, and efficacy evaluation for registration, labeling, and sale of soil amendments. Erosion control PAM formulations have been registered and labeled by individual states where sales and use occur, and farmers should purchase only registered and properly labeled PAM from reputable agrichemical dealers. A compendium of PAM-related research and user information is available at the website http://kimberly.ars.usda.gov/pamPage.shtml.

Availability and Application

Erosion-prevention PAM is available in blocks or cubes, or as a powder, aqueous concentrate or emulsified concentrate. Each form has benefits and drawbacks that would alter efficacy in different settings and with different application methods. Additional factors that affect PAM's effectiveness include irrigation inflow rate, duration of furrow exposure, and soil salinity. Erosion prevention PAM costs range from $3-$8 per pound, depending on the application form purchased, and is typically effective at applications of 1 lb. per crop-acre with each treated irrigation (Sojka, 1999). Amounts applied per crop-acre can be reduced with repeat irrigations.

Application rates of PAM recommended by the Natural Resources Conservation Service (NRCS) and Agricultural Research Service (ARS) are 10 ppm in the irrigation inflow during the furrow-advance period (only). ARS has reported results using the following application methods:

- ☐ adding dry granules to the irrigation water in a gated irrigation pipe;
- ☐ adding a stock solution to furrow heads; and
- ☐ placing 1/2 to 1 oz. powder patches directly on the soil immediately below furrow inlets.

Environmental Pros and Cons

Studies using erosion-prevention PAM have shown a 94% reduction of sediment loss in irrigation runoff, although there is some variability in results due to differing application techniques and management practices. At the same time, PAM has resulted in some cases in higher crop yields, improved crop emergence, and decreased soil crusting. In addition to sediment removal, PAM-based erosion control has been shown to improve off-site water quality through reduction of N, P, BOD, herbicides, pesticides, microorganisms and weed seeds in irrigated runoff contributing to return flows to riparian surface waters (see Table 1).

PAM, like conservation tillage, no-till, and various other infiltration and runoff management systems, increases infiltration. As with any soil management system that reduces return flow pollution through improved infiltration and runoff prevention, greater attention should be paid to irrigation water volume application, inflow control, and crop irrigation scheduling. The NRCS and ARS encourage increasing the furrow irrigation inflow rate, resulting in shortened advance times and preventing leaching of surface applied nutrients or agrichemicals from over-irrigation of the near end of the field when using PAM for erosion control.

Most of the concern regarding PAM has arisen because of acrylamide (AMD), the monomer associated with PAM and a contaminant of the PAM manufacturing process. AMD has been shown to be both a neurotoxin and a carcinogen in laboratory experiments. Current regulations require that AMD not exceed 0.05% in PAM products. At the application rates prescribed by the NRCS, the concentration of AMD in outflow waters is several orders of magnitude less than what is considered toxic. According to the ARS, AMD decomposes in 18 to 45 hours in biologically active environments (Barvenik et al., 1996). Although there seems to be little risk from AMD as a result of prescribed application of PAM, care should be taken to avoid spills, over-application, or other unforeseen accidents as their effects are uncertain (See Table 2).

Table 1. PAM 's beneficial effects on the environment and crop production (Sojka and Lentz, 1996).

What PAM Does	Environmental Benefit
Decrease sediment loading	Decrease turbidity Improve clarity Decrease P, N, pesticides, salts, pathogens Decrease BOD, eutrophication Decrease weed seed in runoff
Improve soil tilth	Increase infiltration Decrease runoff
Binds fine soil particles	Decrease wind erosion Accelerates clarification of turbid water bodies Prevents erosion
Increase soil water storage	Improves irrigation efficiency Decrease plant stress Improve plant vigor

Table 2. PAM 's potential detrimental effects on the environment and crop production (Dawson et al., 1996 in Sojka and Lentz, 1996; Sojka, personal communication, 2000).

What PAM Does	Potential Detrimental Effect	Preventative Measures
Increased infiltration	At prescribed rates on fine or medium textured soil, PAM can increase infiltration comparable to no-till, risking drainage and leaching of nutrient or chemicals.	Increase irrigation flow rate to prevent over-irrigation of the near end of the field.
Reduce infiltration	Over-application of PAM, or use on coarse textured soil, can reduce infiltration.	Careful application suited to site-specific needs.
Unknown effects on fish and wildlife	While safe at prescribed rates, large spills or excessive application may affect habitat.	Take care to avoid spills; use as directed.

Anionic PAM (containing less than 0.05% AMD), the form registered by states for use in erosion control products, is not toxic to aquatic, soil, or crop species when used as directed at specified rates. The molecule is too large to cross membranes, so it is not absorbed by the gastrointestinal tract, is not metabolized, and does not bioaccumulate in living tissue. PAM effects on aquatic biota are buffered if the water contains sediments, humic acids, or other impurities (Barvenik et al., 1996). While assessments of PAM effects directly on wildlife have not been conducted, the fact that PAM is applied in very dilute form to land via irrigation water, and largely stays on targeted fields, coupled with highly positive effects on several important runoff water quality components, suggests little danger if label directions and cautions are followed. This perception is strengthened by the fact that PAM has been used in a variety of industrial water treatment uses and land disposed for decades, with no reported adverse effects on wildlife. Published soil microbial studies have shown no negative impact on soil microflora or microfauna in treated fields. Furthermore, erosion control PAMs are restricted to anionic forms that are also used in human food processing and cosmetic and pharmaceutical preparations.

Conclusion

Anionic PAM has proven an effective erosion control technology since research began in 1991. Continued USDA research and extension efforts since 1995 have resulted in a million acres of PAM use annually since 1998, with no reports of adverse environmental consequences. PAM has been shown to prevent the entry of sediment, nutrients, and pesticides into riparian waters via irrigation runoff and return flows. However, the learning curve for effective PAM use is steep and sometimes counter intuitive. Farmers need to be well informed of PAM properties and application requirements. While PAM is an important additional erosion-combating conservation tool that can often be effective where other approaches fail, it should not be used as a substitute for good overall farm management and a balanced and effective conservation plan. PAM cannot make up for failure to implement effective overall conservation practices and environmentally responsible farm management, but can provide essential erosion protection in many situations where other solutions have proven uneconomical or ineffective.

Tailwater can be prevented in sprinkler irrigation systems through effective irrigation scheduling, but may need to be managed in furrow systems. The reuse of tailwater downslope on adjacent fields is a low-cost alternative to tailwater recovery and upslope reuse (Boyle Engineering Corp., 1986). Tailwater recovery systems require a suitable drainage water receiving facility such as a sump or a holding pond, and a pump and pipelines to return the tailwater for reapplication (Boyle Engineering Corp., 1986). The cost to install a tailwater recovery system was about $125/acre in California (California SWRCB, 1987) and $97.00/acre in the Long Pine Creek, Nebraska, RCWP (Hermsmeyer, 1991). Additional costs may be incurred to maintain the tailwater recovery system.

The cost associated with surface and subsurface drains is largely dependent upon the design of the drainage system. In finer textured soils, subsurface drains may need to be placed at close intervals to adequately lower the water table. To convey water to a distant outlet, land area must be taken out of production for surface drains to remove seeping ground water and for collection of subsurface drainage.

The Agricultural Conservation Program (ACP) has been phased out and replaced by the Environmental Quality Incentive Program (EQIP) in the 1996 Farm Bill. However, the Statistical Summaries (USDA-FSA, 1996) from the ACP contain reliable cost-share estimates. The following cost information is taken from these summaries and assumes a 50% cost-share to obtain capital cost estimates. The ACP program has a unique set of practice codes that are linked to a conservation practice. The cost to install irrigation water conservation systems (FSA practice WC4) for the primary purpose of water conservation in the 33 States that used the practice was about $73.00 per acre served in 1995. Practice WC4 increased the average irrigation system efficiency from 47% to 64% at an amortized cost of $10.41 per acre foot of water conserved. The components of practice WC4 are critical area planting, canal or lateral, structure for water control, field ditch, sediment basin, grassed waterway or outlet, land leveling, water conveyance ditch and canal lining, water conveyance pipeline, trickle (drip) system, sprinkler system, surface and subsurface system, tailwater recovery, land smoothing, pit or regulation reservoir, subsurface drainage for salinity, and toxic salt reduction. When installed for the primary purpose of water quality, the average installation cost for WC4 was about $67 per acre served. For erosion control, practice WC4 averaged approximately $82 per acre served. Specific cost data for each component of WC4 are not available.

Water management systems for pollution control, practice SP35, cost about $94 per acre served when installed for the primary purpose of water quality. When installed for erosion control, SP35 costs about $72 per acre served. The components of SP35 are grass and legumes in rotation, underground outlets, land smoothing, structures for water control, subsurface drains, field ditches, mains or laterals, and toxic salt reduction.

The design lifetimes for a range of salt load reduction measures are presented in Table 4f-12 (USDA-ASCS, 1988).

Savings

Savings associated with irrigation water management generally come from reduced water and fertilizer use.

Steele et al. (1996) found that improved methods of irrigation scheduling can produce significant savings in seasonal irrigation water totals without yield reductions. In a six-year continuous corn field study, a 31% savings in seasonal irrigation totals was realized compared to the average commercial grower in the same irrigation district. Corn grain yields were maintained at 3% above average corn grain yields in the irrigation district.

Table 4f-12. Design lifetime for selected salt load reduction measures (USDA-ASCS, 1988).

Practice/Structure	Design Life (Years)
Irrigation Land Leveling	10
Irrigation Pipelines – Aluminum Pipe	20
Irrigation Pipelines – Rigid Gated Pipe	15
Irrigation Canal and Ditch Lining	20
Irrigation Head Ditches	1
Water Control Structure	20
Trickle Irrigation System	10
Sprinkler Irrigation System	15
Surface Irrigation System	15
Irrigation Pit or Regulation Reservoir	20
Subsurface Drain	20
Toxic Salt Reduction	1
Irrigation Tailwater Recovery System	20
Irrigation Water Management	1
Underground Outlet	20
Pump Plant for Water Control	15