CHAPTER 17

MICROIRRIGATION SYSTEMS

Robert G. Evans (USDA-ARS, Sidney, Montana)
I-Pai Wu (University of Hawaii, Honolulu, Hawaii)
Allen G. Smajstrala (University of Florida, Gainesville, Florida)

Abstract. *Microirrigation, the slow rate of water application at discrete locations at low pressures, includes trickle or surface drip, subsurface drip, microsprinklers and bubblers. It has made tremendous strides in the past three decades, and has become the modern standard for efficient irrigation practices for water conservation and optimal plant responses. Microirrigation is an extremely flexible set of technologies that can be economically used on almost every crop, soil type and climatic zone, but it requires a high level of management. These particular systems and their unique equipment and components have specialized needs and problems. This chapter discusses many of the advantages as well as disadvantages of various microirrigation technologies and their applications to horticultural and agronomic crops. Water quality concerns, filtration and management are addressed in detail*

Keywords. *Bubblers, Design, Drip, Irrigation, Management, Microsprinklers, Trickle.*

17.1 INTRODUCTION

The development of modern drip irrigation technologies in the 1960s marked a significant step in the history of irrigation science and technology. The first attempts were plagued with problems; however, most of these have been solved and almost all aspects of microirrigation have greatly matured since that time, especially in the areas of filtration, water treatment, and emitter technology. Bucks (1995) has provided a knowledgeable and concise summary of the history of microirrigation for those who would like additional information.

Microirrigation includes any localized irrigation method that slowly and frequently provides water directly to the plant root zone. Drip irrigation, trickle irrigation, bubblers, localized small microsprinklers, microspinners, and microsprayers are included in the general term. The slow rate of water application at discrete locations with associated low pressure and the irrigation of only a portion of the soil volume in the field can result in water delivery systems at relatively low cost, as well as reduce water diversions, compared to other irrigation methods.

Microirrigation offers the potential for precise, high level management and is an extremely flexible irrigation method. It can be adapted to almost any cropping situation and climatic zone. Microirrigation can be used over a wide range of terrain conditions, and it has allowed expansion of irrigated crop production into areas with problem soils (such as either very low or very high infiltration rates) and poor water quality that could not be used with other irrigation methods. It can be installed as either a surface or subsurface water application system.

Microirrigation can be used on most agricultural crops, although it is most often used with high-value specialty crops such as vegetables, ornamentals, vines, berries, olives, avocados, nuts, fruit crops, and greenhouse plants. In many cases, it can be economically used for field crops, golf greens, fairways, cotton, and sugarcane. However, the requirements for appropriate designs and management in humid areas can be considerably different from those in arid areas and the technology and techniques suitable in one area may not work in the other. Microirrigation will not be the most appropriate or economical irrigation method in all situations.

The use of microirrigation is rapidly increasing around the world, and it is expected to continue to be a viable irrigation method for agricultural production in the foreseeable future. With increasing demands on limited water resources and the need to minimize environmental consequences of irrigation, microirrigation technology will undoubtedly play an even more important role in the future. Microirrigation provides many unique agronomic and water and energy conservation benefits that address many of the challenges facing irrigated agriculture. Farmers and other microirrigation users are continually seeking new applications, such as wastewater reuse, that will continue to provide new challenges for designers and irrigation managers.

Any irrigation system must be compatible with cultural operations associated with a specific crop. Adoption of microirrigation may require new or innovative adaptations to various cultural practices and even the development of new harvest and tillage equipment. For example, surface lateral lines can hinder traditional harvest operations, requiring pre-harvest removal of the tubing or development of a new harvester and harvesting techniques. Lateral lines can be buried but this generally requires moving to minimal-tillage or permanent bed systems.

An in-depth understanding of the unique benefits and limitations of microirrigation systems is needed to successfully design and manage these systems. As with all other irrigation methods, there are trade-offs with both positive and negative impacts on irrigation scheduling, efficiency, and uniformity, as well as environmental impacts, crop responses, and economics.

17.1.1 Advantages and Disadvantages of Microirrigation

Microirrigation has advantages as well as disadvantages to consider and understand before adopting the technology. Advantages include water conservation and reduced deleterious water quality impacts due to high application efficiencies, automation capabilities, improved or increased yields, ease of chemical applications, and potential sustainability. Disadvantages include a high potential for emitter plugging, high system costs, and required high levels of management.

17.1.1.1 Advantages. Microirrigation is commonly used in areas with limited water and high water costs, but it has great value in other areas as well. Properly designed, installed, and managed microirrigation systems can eliminate surface runoff and associated soil erosion, efficiently and uniformly apply water-soluble fertilizers, and achieve high uniformity and efficiency of water application. They generally tend to have smaller wetted areas, reduced deep percolation, and lower evaporation losses than other irrigation methods. There can be water and chemical savings because of increased efficiency, reduced weed control costs because a limited surface area is wetted, and better productivity can be achieved due to improved control of water and nutrients in the root environment.

Microirrigation generally has high production efficiencies whether expressed as yield per unit water, yield per unit nutrient input, or yield per unit land area. Advanced cultural practices such as the use of plastic or sheet paper mulches to reduce weed growth, heat soils, and decrease soil evaporation are also facilitated by drip irrigation. Due to relatively small pipe and valve sizes, microirrigation systems are easily and inexpensively automated, which reduces labor costs and improves general management flexibility.

Because microirrigation methods can apply water in small amounts that nearly match evapotranspiration, soil characteristics such as hydraulic conductivity and water-holding capacity are usually not limiting. Less salt may be applied with the irrigation water because less water is needed with these potentially highly efficient systems. Low soil matric potentials reduce salinity hazards, improve the ability to manage saline or sodic soils, and permit the use of poorer-quality water than can be used with other irrigation methods. Because of its potential to be highly efficient, microirrigation is often specified as a best management practice for reducing groundwater contamination due to irrigation.

The ability to precisely manage soil water deficits and to make prescription applications of nutrients and other chemicals through the irrigation system often leads to increased yields. In general, a body of research has consistently shown increases in vegetative growth and yields compared to more traditional irrigation techniques as a function of scheduling and management. Perennial crops may also experience more rapid growth and earlier production under microirrigation because water and nutrient stresses on young plants with small root zones may be greatly reduced. Uniformity in plant growth across a field, due to uniform water and nutrient distributions, also contributes to overall yield increases.

Microirrigation must be managed as both a water and a nutrient application system. Fertilizers and other water soluble chemicals such as pesticides (e.g., nematicides, systemic insecticides, herbicides) and soil amendments (e.g., acids, polymers, powdered gypsum) can be efficiently and effectively applied through microirrigation systems. Buried drip irrigation systems are particularly amenable to the application of soil fumigants as well as other chemicals that tend to be fixed by the soil particles (e.g., some pesticides and phosphorus fertilizers).

If designed and managed properly, microirrigation systems can reduce off-site impacts of irrigation on wildlife habitat and aquatic ecosystems compared to other methods. Pesticide use is often reduced because the efficacy of systemic pesticides is enhanced. In arid areas, herbicide expenses are usually less because only a portion of the area is wetted so weed germination is reduced; and because the soil and plant canopy are generally drier, there is often lower fungal disease pressure and fungicide use is generally less (Scherm and van Bruggen, 1995). Plastic films (biodegradable and non-biodegradable), large sheet paper, and other mulches often work very well in drip irrigated crop culture to control weeds (and eliminate herbicide use) and reduce soil evaporation losses.

Microirrigation systems may enhance long-term sustainability of an agricultural operation because of their potential for maximizing water application efficiencies and minimizing chemical applications. Limited water supplies (quality and quantity) can be utilized more efficiently for agricultural production, thus providing more water for competing uses or reducing withdrawals from aquifers. In addition, microirrigation methods are low-pressure systems that typically use less total energy compared to sprinklers.

17.1.1.2 Disadvantages. Because of their relatively small orifice sizes, microirrigation emitters can be easily plugged due to physical, chemical, and biological factors. Clogging adversely affects uniformity, and can negate the benefits and effectiveness of microirrigation.

Microirrigation systems are generally expensive to install and maintain but are similar in costs to most other advanced irrigation methods. For larger systems (e.g., $\geq$10 ha) with relatively close plant spacing, their cost is comparable to permanent solid set sprinkler systems covering the same area although the filtration and chemical treatment systems are major expenses that can vary widely depending on conditions and system size. High-density plantings requiring large amounts of tubing may not be economical. Operational costs will be high due to the need for chemical treatment, filtration, and labor for routine flushing of lines, although lower energy costs and water savings may offset some of this increase. There can also be significant costs associated with the retrieval and disposal of tape/tube and non-biodegradable plastic mulches.

A high level of management is required to operate and maintain a microirrigation system. Managers require a greater level of training and proficiency than for surface or sprinkler systems. They command higher salaries and are usually employed year-round because of the need to retain their skills, however, they can generally cover three to four times as much cropped area as an irrigator using more traditional methods, primarily due to automation. The higher level of management also requires adoption of ancillary technologies (with their associated costs), such as irrigation scheduling, soil water monitoring, and frequent detailed plant tissue nutrient analysis for fertigation programs.

As a general rule, microirrigation systems are less forgiving of mismanagement or poor design than methods that irrigate a much larger portion of the root zone. These problems range from overirrigation and excessive leaching of chemicals to severe drought, salinity, or nutrient stresses.

Uneven distributions of water, nutrients, and roots across a field can create problems unique to microirrigation. The restricted wetted soil volume may affect the extent of the rooting system and the physical stability of a plant. Smaller rooting volumes also limit the amount of soil water available to buffer the plant against drought in the event of an irrigation system failure. In addition, the small wetted soil volumes increase the difficulty of maintaining an optimally balanced soil nutritional status because access to nutrients stored in adjacent nonirrigated soils is limited.

Pest problems may change because the frequent irrigation may create environmental and moisture conditions favorable to fungal diseases or pests that may not be concerns under other irrigation technologies (e.g., mites that favor dry, dusty conditions). Frequent irrigations may also create optimal conditions for some plant diseases requiring special management (e.g., fumigation before and/or after the growing season to minimize inoculum).

Polyethylene microirrigation tubing can be physically damaged by a number of mechanical and natural causes. Damage by farm equipment commonly occurs. Coyotes, rodents, and other animals may damage tubing, especially when looking for water in arid areas. Gophers and other rodents may cut through buried tubing as they burrow. Woodpeckers have been reported to peck holes in tubing. Insects and spiders can plug emitters, but may also enlarge orifices when searching for water. Tall grass, weeds, spider webs, and large insects can stop the rotation of microspinners.

17.1.2 Soil, Water Quantity, and Water Quality Considerations

17.1.2.1 Soils. A microirrigation system must be designed and managed to match the soils on which it is used. Deep sandy soils often have little lateral spreading of water requiring several small irrigations each day and/or microsprinklers to expand the wetted root volumes. Improper scheduling due to poor system design or management can result in excessive deep percolation and leaching of nutrients. When application rates exceed infiltration capacity, soils become saturated, weeds and other problems may be enhanced due to large wetted areas, and runoff may even occur. In addition to environmental pollution considerations, soil waterlogging can result in increased plant disease and induce plant physiological disorders.

Soil salinity will affect system design and management because salts accumulate at the edges of wetted areas and on the soil surface. Deficit irrigation may lead to excessive salt levels in the soil profile. These salts need to be periodically leached, which can be complicated by the development of preferential flow paths. The use of plastic film mulches that reduce soil evaporation have also been found to reduce soil salinity directly under the mulches. Injection of acids (e.g., sulfuric) may sometimes be required to increase the solubility of salts to facilitate leaching.

Maximum leaching of salts will occur near the emitters, with effectiveness decreasing with distance from the emitters. Seed germination of some crops (e.g., lettuce) may require sprinkler irrigation to move salts below the seed bed. In areas of low rainfall, it may be necessary to sprinkler irrigate periodically to drive salts below the tubing depth. Another salinity-control technique is to irrigate during rains, pushing salts to the outside of the wetted volume. Bed shaping—forming beds higher than necessary—has also been used. The drip system is then operated to push the salts to the surface. The salty surface soils are then scraped to the side and the crop planted in the less-saline soil lower in the bed.

A complete soil chemical analysis should be conducted as an initial part of the planning process, for water application as well as for cultural decisions. Salination and/or changes in soil pH may also develop because of the quality of the water supply or as a result of various water treatment and chemical/fertilizer management programs. Soil pH can have major effects on the availability of soil nutrients to the plants and in some cases can cause toxicity. Soil amendments (e.g., gypsum or lime) should be applied prior to planting to ameliorate existing or anticipated problems, although some supplemental gypsum can be injected through the microirrigation system. Producers should annually monitor the soil chemistry in the rooting volume throughout the life of the irrigation system.

17.1.2.2 Water quantity. Timing, availability, and reliability of long-term water supplies must be determined. Seasonal irrigation requirement depths for many crops can range from 100 to as much as 2000 mm. Canal and on-farm delivery systems in many areas of the world are often designed to satisfy the requirements of surface or sprinkler irrigation (e.g., 1.0 L s^{-1} ha^{-1} based on the farm's total irrigated area) or deliveries may be based on calendar rotations (e.g., every 7 days) that are inappropriate for microirrigation designs. ET may be higher with microirrigation due to reduced drought stress, although most of the time it will be less than under other irrigation methods due to reduced soil evaporation losses. Supplemental wells and storage ponds may be required to utilize microirrigation technologies effectively under some conditions.

17.1.2.3 Water quality. Physical, biological, and chemical water quality, including salinity, is a major concern in the management of all microirrigation systems (Nakayama and Bucks, 1991; Lamm et al., 2000). The physical, biological, and chemical characteristics of the water supply from all sources (e.g., wells, canals, reuse ponds) must be considered. The potential for emitters to become plugged by physical, chemical, or biological contaminants can create significant problems. Success hinges on filtering and treating the water to match actual water quality conditions throughout the year with both surface and groundwater. It is sometimes not economically feasible to treat a water source to make it suitable for microirrigation and other irrigation methods should be considered.

A successful water treatment program must accommodate worst-possible conditions while meeting high microirrigation water quality standards. The potential for soil salination due to the water supply must be assessed. Fertigation and injection of other chemicals require knowledge of the water chemical constituents to ensure compatibility between injected chemicals as well as to help determine suitable chemical water treatment needs and procedures.

Laboratory tests are necessary to determine the nature and composition of inorganic contaminants, as well as the relative proportions of each that may create significant problems in the long-term management of the system or affect the crop's utilization of water and nutrients. Specific concerns may be pH, salinity (electrical conductivity), calcium, magnesium, sodium, iron, manganese, carbonates, bicarbonates, and sulfur. Organic contaminants may sometimes be problematic, but these are usually controlled by good filtration and chlorine treatments.

A suitable treatment program may consist of several progressive steps or phases including: settling basins, gravity screens, centrifugal separators, screen filters, disk filters, and/or media filters, plus the injection of chlorine, acids, or other water treatment chemicals. Appropriate design and management of each stage of the treatment system provides the capability of maintaining high water quality standards throughout the life of the project despite variations in the physical and chemical properties over time. More specific and detailed information on water quality concerns related to microirrigation is discussed in several sections later in this chapter

17.1.3 Environmental Considerations

Substantial environmental advantages can result from properly designed, maintained, and managed microirrigation/chemigation systems. Environmental advantages result from reduced diversions of water, reduced chemical usage, and reduced groundwater contamination by reducing leaching of salts and other chemicals below the root zone.

Although microirrigation can achieve highly uniform water applications, it is in fact always less than perfectly uniform. As a result, some portions of the field will be overirrigated and some will be underirrigated. Overirrigation will waste water and cause deep seepage which may contaminate underlying groundwater resources. Deep seepage losses occur due to overestimating ET causing excessive applications; nonuniformity of irrigation; overirrigation because of poor scheduling or lack of automation and feedback; and leaching for soil salinity management. Underirrigation will result in a yield reduction and may cause undesirable soil salinity accumulations.

Improper application of some pesticides and fumigants may negatively affect beneficial soil biota, including earthworms, bacteria, fungi, and insects. Disposal of flush water from filters and lateral lines may sometimes be a problem, especially if pesticides or fertilizers are in the effluent.

17.1.4 Economic Considerations

The ultimate goal of any agricultural activity is to achieve maximum net economic return. The irrigation system uniformity, irrigation scheduling practices, cost of water, yield price, yield reductions by deficit irrigation, and damage caused by overirrigation, including possible groundwater contamination, are all very important factors affecting the economic return from a microirrigated production system. Expected economic returns and the required system uniformity can also affect emitter selection.

17.2 MICROIRRIGATION SYSTEMS

17.2.1 Methods

Microirrigation methods are generally defined by the water emission device. Emission devices range from thin-wall plastic tube with simple orifices, microsprinklers, orifices and long-path laminar flow emitters and microtubing, to more elaborate and efficient turbulent-path and pressure-compensating emitters. Some emission devices are manufactured as an integral part of the plastic tubes and tapes while others are attached during installation.

Surface applicators include emitters (drippers), microsprinklers/ microsprayers, and bubblers, all of which apply water on or above the surface of the soil. Subsurface drip involves the use of point-source emitters or line-source emitter tubing and tapes to apply water below the soil surface at depths depending on the soil type and crop. Surface and subsurface drip have also been used for water table control in some humid areas as a variation of subirrigation, primarily on vegetable crops. Drippers and bubblers are designed to apply water at or slightly above atmospheric pressure, whereas microsprinklers apply water from about 70 to more than 250 kPa.

Two general categories of microirrigation laterals are polyethylene tape and tubing. Tapes are collapsible, thin-walled, low-pressure polyethylene tubes with built-in emitters or orifices. Tubing is more rigid and more expensive than tape, has thicker walls, and may or may not have pre-installed emitters. Tapes and tubing may also be divided into five classes depending on use: (1) disposable, thin-walled surface tape (1-year life); (2) shallow, buried tapes (1-5 year life); (3) reusable/retrievable surface tapes (1- to 3-year life); (4) retrievable surface tubing (multi-year life); and, (5) buried tubing (multi-year life). Tapes are most commonly used on annual or seasonal row crops while tubing is used more often on perennial crops. ASAE Standard S435, Polyethylene pipe used for microirrigation laterals, presents manufacturing and testing requirements for tubing (ASAE, 2005c).

Tapes typically have wall thicknesses ranging from 0.1 mm to 0.64 mm and inside diameters may range from 9.5 to 28.6 mm. Emitters usually have close, uniform spacing (e.g., 3.5-60 cm) along a lateral line and emitters are simple orifices, long path, labyrinth flow paths. or a combination. Emitters may be embossed within the welded seam of the tape or they may be separate, pre-molded devices installed during fabrication. Currently, emitters on tapes are not pressure compensating, and water discharge rates of individual tape emitters range from 0.2 L h^{-1} to over 7.6 L h^{-1}. Tape operating pressures range from 20 kPa to about 140 kPa. They should always be installed with the emitters facing up because of plugging problems due to sediment accumulations in the bottom.

Tubing has wall thicknesses typically ranging from 0.25 mm to over 0.9 mm with inside diameters from 9 mm to over 35 mm. Pre-installed emitters on tubing have uniform spacing, however, in contrast to tapes, point-source emitters and microsprinklers can be installed in the field at any spacing on the tubing to meet specific irrigation requirements. Emitters are either non-pressure compensating or pressure compensating with water discharge rates from 1.5 to over 20 L h^{-1}. Microsprinkler discharge rates range from about 5 to over 40 L h^{-1}. Operating pressures range from about 40 to over 250 kPa.

17.2.1.1 Drip and microsprinkler emitters. Water distribution by drip and microsprinkler emitters can be characterized as line-source or point-source applications for both tapes and tubing. Line sources apply water in a continuous or near-continuous pattern along the length of the lateral. In this category are soaker hoses or porous pipes (line-source emitters) in which the entire pipe wall is a seepage (and filtration) surface, as well as drip tapes with closely spaced (e.g., 15-30 cm) emission points whose water application patterns overlap. Point-source emitters can be grouped based on their flow characteristics into long-path emitters (microtubing, laminar-flow, and turbulent-path emitters), short-path emitters (microsprayers and other orifice emitters), orifice-vortex emitters, and pressure-compensating emitters. These devices apply water at discrete points and overlap between wetting patterns may or may not occur, depending on emitter spacing, irrigation duration, and emitter flow rate.

Orifices and microtubing emitters are the two simplest emission devices. They were common in the early development of drip irrigation, but are currently only used on tapes. Plugging is usually a serious problem for orifice emitters due to small (less than 0.3 mm) outlet diameters and low discharge rates. Orifice-vortex emitters are orifice emitters that have been modified so that water enters the emitter with an angular velocity such that the circular vortex motion provides additional energy loss so that the orifice can be larger and less prone to plugging.

Microtubing is a long-path emitter inserted into the lateral line. Different lengths of microtubing can produce various flow rates depending on their dimensions and water pressure. The size of microtubing typically ranges from 1 to 10 mm in diameter, and the flow characteristics can be either laminar or turbulent, as a function of tube size. The laminar-flow (small-diameter) microtubing tends to accumulate small deposits and is quite susceptible to partial plugging. The long-path or spiral emitter is basically a microtubing emitter that is wrapped around a short, larger plastic tube to make a more compact unit. Larger-sized microtubing with turbulent flow produces a bubbler effect and usually has few plugging problems (Rawlins, 1977).

The labyrinth emitter, designed with long intricate passageways, will create turbulent flow at normal operating pressures and is often called a turbulent or turbulent-path emitter. The turbulent flow resists plugging by allowing the flow path to be as large as possible and preventing small particles from settling or becoming lodged in the passageway. Flow rates from turbulent path emitters are also relatively insensitive to temperature fluctuations (Wu and Phene, 1984; Rodriguez-Sinobas et al., 1999), thus avoiding a major cause of nonuniform water application under field conditions. Currently, most point-source emitters utilize turbulent-flow paths to control the application of water from tubing and some tapes.

Emitters can be inserted or molded into the tubing or tape during the manufacturing process. With internal "in-line" emitters, there are no protrusions to interfere with mechanical installation or retrieval of the tubing or tape. Alternatively, emitters (and microsprinklers) can be attached to the outside of the tubing when the system is installed, usually by manually punching a hole and inserting the barbed end of the emitter. This procedure requires more labor but it allows a system to be customized to match the needs of widely or unevenly spaced plants.

Microsprinkler or minisprinkler emission devices are generally simple orifices and include small, low-pressure minisprinklers, foggers, spitters, jets, and sprayers that are installed in the field on tubing. These typically apply water (at 35 to 70 L h^{-1}) to larger areas than drip emitters, but do not uniformly cover the entire cropped area. They are used to irrigate tree crops, shrubs, widely spaced plantings, and localized grass areas with extensive root systems, especially on sandy soils where lateral movement of soil water is limited by soil hydraulic properties or other areas with greatly restricted root zone depths. Nozzle sizes typically range from 0.5 mm to 2 mm; plugging problems are greatly reduced with nozzle sizes larger than 0.75 mm (Wu et al., 1991) combined with adequate filtration and chemical treatment of the water. Microsprinklers are installed after the lateral tubing or pipe has been laid in the field. They may be inserted with barbed fittings directly into the tube but are more commonly mounted on stake assemblies and connected to the lateral lines with 4-6 mm tubing. Some may also be mounted directly on threaded PVC fittings on the lateral. The state of the art for microsprinklers is advancing rapidly and improved microsprinklers (e.g., pressure-compensating and self-cleaning) are being developed and tested.

A variation of the microsprayer pulses the water jet in short bursts of up to 60-70 cycles per minute, which serves to minimize application rates while maximizing the wetted radius. These can be an advantage on heavy soils with low infiltration rates or soils where poor lateral water movement may be a concern.

Both drip emitters and microsprinklers are available as pressure-compensating devices. These use a flexible orifice that changes its diameter depending on the pressure, thereby regulating the flow. Pressure-compensating devices are used to provide uniform flows from each emitter along a lateral whenever elevation differences or excessive pressure losses to long lateral lengths cause flow variations to exceed design standards. However, these devices are more costly than standard emitter devices.

17.2.1.2 Low-head bubbler irrigation systems. Bubblers are large-orifice, low-pressure emitters that apply water at discrete points but at considerably higher rates than common drip or microsprinkler emitters. Filtration requirements are greatly reduced, but flow rates are often so high that basins or very flat terrain may be required to prevent runoff. Some bubblers are designed to operate on gravity flow or low-head, high-flow pumps (1 to 8 m of head), while others use pressurized (e.g., 200 kPa) pipelines to distribute water. The higher-pressure bubbler systems use special devices with large openings where flow rates can be mechanically adjusted at each location.

Low-head bubbler irrigation systems use microtubing emitters to deliver water to the crop. These systems consists of a main line connected to a water source, a constant-head device, manifolds, laterals, and small-diameter (e.g., 4 mm to 26 mm inside diameter microtube) delivery hoses. Laterals are usually buried and laid between rows. A sufficiently long, large-diameter (e.g., 5 to 25 mm) delivery hose is inserted into the lateral pipe to deliver water to a plant. The delivery hoses are anchored to a tree or stake, and the outlet elevations are adjusted to the hydraulic energy gradient so that water flows or "bubbles" from all hoses at equal rates.

Bubblers are well-suited for economical irrigation of trees and vine crops and are being developed for turf and landscape applications. Bubbler systems do not usually require elaborate pumping and filtration systems, but are not widely adopted (Yitayew et al., 1995). Design considerations and installation of low-head bubbler systems are discussed by Yitayew et al. (1995), Yitayew et al. (1999), Thorton and Behoteguy (1980), and Rawlins (1977).

17.2.2 Wetting Patterns

The applied water moves through the soil largely under unsaturated flow conditions at the wetting front. The distribution of water and the shape of the wetted volume can be predicted from the physical laws of capillary movement for either point sources or line sources (Warrick and Lomen, 1983; Clothier et al., 1985; Philip, 1991; Or and Coelho, 1996; and many others).

A point-source emitter will provide a wetted volume in the soil, which is affected by the initial soil water content, emitter flow rate, irrigation frequency and duration, capillary movement of water and the water-holding capacity of the soil. In arid areas, the emitter creates wetting patterns in the soil that determine the size and shape of the crop root zone.

"Point sources" refer to individual emitters with discrete application points. A point-source emitter or a group of emitters forming a point source are generally used for tree crops or other widely spaced plantings. Microspray emitters with large spacing such that their wetting patterns do not overlap are also point-source emitters. Even groups of emitters with overlapped wetting patterns but designed as a unit, such as around individual trees, can be considered to be a point source.

"Line source" wetting patterns develop when emitter applications along a lateral merge and form a half-cylinder wetting pattern or trough of wetted soil in the field. High-density row crops are usually irrigated with line sources by lateral lines with closely spaced emitters or microsprayers.

The wetting pattern for a point-source emitter in a homogeneous soil is a three-dimensional hemispherical shape with a water gradient from the center (point source) to the edge of the sphere. The wetting pattern for a line-source application by closely spaced emitters will form a two-dimensional half-cylinder shape in homogeneous soil. In layered soils, the wetting patterns will tend to be confined within the top layer so the bottom of the hemisphere or half-cylinder will be relatively flat and form a wetting pattern shaped like a disk or rectangle.

Hardpans in many soils have smaller pore spaces than the material above or below. The hard pan serves as a barrier because capillary water movement does not readily occur from smaller to the larger pores below the hardpan. Likewise, where a fine soil is underlain by a coarser material, irrigation must saturate the upper soil before water will enter the coarser layer.

17.3 DESIGN FACTORS

17.3.1 General Considerations

The design of a water application system will determine the maximum potential performance level for any proposed crop use, whereas management dictates the actual benefits received and the magnitude of any ecological impacts. High-quality installations are more easily maintained and are much less expensive to operate over time than a substandard design that requires frequent repairs and has a shorter operational life. Minimum requirements for the design, installation, and performance of microirrigation systems are presented in ASAE Engineering Practice EP405.1, Design and Installation of Microirrigation Systems (ASAE, 2005b).

The first rule of microirrigation design is the same as for all irrigation systems: keep it as simple as possible. The system must be designed to meet the users' level of expertise and it must fit within their perceived needs and cultural practices. It must be reliable and sustainable, able to manage salts, easy to maintain, and allow for needed tillage and harvest operations.

The design and installation must be site-specific. They are governed by soil type and depth distributions, topography, climate, water quality, water quantity, the proposed crops and cropping systems, as well as the preferences of the irrigator. However, the fundamental aspects of high-frequency irrigations, limited wetted rooting volumes, filtration and chemical treatment of the applied water, and extraordinary consideration of the spatial uniformity of water applications per emission device are common to all microirrigation systems. Designs should facilitate maintenance. Ponds and chemigation installations should be fenced for safety of workers, children, and animals. Water treatment, filtration, and lateral line flushing must be high priorities.

Due to low operating pressures and chemigation requirements, hydraulic variables are more rigorous for microirrigation systems than for other types of systems operating at higher pressures. Total system pressures should normally not be permitted to vary by more than 20% unless pressure-compensating emitters are used.

The total allowable pressure loss of the whole system, which provides the desired design uniformities, is selected at the start of the design process and depends on the preferred pressure regulation strategy (e.g., optimal combinations of valves, pressure-compensating emitters, and topographic layouts). Lateral, subunit, submain, mainline, and control head system pressure losses are assigned so that the sum does not exceed the total system design criteria.

As much as possible, the systems should be designed based on anticipated actual installed emitter discharges, which are often different from the manufacturer's literature due to factors such as unit-to-unit variation in manufacturing, system elevation changes, system pressure variations, emitter wear, pressure losses in stake assemblies (microsprinklers), and varying lengths of small-diameter (e.g., 4- to 6-mm diameter) supply tubing from the lateral to the emission devices. The coefficient of flow variation of the emission devices should always be less than 10%. Distribution uniformities should normally be greater than 90%, especially when chemigation will be used.

Pipelines (usually PVC) should be placed at sufficient depths to avoid damage from farm and construction equipment. Concrete blocks to prevent pipeline movement (thrust blocks) need to be placed at appropriate locations to prevent failure of pipelines, valves, and other components. Adequate air relief, vacuum breakers, and pressure relief valves must be sited appropriately to ensure proper operation. Information and procedures for installation of PVC pipe can be found in ASAE Standard S376.1, Design, Installation and Performance of Underground, Thermoplastic Irrigation Pipelines (ASAE, 2005a). Some emitters are also designed to facilitate air relief in the laterals used on highly variable topography.

Designing for ease of maintenance is critical. It is important to ensure that there is easy access to all equipment and various system components for maintenance and replacement whether buried or on the surface. All aboveground components are typically at least 0.4 m but not more than 1.5 m above concrete or soil surfaces for ease of maintenance. All pipe nipples should have sufficient length for wrenches. Fenced areas should have provisions for equipment access.

Valves should be installed to hydraulically isolate components requiring frequent cleaning, repair, or replacement, such as inline filters. Likewise, it should be possible to isolate blocks within a field for maintenance without shutting down the entire system. Unions, flanges, or Victaulic couplings should be provided for easy removal of the affected components. In areas of cold climate, there must be the capability to winterize the entire system, including drain valves, infiltration pits and, if necessary, provisions for using compressed air to remove water when pipelines do not have appropriate slopes for gravity drainage. Pumps, filters, flow meters, gauges, tanks, and valves may also require special fittings or removal for cold-temperature protection. Pumps and electrical panels should be protected from exposure to the sun by covers or shading to reduce heating and maximize their useful life.

A lack of understanding of the fundamental benefits and limitations of microirrigation has resulted in many systems that are unintentionally under-designed. The most common signs of an under-designed system are the inability to fully provide for the water needs of the crop during peak water use periods and inadequate line flushing velocities. Operational flexibility may also be limited by a poor design.

External factors such as soil salinity, soil hydraulics, crop sensitivity, water quantity, water quality, and any environmental concerns must be addressed from the beginning of the design process. These concerns will guide the selection of the tubing, emitters, and emitter spacing.

17.3.2 Field and Crop Considerations

Microirrigation distributes water directly into the root zone of crops, so the selection of emitters must consider the rooting characteristics of the crop, the expected volume of soil to be wetted in the field, the total amount of water to be applied, and the estimated total allowable time per irrigation per day. The selection of emitters and spacing will be based on the maximum application amounts, estimated irrigation times, water supply considerations, and hydraulic capacities.

Perennial crops may require one to five emitter laterals per plant row to adequately supply water needs depending on soil types, water emission device, size of plants and climate. Established, widely spaced plantings, such as pecan trees, should have at least two lines, 2 to 3 m on either side of the row. More closely spaced perennial crops, such as asparagus, grapes, and hops, may need only one lateral per row or bed. Plantings in humid regions may require more laterals and microsprinklers due to the extensive rooting systems that are stimulated by recurrent rainfall to ensure adequate delivery of water and nutrients to the roots.

Crops using line-source drip tapes, such as row crops and shallow-rooted or closely spaced perennials, are usually designed based on flow rate per unit lateral length. Widely spaced permanent crops using tubing with discrete emitters are usually designed using discharge per outlet.

Point-source emitters with non-overlapping wetting patterns, including microsprinklers, are usually selected for low-density plantings of trees, vines, or vegetables. Emitter locations should ensure that the wetting patterns are within the plant's root zone and that 25% to 50% of the potential root zone is irrigated. High-density row crops are generally irrigated by tapes or line-source lateral lines. Line-source systems should be designed so that the entire root system of high-density crops is within the wetting pattern.

Microsprinklers may be required to increase the wetted area to maximize soil water availability and avoid leaching on light, highly permeable soils or areas with shallow root zones. Widely spaced permanent crops, such as citrus, may require microsprinklers to irrigate a relatively large fraction (e.g., > 50%) of the root zone for peak productivity, especially in humid areas.

For the same lateral diameter, emitters with higher flow rates will have a larger pressure variation per lateral length compared to low-flow emitters. High flows per unit length of tubing will also limit lengths of runs.

It is generally desirable to have the highest discharge rates that meet soil hydraulic conditions, because higher-flow tapes and emitters have larger orifices and are less subject to plugging and thus provide higher uniformity and maximum operational flexibility in scheduling. Buried drip systems are strongly affected by the saturated hydraulic conductivity of the soil and emitter flow rates are selected depending on whether the grower wants to be able to wet the soil surface.

17.3.3 System Considerations

System hydraulic capacity for irrigation should be based on peak evapotranspiration demands for the most critical period for a mature planting, usually in the range of 5 to 10 mm per day depending on the crop, climate, and application efficiencies. If economical and practical, a design should aim to supply about 120% of peak ET to provide the capacity to catch up in the event of maintenance down times, line breakage, equipment failures, electrical outages, or other problems.

17.3.3.1 Pipe systems. Main and submain lines utilizing PVC pipe that is not UV-protected should be buried. It is advisable to keep control valves above ground to facilitate maintenance and keep submains full of water to minimize system drainage and decrease startup times. Each block should have isolation valves so that it can be maintained without shutting down the entire system. Pipes, fittings, and valves should have sufficient pressure ratings to withstand waterhammer surges and static pumping heads.

The proper size of mainlines, submains, headers, manifolds, and valves, as well as operating pressures, may be dictated by flushing requirements. Most systems will not have sufficient hydraulic capacity to flush the entire system at once. More often, the system will be flushed in zones, with other zones shut off so that sufficient pressure and flow will be available to flush each zone.

Even small changes in elevation at the low pressures common to microirrigation can cause large flow variations. Pressures can be managed by proper pipe sizing, special valving, and/or carefully controlling elevation differences within blocks. Pressure regulation must be designed to ensure uniform water distribution to various parts of the microirrigation system and to reduce fitting failure due to excess pressure build-ups. Non-pressure-compensating emitters and tapes must operate at consistent inlet pressures and be properly sized with appropriate run lengths and lateral diameters while considering field slope to optimize application uniformities. Inlet pressure regulation with very low-pressure systems (e.g., <50 kPa) are often adjusted by varying the length and diameter of the tubing connecting the tape to the manifold. As a minimum, pressure gauges should be placed at the pump discharge, at both sides of the filters, and at the entrance to each zone.

The maximum allowable flow velocities in main and submain pipes should normally be less than 1.5 m/s at the maximum expected flow rates to avoid excessive friction losses and surge problems. When unconstrained pipe fittings are used, thrust blocks should be used at all elbows, tees, control valves, dead ends, etc.

Lateral lines should always run across or down slope to obtain high uniformity and ensure adequate flushing velocities to minimize plugging problems. They should not run up slope if possible because particulates tend to settle at the lower elevations and cannot be easily flushed. Likewise, lateral-flushing requirements mandate that emitter lines be supplied water from only one direction because it is desirable to have particulates accumulate at the distal ends of the laterals for flushing.

Systems of pressure-compensating emitters generally follow the same guidelines as systems of non-compensating emitters. These are mostly used when topographic conditions cause significant pressure differences due to elevation changes. Pressure-compensating emitters are also used when lateral lengths or elevations are such that pressure losses from friction and other losses are too high for uniform flow rates from emitters. In this case, line pressures can be boosted to match the operating range for the pressure-compensating emitters to ensure more uniform flows. These devices are not always economical and their use needs to be evaluated on a case-by-case basis.

17.3.3.2 Filtration. A well-designed and well-managed filtration system is critical for every microirrigation installation. It must be supported by appropriate chemical and biological water treatments (Bucks et al., 1979). These systems are required because open ditches, canals, and ponds generally contain organic contaminants and particulate matter. Pumps on wells may also introduce sand particles into the water stream. Suspended solid concentrations greater than 100 mg L^{-1} will require extraordinary filtration systems. These contaminants must be removed before entering the irrigation system. Filter operation requires pressures in excess of the normal system operational pressures, which reduces potential energy conservation benefits of low-pressure systems. Specific filtration devices and concerns are discussed in Section 17.8.2, and in much more detail in Nakayama et al. (2007).

17.3.4 Tubing Selection and Spacing

Tubing should be selected based on the proposed economic life of the installation as well as cultural practices, harvesting equipment, and environmental conditions. For example, buried installations that will be subjected to direct equipment traffic should specify heavy-walled hose rather than thin-walled tape products. Highly variable topography or extraordinary long runs may require large-diameter hose with high bursting strengths.

The lengths of run will depend on the specific hydraulic properties of each tubing type, emitter flow requirements, and field slope. To maintain high uniformities, lateral lengths of low-flow, low-pressure, thin-walled (e.g., <0.25 mm thickness) tapes should normally not exceed 200 m. Thin-walled, high-flow tapes are normally less than 150 m in length. Large-diameter, thicker-walled (>0.25 mm thickness) hoses and tapes can sometimes be as long as 400 m or more. Pressure-compensating emitters may be required for small-diameter tubing, high operating pressures, long runs or steep slopes.

Placement of tubing with respect to plants depends on expected cultural operations, emitter spacing, emitter flow rate, size of the root zone, and soil hydraulic characteristics. Typically, row crops have the tubing placed within 0.05 to 0.10 m of the plant for seed germination and tillage. Placement on permanent crops can vary from 0.1 to 2 m although most are within 0.5 m of the plant row. Tubing can be moved as the plant matures. Tubing can also be suspended above the ground on trellised crops allowing for easier maintenance, weed control, and less damage by mechanical operations.

The spacing between drip lines depends on the crop being irrigated, the lateral extent of the crop root zone, and water redistribution in the soil. Installations in humid areas may require that a larger portion of the root zone be wetted to match crop rooting characteristics and increase uptake efficiency of water and nutrients. Widely spaced trees and vines typically have one or two dripper lines per crop row. Sandy soils with little lateral movement as well as areas susceptible to wind and water soil erosion may require several drip lines or the use of microsprinklers to cover a larger portion of the root zone.

17.3.5 Emission Device Selection and Spacing

The selection of the specific water-emission device determines many of the operational characteristics of a microirrigation system. For example, labyrinth turbulent-flow emitters are commonly used because they have an equivalent hydraulic diameter of 0.75 mm and, thus, a low plugging potential.

Emitter spacing should be selected to irrigate a sufficient root zone volume to provide for the water needs of the crop. Low-density plantings, such as tree crops, may have several emitters per tree, but emitter spacing can be flexible as long as an adequate volume of root zone is irrigated (e.g., >25% in arid regions, >50% in humid regions). For high-density plantings such as row crops, the root systems merge along the row, and closely spaced emitters or line-source systems should be used to apply water uniformly along the row length.

17.3.6 Emitter Plugging Potential

The characteristic low application rates, low pressures, and small orifice openings that are unique to microirrigation systems also create emitter plugging problems. Selection of the proper type and size of emitters will reduce the potential for plugging, although all emitter types can completely or partially plug. Less plugging will occur when irrigation water is applied with proper filtration and water treatment.

When a number of emitters are considered as a unit, such as several emitters grouped to irrigate a single tree, the uniformity of water application will be much improved as compared to using a single emitter per tree (Wu et al., 1988b). System variability can be controlled within 10% when plugging is zero and at least two emitters are used in a group.

The effect of plugging on water application uniformity in the field can be minimized by closer emitter spacing or emitter grouping (Bralts et al., 1987b). A study of contiguous, random plugging (Wu et al., 1991) showed that even with as much as 20% to 30% total plugging, only 1% of the plugging consisted of four to five consecutively plugged emitters. When the coefficients of hydraulic and manufacturer's variation are both less than 10% and emitters are placed in groups of four per tree, 10% to 20% random plugging will still maintain an overall coefficient of variation (CV) of 17% to 25%, respectively (Wu, 1993a). For high-density row crops when the coefficients of hydraulic and manufacturer's variation are less than 10% and the emitter spacing is half of the wetted diameter, a 10% to 20% plugging will produce an overall CV of about 20% to 30%, respectively.

A superposition technique (Wu et al., 1989) was used to evaluate the spatial uniformity along the lateral by adding soil-water patterns from all emitters at various specified spacings. This work showed that plugging, followed by emitter spacing, were the most significant factors affecting the spatial uniformity. Wu (1993a) showed that emitter grouping was as significant as spacing. Both the hydraulic design and manufacturer's variation were less significant than plugging, grouping, and emitter spacing as long as their individual coefficients of variation were less than 10%.

Neither the soil-wetting patterns nor the plugging distributions were highly significant when soil-wetting patterns overlapped by 50% along a lateral. When the hydraulic design of a drip irrigation system is based on a 20% emitter flow variation, a 90% and 70% uniformity coefficient can be achieved for 0% and 20% plugging, respectively, as long as the emitter spacing is designed for 0.5 of its wetted soil diameter (Wu, 1993b).

17.4 HYDRAULICS OF EMITTERS AND EMITTER DESIGN VARIATION

The basic relationship between emitter flow rate and pressure is given as:

$$q = ch^x \tag{17.1}$$

where q = flow rate
c = emitter discharge coefficient
h = pressure head
x = emitter discharge exponent.

The x value is used in emitter selection because it characterizes the flow type in the emitter and varies from 1 to near zero. When $x = 1$ the emitter is a laminar flow emitter (capillary) whereas x will have a value around 0.85 for microtubes, 0.65 for long or spiral path emitters, 0.5 for fully turbulent flow emitters, about 0.4 for a vortex emitter, and near zero for a fully pressure-compensating emitter. For a given hydraulic variation, less flow variation will occur with turbulent flow emitters than laminar flow emitters. When the hydraulic design is based on a 20% pressure variation in the microirrigation system, fully turbulent flow emitters ($x = 0.5$) will produce only about 10% emitter flow variation while the laminar flow emitters ($x = 1.0$) will produce 20% emitter flow variation.

17.4.1 Hydraulics of Orifice Emitters

The discharge rate from an orifice or a short-length nozzle is determined by the hydraulic pressure inside the lateral line at the orifice and the orifice dimensions. When the flow path is fixed and the flow cross-section area is constant, the emitter flow rate will be affected by only the hydraulic pressure.

The flow rate from an orifice or nozzle type emitter can be theoretically expressed as:

$$q = c_1 a \sqrt{2\,gh} \tag{17.2}$$

where q = emitter flow rate
c_1 = discharge coefficient
a = cross-sectional area of flow
g = acceleration due to gravity
h = pressure head at the base of the emitter.

When the cross-sectional area is constant, Equation 17.2 can be rearranged as a simple power function similar to Equation 17.1:

$$q = C\, h^{0.5} \qquad (17.3)$$

where C is the emitter discharge coefficient and equal to $c_1 a\sqrt{2\,g}$.

17.4.2 Hydraulics of Microtube Emitters

A microtube is a small pipe. The hydraulics of microtubes is the same as for pipe flow. Thus, the equation for energy drop by friction in the microtube can be expressed by a simple power function:

$$h = K\frac{q^m}{D^n}L \qquad (17.4)$$

where h = head loss due to friction and is also the pressure head at the inlet of a microtube
K = emitter discharge coefficient
q = emitter flow
m = flow rate (q) exponent (m is 1 for laminar flow, 2 for complete turbulent flow and 1.75 for turbulent flow in a smooth pipe)
D = inside diameter
n = diameter exponent
L = length of microtube.

Microtube discharge can be determined by rearranging Equation 17.4 as:

$$q = \left(\frac{D^n}{K\,L}h\right)^{\frac{1}{m}} \qquad (17.5)$$

For a given microtube emitter in which the length, L, and diameter, D, are fixed, the emitter flow and hydraulic pressure head is often presented as a simple power function (Equation 17.1) where C is a coefficient and is a constant, $x = 1/m$ and is 0.5 for turbulent flow and 1 for laminar flow. Depending on turbulent flow conditions, x will be between 0.5 and 1.0.

17.4.3 Hydraulics of Long-Path and Labyrinth Emitters

The relationship between flow rate, q, and pressure head, h, can be expressed by the same relationship given above for long-path (including spiral-path) and turbulent-flow emitters. The two power function coefficients, C and x for individual long-path and labyrinth emitter, are determined by hydraulic laboratory testing. Values for x will range between 0.5 and 1.0 but are typically 0.65 to 0.85.

17.4.4 Hydraulics of Pressure-Compensating Emitters

When an emitter is designed so that the cross-section area decreases with respect to pressure,

$$a = b\, h^{-y} \qquad (17.6)$$

where a is the cross-sectional area of the emitter flow path, a nozzle, or microtube; b

and y are coefficients. By introducing Equation 17.6 into Equation 17.2 and rearranging, the emitter flow and water pressure can be shown as:

$$q = C_2 h^{0.5-y} \tag{17.7}$$

where C_2 is a coefficient. Equation 17.7 shows that the exponent, $0.5 - y$, can be smaller than 0.5, which indicates a reduced effect of pressure head on emitter flow as compared to a turbulent flow emitter. If the y value is 0.5, the exponent will be zero and no changes in emitter flow will occur. When this occurs, an increase of water pressure will cause a decrease in cross-sectional area of flow that exactly compensates for the increase in pressure, and the emitter will be fully pressure compensating. However, if y is greater than 0.5, the exponent will be negative and flow rate will decrease with increasing pressure. The concept of pressure compensation can also be applied to microtube emitters in a similar manner.

17.4.5 Emitter Flow Variation

Microirrigation is characterized by frequent water applications at low application rates. Thus, even small variations in the magnitude of the emission device's flow rate may cumulatively represent relatively large changes in the total seasonal water applications. Factors that may affect emitter flow rate include manufacturing variation, temperature effects, plugging, emitter wear with time, elevation changes, and microsprinkler stake assembly losses.

17.4.5.1 Manufacturer's flow variation of emitters. The basic emitter flow, q, and water pressure, h, relationship (Equation 17.1) shows that if there is no pressure variation in the microirrigation system, all emitter flows should be constant and the emitter flow variation will be zero. However, in an actual field situation, there will always be emitter flow differences even under constant water pressure conditions. This variation is caused by small errors in the manufacturing process that result in flow differences from one emitter to the next. Any deviation in the flow passage area or shape from a standard size will cause emitter flow variation.

The manufacturer's variation is the variation in emitter flows from a random sample of emitters operated at the same pressure, and is expressed statistically as the coefficient of variation of emitter flow, CV_M, which is the standard deviation of emitter flow, S, divided by the mean value of emitter flows, $\bar{q}$.

$$CV_M = \frac{S}{\bar{q}} \times 100 \tag{17.8}$$

Test results show that the coefficient of variation for microirrigation emitters typically range from 3% to 20% (Solomon, 1979). Microsprinklers, microsprays, and minisprinklers usually have low manufacturer's flow variations of less than 3%, although there can be large differences in the uniformity of water application patterns. Emitters with CV_M values greater than 0.20 are not acceptable for microirrigation system design.

17.4.5.2 Temperature effects on emitter flow. The water temperature in a microirrigation line will be affected by the temperature of the air and soil surrounding the line. Exposed laterals and water will also be heated by solar radiation. Water temperature in a lateral line showed a 12°C to 17°C increase in bright sun (Gilad et al., 1968; Parchomchuk, 1976).

The temperature effect on a microirrigation system can be considered in two parts: the effect on emitter flow and the effect on lateral-line hydraulics. The first one depends on the design and shape of the emitter and the second one depends on the friction situation in the line caused by the increase or decrease of viscosity of water due to temperature changes. The hydraulics of a lateral line determines the pressure distribution and water movement in the system which, in turn, affects the temperature variation in the microirrigation system. Emitter flows will be affected by the water temperature at the base of the emitters along the lateral lines.

The effect of temperature on emitter flow depends on the type of emitter (Keller and Karmeli, 1974; Parchomchuk, 1976; Moser, 1979; Zur and Tal, 1981; Wu and Phene, 1984; Rodriguez-Sinobas et al., 1999). Temperature effects can be considered as insignificant when using both orifice and labyrinth-type turbulent-flow emitters (Wu and Phene, 1984; Rodriguez-Sinobas et al., 1999). Long-path laminar-flow emitters show an increasing emitter flow with increasing temperature. Vortex-type emitters show a decreasing emitter flow with increasing temperature (Rodriguez-Sinobas et al., 1999). The relationship between the emitter flow and temperature change can be expressed as a linear function.

The temperature profile along a lateral line can be shown as a power function (Solomon, 1984) or a straight line when the temperature of the last point was considered to be caused by end effect and neglected (Wu and Phene, 1984). A theoretical evaluation of friction drop along a lateral line with a linear temperature gradient showed that the shape of the energy gradient line is not affected (Peng et al., 1986).

17.4.6 Emitter Variation

The emitter exponent, x, also affects the relationship between emitter flow variation, q_{var}, and pressure variation, h_{var}, of a microirrigation system. This can be derived from Equation 17.1 (Wu et al., 1979) as:

$$q_{var} = 1 - (1 - h_{var})^x \tag{17.9}$$

where q_{var} can be simply expressed as the range of variation (Wu and Gitlin, 1974):

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \tag{17.10}$$

where q_{max} is the maximum emitter flow and q_{min} is the minimum emitter flow. The pressure variation, h_{var}, is derived in the same fashion as emitter flow variation, but should be within ±10% of the average emitter pressure.

Equation 17.9 shows that emitter flow variation is zero when $x = 0$, regardless of the pressure variation in the system. When $x = 1$, the emitter flow variation will have the same variation as pressure variation. This indicates that when the pressure variation, h_{var}, is 20%, the emitter flow variation for laminar flow emitters will also be 20%. But, for turbulent flow emitters, x equals 0.5, and a pressure variation of 20% in a microirrigation system will produce only about 10% emitter flow variation.

17.4.6.1 Combined variation. In the field, emitter flow rate variations are due to the combination of hydraulic variation and manufacturer's variation. The relationship between them was first determined statistically (Bralts et al., 1981; Bralts et al., 1987a) and then verified by computer simulation (Wu et al., 1985). The total emitter flow variation caused by both hydraulic and manufacturer's variation can be expressed by:

$$(CV)_{HM}^2 = (CV)_H^2 + (CV)_M^2 \tag{17.11}$$

where $(CV)_{HM}$ is the coefficient of variation of emitter flows caused by the combined effects of both hydraulic and manufacturer's variation; $(CV)_H$ and $(CV)_M$ are the coefficient of variation of emitter flows caused by hydraulic design and manufacturer's variation, respectively.

17.4.6.2 Grouping effects. When a number of consecutive emitters are grouped and considered as a unit (e.g., several emitters to irrigate a single tree), the uniformity of water application per tree will be improved (Wu et al., 1988b). The improvement depends on the magnitude of emitter flow variation caused by the hydraulic and manufacturer's variations. For the case in which the emitter flow variation is caused by hydraulics only and the manufacturer's variation is zero, there will be no grouping effect; that is,

$$[(CV)_H]_g = (CV)_H \tag{17.12}$$

where $[(CV)_H]_g$ is the coefficient of variation of emitter flow by hydraulics after grouping and $(CV)_H$ is the coefficient of variation of emitter flow from only hydraulics.

For the case in which emitter flow variation is caused by manufacturer's variation only and hydraulic variation is zero, the emitter flows will follow a normal distribution and the grouping effect will be shown by the relation

$$[(CV)_M]_g = \frac{(CV)_M}{\sqrt{N}} \tag{17.13}$$

where $[(CV)_M]_g$ = coefficient of variation of emitter flow by manufacturer's variation after grouping

$(CV)_M$ = coefficient of variation of emitter flow by manufacturer's variation only

N = number of emitters grouped together.

When the emitter flow is affected by both hydraulic and manufacturer's variations, the grouping effect can be expressed by the regression equation (Wu et al., 1989),

$$[(CV)_{HM}]_g = \frac{A}{\sqrt{N}} + 1.2487B - 5.3935B^2 + 7.6749B^3 + 2.3113AB \tag{17.14}$$

$$(R^2 = 0.99)$$

where $[(CV)_{HM}]_g$ = coefficient of variation of emitter flow caused by both hydraulic and manufacturer's variations after grouping

$A = (CV)_M$

$B = (CV)_{HM} - (CV)_M$

N = number of emitters grouped together.

Equation 17.14 can be used for up to 17 emitters per group.

17.4.7 Effects of Plugging on Design

A major problem encountered in drip irrigation is the plugging or clogging of emitters. Emitter plugging can adversely affect the rate of water application and the uniformity of water distribution. The combined effect of hydraulics, manufacturer's variation, and plugging was evaluated statistically (Bralts et al., 1981) and verified through computer simulation (Wu et al., 1988a). The coefficient of variation of emitter flow caused by hydraulics, manufacturer's variation, and plugging can be expressed as:

$$(CV)^2_{HMP} = \frac{(CV)^2_{HM}}{1-P} + \frac{P}{1-P} \tag{17.15}$$

where $(CV)_{HMP}$ is the total emitter flow variation affected by all three factors; hydraulics, manufacturer's variation, and plugging (complete plugging only) and P is the fraction of emitters completely plugged. For the case where $(CV)_{HM}$ is zero, the coefficient of variation caused by plugging alone can be expressed simply as a function of P:

$$(CV)_P = \sqrt{\frac{P}{1-P}} \tag{17.16}$$

where $(CV)_P$ is the coefficient of variation of emitter flow caused by plugging alone. Equation 17.16 shows that plugging can affect the uniformity tremendously. For example, 10% plugging will produce $(CV)_P$ of 33% for emitter flow while the ranges of $(CV)_H$ and $(CV)_M$ are 0.03 to 0.07 and 0.03 to 0.20, respectively, for the same impact.

Similar to the situation of grouping emitters, an evaluation of contiguous plugging (Wu et al., 1991) showed that effect of four or more emitters plugged together is less than 1% for 10% and 20% plugging, respectively. Therefore, if four or more emitters irrigate a tree, the chances that a tree would receive no water because of plugging are greatly reduced.

17.5 MICROIRRIGATION DESIGN

17.5.1 Performance-Based Criteria

Design calculations can proceed once the emission device, the required average emitter flow rate, emitter spacing, emitter variation, allowable pressure losses, and other criteria are determined. Microirrigation systems are designed based on the uniformity of water application with respect to crop needs. Two primary uniformity considerations used for performance based designs are the system emission uniformity and the spatial uniformity of the irrigation water in the crop root zone. However, the design procedures are basically the same regardless of the selected uniformity criteria.

Emission uniformity (EU) describes how uniformly the overall system can distribute water from each emission device in the field and should be designed for at least 80% (90% with chemigation). The design criteria affecting the system emission uniformity include hydraulic design, manufacturer's variation, temperature, plugging, and the number of emitters per plant. System emission uniformity is usually the most appropriate for design for microirrigation systems designed for widely spaced trees.

Spatial uniformity is a measure of the distribution of the irrigation water in the crop root zone across the field. The primary design criteria affecting spatial uniformity include system uniformity, pattern of soil wetting, and emitter spacing. Spatial uniformity is more meaningful than system uniformity for irrigation of high-density plantings and is often used for designs where emitter wetting patterns overlap.

Other uniformity metrics that may also be useful as design criterion include Christiansen's uniformity coefficient, CU, and the coefficient of variation, CV. These uniformity measures are related as expressed by the following regression equations (Wu and Irudayaraj, 1987):

$$CU = 1.0865\ CV \qquad (r^2 = 0.999) \tag{17.17}$$

$$CV = -0.0095 + 0.4288\ q_{var} \qquad (r^2 = 0.97) \tag{17.18}$$

$$CU = 1.0085 - 0.3702\ q_{var} \qquad (r^2 = 0.97) \tag{17.19}$$

The high correlation between any pair of the uniformity measures expressed in Equations 17.17, 17.18, and 17.19 indicates all three uniformity measures can be used as criteria for hydraulic design. This justifies using the simple uniformity value, q_{var}, which is determined by only the maximum and minimum emitter flows for a lateral line or submain unit.

17.5.2 Emission Uniformity

ASAE Engineering Practice EP405.1 (ASAE, 2005b) defines the emission uniformity (*EU*), also often referred to as distribution uniformity (*DU*) (Burt and Styles, 1994), of a microirrigation system for design purposes as:

$$EU = 100\left[1 - \left(1.27 \times \frac{CV_M}{\sqrt{n}}\right) \times \left(\frac{Q_m}{Q_a}\right)\right] \qquad (17.20)$$

where CV_M is the manufacturer's coefficient of variation for point- or line-source emitters expressed as a percent. However, it is appropriate to use a combined representative CV including values presented above as well as other factors such as uneven drainage (during shutoff) and unequal spacing for initial design calculations because the actual EU will usually be less than the design EU. Q_m is the minimum flow rate at the minimum pressure in the system, Q_a is the average (or design) emitter flow rate at the average (or design) pressure, and *n* is the number of emitters per plant or the rooting diameter of plants divided by a given length of lateral line (often equals 1). The first factor represents the flow rate variation due to manufacturing (or combined) variation, and the second factor, Q_m/Q_a, expresses the variation resulting from system pressure changes. It should be noted that for evaluation purposes, $EU = 100\ (q_{LQ}/q_a)$ where q_{LQ} is the average measured discharge in the lowest quarter of the measured field values while q_a is the average of all measured values. The correlation coefficient (CV) is also related to the EU by the following relationship:

$$CV = 0.77 \times (1 - EU) \qquad (17.21)$$

The general recommendation is that the selected combined flow variation and the flow variation ratio (Equation 17.20) should always result in a design EU above 80%. However, the actual selection of CV, CU, or DU depends on a number of factors including the cost of the system, the cost of water and related costs; the sensitivity of the crop (yield and quality) to stresses caused by nonuniform irrigation; the market value of the crop; and environmental concerns (e.g., leaching of agrichemicals to groundwater). Table 17.1 presents suggested ranges of uniformity values to use in design based on these factors.

Table 17.1. Suggested range of design criteria for different uniformity expressions based on various economic, water supply, and environmental conditions.

Design Considerations	CV	CU	EU
Abundant water and no environmental pollution problems	20%–30%	75%–85%	60%–75%
Abundant water but environmental protection considerations are important	10%–30%	80%–90%	75%–85%
Limited water resources but no environmental concerns	15%–25%	80%–90%	70%–80%
Limited water resources combined with the need for environmental protection	5%–15%	85%–95%	80%–95%

17.5.3 Hydraulic Design of Laterals

The hydraulic design of a microirrigation subunit is based on the energy relations in the drip tubes, including the friction losses and energy changes due to slopes in the field (Bralts and Segerlind, 1985). Direct calculations of water pressures along a lateral line or in a subunit can be made by using an energy-gradient line approach (Feng and Wu, 1990; Wu and Gitlin, 1974). All emitter flows along a lateral line and in a manifold can be determined based on the corresponding water pressures along the lateral and manifold pipeline. When all the emitter flows are determined, the emitter flow variation, q_{var}, can be expressed by Equation 17.10.

In general, the emitter flow variation, q_{var}, is used for hydraulic design. The design criterion for emitter flow variation, q_{var}, for drip irrigation design is recommended to be 10% to 20%, which is equivalent to a coefficient of variation from 0.033 to 0.076, respectively (ASAE Standard EP405.1, ASAE, 2005b). However, if justified, values from Table 17.1 may be used for design.

Microsprinklers are often designed with orifice sizes over 1 mm in diameter to reduce plugging. These emitters can usually achieve system uniformity coefficients in the field above 90%. However, the individual water distribution patterns of these devices can be quite variable, which would not be evident from a uniformity coefficient based on flow rates.

17.5.4 Hydraulic Design for Subunits

A microirrigation subunit is a fraction of the microirrigation system than is usually operated separately from other subunits but may be operated simultaneously with other subunits. For reasons of economy and water availability, microirrigation systems are often designed in four or more subunits. Thus, the irrigation pump, power supply, filtration system, and other water supply components can be smaller than if the entire production system was irrigated as one unit. However, it is sometimes desirable or necessary to operate the entire microirrigation system as one unit, such as when microsprinklers are used for frost/freeze protection (Evans et al., 1988; Evans, 1994), but this increases capital costs because many of the various system components must be considerably larger.

A subunit consists of an irrigation manifold (or header) pipeline with laterals that are supplied water from the manifold. A valve (usually a solenoid valve) is used at the entrance to the manifold to control water applications to the subunit. A pressure gauge, flow meter, pressure regulator, and chemical injection port may also be located at the manifold entrance as needed.

If there are several smaller blocks in a subunit, the design should prevent drainage from blocks at higher elevation causing excess applications in lower blocks by elevation control or the use of spring-loaded check valves. This also provides for more rapid pipe filling and better system uniformity because the piping system does not have to be recharged for each irrigation.

Water is provided to the subunit by main or submain pipelines that are hydraulically much different from subunit pipelines. Subunits consist of multiple outlet pipelines with uniformly spaced outlets removing water along their lengths. Conversely, mainlines and submains have uniform flow along their lengths, leading to greater friction losses for the same pipe diameters and inflow rates.

Subunit pipelines are designed to meet two criteria: high uniformity and low cost. However, these criteria often oppose each other because high uniformity is achieved by uniform pressures and minimal pressure losses that are accomplished by increasing pipe sizes, additional control valves, and other measures causing higher costs. For this reason, standards have been developed to define an acceptable degree of uniformity of water application (e.g., ASAE Standard EP405.1, ASAE, 2005b). These standards were written with the realization that it is expensive to achieve very high uniformities. Emission uniformities in the range of 70% to 95% are generally acceptable (Wu and Irudayaraj, 1992). Higher values may be appropriate on flat surfaces where it is less costly to achieve higher uniformities, while lower values are more acceptable on steeply sloping areas unless chemigation is used.

Subunits must be designed considering head losses in both the manifold and lateral pipelines. Because some subunit head losses occur in both the manifold and the laterals, it is not appropriate to base the design on flow uniformity only in the laterals unless pressure is regulated at the entrance to each lateral. These differences may be especially significant when field slopes are large and the manifold is positioned up-and-down slope. Subunits can be designed including both the laterals and manifolds by the following steps:

1. Select the design emission or spatial uniformity based on ASABE Standards or other sources.
2. Calculate the allowable flow rate variation within the subunit from the emission uniformity equation.
3. Calculate the allowable pressure variation within the subunit from the emitter hydraulic characteristics and the allowable flow rate variation.
4. Design the lateral using a fraction (e.g., 60% on first approximation) of the allowable pressure loss within the subunit (which is a proportion of the allowable whole system pressure losses).
5. Design the manifold using the remaining allowable head loss in the subunit that was not used in the lateral design.
6. Repeat steps 4 and 5 in a trial-and-error procedure that changes the split between the lateral and manifold pressures losses until a minimum-cost solution is obtained.

Lateral calculations can be based on the energy gradient line (EGL) or revised energy gradient line (REGL) method (Wu, 1992a; Wu and Yue, 1993). Design charts were developed for lateral and submain designs for simple EGL (Wu and Gitlin, 1974) and REGL (Wu, 1992b) methods. The design criteria for the lateral line is calculated based on design emission uniformity criteria. Subunits have also been designed using a finite element approach (Bralts and Segerlind, 1985).

Flow conditions in the laterals and manifold decreases steadily along their length, but can vary spatially depending on the layout (Howell and Hiler, 1974; Anyoji and Wu, 1987). A lateral line with hundreds of emitters makes a step-by-step (SBS) calculation for all sections between emitters very tedious. An energy-gradient line (EGL) approach was applied for determining pressure variation along the lateral (Wu and Gitlin, 1974). The concept of energy-gradient line offers a direct calculation of emitter flows along the lateral line because simple equations can be derived to determine all emitter flows along a lateral.

There are several good commercial programs and spreadsheets available for computer-aided design of these systems. For example, computer programs have been developed for microirrigation design using a finite-element approach (Bralts and Segerlind, 1985) and step-by-step calculations (Pitts et al., 1986; Meshkat and Warner, 1985). The energy-gradient line concept has also been applied in developing computer-aided design for microirrigation systems (Feng and Wu, 1990).

17.5.5 Main and Submain Pipeline Design

Main and submain pipelines must deliver the necessary amount of water and energy (pressure) to the entrance of each subunit to meet emission uniformity criteria. They must be properly pressure-rated to withstand operating plus surge pressures. This generally requires that pipeline velocities be limited to values that limit surge pressures to acceptable levels (e.g., 1.5 m/s or less).

Thus, main pipelines are designed based on economics using pipe and fittings that meet the required pressure ratings. A cost analysis of materials and energy use is required to determine the lowest-cost pipeline for the required flow rate and estimated hours of operation per analysis period. These analyses are usually made on an annual basis to amortize initial capital and installation costs and compare them with estimated annual operating costs.

17.6 DESIGNING THE SYSTEM CONTROL HEAD

The microirrigation system control head is defined as all of the pumps, valving, filters, injectors, controllers, monitoring equipment, and other facilities required to deliver water at sufficient pressures and appropriate quantity and quality to the irrigation system. The irrigation system control head must be located with convenient access for maintenance and operation. Figure 17.1 presents a schematic of the various components and their placement in a typical microirrigation system control head.

Site preparation should ensure drainage of excess storm water from the control head area as well as providing reliable access under adverse climatic conditions. The

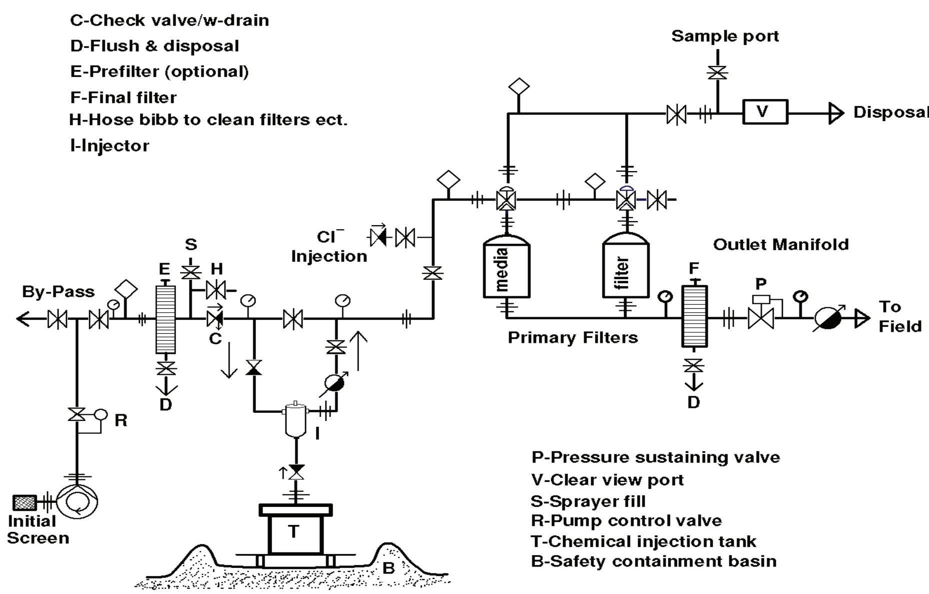

Figure 17.1 Schematic representation of the all the components typically required in the system control head for a microirrigation system.

control head should be installed on a level concrete pad of sufficient strength and size to mount all pumps, filters, flow meters, electrical control panels, valves, injectors, and other equipment. This provides a stable foundation to which equipment can be bolted to reduce vibration, avoid structural stresses, and facilitate maintenance. Thrust blocks may also be required at inlet and outlet pipes. Suitable supports must be provided beneath heavy components such as flow meters, control valves, and filters.

Protect the installation from accidental mechanical damage by agricultural implements, vehicles, and tractors. The control head, ponds and settling basins, and chemical tanks should be fenced to keep children, unauthorized people, or animals from damaging the components or being exposed to dangerous chemicals.

Drainage and/or spill-containment facilities should be provided around any chemical or fertilizer supply tanks to prevent direct contamination of any surface water from spills. Likewise, the wellhead should be protected to prevent contamination of the subsurface waters from bacterial and/or chemical sources. Filter backwash or other potentially contaminated water should be disposed of by land spreading (e.g., dust suppression) and not allowed to flow into drainageways, especially if it contains injected chemicals.

A suggested checklist for considerations during structural design of the system control head is:

1. Design the height of the control head installation for convenient dismantling and assembly of the various components for cleaning, repair, and replacement, while minimizing the potential for debris or other contaminants to enter the system. Components should generally have a minimum height of about 0.4 m above the concrete surface to provide adequate working space.
2. Maintain appropriate distances between various components to ensure reliable function of meters and gauges and facilitate operation, maintenance, and cleaning of filters, and dismantling and replacement of defective parts. Make sure that the direction-of-flow arrows on components such as flow meters and check valves are in the direction of flow.
3. Ensure that the components can be isolated by valves for repair and maintenance work and that sufficient unions, Victaulic couplings, and/or flanges are installed to facilitate dismantling and repair of components. Locate all valves for easy access, opening, maintenance, and removal. Avoid directly joining dissimilar metals without a dielectric union to prevent electrolysis and corrosion of fittings. The exposed length of threaded steel pipe nipples after assembly should enable convenient access for a pipe wench.
4. Select resistant materials for all pipes and components that may come in contact with concentrated chemicals, including fertilizers. Special coatings or linings may sometimes be required to protect hydraulic components from direct chemical effects.
5. Pressure gauges or pressure-measurement taps should be provided immediately upstream and downstream of all major components that modify pressure (e.g., pressure regulators, filtration devices, fertilizer injectors, pressure sustaining valves, etc).
6. Electrical and hydraulic interlocks are required for injection equipment to prevent backflows from contaminating water supplies and to prevent chemical injection when the main water-supply pumps are not operating. Likewise, chemi-

cals (except biocides such as chlorine) should not be injected during filter backwashing and flushing activities. Installation of backflow-prevention system interlocks, injection-line check valves, and other safety devices must be in accordance with local standards or regulations.

7. Solenoid valves should have manual-override or hydraulic-bypass capabilities. They should take 1 to 5 seconds to open and close to avoid waterhammer problems.
8. Pump-control valves that slowly bring the system online without water hammer and protect the pumps on shutdown are recommended, especially for turbine pump installations. Pumps should have low-pressure switches to prevent damage to the pump in case of water loss.
9. Protect workers from electrical hazards by installing and maintaining proper shielding, interlocks, and by providing adequate grounding of all electrical equipment. Ground-fault circuits should be provided for all injection pumps.
10. Pump motors or engines should have a cover to shield them from direct sunlight. This will increase the life of the components and reduce overheating.
11. Electric pump motors should have ammeters installed at the panel and the readings recorded as part of normal regular maintenance record-keeping programs.

17.7 INSTALLATION

One of the most important considerations for installation of a microirrigation system is worker safety. Adequate room and suitable topography for equipment to operate safely without endangering the operator and other workers must be ensured. Trenches and other excavations deeper than 1 m must be sloped or special protective measures provided to protect workers from side-wall failures.

The contractor should implement a quality control program during installation to ensure that all connections are made correctly and avoid entry of soil and debris into pipes and tubing. All mains and submains should be thoroughly flushed before hooking up tubing. Microirrigation systems should be thoroughly flushed immediately after installation is completed as well as after any new construction or repairs. The contractor should ensure that valves, pumps, and filters are properly installed and adjusted.

The contractor should also test the system for proper pressure and flow distributions and ensure that there are no leaks. The emission uniformity of the new system should be evaluated to determine if the new system meets design specifications. Additional guidelines for the installation and post-installation evaluation of new microirrigation systems are presented in ASAE Engineering Practice EP405.1, Design and Installation of Microirrigation Systems (ASAE, 2005b).

The irrigator should become familiar with the controls and characteristics of the new system. A suitable water management program should be implemented and new cultural and harvesting practices adopted as necessary.

17.8 MAINTENANCE

Implementation of a diligent and rigorous maintenance program is central to the long-term success of microirrigation. A good maintenance program involves implementing good record keeping, an appropriate chemical water-treatment program and regular flushing to keep pipelines clean.

Many maintenance problems can be circumvented by consistent records of flow meters and pressure gauges. This process can be greatly facilitated by remote communication technologies tied to local computers. Frequent visual inspections are also required to ensure that all system components are functioning properly. Regular field inspections will help find emitters that are plugged, identify improperly working flush valves, and locate pipes and tubing damaged by coyotes, small rodents, insects, and other causes, including farm equipment.

17.8.1 Field Evaluation of Microirrigation Operation and Uniformity

Water distribution uniformity measurements should be made on newly installed microirrigation systems to confirm that the system has been properly designed and installed as well as to provide a basis for later comparisons. Measurements of the uniformity of water distribution should be made before each crop season and compared to the new system evaluations. If this is too labor intensive or is impractical (as may be the case for subsurface systems), then, as a minimum, the irrigator should compare actual system flows and pressures at the inlet and distal ends of the system with the initial evaluations. Additional tests may be required for evaluation and adjustment of maintenance and operational procedures during the growing season, particularly where emitter plugging problems are severe.

Decreases in distribution uniformity over time are a cause for concern. Although regular visual inspections will locate emitters that are completely or almost completely plugged, they will not identify small changes in emitter flow rates from partial plugging. Frequent examinations of flow-meter records and periodic field measurements of emitter flow rate and pressure variations will help ascertain changes in system performance. Early identification of problems should indicate the need for special chemical water treatments to clean partially plugged emitters before the problem becomes more serious. Subsequent comparisons, where partial emitter plugging may be present due to chemical precipitation, algae, or other causes, may be made using the Christiansen uniformity coefficient (CU) or other statistical measures of uniformity discussed in Chapter 5 and in Pitts et al. (1996). Emitter damage and wear will also affect flow rates as the emitters age.

If the uniformity is low, additional samples should be taken to improve the statistical confidence. If the additional samples of emitter flow rate indicate that the distribution uniformity is still low, pressure distribution tests should be conducted to assist in identifying the cause(s). Crimped or leaking pipelines and laterals, improperly adjusted pressure regulators, improperly sized pipelines or fittings, and valves that fail to operate properly are all factors that can result in high hydraulic pressure variations. Conversely, if the hydraulic variation is low, then the poor water distribution uniformity is likely a problem with plugging or incorrect emitter selection.

The water application by the drip irrigation system as well as the water infiltration in the field can usually be considered as a normal distribution as long as the coefficient of variation of emitter flow or spatial uniformity is less than 30% (Wu, 1988). The cumulative frequency distribution of a normal distribution can be approximated by a straight line. The linear distribution of irrigation application will produce both under- and overirrigated areas, which can be quantitatively determined by simple mathematical equations (Karmeli, et al., 1978; Seginer, 1978; Sammis and Wu, 1985; Wu, 1988).

ASAE Engineering Practice EP-458, Field Evaluation of Microirrigation Systems (ASAE, 2005d), defines general procedures for field emitter evaluations. EP-458 assumes a normal distribution of emitter flow rates measured in the field. However, even with partial plugging of emitters, the uniformity will usually be overestimated because plugging and pressures are not normally distributed throughout the system. In general, criteria for emitter flow variation are: 5% or less, excellent; 5% to 10%, very good; 10% to 15%, fair; 15% to 20%, poor; and greater than 20%, unacceptable. Hydraulic coefficient of variation criteria are: 10% or less, excellent; 10% to 20%, very good; 20% to 30%, fair; 30% to 40%, poor; and greater than 40%, unacceptable. Bralts et al. (1987a; 1987b) discussed statistical considerations in the determination of distribution uniformities. Camp et al. (1997) evaluated several different distribution uniformity evaluation techniques and discussed the limitations and advantages of each.

Because many of the economic and environmental impacts are functions of climate, topography, and crop production systems, guidelines for acceptable uniformity often exist for specific locations. Smajstrla et al. (1997) presented specific steps for field evaluations in humid regions (also assuming statistically normal emitter-flow distributions). They presented tabular and graphical procedures that simplify data analysis for both flow rate and pressure variation to identify nonuniformity problems, to determine the required number of emitters to test, and to determine the cause of any nonuniformity observed. The graphical procedures require that a minimum of 18 emitters be randomly sampled in each subunit evaluated.

17.8.2 System Maintenance

Manufacturer's recommendations for maintenance should be followed for all components. Each component should be routinely inspected and tested to ensure that it functions properly. Consistency in all aspects of the maintenance program is the key to successful microirrigation. Keeping detailed records of irrigation schedules, chlorination, chemical treatments, chemigation, and maintenance activities is critical to document maintenance problems, properly schedule required maintenance, conduct financial analysis, and plan for future improvements.

Inspection of buried pipelines and equipment is difficult. Therefore, indirect monitoring and evaluation by routinely charting flow-meter readings and pressures can be used to check the performance of subunits or the entire microirrigation system. Changes in system performance will indicate maintenance needs, even when such changes occur slowly. Monitoring pressures and flows identifies leaks or emitter-plugging problems and documents how fast the problems are progressing. For example, gradually decreasing flow rate and increasing pressure may indicate gradual emitter plugging, while rapidly increasing flow rate and decreasing pressure can indicate leaks or broken pipelines. Instrumentation such as tensiometers or other soil-water sensors can also help call attention to field distribution problems. Periodic calibration or replacement of flow meters and pressure gauges will also be required.

Mainlines, submains, and laterals should be flushed to remove sediments at least once each month or as needed during the season, depending on water conditions. Mainlines should be flushed first, then submains, manifolds, and finally laterals. Systems can be manually or automatically flushed. The whole system should be flushed at seasonal startup, at the end of the season, and whenever repairs are made. Flushed materials should be inspected for signs of chemical precipitations, algal buildups, or root intrusion.

Monitoring the frequency of primary filter backwashing and pressure drops can direct attention to developing filtration problems. Filtration media should be replaced as needed. All filters should be manually inspected and cleaned on a regular basis. Ponds, canals, and settling basins require periodic mechanical or chemical cleaning to control sediment accumulations, aquatic weeds, and algae.

Weed control with microirrigation can be a challenge because both wet and dry soil conditions exist over short distances. Widely different weed species, requiring different herbicides for control, will inhabit small areas, but most weeds will be in the fringe areas between the wet and dry soil zones. Fortunately, herbicides labeled for direct application through emitters tend to work well. However, high soilwater conditions can cause rapid leaching or degradation of many herbicides. Weeds are often successfully controlled using plastic mulches or multiple spray applications of glyphosate or other herbicide depending on the crop and location. It is also important to keep the control area free from weeds, brush, vines, or other materials that might block access or hinder maintenance activities.

As mentioned earlier, coyotes, rodents, and other animals may damage tubing. This generally occurs when they are looking for water. Daily monitoring of system flow rates and visual inspections will help reduce resulting water distribution problems. If these are chronic problems, bitter oils can be periodically injected and strategic placement of water dishes around the field may be beneficial.

Other, less regular, maintenance activities include flushing injection equipment with clean water after each use for safety and to avoid corrosion. Pumps, filters, valves, gauges, injectors, tanks, pipelines, and other hydraulic components must be protected from freezing in winter by removal or draining in cold climates. Insects may also enter air vents and cause them to leak. Electrical panels need to be kept free of moisture and dust.

17.9 MANAGEMENT

In general, microirrigation requires higher levels of management than other irrigation methods because decisions must be made daily or more frequently. Specific management decisions will depend on crop, site, soil, and environmental conditions. Schwankl et al. (1995) discussed water management of microirrigated tree and vine crops while Hanson et al. (1994) presented a similar discussion for row crops.

The questions concerning microirrigation management generally center on when to irrigate, how much to apply, how to accurately evaluate the water status of the plant, and integration of other cultural activities with irrigation needs. These decisions are facilitated by adoption of a sound irrigation scheduling program, which may be supported with automation and monitoring instrumentation. Chemical treatment of water, filter cleaning, routine flushing of pipelines and laterals, and a good overall maintenance program are also fundamental to good management.

17.9.1 Management in Arid Areas

One of the most important microirrigation management considerations for arid areas is that active rooting volumes are small because water is often applied to 30% or less of the total potential rooting area. This can physically limit water and nutrient uptake causing stress during high ET-demand periods. Thus, management must focus on optimizing the use of a limited wetted soil volume for both water and nutrients. Increased sizes of wetted areas by microsprinklers instead of drippers may be required on sandy soils to improve soil water and nutrient availability.

Reduced wetted volumes compared to other irrigation methods can affect management decisions regarding soil salinity and leaching, applied water quality (e.g., salts), plant nutrition, soil pH, and micronutrient availability. Because of the restricted root zone, however, fertigation programs work well on a high-frequency basis where nutrients can be applied as needed in small amounts with rapid uptake and minimal leaching, although foliar applications of micronutrients may be required in some cases.

Water table contributions to plant ET may be a significant factor in irrigation water requirements for microirrigated crops depending on seasonal variations in aquifer depth. The benefits of maintaining slightly reduced root zone soil water levels for storage of precipitation are limited because soil water levels are already substantially reduced outside the wetted root zone areas, thus providing abundant storage for any precipitation.

17.9.2 Management in Humid Areas

The crop-rooting volume is not limited to the irrigated zone in humid areas. Water supplies are plentiful and frequent rains allow root development and associated water and nutrient uptake to occur outside of the irrigated zone. Thus, it is important that the irrigated rooting volume be large enough to minimize stress because roots are not concentrated near emitters. It is generally recommended that a microirrigation system be designed to irrigate at least 50% of the crop root area in these situations. When drippers are used, low-flow emitters are relatively closely spaced with close lateral spacing to ensure optimum crop yields.

There are tremendous advantages to microirrigation in humid areas. The cost of water applications is normally low because of the small amounts of water applied over a season and the low pressure requirements of these systems, but crop yield and quality increases can be substantial by avoidance of short-term drought effects. Irrigations can also be applied without wetting the plant foliage and maximize the time that the foliage remains dry between rainfall events which greatly reduces the incidence of foliar plant diseases that require the use of fungicides or other agrichemicals.

Fertigation is highly effective in humid areas; however, leaching of nutrients is often a significant problem due to both heavy rainfall and overirrigation. Thus, microirrigation systems must be properly managed to avoid leaching and the associated problems of contamination of groundwater or surface water systems. This requires that both water and chemicals be applied in small doses so that the leachable quantity of chemicals is limited in anticipation of large rainstorms.

As contrasted to microirrigation management in arid areas, excess water applications are rarely needed for salinity control in humid regions. Exceptions occur where very poor-quality irrigation water is used, when very salt-sensitive crops are grown, or during extended drought periods. The relatively frequent occurrence of large rainstorms normally provides adequate leaching and soil salinity management in humid areas. Boman and Parsons (1998) discuss the selection and design of microsprinkler systems for tree crops in humid regions.

As in arid areas, water table contributions to crop water requirements can be significant. The amount will be site specific and must be considered in scheduling irrigation applications. These shallow aquifers are also easily contaminated, and irrigation schedules must be developed that avoid leaching.

Both surface and subsurface drainage systems are often required in humid areas, especially on heavy soils or light soils in flat areas with restrictive layers that perch water tables near the soil surface. These drainage needs are reduced but not eliminated by microirrigation because of numerous high rainfall events.

There is little benefit from delaying or reducing irrigation applications in anticipation of rainfall, thus full irrigations are normally applied for most crops to optimize yield and quality. The primary exception to this practice is microspray or microsprinkler irrigation of tree crops where the irrigated volume of soil is normally large enough to significantly increase effective rainfall by delaying or reducing the amount of irrigation.

17.9.3 Controlled Root Volumes

Efficient root concentration within a limited wetted soil volume is readily achievable with microirrigation in arid areas. Benefits of maintaining concentrated root systems under an emitter may be: (1) improved water availability due to the reduced importance of soil hydraulic conductivity; (2) efficient application of water by minimizing losses due to evaporation and deep percolation; (3) efficient application of fertilizers and other water-soluble chemicals, particularly those which tend to be fixed by the soil particles (e.g., potassium and phosphorus); and (4) inducing physiological root restriction or drought effects on perennial plants to cause reduced vegetative-to-reproductive growth ratios and better light penetration into the canopy. There are basically three variations of controlled root zone strategies, including regulated-deficit irrigation, controlled-deficit irrigation, and partial root zone drying. These are discussed below.

17.9.3.1 Regulated-deficit irrigation. One controlled root-volume technique is regulated-deficit irrigation (RDI), which is limited to relatively arid areas. This technique deliberately imposes specific plant water stresses during specific growth stages (usually early in the season) using daily irrigations but only replacing 10% to 30% of the plant's daily water use. The wetted soil volume contracts from the sides and bottom of the root zone. At the end of the stress period (as indicated by various physiological markers), water application amounts are increased (e.g., up to 85% to 100% daily actual evapotranspiration), but soil water profiles are not refilled and the size of the small wetted soil volume remains constant. Vegetative growth must not be reinitiated by excess soil water conditions. RDI requires that adequate allocations of late-season water be available to "finish the crop" and that the system be designed to apply at least peak crop water use on a daily basis throughout the entire growing season. Automated microirrigation is highly desirable.

To date, RDI has only been investigated on perennial crops. Research in Australia on peaches (Chalmers et al., 1981) and pears (Mitchell et al., 1984), Washington on apples (Proebsting et al., 1977; Middleton et al., 1981; Peretz et al., 1984; Evans et al., 1993, Ebel et al., 1995; Drake and Evans, 1997) and grapes (Evans et al., 1990; Wample, 1996, 1997) have produced beneficial responses. Additional work in California, Israel, Australia, Chile, and other arid locations on several crops has also shown that carefully managing the severity and duration of a uniform, constant level of water stress on fruit trees, wine grapes, and some other perennial crops can be advantageous. RDI has been found to control vegetative growth, increase fruiting, advance fruit maturity, increase precocity, and increase soluble solids in fruits. Annual water diversions can be reduced by 20% or more. The key to successful RDI is rigid control of soil water volumes to control vegetative growth. It is made possible by the practical ability to achieve high-frequency irrigation regimes and the capacity to carefully restrict soil water by controlling the application amount and the size of the wetted volume of soil available to the roots.

17.9.3.2 Controlled-deficit irrigation. Controlled-deficit irrigation (CDI) generally refers to irrigation strategies that apply less than actual water use late in the growing season. For example, CDI is often used as a water conservation technique with perennial crops in arid areas, such as peaches, plums, or cherries, which are harvested in early to mid-summer Similarly, carefully managed CDI may also be used to induce a plant physiological response, such as inducing winter hardiness of perennial crops that are not physiologically adapted for growth in arid areas with cold winters.

Irrigations are maintained at a reduced level after harvest for the remainder of the season; however, drought stress is not allowed to reach severe levels that would affect next year's crop. The saved water is then used for other crops.

17.9.3.3 Partial root zone drying. Partial root zone drying is a simple drip irrigation technique on perennial tree and vine crops that utilizes drip lines located near the middle of the alley between plant rows (Leib et al., 2006). The systems are used in a manner similar to RDI in terms of timing; however, only one drip is irrigated at a time allowing the soil volume covered by the line on the other side of the plant to dry out. The next irrigation will apply water through the second drip line allowing the other side to dry to low soil water levels. Physiological responses are similar to those reported for RDI. This practice is commonly used on European (*Vitis vinifera*) wine grapes in south-central Washington, west-central Idaho, western Colorado, and north-central Oregon.

17.10 SCHEDULING MICROIRRIGATION

The basic philosophy of microirrigation is to *replace* water in the root zone in small increments as it is used by a plant at intervals ranging from several times a day to once every two to three days, rather than *refilling* a much larger soil water reservoir after several days or weeks. Thus, the major concern for scheduling microirrigation systems is how much to apply during an irrigation because the irrigation interval is often fixed by other factors.

The estimated crop water use (ET), combined with the percent of the area that is irrigated, will determine the total volume of water to be applied (Clark, 1992). The maximum interval between irrigations is primarily controlled by soil hydraulic characteristics, soil profile layering, and tubing placement. The depth of soil, saturated hydraulic conductivities, and soil water-holding capacities will control the volume applied in a single irrigation to avoid runoff or excessive deep percolation.

It is sometimes not possible to achieve optimum irrigation schedules because of irrigation system limitations. These may include inflexibility in controls and instrumentation, inadequate system hydraulic capacities (including fill times and system drainage), and the quantity and quality of available water throughout the season.

Management considerations such as the quality and quantity of available labor can affect the ability to implement scheduled irrigations. Likewise, timing, amount, and label requirements for chemigation may influence irrigation timing and depth of application that can affect prior as well as subsequent irrigation schedules. Excess applications may have to be periodically scheduled to leach salts. Irrigation schedules may also have to be adjusted because of other cultural or harvesting considerations.

Once the above factors are considered, irrigations can be scheduled whenever an estimated allowable depletion level has occurred, or to replace estimated or measured ET each day. Alternatively, irrigations can be automatically initiated and stopped whenever soil water matric potentials at selected points in the wetted soil volume reach predetermined levels as measured by soil water sensors. An economically optimal microirrigation schedule (Wu, 1995) can also be developed based on irrigation system uniformity and costs associated with supplying water, value of the yield, and the costs related to groundwater contamination due to seepage.

17.10.1 ET Estimation

Irrigation scheduling must be a dynamic process because ET will vary spatially and temporally during the growing season. ET depends on the plant, soil, local environmental conditions, the percentage of the root zone irrigated, planting density, rooting characteristics, and canopy size. Pest and disease problems also reduce crop water use, and are usually variably distributed across a field, creating opportunities for localized excess applications and leaching. Likewise, nutrient availability and the plant's uptake can strongly influence canopy growth affecting the total and the spatial distribution of water use. The calculation of ET is covered in Chapter 8.

Rainfall will lessen the irrigation water requirements by the effective rainfall amount (Kopec et al., 1984). The contributions to ET from shallow water tables will likewise reduce irrigation requirements. The most reliable ET estimates are based on field irrigation experiments conducted with a wide range of irrigation treatments (e.g., Doorenbos and Kassam, 1979), lysimetry, or determined by calibrated ET models using weather variables (Jensen et al., 1990).

ET under nonstressed conditions, such as those commonly found under microirrigation, may be higher than previously determined values which were developed under more traditional forms of irrigation. Conversely, total ET from widely spaced tree and vine crops may be reduced because soil evaporation and transpiration from grass under the crop canopy are less. Any deviations in estimating ET different from actual can result in reduced yields, wasted water, undesirable plant physiological responses, or a combination of these and other factors. Consequently, these uncertainties require that soil water or plant water potentials be monitored under all microirrigation methods for proper irrigation scheduling.

The irrigated area, in general, is taken as the total surface area for row crops and other high-density plantings, considering that eventually most of the area is shaded when the crop matures. However, for low-density or very young plantings with small root zones, water applications and schedules should use projected canopy area or other measures of the affected cropped area.

17.10.2 Irrigation Frequency

More than one water application per day may be required because either the total actual daily evapotranspiration cannot be stored in the limited wetted root zone volume (e.g., small vegetable crops) or single large water applications at a point may cause excessive deep percolation losses and leaching. Conversely, on heavier soils with high water-holding capacities or poor drainage, optimal irrigations might be only every second or third day.

Some crops (e.g., cantaloupe, cotton, and many perennial crops) may perform better with less frequent irrigations (e.g., every 2 to 4 days) especially on heavy soils, whereas more water-sensitive crops (e.g., tomatoes, watermelons, lettuce) may need at least daily irrigations for best yields and quality.

If leaching of fertilizers or other chemicals is a major concern, then sensor-controlled, ultra-high frequency (e.g., 8 to 10 times/day) pulsed irrigation systems may be an option. Shallow-rooted crops often benefit from light, high-frequency irrigations. High-frequency microirrigation techniques have been shown to increase lateral wetting and reduce water and nutrient stresses, especially when used with fertigation, but the small wetted soil volume will reduce the plant's ability to endure a drought stress of even short duration. However, growers need to be aware of management and soil water problems caused by frequent filling and localized draining of lines under high-frequency strategies.

On the other hand, less-frequent irrigations may be beneficial to manage so that humidity levels in dense crop canopies are lowered to reduce incidence of fungal diseases (e.g., *Botrytis* on grapes). Irrigation deficits may be intentionally imposed at times to attain certain desirable crop quality or other plant physiological responses.

17.10.3 Monitoring Soil Water

Soil water sensors make point or small-volume measurements in a field to monitor soil status and to control irrigations. All soil water monitoring devices should be placed at appropriate depths and locations to ensure that irrigation scheduling will be appropriate to optimize yields, minimize water usage, and minimize leaching to the groundwater. However, microirrigated soil water distributions are highly variable and there are major questions on determining suitable sensor locations and the correct interpretation of the readings. Preferential flow of soil water is often a major, but largely unquantifiable, factor in soil water distributions. Consequently, microirrigation scheduling is often "calibrated" to particular sensor placements with respect to a water-emission point that is correlated with plant water potential measurements or other independent variables. Calibration is typically required to optimize both water and nutrient utilization (Smajstrla and Locascio, 1996). The number of required sensors can be minimized by choosing representative plants and soil types across a field.

Optimal sensor location will also be influenced by irrigation interval because a soil water gradient will develop from the emitter to the perimeter of the wetted volume during irrigation. This gradient decreases after irrigation due to water redistribution and the wetted soil volume approaches relatively uniform water content. Thus, sensors to control daily or more frequent irrigations are generally located within 10 to 15 cm of the emitters but may be located further away for less-frequent irrigations. Electronic soil matric potential sensors are often appropriate for these applications.

Sensors that determine when to irrigate are normally placed in the upper one-fourth to one-half of the root zone within the most active areas of water and nutrient uptake. Sensors located in the lower portion of the root zone can be used to control the amount of water applied and avoid excessive applications.

17.10.4 Scheduling Criteria for Design

Microirrigation systems are commonly designed for a 90% uniformity coefficient, especially when agrichemicals are to be injected through the system. Even with a 10% emitter plugging the uniformity will still be greater than 70%. Consequently, a field "scheduling" efficiency of 80%, which includes effects of emitter and hydraulic non-uniformities, is often used. The efficiency relationships between gross and net applications are discussed in Chapters 5 and 21 and will not be expanded here.

17.11 PLUGGING OF MICROIRRIGATION SYSTEMS

Partial or total plugging of emitters is a chronic problem and the most serious constraint to the long-term operation of any microirrigation system. Inadequate consideration of the physical, biological, and chemical characteristics of the water supply will result in serious plugging problems. The most critical design factors affecting plugging are emitter design, filtration, and the chemical water treatment system. System operation and maintenance, including inadequate flushing of pipelines, will have major effects on microirrigation plugging problems. Improper installation, such as placing tapes with emission points facing down, may also contribute to plugging problems due to sediment accumulations along the bottom of the tape.

17.11.1 Causes of Plugging

Plugging of microirrigation systems may occur from single or multiple factors. Physical factors such as suspended colloidal clays, silts and other materials passing through filters, broken pipes, root intrusion, and aspiration of soil particles into the emitter orifices are common physical causes of plugging. Chemical factors such as precipitation of carbonates and iron oxides, and precipitates from chemical injections are also significant causes of emitter plugging. Likewise, organic and biological factors such as oils, algae, aquatic weeds, bacterial slimes, fungi, as well as spiders, insects, worms, fish, frogs, snails, clams, and their eggs or larva can be major contributors. Low system pressures and flow rates will exacerbate plugging problems.

17.11.2 Sediment

Routine flushing of pipelines is required to prevent emitter plugging from the gradual accumulation of particles which are too small to be filtered, but which settle out or flocculate at the distal ends of pipelines. Flushing velocities should be about 0.6 m s^{-1} to ensure transport and discharge particulate matter from the pipelines. This requires flow rates at the ends of the lines of about 0.12 L s^{-1} for 15-mm tubing and 0.22 L s^{-1} for 22-mm tubing. Flushing frequency should be at least once a month, but will vary through the season depending on the rate debris and particulates accumulate. Applying surfactants or dispersing agents such as sodium hexametaphosphate through the microirrigation system may reduce some plugging problems by preventing the flocculation of silts and colloidal clays, allowing them to easily pass through the emitters or be flushed from pipelines.

Automated flush valves are sometimes used at the ends of the laterals to help flush fine particulates at the start of each irrigation; however, periodic manual flushing is still required. Use of these valves is generally not recommended because they tend to leak and waste water, requiring extra maintenance in addition to the added purchase cost. Use of these valves with chemigation may also be problematic due to leaks and the potential for chemicals to accumulate in these locations.

17.11.3 Algae and Bacterial Slimes

Chlorine injection is the most common and least expensive method to prevent clogging by biological growth (algae, colonial protozoa, sulfur bacteria, and other mucous organisms). Bacteria that precipitate iron, sulfur, and manganese can also be effectively and economically controlled by chlorine treatments.

Copper sulfate, chlorine, and organosulfur compounds are used to control algae and/or bacterial slimes in drip systems as well as in ponds or canals. The degree of control will vary with light and water temperature conditions. Some chemicals such as quaternary ammonium are effective when algal growth is slow to moderate, but will fail under conditions of rapid growth. Organic growers may be limited to copper sulfate at 100 to 200 mg L^{-1} concentrations for controlling algae, depending on local regulations.

Soil bacteria can sometimes be aspirated back into an emitter and produce slimes that glue small particles together and plug the orifices. These have been fairly successfully, but expensively, removed by strong solutions of hydrofluoric acid (1000 mg L^{-1}) combined with a surfactant (Wuertz, 1992).

17.11.4 Chemical Plugging

Chemical precipitates can cause plugging of irrigation systems (Nakayama and Bucks, 1986; Hills et al., 1989, Burt and Styles, 1994; Burt et al., 1995). Precipitates of iron oxides (reddish-brown color), iron sulfides (black color), calcium carbonates (white color), and manganese oxides (black color) in irrigation water can clog emitters. Changes in water pH, temperature, pressure, dissolved oxygen levels, and injections of chlorine and other chemicals (e.g., some fertilizers) can induce chemical precipitations. Groundwater supply systems tend to have greater problems with chemical precipitates than surface water, and the insoluble precipitates that form may not dissolve even after treatments such as lowering the water pH or injection of special solvents .

Concentrations of 0.15 to 0.22 mg L^{-1} of iron ($\geq$2 mg L^{-1}) in irrigation water may be problematic when water pH exceeds 5. Manganese and iron oxides greater than 2 mg L^{-1} will need treatment if water pH is 4 or greater. Chlorine injection will cause oxidation and precipitation of iron and manganese (plus kill any iron and other precipitating bacteria that are present). The general recommendations are to inject 1 mg L^{-1} of free chlorine per 0.7 mg L^{-1} soluble iron or 1.33 mg L^{-1} free chlorine per mg L^{-1} of soluble manganese prior to the filtration system. Calcium and magnesium problems are best addressed by the injection of acids to maintain a water pH between 6.0 and 6.6. Temporary storage of water in ponds or other open containers with agitation is a recommended pretreatment for elevated levels of iron (>4 mg L^{-1}) and manganese to facilitate more oxidation and precipitation before entering the irrigation system.

Plugging by other chemical precipitates can often be reduced by acid treatment to lower pH and prevent precipitates from forming, avoiding the injection of insoluble fertilizers or incompatible fertilizer/chemical mixes, and regular flushing of lines. It is possible to reduce the risk of precipitation problems by carefully injecting various incompatible chemicals at different locations in a mainline so that they are sufficiently diluted and mixed before the next chemical is injected. For example, injection points for acid and chlorine should be a minimum of 1 m apart.

17.12 SUBSURFACE DRIP IRRIGATION

Subsurface drip irrigation (SDI) uses buried lateral pipelines and emitters to apply water directly in the plant root zone. Laterals are placed deep enough to avoid damage by normal tillage operations, but sufficiently shallow so that water is redistributed in the active crop root zone by capillarity. SDI systems must be compatible with the total farming and cultural systems being used.

Current commercial and grower interest levels indicate that future use of SDI systems will continue to increase. SDI requires the highest level of management of all microirrigation systems to avoid remedial maintenance. A poorly designed SDI system is much less forgiving than an improperly designed surface drip system. Deficiencies and water distribution problems are difficult and expensive to remedy. Lamm and Camp (2007) present an excellent, detailed review of SDI.

These systems require safeguards and special operational procedures to prevent plugging and facilitate maintenance, but they also have numerous advantages. Jorgenson and Norum (1992) have presented an overview of the theory behind SDI as well as varied grower experiences and applications. Camp (1998) has prepared an excellent summary and analysis of published subsurface drip irrigation research results.

Phene et al. (1987a; 1992) and Phene (1995) listed four operational characteristics of SDI relative to surface drip irrigation installations with respect to water conservation and salinity. These were:

- The top of the soil surface remains dry, limiting surface evaporation to the rate of vapor diffusion transport and preventing salt accumulations on the surface.
- The use of a very high irrigation frequency (several times per day) that matches actual crop water use will result in a constant wetted soil volume and a net upward hydraulic gradient, which minimizes leaching.
- Supplying water and nutrients directly to the root zone allows root uptake to be more efficient if irrigation and fertilization schedules are appropriate.
- Soil crusts, which may impede infiltration and cause ponding and runoff, are bypassed so that surface infiltration variability becomes insignificant.

Also, Camp et al. (1987) and Grimes et al. (1990) found more uniform soil water distribution under subsurface than surface drip systems.

Under proper management, properly designed and managed SDI irrigation systems offer several other advantages to growers because of their potential for:

- maintaining access to fields with tillage, planting, spray and harvest equipment that is not restricted by irrigation;
- obtaining better weed suppression with minimal chemicals because there is less seed germination with dry soil surfaces;
- efficiently and safely applying labeled plant-systemic pesticides and soil fumigants for improved disease and pest control;
- reducing surface wetting often reduces fungal disease incidence (e.g., molds, mildews) by maintaining dryer plant surfaces and lower air humidity within the plant canopy;
- reducing pesticide exposures for workers when chemicals are applied below the soil surface;
- implementing minimum tillage, permanent beds, and multiple cropping systems (Bucks et al., 1981), although much of the necessary equipment modifications and farming techniques remain to be developed; and
- minimizing flow-rate sensitivity to temperature fluctuations because emitters are buffered by the soil.

Phene et al. (1987a; 1992) and Phene (1995) also listed several disadvantages, including:

- initial system cost may be high;
- potential for rodent damage;
- salt may accumulate between drip lines and soil surface;
- low upward water movement in coarse-textured soils;
- high potential for emitter plugging; and
- insufficient technical knowledge, dissemination, and hands-on experience by growers and researchers.

Specific problems that have been observed include plugging by root intrusion (Tollefson, 1988; Bui, 1990); pinching of hoses due to compaction or squeezing by large roots (Bui, 1990); and rodent and insect damage (Bui, 1990). In addition, fertility management becomes more critical with SDI because roots tend to grow deeper than with surface drip systems and some surface applied nutrients may not be sufficiently available (Phene, 1995).

A broad range of yield increases have been observed under SDI when compared to surface, sprinkler, and even surface drip irrigation systems from small to up to more than a 100% difference. SDI research has been reported on crops including cotton (Plaut et al., 1985; Tollefson, 1988; Constable and Hodson, 1990; Hutmacher et al., 1995), field corn (Lamm et al., 1995), sweet corn (Bar-Yosef et al., 1989), tomatoes (Davis et al., 1985; Phene et al., 1987a; Grattan et al., 1988; Bogle et al., 1989), cantaloupe (Phene et al., 1987b), potatoes (Bisconer, 1987), asparagus (Sterret et al., 1990), alfalfa (Oron et al., 1989; Bui and Osgood, 1990), cabbage and zucchini (Rubeiz et al., 1989). Most yield increases have been attributed to better fertilization, better water management, improved water distribution uniformities, and improved disease and pest control. Grattan et al. (1988) cited better weed control as the major factor in their observed yield increases. Moore and Fitschen (1990) reported that the conversion of 5900 hectares of sugarcane in Hawaii from furrow to SDI over a period of 12 yr resulted in an average 27% net yield increase.

17.12.1 Design of SDI Systems

Designs should follow the same general requirements as for all microirrigation systems. However, extra attention to filtration, water treatment, pressure regulation, proper location of check and air-vacuum relief valves, and flushing are crucial to the success of SDI systems. As with surface microirrigation systems, injected chemicals and fertilizers must be compatible with all other injected chemicals, and control of water pH is critical.

Both tapes and tubing have been used successfully for SDI. Solomon (1992) discussed trade-offs and selection criteria of emission devices for SDI. A major factor in the life of these systems is tape wall thickness with thicker-walled tapes generally lasting longer. However, even thicker tapes require special considerations and must be buried deep enough to avoid being disturbed by tillage or harvesting equipment, but shallow enough to prevent permanent collapsing of the tape by soil weight or cultural operations. SDI tapes are often used with high-value, shallow-rooted (e.g., strawberries) and annual or biannual crops (e.g., various vegetables, melons, sugar cane, cotton). They are typically placed at shallower depths in semipermanent minitill beds on land with little slope or short runs because tapes are not pressure-compensating. As a general rule, there should never be any farm equipment wheel traffic or other activities directly over the tape that would compact the soil and flatten the tape, permanently destroying its utility.

Tubing is used more often than tape for SDI on perennial crops, and may be placed at deeper depths than for annual crops. Pressure-compensating emitters on tubing allow SDI systems to be used on diverse topography with steep slopes. Tubing is more rigid and thus more resistant to pinching and compaction, but the same general operational considerations for tapes should also be followed.

Individual SDI laterals are often connected with manifolds at both the top and distal end of the tubing. The bottom manifold typically provides greater flexibility and saves time with flushing operations. The additional expense also creates a hydraulically looped system that can supply water from both ends of a lateral. This can be beneficial over the short term if an individual lateral is pinched by roots or soil compaction caused by farm equipment. Provisions for adequate air-vacuum relief on both the head and flushing manifolds is critical to reduce emitter plugging due to soil particles being pulled into the orifices by vacuum conditions at shutdown.

Wetting the soil surface, or "surfacing," negates many of the benefits of SDI and is usually undesirable, especially on permanent crops. It can increase weed growth, move salts to the surface, increase soil evaporation, and increase fungal disease incidence. Reducing the negative effects of surfacing may require plastic film mulches and more aggressive water and soil management practices. On the other hand, surfacing is sometimes appropriate to ensure adequate wetting across the full width of a bed for germination, fumigation, and/or proper growth of shallow-rooted crops (e.g., onions).

Surfacing is primarily the result of water application rates exceeding the saturated hydraulic conductivity. However, it may also occur if the tubing is placed too shallow and the surface is wetted by capillarity, or if water from several emitters runs along the lateral and collects at a point and the low gravity head forces water to the soil surface. In addition, surfacing may be the end result of chemical processes that effectively reduce saturated hydraulic conductivity, including high-bicarbonate waters that precipitate calcium and plug soil pores, application of irrigation water with low electrical conductivity on saline or sodic soils, or application of water with high sodium levels (see Chapter 7). Some growers in California have reportedly tried using narrow shanks ahead of the buried tubing installation machine to till deeper than tubing placement as a way to discourage surfacing, with mixed results.

Nevertheless, exceeding the effective saturated hydraulic conductivity with SDI systems causes water to be discharged against higher-than-atmospheric pressures, forcing the water to the soil surface. Because manufacturers design drippers to apply water at atmospheric pressure, this back pressure reduces emitter flow rates as much as 50% (Sadler et al., 1995; Shani et al., 1996; Warrick and Shani, 1996). Thus, surfacing negatively affects uniformity, the ability to accurately schedule water application amounts, and presents significant design as well as management implications.

The surfacing process often creates light-textured "chimneys" where the fine soil particles are flushed from around the emitter resulting in a direct, low-pressure pathway to the soil surface that tends to make the problem worse. These chimneys will sometimes disappear after a year or two as the soil structure adjusts or pathways along the tubes disperse, but they usually require tillage for remediation. Short, frequent pulsing of water applications throughout the day may help reduce surfacing problems. Low-EC waters may require injection of finely powdered gypsum (e.g., $\geq$2.5 meq L^{-1}) or other amendments into the water to improve infiltration on sodic soils.

To avoid surfacing problems, emitters on SDI tend to have smaller flow rates and closer spacing than surface drip systems, thus creating a higher potential for plugging. Consequently, filters should be designed to remove particles as small as 150 to 200 microns. Check valves, vacuum breakers, and air vents must be installed to prevent backsiphoning and aspiration of soil particles into the emitter orifices at system shutdown. Designs must ensure that each lateral can be flushed properly.

17.12.1.1 Depth considerations. The ideal depth of buried SDI laterals depends on discharge rate, emitter spacing, soil type, root distributions of crops in a rotation, water movement for seed germination (also affected by seed depth and soil salinity), chemigation programs, and the desirability of surface wetting. The tubing must be buried deep enough so that it is not damaged by equipment, but shallow enough to effectively move water into the crop root zone. Tubing and tape depths may be adjusted on bed systems by use of equipment to remove or replace soil.

It is generally recommended that the tubing be placed as shallow as possible without surface wetting because most of the roots, air exchange, and biological activity is located in the upper soil layers. As a general rule, tubing is placed at shallower depths on coarse-textured soils and slightly deeper with finer-textured soils. Most SDI systems are installed at 10 to 50 cm depths. SDI can be installed on shallow-rooted row crops such as strawberries or onions at 2- to 8-cm depths up to 40 to 50 cm deep for crops such as cotton, maize, potatoes, or sugar beets. Many vegetable crops use SDI laterals at 15- to 20-cm depths near the plants. Thin-walled tape products are rarely buried more than 15 cm below the surface in beds.

There are trade-offs with tube placement depth. Philip (1991) showed for a steady state subsurface irrigation source that the deeper the source relative to the roots, the larger the deep percolation and the smaller the soil evaporation. Barth (1995) discussed placing V-shaped impermeable foil barriers under the SDI lateral to control downward movement of water and reported good results on sandy soils. Deeper installations reduce surface weed germination and allow more tillage operations. However, if laterals are too deep, much of the water is applied below the crop root zone, reducing biotic activity (critical to nutrient uptake) in the shallow soil layers. In addition, deep installations may limit crop germination potential and limit use of some surface-applied chemicals. It may be possible to inject air through deeper lines to encourage more root development and soil biota as well as aerate waterlogged soils, but this practice has not been thoroughly investigated. Shallow depths may result in excessive surface soil salinity when using saline waters and may also be more subject to damage from burrowing rodents and insects. Deeper tubing placements will require more tractor power for installation.

Shallow tube placement may be necessary to supply water near the soil surface on plantings with limited root zones. For some soils it is possible to wet a seed bed from a depth of 30 to 50 cm. However, on coarse-textured soils, emitter lines may have to be within 5 to 20 cm of the surface.

17.12.1.2 SDI on annual row crops. Hanson et al. (1994) discussed installation, operation, and maintenance of SDI for row crops. Annual row crops can be grown on temporary or permanent beds with or without plastic mulches However, it is sometimes necessary to use sprinkler irrigation for activating herbicides or germination of small-seeded crops such as lettuce or onions, particularly under saline soil conditions. Emitters with high flow rate or tapes with closely spaced emission points (every 20 to 45 cm) that wet the soil surface are common on annual crops. Shallow tapes are generally expected to last 1 to 2 yr, although some installations of thicker-walled tapes on permanent beds may last 5 to 15 yr. These require special tillage and cultural practices (such as controlled traffic and permanent wheel tracks) to avoid damage. To ensure adequate wetting of the root zone of annual crops and to avoid dry areas due to emitter plugging, emitters should be spaced close enough together to produce an overlapped, line-source wetting pattern. Spacing between emitter lines or tapes are often 1 to 1.5 m but will vary depending on soil type, crop characteristics, and cultural practices.

Use of semi-permanent SDI on annual or biannual row crops requires the establishment of consistent row spacing for all crops used in the rotation and replanting at the same locations. If these practices are not followed, the drip lateral position may vary from being centered under the bed and row to being located under the furrow. However, research results have demonstrated that yields were not reduced when the drip tubing was not exactly centered under the bed (Ayars et al., 1995) on cotton. But, the incidence of mechanical damage increased as the lateral line was moved from the center towards the edge of the bed. Emerging technologies such as auto-steer on tractors and harvesters will help ensure proper alignment between beds and drip lines year after year..

17.12.1.3 SDI on perennial crops. SDI systems on perennial tree and vine crops should have a life expectancy of 7 to 20 yr with appropriate design and maintenance. Depths of 20 to 40 cm are common with some as deep as 1 m depending on crop root development patterns and soil type. Generally, low-flow emitters (<4 L h^{-1}) are used to keep the soil surface dry and to reduce annual weed growth. Schwankl et al. (1995) presents a detailed discussion on microirrigated tree and vine crops.

17.12.2 Installation

Most SDI systems are installed by tractor-mounted, parabolic-shaped injector shanks with mole- or bullet-shaped tips to create a cavity for the tape or tubing. Vibrating shanks are recommended for SDI installations deeper than 20 cm because less horsepower is needed, cutting through roots and around rocks is easier, and the cavity around the tubing tends to quickly backfill. As mentioned earlier, emitters should face upward to minimize plugging due to particulate accumulations in the bottom of the lines between flushing events. Kinking as well as excessive stretching of the dripper lines must be avoided during installation. Lamm et al. (1995) discusses some problems associated with installation of SDI systems.

Laterals are normally installed first. Headers or manifolds are cross-trenched to a depth of about 0.3 to 0.5 m deeper than the laterals, cutting through the pre-installed laterals. The trenches should be as narrow as possible to provide lateral support for the low-pressure PVC pipes. The mains and submains are often assembled on the surface and lowered into the trenches. Open trenches provide for easier connections and facilitates hydraulic testing of all fittings and laterals by allowing visual inspection to ensure proper operation. In addition, leaks can be easily repaired. Any metal fittings or wire used to make connections should be stainless steel.

Laterals are connected to the manifolds with 6- to 13-mm flexible PVC or polyethylene tubing. Connections to the dripper tubing or tape must avoid any kinking or sharp bends. Installers should leave adequate amounts of tubing at the distal ends so that flushing connections can be made correctly. Laterals should be kept as uniformly deep and as straight as possible. In addition, submains and headers should be deeper than the laterals to prevent them from draining, and to facilitate rapid startup and pressurizing of the system. Likewise, control valves should be located aboveground for easy access and to help keep mains and submains full of water. If laterals are connected by manifolds for flushing, properly sized flushing manifolds should be at the same depth as the laterals.

17.12.3 Root Intrusion

Root intrusion is a major problem with SDI. It can be minimized by chemicals, emitter design, and water management. Chemical controls include the use of slowrelease herbicides (e.g., triflurilan) embedded into emitters or injected at low rates (where permitted by the pesticide label) or careful, periodic injections of soil fumigants (e.g., metam sodium) through the water. Other chemical measures include frequent injection of chlorine (e.g., 7 to 8 mg L^{-1}) to discourage root growth near emitters. Injection of high quality phosphoric acid at about 15 mg L^{-1} on a continuous basis will reduce root growth by acidifying the soil and also provides some control for algae, but may not affect certain bacteria. Root-intrusion control programs often require use of several measures.

Emitters that are plugged by roots may sometimes be cleared by increasing pressures coupled with injections of acids that drop the pH to very low levels (e.g., pH <4) combined with very high doses of chlorine (e.g., 300 to 500 mg L^{-1}) that are left in the lines for at least 24 hours before flushing to "burn" the roots out. Injection of copper sulfate (about 15 mg L^{-1}) is sometimes beneficial. But, these practices can damage certain types of emitters and tubing. In addition, long-term, low-pH water applications may make some nutrients unavailable and create toxic soil conditions.

Emitter design appears to be a factor in root intrusion. It has been observed that roots tend to follow the seam in a tape and emitters located on or near the seam are more subject to root intrusion problems. Some emitters and tapes are constructed with special physical barriers to root intrusion, but most of these are less successful than chemical controls. SDI emitters, porous tubes, or tapes that are not chemically treated and/or have a physical barrier will suffer from root intrusion problems. Smaller orifices tend to discourage root intrusion, but are more easily plugged by other means (Tollefson, 1988; Bui, 1990).

Deficit irrigation is sometimes desirable to increase quality, yields, or to control vegetative growth, but its use will increase chances for root intrusion due to increased root concentrations in the wetted area around the emitters. Very high frequency pulsing to frequently saturate the soil volume will discourage root growth of many plants around the emitter, but roots of some water-loving plants such as celery will actively grow in saturated soils and can plug emitters.

17.12.4 Flushing

Because SDI systems are buried, it is often convenient to install flushing manifolds at the distal end of the laterals, especially with closely spaced (e.g., every 30 to 120 cm) lines. It is usually more economical and effective to individually flush laterals with widely spaced laterals. Flushing design requirements are the same as for surface systems, but may be compromised by pinching of tubing either by roots or soil compaction caused by farm equipment operations.

17.12.5 Salinity Management

Salinity may be a problem with SDI in arid and semiarid areas because any leaching above the tubing occurs only as the result of rain. Thus, salts tend to accumulate in this area during the season. High salt concentrations exceeding 10 dS m^{-1} have been found in the top 6 to 10 cm of the soil profile (Ayars et al., 1995). Salinity distribution measurements have showed that salts are moved to below the plant row when the laterals are placed under the furrows rather than under the beds (Ayars et al., 1995). Similar results were reported by Hanson (1993).

17.13 SUBIRRIGATION

A nontraditional use of microirrigation is to improve the efficiency of subirrigation. With subirrigation, the water table in the field is controlled at a level just below the crop root zone so that water flows upward into the root zone by capillarity. Because shallow water tables must be established and maintained, subirrigation can only be used on relatively flat lands where large water supplies are available, the lateral permeability of surface soil layers is high, and uniform restrictive soil layers or permanent shallow water tables already exist. The requirement for large, inexpensive water supplies generally limits the use of subirrigation to humid regions without salinity problems.

The water table may be controlled at a constant depth or at a depth that is allowed to fluctuate as the root zone changes with crop growth. In either event, diurnal water table fluctuations occur as the water table drops due to peak ET rates, then recovers overnight or during low ET demand. With conventional subirrigation systems, the water table in the field is controlled by physically regulating water levels in open field drainage ditches or controlling the head on subsurface drainage tubing. Open field ditches are most often used because of their low cost, and, in some areas, subsurface drain tubes can become plugged by iron ochre or by other chemical precipitates.

In recent years both surface and subsurface drip irrigation systems have been used for subirrigation water applications in place of the drainage system. Water applied at high rates by the drip system rapidly percolates to the water table. This excess water raises the water table across the field somewhat above the bottom of plant root zone, thereby creating a temporarily high water table that slowly drains away with time.

Advantages of drip systems for water table control are increased uniformity of water application distributions and reduced irrigation water requirements. Uniformity is increased because water is distributed by lateral pipelines which are controlled by the system hydraulics. Water requirements are reduced because water is placed directly into the plant beds, some water is supplied by the water table, and the potential for surface runoff is greatly reduced. However, some runoff may occur because a minimum soil surface gradient is needed to provide adequate drainage of excess rainfall.

Stanley and Clark (1991) reported that irrigation water requirements for tomato production in south Florida were reduced 33% to 40% with subsurface drip irrigation as compared to conventional open-ditch subirrigation systems because of reduced runoff rates. Smajstrla et al. (1995) reported that potato yields were statistically similar but 33% less water was applied for water table control with a subsurface drip irrigation system compared to a conventional open-ditch subirrigation system.

17.14 MICROIRRIGATION IN NURSERIES AND GREENHOUSES

Many greenhouse and nursery plants can be effectively and economically irrigated with several conventional irrigation methods including drip, microsprinklers, misters, impact and other rotating sprinklers, ebb-flow systems, traveling boom sprays, and hand watering systems. Ebb-flow systems are used with potted plants in an impervious basin that is periodically flooded and then drained. Excess water is used for irrigation of the next basin, thus water is used without waste. Traveling boom spray systems apply water with spray nozzles on a lateral pipeline that travels on rails mounted above the plants. The travel speed is adjusted to apply the required amount of water.

This system is primarily applicable to greenhouse production systems and is most efficient on closely spaced containers so that water loss between containers is minimized. Hand watering, which has low maintenance costs, can be an economical alternative to microirrigation in some production systems and areas where labor costs are low.

Microirrigation offers a number of advantages for many nursery and greenhouse production systems, especially reducing water and nutrient requirements as well as lowering labor costs (Ross, et al., 1990; Ross, 1994). However, microirrigation systems often have a higher capital cost than conventional irrigation methods, especially for irrigation of small, closely spaced plants, because of the extensive network of pipelines and large numbers of emitters that are required. These initial high capital costs can often be offset by savings in operational costs (labor, water, fertilizer, etc.). The useful life of the system emitters can be 4 to 5 yr with proper maintenance. Except for accidental damage, the distribution system can last for 10 to 15 yr.

Microirrigation is often the most cost effective and adaptable to large or widely spaced plants which minimize the number of laterals and emitters required, thus reducing system cost. Drip systems are regularly used for high-valued plants in containers as small as 15 cm in diameter. Over-crop sprinkler irrigation cannot be used in some ornamental plant production systems because of plant disease problems resulting from frequent wetting of the foliage, or the water quality is such that the plant would be damaged by direct wetting of leaves, fruits, or stems.

The potential exists for extensive use of drip irrigation for most container-grown crops, ranging from plants in larger containers (e.g., larger than 4 L) to as small as one liter, depending on the plant density (pot-to-pot spacing) and the economic value of the crop. Microsprinkler systems are often preferred for applications under the plant canopy to crops such as larger ornamental tree and shrubs that are in large beds (e.g., balled-and-burlapped plants). Water-soluble fertilizers can be effectively applied through drip systems directly to the plant and irrigations can be scheduled as necessary without interfering with other nursery operations. Foliar-applied chemicals with microsprinklers tend to be more effective than sprinkler applications because the low-water applications minimize washing the material off the foliage.

Bedding plants and many of the smaller potted flowering plants that are grown in trays are typically sprinkler irrigated (fixed or moveable boom) or hand watered. The containers are typically small (less than 2 L) and closely spaced. Microirrigation systems are not used for bedding plants grown in flats or trays. Potted foliage plants are often hand watered or irrigated with traveling boom spray systems.

Most woody ornamental field nurseries use drip irrigation, while some use sprinkler or microsprinkler systems. Woody container plants are often sprinkler irrigated, although microirrigation systems are commonly used for plants in containers larger than 4 L.

Drip irrigation systems are not readily adaptable to plantings of sod, ornamental fern, or similar crops with continuous lateral root development and canopies that cover the entire soil surface. In these cases, drip and microsprinkler systems tend to perform poorly because they are most adaptable to partial root zone or concentrated water applications rather than the uniform, shallow wetting patterns required for these crops. Lateral water movement from drip irrigation systems is limited by the hydraulic characteristics of the potting growth medium because of its high porosity and drainage capability.

Crops with broad, shallow lateral rooting systems are most effectively irrigated with sprinkler, surface, or subirrigation systems that distribute water uniformly over the entire surface rather than only partially cover the root zone as is characteristic of microirrigation. For example, sod is grown using irrigation methods that encourage shallow root development to facilitate harvest. This is accomplished with sprinkler or subsurface systems, using frequent, small applications with sprinklers or otherwise artificially maintaining a high water table. The irrigation method will also affect how effectively specific crops are harvested and transplanted by various methods and available equipment.

Some crops, such as ornamental fern, may use over-crop sprinkler irrigation because it may be necessary for freeze protection. In these cases, sprinklers are also used for irrigation; however, water use efficiency is poor.

Microirrigation systems in nurseries and greenhouses also require special filtration and chemical water treatment systems to prevent emitter plugging, like those required for field crops. Also, the aisles between plant beds may become dry when microirrigation systems are used, and quality problems may occur due to blowing sand or dirt, which may require the extra expense of a sprinkler system or periodic hand watering for dust control. However, a dry aisle may be desirable to reduce plant diseases, insects, weeds, and to facilitate human traffic. These higher costs can usually be economically justified by the high cash value for many (but not all) ornamental and landscape plant applications.

Water collection systems to recycle runoff and leachate from pots and containers are commonly used with all greenhouse and nursery irrigation techniques. Some reuse systems utilize impervious surfaces in greenhouses and nurseries to route and collect runoff and drainage to a collection tank. This method is highly efficient and environmentally friendly because excess water and nutrients are reused on subsequent irrigations. However, the potential for increased plant disease and enhancement of insect propagation is ever present with collection and reuse systems. Sanitation and potentially extraordinary chemical water treatment procedures may be required to prevent the spread of plant disease and other pests from the recycled water.

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