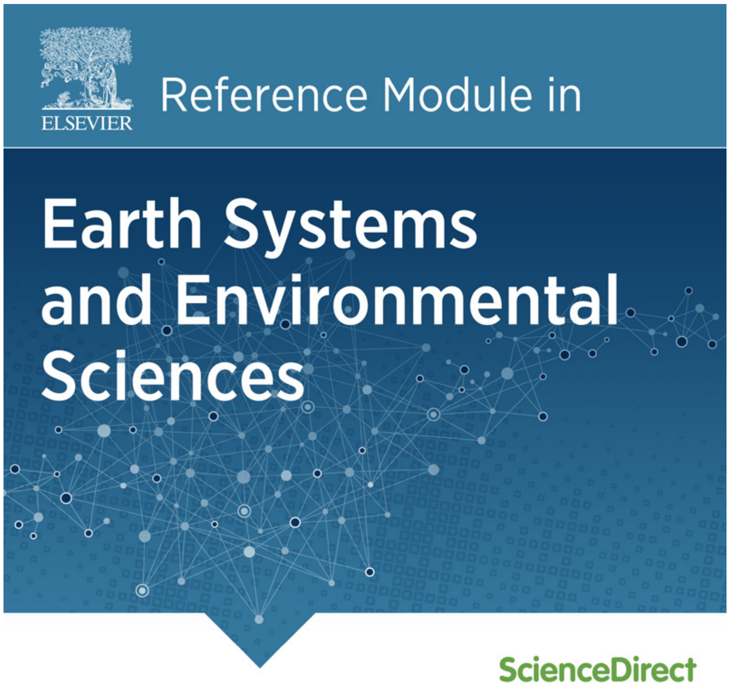

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IRRIGATION | Methods☆

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Introduction 1
Surface Irrigation 1
Furrow Irrigation 2
Basin and Border Irrigation 2
Sprinkler Irrigation 4
Solid-Set Sprinkler Systems 4
Set-Move Sprinkler Systems 5
Moving Sprinkler Systems 5
Microirrigation 6
Subirrigation 7
Salinity Hazards 7
Choosing an Irrigation System 8
References 9

Nomenclature

ha	hectare
kPa	kiloPascal
$L\ h^{-1}$	liters per hour
$L\ min^{-1}$	liters per min
$L\ s^{-1}$	liters per second
m	meters
mm	millimeters
m^2	square meters
Mha	million hectares

Introduction

Irrigation is the process of applying water to soil, primarily to meet the water needs of growing plants. Water from rivers, reservoirs, lakes, or aquifers is pumped or flows by gravity through pipes, canals, ditches or even natural streams. Applying water to fields enhances the magnitude, quality and reliability of crop production. According to the Food and Agriculture Organization of the United Nations, irrigation contributes to about 40% of the world's food production on 20% of the world's crop production land.

Various irrigation methods have been developed over time to meet the irrigation needs of certain crops in specific areas. The three main methods of irrigation are surface, sprinkler and drip/micro. Water flows over the soil by gravity for surface irrigation. Sprinkler irrigation applies water to soil by sprinkling or spraying water droplets from fixed or moving systems. Microirrigation applies frequent, small applications by dripping, bubbling or spraying, and usually only wets a portion of the soil surface in the field. A fourth, and minor, irrigation method is subirrigation where the water table is raised to or held near the plant root zone using ditches or subsurface drains to supply the water.

According to the International Commission on Irrigation and Drainage, surface irrigation is used on about 85% of the 299 Mha of irrigated crop land in the world. India and China each irrigate more than 60 Mha of crop land, accounting for almost half of the irrigated land in the world (FAO, 2013). Approximately 95% of the irrigated land is surface irrigated in India and China. The United States and Pakistan each have about 20 Mha of irrigated land. All other countries each have less than 10 Mha of irrigated land. In the United States, sprinkler and microirrigation are used on a greater percentage of irrigated crop land compared to the other three countries, and the percentages have steadily increased during the past 20 years. Sprinkler irrigation is used on 54% of the 22 Mha of crop land irrigated in the United States, while microirrigation is used on about 7% of the irrigated crop land (USDA NASS, 2008).

Surface Irrigation

Surface irrigation entails water flowing by gravity over soil. Water is usually supplied by gravity from the water source through canals, pipes or ditches to the field. In some locations, however, water may need to be pumped from the source to a field at a higher

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Table 1 Typical application efficiencies for irrigation systems

System type	*Application efficiency*
Surface irrigation[a]	
Furrow	50–70%
Level basin	60–80%
Border	60–75%
Sprinkler irrigation	
Solid set	60–85%
Set move	60–75%
Moving[b]	75–95%
Traveling gun	55–65%
Microirrigation[c]	80–95%
Subirrigation	50–80%

[a]Surface irrigation efficiencies can be greater if runoff is reused.
[b]Includes center pivot, linear move and LEPA systems.
[c]Efficiency can decrease to 50% with poor management.

elevation. Types of surface irrigation systems include furrow, basin and border irrigation. Surface irrigation systems are typically used for field crops, pastures and orchards. Efficiency of surface irrigation systems vary tremendously because of variations in soil type, field uniformity, crop type and management. Surface irrigation is often considered less efficient than sprinkler irrigation or microirrigation because soil, not a pipe, conveys the water within surface irrigated fields. However, a well managed surface irrigation system on a uniform soil with a runoff reuse system can approach 90% application efficiency (Table 1).

Furrow Irrigation

When furrow irrigating, water flows in evenly spaced furrows or corrugates that are typically 0.1–0.3 m wide on fields with slopes of 0.1–3%. Water commonly flows in furrows for 12–24 hours during an irrigation, but shorter or longer durations may be used depending on furrow length, soil properties, and water management considerations. Inflow rates for individual furrows can vary from about 10 to 100 L min^{-1}, again depending on soil, slope, field length and management considerations. Ideally, water should advance across the field in about 25% of the total irrigation time to uniformly irrigate the field. Since soil erosion increases as field slope and inflow rate increase, flow rate must be carefully managed on fields with steeper slopes (>1%). Low inflow rates and long irrigation durations may be needed to apply the desired amount of water during an irrigation on soils with low infiltration rate. Conversely, higher inflow rates are often needed on fields with low slopes and/or high infiltration rate soils in order for the water to flow across the field and uniformly irrigate the upper and lower portions of the field (Figure 1).

Inflow to irrigation furrows may be supplied from gated pipe or ditches (earthen or concrete). Siphon tubes are frequently used to convey and regulate water flow from ditches to individual furrows. By creating a siphon, water flows through the tube, over the ditch bank and into the furrow as long as the tube outlet is lower than the water elevation in the ditch. Furrow inflow rate is controlled by tube diameter and the elevation difference between the ditch water level and tube outlet. Gated pipe distributes water to furrows through evenly spaced outlets on the pipe. Furrow inflow rate is controlled by outlet opening and water pressure within the gated pipe. With earthen ditches, water flows through a breach or other opening in the ditch bank to individual furrows or a smaller feed ditch that distributes water to several furrows. It is much more difficult to regulate flow through a breach in an earthen ditch than through siphon tubes or pipe gates (Figure 2).

Furrow irrigation requires lower capital investment, less technical knowledge and greater labor than most other irrigation systems. Fields can be irrigated without leveling or grading because water flows in furrows. Furrow irrigation is not well suited to automation because water flow rate must be adjusted for each furrow for each irrigation.

Basin and Border Irrigation

Basin and border irrigation systems are similar in that both involve a uniform sheet of water flowing over the soil. The general difference is that basin irrigation involves applying water to a nearly level field and may include ponding for extended time periods. With border irrigation, water flows between dikes that divide a sloping field into rectangular strips with free drainage at the end. The purpose of the dikes is to contain water as it flows across the field, unlike basin irrigation where the dikes pond the water (Figure 3).

Basins can be as small as a few square meters for a single tree or as large as several hectares with >100 L s^{-1} inflow rates. Basin size is a balance of soil infiltration rate, slope and water supply. Water depth in basins varies from about 5 to 20 cm, with typical depths of 10–15 cm. Efficient basin irrigation requires a level soil surface with uniform soil texture and adequate water supply so the basin is quickly and uniformly covered with water. If the basin is not level, the higher elevation areas will receive less water than

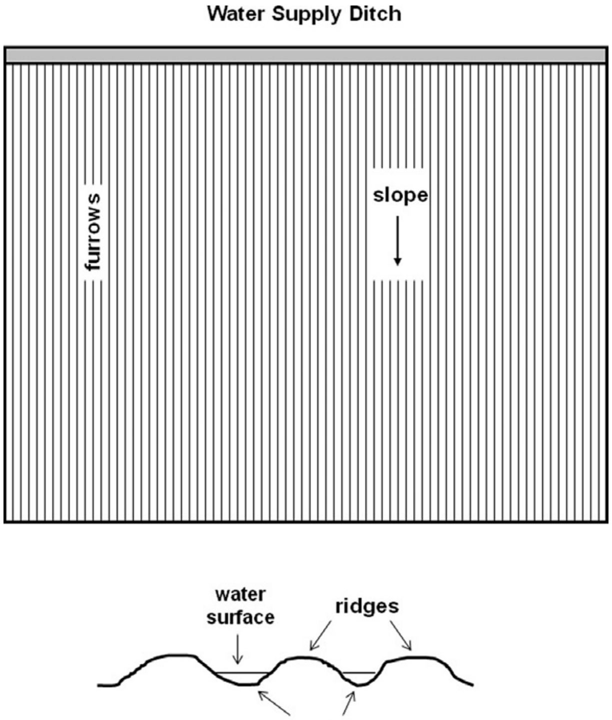

Figure 1 Schematic diagram of a furrow irrigated field where water flows in evenly spaced furrows or corrugates.

Figure 2 Furrow irrigated lettuce field with water supplied by siphon tubes from a concrete ditch. Photo courtesy of USDA Natural Resources Conservation Service.

the low areas. If the basin inflow rate is inadequate, water will slowly advance, causing large differences in infiltration opportunity time within the basin (Fangmeier et al., 1999).

A special type of basin irrigation is a drain-back level basin. Drain-back level basins have a series of parallel basins that receive inflow from a shallow, 5–10 m wide ditch. After the first basin is filled, a gate opens to start filling the adjacent basin, which is at a lower elevation. Water near the inflow end of the first basin drains back to the inflow ditch and flows to the next basin. This procedure is repeated until every basin has been irrigated. The drain-back phase improves uniformity by reducing the amount of water that infiltrates near the inflow end and initially increases the inflow rate to the next basin, which increases the advance rate.

Border irrigation systems are better suited for sloping fields than basin systems because water flows between dikes rather than ponded within basins. The irrigated areas between dikes may be 3–30 m wide and up to 400 m long. The field slope between dikes (perpendicular to water flow direction) should be nearly level so water flows uniformly down the field. The slope along the dikes can be similar to furrow irrigation, but border systems often have slopes less than 0.5%.

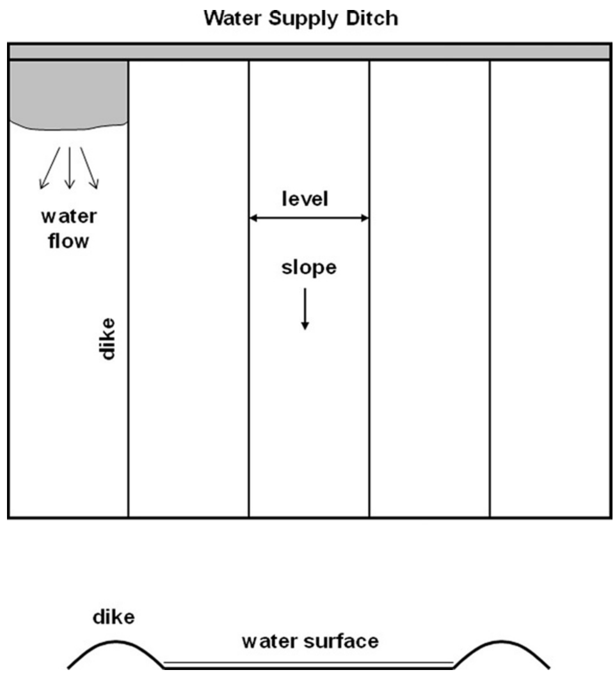

Figure 3 Schematic diagram of a border irrigated field when a uniform sheet of water flows between dikes.

Water can be supplied to borders and basins from open ditches with gates, breaches or siphon tubes or from above or below ground pipes. Typical inflow rates vary from 10 to 100 L s^{-1}, but vary widely depending on size of the basin or border, soil texture and slope. Border and basin irrigation require less labor than furrow irrigation because water is supplied to a larger area with a single outlet.

Sprinkler Irrigation

Sprinkler irrigation applies water to soil by spraying or sprinkling water through the air on to the soil surface. Water is pressurized and delivered to the irrigation system by a mainline pipe, which is often buried so it does not interfere with farming operations. Three main categories of sprinkler irrigation systems are solid-set, set-move and moving. Sprinkler irrigation is used for a wide variety of plants including field crops, vegetables, orchards, turf and pastures. Sprinkler systems are also installed for applying wastewater, protecting plants from frost, and dust control in confined animal operations.

Solid-set systems may be installed for a single season for certain field crops or permanently for turf, orchards or permanent crops. Set-move systems are manually or mechanically moved to another part of the field after the irrigation set is complete in the present location. Moving systems, such as center pivots or traveling guns, apply water as the system slowly travels through the field.

Sprinkler irrigation is often more efficient than surface irrigation because water application is more controlled. In hot and/or windy areas, however, sprinkler irrigation can have significant water losses to evaporation and wind drift. Maintenance is also important for efficient sprinkler irrigation; worn nozzles and leaking pipe connections reduce application uniformity and system efficiency.

Solid-Set Sprinkler Systems

Solid-set sprinkler irrigation systems are typically designed to apply frequent, small amounts of water to meet plant water needs every 1 to 5 days. Water application rates can vary from about 4 to 6 mm h^{-1} for field crops up to 5 to 30 mm h^{-1} for turf applications. Overhead costs are greater for solid-set systems compared to other sprinkler systems because the entire irrigated area must be equipped with sprinklers and pipe. However, permanently installed systems can be automated to reduce labor and allow irrigation at any hour of the day, which reduces the opportunity for plants to be stressed. When properly designed, solid-set systems have high application uniformity. While solid-set systems are most commonly used with turf, landscape and permanent crops, these systems are also used for some high-value annual crops with low tolerance for water stress.

Solid-set system designs are as varied as the applications; small sprinklers may irrigate 20 m^2 or large, gun-type sprinklers may be spaced 50 m apart. Plastic pipe is frequently used for buried applications, but it is also used in some above ground applications. Aluminum pipe (50–100 mm diameter) is often used for field crops when the system is installed after planting and removed before harvest. Most systems are divided into zones so a portion of the area is irrigated at one time. Solid-set systems used for frost control, however, must be designed to simultaneously water the entire area.

Set-Move Sprinkler Systems

Set-move sprinkler irrigation systems are designed to slowly apply water during the irrigation set (e.g. 4–6 mm h^{-1}), which often lasts 8 to 24 hours. After completing the irrigation set, the sprinkler system is moved to an adjacent area for the next set. Adequate water should be applied during an irrigation set to meet crop water needs until the system is moved back to the area, often in 7 to 10 days (Figure 4).

The common types of set-move irrigation systems are hand-move and side-roll systems. Hand-move systems can be a single sprinkler or a line of sprinklers. A line of hand-move sprinklers, sometimes called handlines, is typically 9- or 12-m long pieces of 75- or 100-mm diameter aluminum pipe with a sprinkler mounted on one end or in the center. Individual pipes are connected to form an irrigation line, usually not more than 400-m long. After an irrigation set is completed, the line is disconnected and each piece is moved by hand 10–20 m to the next set. A slight variation to the handline is the dragline or end-pull system. These systems, which are less common, have special connections between sprinkler pipes that allow the irrigation line to be pulled by a tractor to the next set.

Side-roll systems, also called wheel lines, are similar in principle to handlines except a large diameter wheel (1.5–3 m diameter) is mounted in the center or on the end of each piece of aluminum pipe (100–125 mm diameter) to elevate the sprinkler. The sprinkler pipe is the axle for the side-roll. When an irrigation set is completed and the pipe has drained, the wheel line, powered by an engine, is rolled to the next position. Self-leveling sprinklers are used so the side-roll does not have to be exactly positioned for the sprinklers to operate correctly.

Moving Sprinkler Systems

Moving irrigation systems include center pivot, linear-move and traveling gun systems. A traveling gun has a large capacity sprinkler on a cart that is pulled across the field by a cable or by the water supply hose. These systems irrigate an area 50–100 m wide and up to 400 m long. A traveling gun can be considered a moving, set-move system because water is applied as the cart moves across the field and then the system is moved to another area in the field for the next irrigation set. For cable tow systems, a winch on the cart winds the cable, pulling the cart and a soft hose across the field. A hose reel system pulls the cart as a hard plastic hose (polyethylene) is wound around a reel on a trailer anchored at the end of the run. The reel or winch is powered by an engine or a water turbine. Smaller versions of traveling guns are available for irrigating athletic fields, small pastures or arenas. In some specialized situations, the single large sprinkler is replaced with a 20- to 60-m long irrigation boom containing multiple sprinklers that are similar to those on center pivot systems.

Center pivot and linear-move systems are similar in design and appearance. These systems consist of one or more spans of sprinkler pipe elevated by "A-frame" towers. Span length varies from 30 to 65 m. Towers, powered by hydraulic or electric motors, elevate the sprinkler pipe 2–4 m above the ground. The center pivot has a stationary pivot point so the towers move in a circle. Water and power are supplied to the system through the pivot point. A typical center pivot in the United States has eight spans,

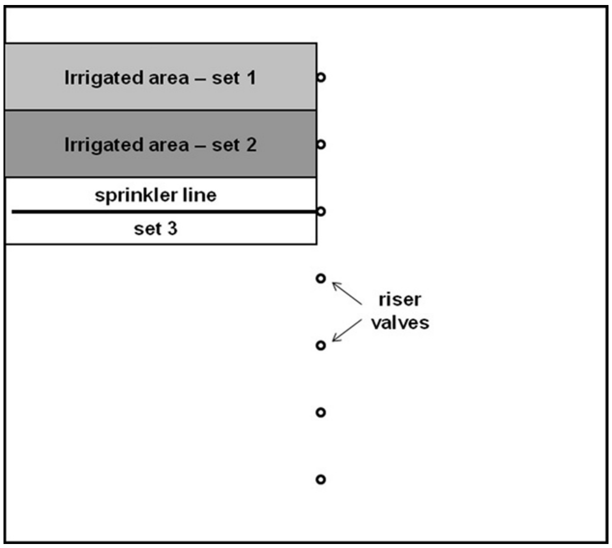

Figure 4 Schematic diagram of a set-move irrigated field where the irrigation system is moved to the adjacent area after completing an irrigation set.

Figure 5 Center pivot irrigation system irrigating barley.

a total length of about 400 m, and irrigates 50–60 ha. Center pivots are extremely popular because water is uniformly applied to a large area with little labor. Furthermore, once a circular field has been irrigated, the center pivot is in position to start the next irrigation. In 2008, center pivots were used on 45% of the irrigated land in the United States, which is an increase of 124% since 1988 (USDA NASS, 2008) (**Figure 5**).

System cost per irrigated area is reduced by increasing the total length of a center pivot because irrigated area per unit length increases with distance from the pivot point. Consequently, water application rate also increases with distance from the pivot point because each span must irrigate a larger area per revolution (a 50 m span at the pivot point irrigates 0.8 ha while a 50 m span that is 350 m from the pivot point irrigates 12 ha). Application rates often exceed the infiltration rate of the soil under the outer spans of center pivots. Thus, the opportunity for runoff increases as center pivot length increases. Center pivots can also irrigate fields with rolling terrain that are difficult or impossible to irrigate by surface irrigation methods, however these conditions can create additional management challenges.

Linear-move systems have a control unit on one end, or in the center on longer systems, that moves the towers in a straight line to irrigate rectangular-shaped fields. Power is supplied by an electrical drag cord or by an engine-powered generator mounted on the control unit. Water is typically supplied to the drive unit by a drag hose connected to a buried or above ground pipe. Drive units can be equipped with a pump so water can be supplied from an open ditch flowing parallel to the travel direction. System cost per irrigated area is reduced by increasing the distance the system travels. Since hose length is limited to about 150 m, the system can move 300 m before the hose must be connected to the next riser. Similar to set-move systems, adequate water must be applied to meet crop needs until the linear-move can irrigate the area again.

Early center pivots had impact sprinklers mounted on top of the irrigation pipe that required 500–600 kPa. Most new systems have low pressure sprinklers (70–200 kPa) mounted on tubes that extend below the irrigation pipe so sprinkler height varies from 1 to 3 m above the soil and wetted diameters vary from 3 to 20 m. Manufacturers make numerous types of low pressure sprinklers with fixed or rotating spray plates that provide a wide range of application rates and water droplet sizes to meet field conditions and operator preferences. A common feature to all sprinkler types is a pressure regulator that maintains constant nozzle pressure as the system travels across a field with varied elevation. Recently, manufacturers have started making low pressure sprinklers that mount on top of the lateral so the sprinklers are above the canopy for tall crops like corn. These sprinklers have defined streams to minimize drift and can apply wet a 20 m diameter area with 100 kPa nozzle pressure.

Technology for controlling center pivot operation is continually changing from the on/off switch and speed control dial. Operators can now communicate with irrigation machines by cell phone, satellite radios and internet-based systems (Kranz et al., 2012). Center pivot manufactures now offer speed control and zone control to vary water application within a field. Speed control allows the operator to change the system rotational speed every 2 degrees so more or less water is applied to pie-shaped areas in the field. Zone control allows individual or groups of sprinklers to be pulsed on and off to vary water application rate along the lateral. Integrating information from various sensors into a decision support program is the next potential advancement to precisely apply the right amount of water at the right time to unique areas within a field (Evans and King, 2012).

Microirrigation

Microirrigation applies water at low rates and pressures to discrete areas so irrigation water reaches the root zone with minimal losses. Water drips from emitters in plastic pipe or tape, or bubbles or sprays from small emitters that only wet a portion of the soil surface. Microirrigation systems are popular for permanently installed systems that irrigate trees, vineyards, orchards and shrubs. These systems are typically automated so that water is applied frequently (e.g. daily or multiple times per day) to maintain

Figure 6 Drip irrigation in a vineyard. Photo courtesy of USDA Natural Resources Conservation Service.

optimum soil water content near the plants. Filtration is important for microirrigation because sediment and algae can plug the small openings on drip emitters, bubblers and microsprays. Chemical treatment may also be necessary to reduce salt or mineral deposits that can plug emitters.

Drip irrigation emitters are pre-installed within polyethylene pipe at regular intervals or emitters are attached to the outside of the pipe at desired locations. Emitter flow rates typically vary from 2 to 7.5 $L\,h^{-1}$. Pressure-compensating emitters maintain a constant flow rate as pressure varies from about 70 to 200 kPa. This type of system is common in vineyards or other above ground applications (**Figure 6**).

Drip tape is thin walled (0.1–0.375 mm), plastic tubing (10–20 mm diameter) with outlets at 100–600 mm intervals. Flowrates can vary from 100 to 400 $L\,h^{-1}$ per 100 m of length. Typical operating pressure for drip tape is 35–100 kPa. Drip tape is commonly installed below the soil surface where there is less opportunity for damage. Buried drip tape can be used for several seasons or retrieved after a single season, depending on crop types and farming practices. Subsurface drip irrigation can significantly improve yield and water use efficiency compared to surface irrigation (Ayers et al, 1999) Although the total area is still small, use of subsurface drip irrigation is gaining acceptance in some water-limited areas like the southern Great Plains in the United States (Lamm et al., 2012) (**Figure 7**).

Bubblers and microsprays are often used for irrigating trees, shrubs or ornamental plants. Bubblers discharge water with low energy to essentially flood a small area. Flow rates up to 100 $L\,h^{-1}$ can apply water to 4 m diameter areas, depending on nozzle size, type and pressure. Microsprays apply a fine spray or mist with similar flow rates and wetted areas as bubblers.

Subirrigation

Subirrigation applies water below the soil surface to raise the watertable into or near the plant root zone. Subirrigation is not often used in arid or semi-arid irrigated areas where irrigation is often needed to germinate crops. It is typically used in conjunction with subsurface drainage, or controlled drainage. Subsurface drainage lowers the watertable and removes excess water through open ditches or perforated pipe. Watertable depth can be controlled by installing a weir on the drainage system. During wet periods, the watertable is lowered so the root zone remains unsaturated. During dry periods, water is pumped into the drainage system to raise the watertable and provide additional water for plant growth. In some situations, drained water can be stored for use when irrigating.

Salinity Hazards

Salinity problems are more closely associated with soil and water chemistry than the type of irrigation system, however, the irrigation system can accentuate salinity problems and affect how salinity is managed. Basin and border irrigation can uniformly leach salts from the soil when infiltration is uniform. Sprinkler irrigation can also uniformly leach salts, but sprinkling can injure sensitive plants when highly saline water is applied to foliage. Furrow irrigation leaches salt from soil below the furrow while increasing salt concentrations in the bed. Tilling before planting crops tends to minimize salinity problems by mixing salts in the soil. Salt concentration tends to increase radially from a drip emitter or laterally from a line source such as drip tape. Well managed drip irrigation can minimize salt-induced stress by maintaining a high soil water content with frequent irrigations.

Figure 7 Drip tape installed on the soil surface to irrigate edible beans in a research plot. Drip tape is more commonly installed below the soil surface.

Table 2 Typical advantages and disadvantages of irrigation systems

System type	*Advantages*	*Disadvantages*
Surface irrigation		
Furrow	low capital and maintenance cost, water flows in small channels	high labor, less water control, soil erosion, possible runoff and percolation losses
Level basin	efficient with good design, less labor than furrow	ponded water, sloping fields must be leveled
Border	less labor and less runoff than furrow, easier to manage infiltration depth	water flows over entire soil surface
Sprinkler irrigation		
Solid set	good water control, possible to automate and frequently irrigate, fits odd-shaped fields	high capital costs, system may interfere with field operations
Set-move	lower capital cost than other sprinkler systems	more labor than other sprinkler systems, poor uniformity in windy conditions, greater application depth
Moving[a]	high uniformity, low labor	high capital and maintenance costs, not suitable for odd-shaped fields, potential wind and evaporation losses
Traveling gun	lower capital cost than other sprinkler systems	higher operating costs, wind and evaporation losses
Microirrigation	excellent water control, frequent applications possible	higher capital costs, requires clean water or treatment and filtration

[a]Includes center pivot, linear move and LEPA systems.

Choosing an Irrigation System

Choosing an irrigation system is a difficult task. Irrigation systems are as varied as the people who use them. The right selection for a user depends on soil, water and climatic conditions as well as crop types, user knowledge and preference, capital and operating costs, and infastructure availability. No system is best for all situations. Some typical advantages and disadvantages of irrigation systems are shown in Table 2. Sprinkler and microirrigation are often better choices than surface irrigation on sandy soil where excessive percolation is a problem. Surface irrigation may be better in arid, windy areas where wind and evaporation losses can be significant. Surface irrigation offers less control of application depth so small, frequent irrigations are not practical for water sensitive crops, which are better suited to microirrigation, solid-set or center pivot systems.

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