Recent developments in irrigation technology are helping to improve irrigation efficiency and to reduce the drainage water volume that requires disposal. For example, sprinkler and drip irrigation systems facilitate the fine-tuned control of fertilizer applications in order to minimize fertilizer residue remaining in the soil after the harvest of crops. The new irrigation technologies that facilitate the application of fertilizers along with irrigation water should be adopted and used widely. Irrigation water requirements are least, for example, with drip systems that supply water and fertilizers directly into the root zone where they are needed. The crop utilizes nearly all of the fertilizer applied, leaving the least residue in the soil after harvest.

Over-use of pesticides is now being replaced with integrated pest management practices that take advantage of the biological control of insects and pests in addition to the use of chemical sprays. However, efforts are still needed to create public awareness of the importance of conservation of soil and water for meeting the needs of present and future generations.

Training farm advisers and extension workers on effective management practices of land preparation and soil tillage, and use of pesticides and fertilizers will help to minimize pollution attributable to agricultural activities. Adopting advanced irrigation technologies supported by governmental subsidies or low-interest loans (if needed), and drafting and enforcing legal codes for preventing pollution of water and soil resources will contribute to the environment-friendly and sustainable practice of irrigated agriculture. Presently available technical knowledge on irrigation is adequate for developing sustainable agricultural practices to keep pace with the food and fiber demands of the increasing world population. To this effect, despite the drawbacks, irrigated agriculture has an important role to play in world food production.

See also: **Civilization, Role of Soils**; **Drainage, Surface and Subsurface**; **Salination Processes**; **Salinity:** Management; **Salt-Affected Soils, Reclamation**

Further Reading

Alexandratos N (ed.) (1995) *World Agriculture: Towards 2010. An FAO Study.* Chichester, UK: FAO/John Wiley.

Barrios A (2000) *Agriculture and Water Quality.* CAE Working Paper Series, WP00-2. DeKalb, IL: American Farmland Trust's Center for Agriculture in the Environment.

Daugherty TC and Hall AW (1995) *Environmental Impact Assessment of Irrigation and Drainage Projects.* FAO Irrigation and Drainage Paper 53. Rome, Italy: FAO.

Donaldson D, Kiely Timothy, and Grube A (2002) *Pesticides Industry Sales and Usage. 1998 and 1999 Market Estimates.* Biological and Economic Analysis Division Office of Pesticide Programs, Office of Preventation, Pesticides, and Toxic Substances, US Environmental Protection Agency. Washington, DC: US Government Printing Office.

FAO (2002) *Deficit Irrigation Practices.* Water Reports 22. Rome, Italy: FAO.

FAO (2002) *World Agriculture Towards 2015/2030. Summary Report.* Rome, Italy: FAO.

Hornsby AG (1990) Pollution and public health problems related to irrigation. In: Stewart BA and Nielsen DR (eds) *Irrigation of Agricultural Crops*, pp. 1173–1188. Agronomy Monograph No. 30. Madison, WI: American Society of Agronomy.

Kirda C, Moutonnet P, Hera C, and Nielsen DR (eds) (1999) *Crop Yield Response to Deficit Irrigation.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

Marr PD (1969) The social context of irrigation. In: Hagan RM, Haise HR, and Edminster TW (eds) *Irrigation of Agricultural Lands*, pp. 12–22. Agronomy Monograph No. 11. Madison, WI: American Society of Agronomy.

Shah T, Molden D, Sakthivadivel R, and Seckler D (2000) *The Global Groundwater Situation: Overview of Opportunities and Challenges.* Colombo, Sri Lanka: International Water Management Institute.

Shiklomanov LA (1999) *World Water Resources at the Beginning of the 21st Century.* IHP Report. Paris, France: UNESCO.

Tanji KK (ed.) (1990) *Agricultural Salinity Assessment and Management.* Manuals and Reports on Engineering Practice No. 71. New York: American Society of Civil Engineers.

Umali DL (1993) *Irrigation Induced Salinity: A Growing Problem for Development and the Environment.* World Bank Technical Paper 215. Washington, DC: The World Bank.

Wagner RH (1971) *Environment and Man.* New York: Norton.

Methods

D L Bjorneberg and R E Sojka, USDA Agricultural Research Service, Kimberly, ID, USA

Published by Elsevier Ltd.

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 – approximately 30% of the world's food is grown on irrigated land, which accounts for only about 15% of the world's land used for crop production.

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 or microirrigation. In surface irrigation, water flows over the soil by gravity. 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. 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.

More than 90% of the approximately 270 Mha of irrigated crop land in the world is surface-irrigated; less than 1% is irrigated by microirrigation. In the USA, sprinkler and microirrigation are used on a greater percentage of irrigated cropland, primarily to reduce labor and improve control of water application. Approximately 45% of the 20 Mha of cropland irrigated in the USA is sprinkler-irrigated, and microirrigation is used on approximately 4% of the irrigated cropland.

Surface Irrigation

Surface irrigation entails water flowing by gravity over soil. Water is usually supplied by gravity through canals, pipes, or ditches from the water source to the field. In some locations, however, water may need to be pumped from the source to a field at a higher 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 varies tremendously because of variations in soil type, field uniformity, and management. Surface irrigation is often considered less efficient than sprinkler irrigation or microirrigation, because soil, not a pipe, is the water-conveyance system for surface irrigation (**Table 1**). However, a well-managed surface irrigation system on a uniform soil with a runoff-reuse system can approach 90% application efficiency.

Table 1 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 low-energy precision application (LEPA) systems.

[c] Efficiency can decrease to 50% with poor management.

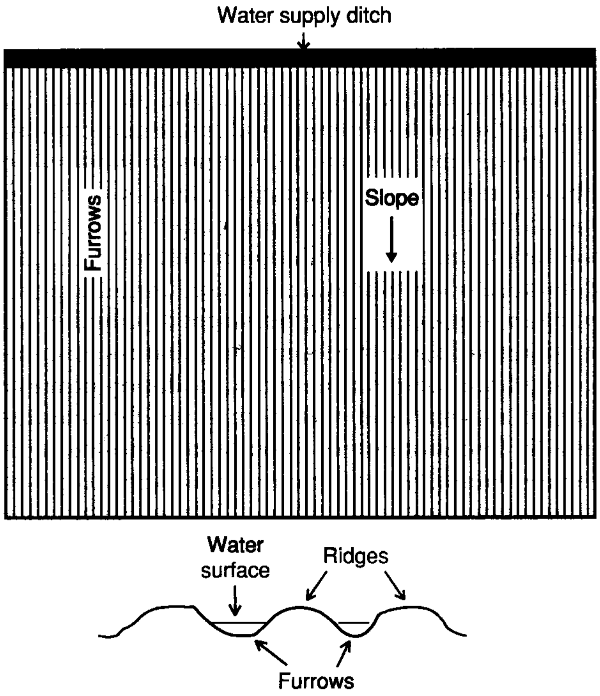

Figure 1 Schematic of a furrow-irrigated field, where water flows in evenly spaced furrows or corrugates.

Furrow Irrigation

In furrow irrigation, water flows in evenly spaced furrows or corrugates that are typically 0.1–0.3 m wide (**Figure 1**) on fields with slopes of 0.1–3%. Water commonly flows in furrows for 12–24 h during an irrigation, but shorter or longer durations may be used depending on furrow length and soil, water, and management considerations. Inflow rates for individual furrows vary from approximately 10 to $100\,\mathrm{l\,min^{-1}}$, again depending on soil, slope, field length, and management. Ideally, water should advance across the field in approximately 25% of the total irrigation time to irrigate the field uniformly. Since soil erosion increases as field slope and inflow rate increase, flow rate must be carefully managed on fields with steeper slopes (greater than 1%). Low inflow rates and long irrigation durations may be needed to apply the desired amount of water during

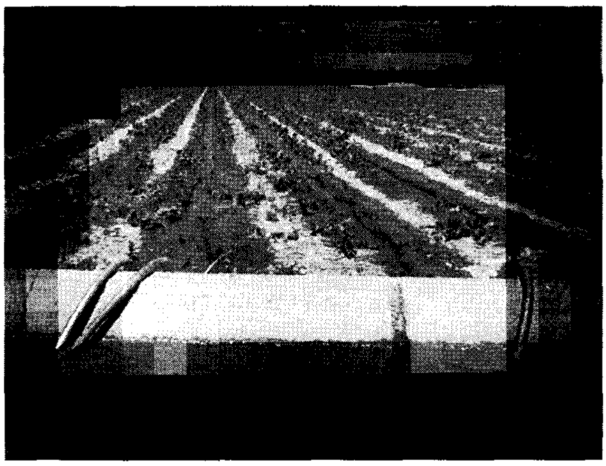

Figure 2 (see color plate 32) Furrow-irrigated sugar beet field, with water supplied by siphon tubes from a concrete ditch.

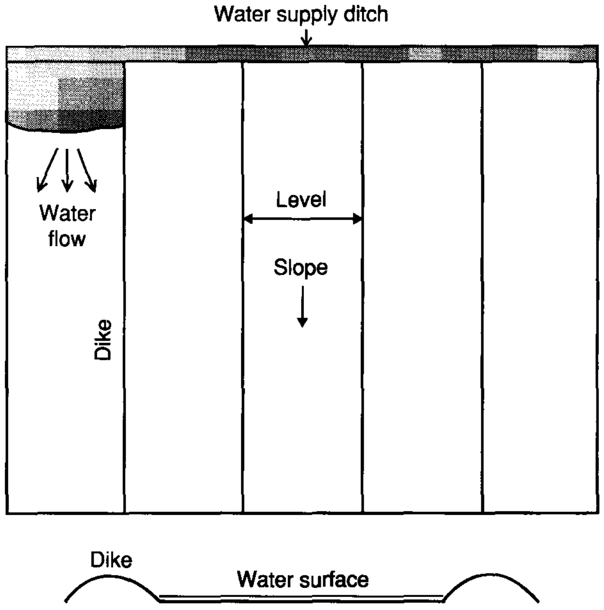

Figure 3 Schematic of a border-irrigated field, where a uniform sheet of water flows between dikes.

an irrigation on soils with low infiltration rate. Conversely, higher inflow rates are often needed on fields with low slopes and/or high infiltration rates in order for the water to flow across the field and uniformly irrigate the upper and lower ends of the field.

Inflow to irrigation furrows may be supplied from gated pipes or ditches (earthen or concrete). Siphon tubes are frequently used to convey and regulate water flow from ditches to individual furrows (**Figure 2**). 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 pipes distribute water to furrows through evenly spaced outlets on the pipes. With earthen ditches, water can flow 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.

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 (**Figure 3**). The purpose of the dikes is to contain water as it flows across the field, unlike basin irrigation where the dikes pond the water.

Basins can be as small as a few square meters for a single tree or as large as several hectares with greater than $100\,\mathrm{l\,s^{-1}}$ inflow rates. Basin size is a balance between soil infiltration rate, slope, and water supply. Water depth in basins varies from approximately 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 the low areas. If the basin inflow rate is inadequate, water will slowly advance, causing large differences in infiltration opportunity time within the basin.

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 ponds within basins. The irrigated areas between dikes can 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 of less than 0.5%.

Water can be supplied to borders and basins from open ditches with gates, breaches, or siphon tubes or from above- or belowground pipes. Typical inflow rates vary from 10 to 100 l s^{-1}, but vary widely depending on the size of 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, orchard trees, turf, and pasture. Sprinkler systems are also installed for applying wastewater and protecting plants from frost.

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 (**Table 1**). In hot and/or windy areas, however, sprinkler irrigation can have significant 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

Most solid-set sprinkler irrigation systems are designed to apply frequent, small amounts of water to meet plant water needs (e.g., daily). Water application rates can vary from approximately 4–6 mm h^{-1} for field crops to 5–30 mm h^{-1} for turf applications. Overhead costs are greater for solid-set systems than 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, and 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 aboveground applications. Aluminum pipe (50–100 mm in 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 water the entire area simultaneously.

Set-Move Sprinkler Systems

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

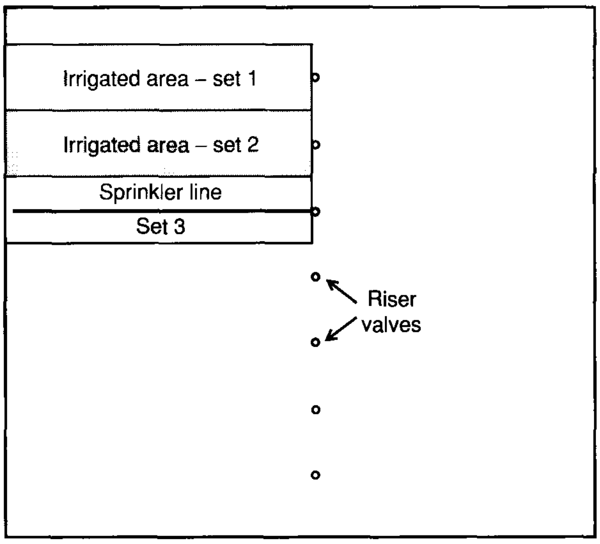

Figure 4 Schematic of a set-move-irrigated field, where the irrigation system is moved to the adjacent area after completing an irrigation set.

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 composed of 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 in diameter) is mounted in the center or on the end of each piece of aluminum pipe (100–125 mm in 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. 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 (**Figure** 5). Water and power are supplied to the system through the pivot point. A typical center pivot in the USA has eight spans, a total length of approximately 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. 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 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 aboveground pipe. Drive units can be equipped with a pump so water can be supplied from an open ditch flowing parallel to the travel direction, but this is not commonly used, because it requires a nearly level ditch. System cost per irrigated area is reduced by increasing the distance the system travels. Since hose length is limited to approximately 150 m, the system can move 300 m before the hose is 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 nozzles (70–200 kPa) mounted on tubes that extend below the

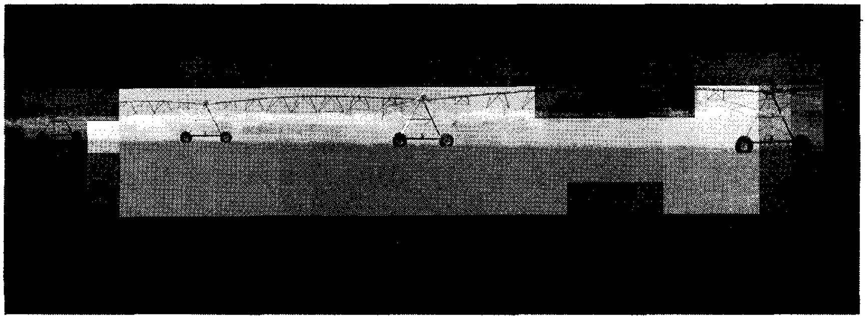

Figure 5 Center-pivot irrigation system.

irrigation pipe, so nozzle height varies from 1 to 3 m above the soil. Manufacturers make numerous types of low-pressure nozzles with fixed or spinning 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 nozzle types is a pressure regulator, which maintains constant nozzle pressure as the system travels across a field with varied elevation.

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 (polyethylene) hose 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 athletics fields, small pastures, or arenas.

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) to maintain 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 preinstalled 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 $\mathrm{l\,h^{-1}}$. Pressure-compensating emitters maintain a constant flow rate as pressure varies from approximately 70 to 200 kPa (**Figure 6**). This type of system is common in vineyards.

Figure 6 Pressure-compensating drip emitter watering ornamental plants.

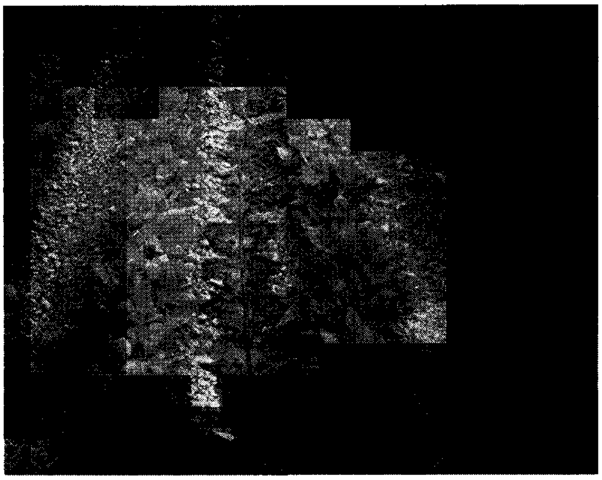

Figure 7 Drip tape installed on the soil surface to irrigate edible beans.

Drip tape is thin-walled (0.1–0.375 mm) plastic tubing (10–20 mm in diameter), with outlets at 100–600-mm intervals (**Figure 7**). Flow rates can vary from 100 to 400 $\mathrm{l\,h^{-1}}$ 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.

Bubblers and microsprays are often used for irrigating trees, shrubs, or ornamental plants. Bubblers discharge water with low energy to flood a small area. Flow rates up to 100 $\mathrm{l\,h^{-1}}$ 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 water table into or near the plant root

Table 2 Typical advantages and disadvantages of irrigation systems

System type	*Advantages*	*Disadvantages*
Surface irrigation		
Furrow	Low capital and maintenance costs; 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 cost; 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 cost; wind and evaporation losses
Microirrigation	Excellent water control; frequent applications possible	Higher capital cost; requires clean water or treatment and filtration

[a] Includes center-pivot, linear-move, and low-energy precision application systems.

zone. Subirrigation is not often used in arid or semiarid irrigated areas; it is typically used in conjunction with subsurface drainage. Subsurface drainage lowers the water table and removes excess water through open ditches or perforated pipe. Water-table depth can be controlled by installing a weir on the drainage system. During wet periods, the water table is lowered so the root zone remains unsaturated. During dry periods, water is pumped into the drainage system to raise the water table 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.

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 infrastructure availability. No system is best for all situations. Some typical advantages and disadvantages of irrigation systems are shown in **Table 2**. Sprinkler or 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.

List of Technical Nomenclature

ha	hectares
kPa	kilopascals
$\mathrm{l\,h^{-1}}$	liters per hour
$\mathrm{l\,min^{-1}}$	liters per minute
$\mathrm{l\,s^{-1}}$	liters per second
Mha	million hectares
m	meters
$\mathrm{m^2}$	square meters
mm	millimeters

See also: **Crop Water Requirements**; **Evapotranspiration**; **Fertigation**; **Infiltration**; **Irrigation**: Environmental Effects; **Salinity**: Management; **Water Harvesting**; **Water-Use Efficiency**

Further Reading

Brouwer C, Prins K, Kay M, and Heibloem M (1988) *Irrigation Water Management: Irrigation Methods.* Training manual No. 5. Rome, Italy: Food and Agriculture Organization of the UN.

Cuenca RH (1989) *Irrigation System Design: An Engineering Approach.* Englewood Cliffs, NJ: Prentice-Hall.

FAO *Aquastat – Information System on Water and Agriculture.* Rome, Italy: Food and Agriculture Organization of the UN.

Hoffman GJ, Howell TA, and Solomon KH (1990) *Management of Farm Irrigation Systems.* St. Joseph, MI: American Society of Agricultural Engineers.

Jensen ME (1983) *Design and Operation of Farm Irrigation Systems.* ASAE Monograph No. 3. St. Joseph, MI: American Society of Agricultural Engineers.

USDA (1997) *1997 Census of Agriculture*, vol. 1. *National, State, and County Tables.* National Agricultural Statistics Service. Washington, DC: US Government Printing Office.

ISOTOPES IN SOIL AND PLANT INVESTIGATIONS

K Reichardt and O O S Bacchi, Center for Nuclear Energy in Agriculture, Piracicaba, Brazil

Introduction

Isotopes, both radioactive and stable, have been used successfully as tracers in environmental studies involving the soil–plant–atmosphere system. Each chemical element of the periodic table has isotopes, which are atoms of the same species, behaving chemically and biologically in the same manner, differing only in some of their physical properties. They have in their nuclei the same number of protons, which defines the element, but different number of neutrons, which makes them different in terms of mass. Most of them are natural, i.e., present in nature since the formation of the Earth, and some are artificial, laboratory-made through nuclear reactions. When stable, they differ only by their atomic weight, and, when radioactive (unstable), they emit radiation. The important thing is that they differ in a measurable way and can be detected. Stable isotopes are detected by mass spectrometry, with instruments capable of distinguishing atomic weights, and radioisotopes, by radiation detection, made by a wide range of detectors, depending on the type of the radiation. One important feature of these methodologies is that they are able to measure extremely low amounts of isotopes.

Radioisotopes as Tracers

Radioisotopes are unstable isotopes that approach stability by emitting radiation. This radiation can easily be detected even in extremely low amounts. Radioisotopes can be traced at concentrations as low as 10^{-11} (1/100 billion). Each radioisotope has its own characteristics and emits one or more radiation types (mainly α (alpha), β^- (beta negative), β^+ (beta positive), γ (gamma), and n (neutron)), with one or more energies, and at a given rate that depends on their half-lives. Since this rate decreases exponentially with time, the half-life T is defined as the time in which any emission rate decreases by half. The type and energy of radiation affect detection of radioisotopes and a short half-life can limit their use in long-term experiments.

Radioisotopes can be found naturally, for example, ^{3}H, ^{14}C, ^{40}K, ^{226}Ra, and ^{235}U, some of them being continuously produced by natural processes occurring in the upper atmosphere which are induced by solar or cosmic radiation. In this case the production rate of the radioisotope is in equilibrium with its decay rate. Some radioisotopes have half-lives longer than the age of our planet, therefore they are present naturally in the environment. The great majority of radioisotopes used as tracers are, however, artificially produced in nuclear reactors. **Table 1** presents the principal tracer isotopes used in environmental studies, mainly in plant biology and soil studies.

To use isotopes as tracers, they are added to the respective stable isotope in amounts that allow their detection to the end of the experiment. Whenever possible they should be added in the same chemical form as the stable compound, e.g., if a phosphorus study is performed using superphosphate, the radioactive ^{32}P has to be present also in the form of superphosphate. Sometimes this is costly, as is the case in herbicide studies in which the radioactive ^{14}C has to be incorporated into the same molecular species.