Components of an Irrigation System 183

Water Supply and Quality 187

System Testing and Maintenance 187

Irrigation Scheduling 189

Effect of Irrigation on Disease 195

References 195

11 Irrigation

Ben Faber and David A. Goldhamer

A large number of irrigation choices are available to citrus growers. In the past, the choices were limited to flood, furrow, and high-pressure sprinklers, but in the 1970s, drip irrigation became available, followed by a great number of other low-flow (low-volume) systems. Low-flow systems include drip, microsprinklers, fan sprays, and a host of new technologies such as vortex emitters and fan jets. Low-flow is distinctive in that emitter output is measured in gallons per hour (gph) rather than gallons per minute (gpm). Using low-flow emitters instead of high-flow impact sprinklers allows for a lower operating pressure, which permits the use of systems that are lighter, less expensive, more easily constructed, and more energy efficient.

Compared with high-flow full-pattern sprinklers or surface methods such as furrow irrigation, low-flow systems can improve the efficiency of irrigation and chemical application and can also reduce weed growth. These advantages, however, come at a cost. More maintenance is required on low-flow systems, and the root zone is restricted to the wetted pattern, reducing the soil volume available for water and nutrients.

Most citrus in California is grown on low-flow systems, so they are the focus of this chapter. However, the principles of water management are the same for all systems, so the ensuing discussion will be applicable to all systems. These principles strive to ensure a healthy, producing orchard.

Components of an Irrigation System

Before planting the citrus orchard, the irrigation system must be in place and ready for the trees. The various parts of the system can be assembled and installed by the grower (fig. 11.1), but it is usually best to have a qualified designer of low-flow irrigation systems create a master plan. The system should be designed to meet the water needs of the full-grown orchard during the peak irrigation periods. It should also be designed so that daily operation does not exceed 16 to 18 hours. Allowing some down time gives time for catch-up in case of a breakdown in the system, such as a pump that requires repair (see Schwankl et al. 1998).

Although many growers have water delivered by an irrigation district, in some instances it may be cheaper (or the only option) to drill a well. If a well is the source of water, select a pump and motor that will deliver the correct pressure and flow rate at the highest possible efficiency. The system designer determines the flow rate and pressure to be delivered by the pump, and the pump dealer matches the motor to the pump for the greatest efficiency.

A flowmeter and pressure gauges are critical parts of the system. The flowmeter indicates how much water is being applied, which is critical information for efficient irrigation and scheduling. For example, a decreasing flow rate measured at a given pressure might indicate clogging of the system; an increasing flow rate might suggest a leak in the system.

Valves help control the system. A main control valve is very important, particularly when using a well and pump, to prevent contamination of the water source or wellhead. A backflow prevention device should also be installed. Air or vacuum relief valves allow air to escape when the system is turned on and prevent air from entering when the system is shut down. Check valves prevent undesirable flow reversal in hilly terrain (see Brown 1972).

Filters should be used in low-flow systems because the emitter orifices have a great tendency to

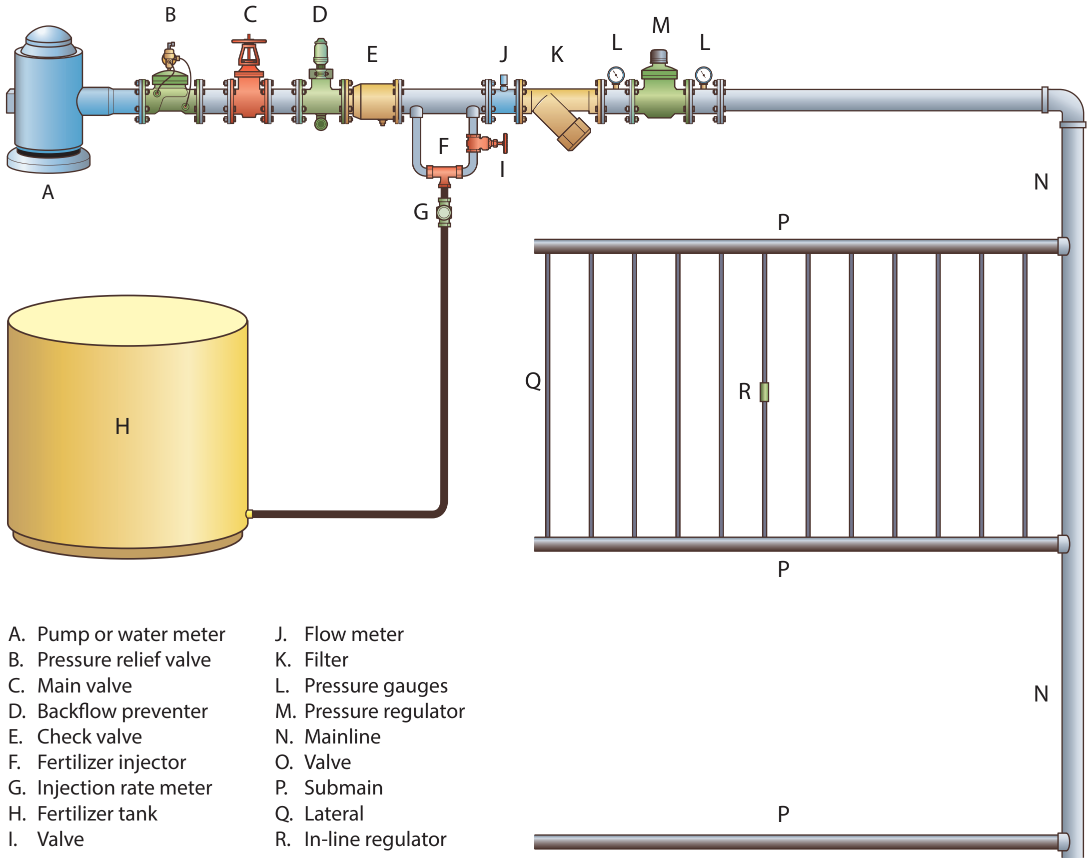

Figure 11.1 Parts of an irrigation system.

clog. Choices of filters include media (sand), disk, and screen (fig. 11.2). Typically, media filters are used with surface water that has a large load of organic sediment that would rapidly clog a screen filter. Screen filters are less expensive and should be used with well water that needs relatively less filtration. Disk filters with automatic backflushing are a happy medium between price and effectiveness for the removal of most sediments. If the water contains a high level of sand sediments, a sand or cyclone separator should be installed upstream from the filter.

Injection equipment is critical in preventing clogging of low-flow systems (fig. 11.3), but it is also a great convenience for fertilizer application (see Hanson et al. 2006). Differential pressure tanks, or batch tanks, are the simplest. Irrigation water flows passively in and out of the tank under line pressure. The major disadvantage of batch tanks is that as irrigation continues, the chemical concentration in the irrigation water decreases. If the chemical concentration must be kept constant, such as when injecting chlorine to prevent clogging, a batch tank should not be used; however, in most fertilizer applications, constant chemical concentration is not important. Venturi injectors, which are simple and inexpensive, rely on a pressure drop of 10 to 30% between the inlet and outlet of the injector. Venturis are better at maintaining a constant concentration of material than are batch tanks, but neither is as good as a positive displacement pump. These are powered by electricity, gasoline, or water and are the most complicated and expensive option. Most citrus growers find them to be unnecessary.

Mains and submains deliver water to the lateral lines and emitters. The size of the lines must be balanced between the cost of larger pipe versus the pressure loss when water moves through smaller lines. Lateral lines, usually polyethylene or PVC, deliver water to the emitters. The length and diameter of the laterals must not be too long or too small; if they are, the emitters may discharge water at different rates, resulting in nonuniform irrigation.

Pressure regulators can be installed as pressure-regulating valves after the filter at the head of the system, as preset regulators at the head of laterals, as in-line pressure regulators, or as a part of the

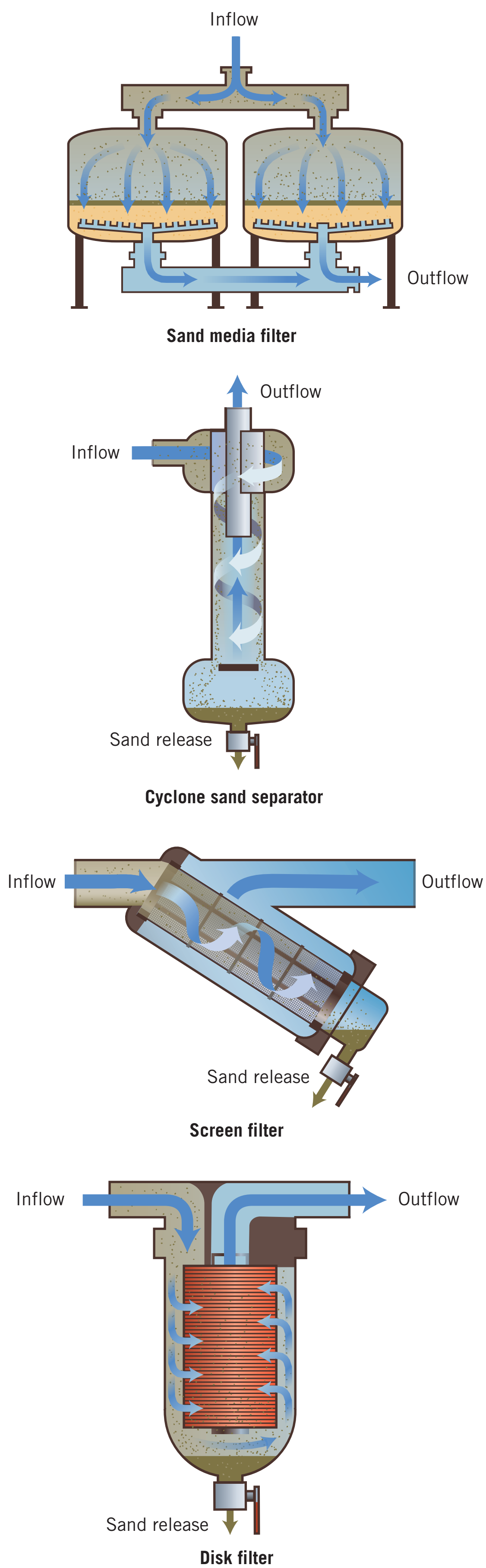

Figure 11.2 Various types of filters.

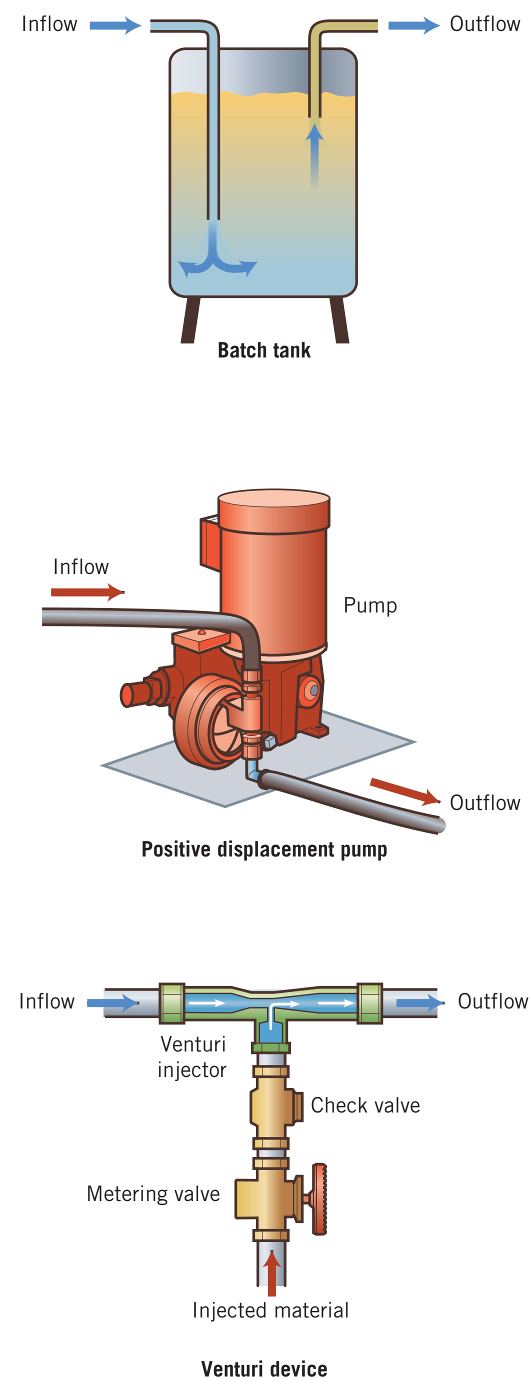

Figure 11.3 Various injectors.

emitter itself (pressure-compensating emitters). Pressure-compensating emitters are more expensive than standard emitters and may wear out sooner. However, pressure regulation is critical for uniform application of water, since the output of standard emitters varies with pressure.

Emitters come in many sizes and shapes, including drippers, microsprinklers, and fan sprays (fig. 11.4). They do not wet the entire orchard floor. Drip emitters with outputs of 0.5 to 4 gallons per hour wet a small spot at the surface, reducing weed growth and applying water only where it is needed. The wetted pattern enlarges below the soil surface; depending on the soil texture, this pattern can be a very bulbous onion shape (heavier soils such as clay) or more like a stove pipe (lighter, more sandy soils). Drippers are very good with young trees, since they wet only the area of the young roots. As the trees grow, more emitters and a second lateral should be added to accommodate the increasing water demand. Typically, six drip emitters should be able to meet the requirements of a mature citrus tree, depending on the soil type. However, drippers are notorious for their maintenance requirements. Tortuous path emitters have fewer problems, as they rely on a long, relatively large channel to reduce water flow, rather than just a small opening. Injecting chlorine or acid reduces clogging problems, but walking the lines must always be done.

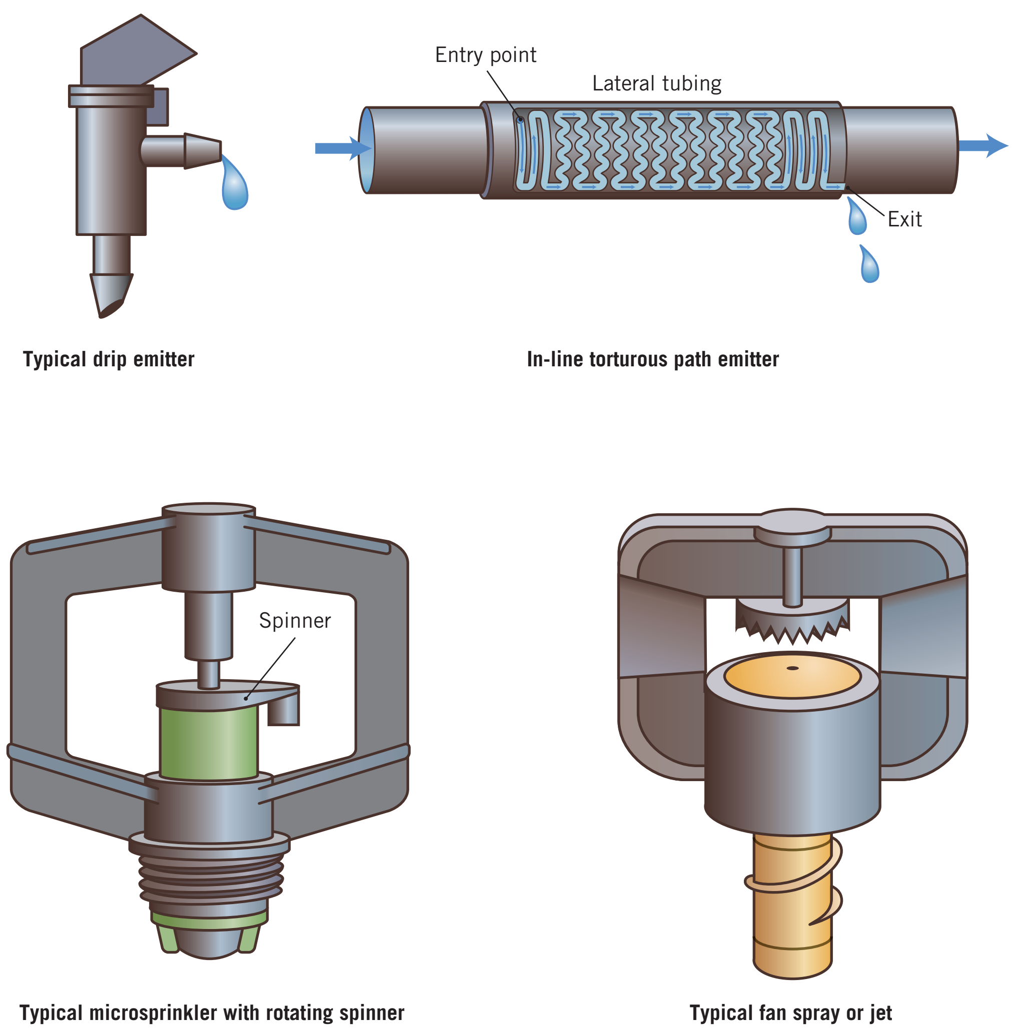

Figure 11.4 Various emitter types.

Microsprinklers, most of which have a rotating orifice called a spinner, put out 4 to 30 gallons per hour and wet a much larger surface area than do drip emitters. They clog less than drippers because the discharge flow rate is higher and their orifice is larger. However, they still need filters upstream. In sandier soils, where lateral subsurface movement of water is small, a microsprinkler is often the preferred choice. One of the major drawbacks of some microsprinklers is that output from the emitter varies with distance: the amount of water deposited on the outside two-thirds of the wetted pattern may be as little as one-third of the amount deposited on the inside of the wetted pattern. Near the emitter, the soil is often wetted below the root zone.

Fan sprays can overcome the poor output uniformity of microsprinklers by directing fingers of water in various directions. A number of patterns can be obtained, such as butterfly, rectangular, and so on. Microsprinklers and fan sprays can be found in patterns of less than 360°. To prevent disease, the tree trunk must not be wetted; with all of these emitters, a pattern should be selected that keeps the trunks dry.

Many brands and models of emitters are available. Although the quality of low-flow emitters has markedly improved in the last 10 years, there can be problems in their manufacture. Information about specific emitter performance can be obtained from the Center for Irrigation Technology at Fresno State University, http://www.fresnostate.edu/jcast/cit/index.html, and through Cooperative Extension in the UC Davis Department of Land, Air, and Water Resources, http://lawr.ucdavis.edu/cooperative_extension.htm.

Water Supply and Quality

Most low-flow systems require relatively frequent applications of water during peak demand periods. With drip systems, irrigations may be as frequent as once or twice a day. In some irrigation districts, water deliveries may not meet irrigation scheduling demands; in this case, it is necessary to work out an agreement with the agency supplying water. If frequent deliveries are not possible, a pond or tank system should be installed to provide a reservoir, or a supplemental well should be considered.

Water quality can affect plant health as well as the operation of low-flow systems. Organic or mineral sediments that clog emitters are a major water quality concern. These sediments can be filtered, but if major problems with backflushing occur, a continual injection of 2 parts per million (ppm) of chlorine prior to filtration may be required to control organic sediments, or a prefilter may be needed for sand sediments.

With private and municipal well water, chemical precipitation leading to clogging is the major problem. Lime (calcium carbonate) or iron or manganese precipitates are the most common sources of clogging. The presence of white or reddish to blackish deposits is associated with these two types of precipitates. If water contains more than 100 ppm (or 2 milliequivalents per liter, meq/l) bicarbonates and has a pH greater than 7.5, lime precipitation will eventually clog the emitter orifice. Keeping the water pH below 7 will help considerably. Injecting urea sulfuric acid products in the system, or the more dangerous sulfuric or phosphoric acids, decreases this problem. Acid injection rates vary with water quality but typically consist of 1 to 2 gallons of acid per 5,000 gallons of water; fertilizer supply houses may provide a recommendation based on a water sample. Iron and manganese precipitates can be much more difficult to control. Prior to running the water through the system, it is helpful to allow the water to settle out in a pond. Injecting chlorine and installing filters are other methods for controlling precipitates. Running acid water through the system for an hour may dissolve iron precipitates, but it may be necessary to inject acid and let it sit in the lines overnight before flushing. Some pressure-compensating emitters are damaged by water with a pH of 4 or below. Check with the manufacturer before lowering the pH of the water. It may be necessary to run chlorine or calcium hypochlorite through the system at the end of the irrigation if bacterial slimes caused by precipitates persist.

Water quality is also an important consideration for plant growth. The specific salts of boron, chloride, and sodium and the general salinity (total dissolved solids, or TDS, and electrical conductivity, or EC) must be considered. For more information, see chapter 8, "Soil and Water Quality and Amendment."

System Testing and Maintenance

Distribution Uniformity

The efficiency of an irrigation system is indicated by its distribution uniformity (DU). A 100% DU means that every emitter is putting out exactly the same amount of water. If the DU is low, the system must run longer to provide all trees with enough water, but this will cause some trees to get more water than they need, which wastes water and may not be good for the trees. Pressure losses in lines and uneven terrain can make it impossible to achieve 100% DU, but 80% is attainable and 95% is not unheard of. Even in well-designed new systems, clogging and leaks can rapidly reduce distribution uniformity; the way to ensure a high DU is through annual monitoring and regular maintenance.

Measuring DU

Distribution uniformity is obtained by measuring the output of a specified number of emitters. For example, if a block has 100 emitters, lay out an evenly spaced grid across the orchard so that all parts of the orchard can be sampled. Identify a minimum of 12 emitters to sample; the more emitters sampled, the more accurate the DU.

Turn the system on and invert the first emitter to be sampled over a graduated cylinder or measuring cup, capture the water for a specified time (such as 15 seconds), and record the volume of water emitted. After sampling each emitter, arrange the volumes from low to high. Add the values and find the average. Then select the volumes from the one-quarter of the emitters that put out the least, calculate their average, and divide it by the average of all the emitters. Multiply the result by 100 to get the percentage of DU (see the example below). If the DU is less than 80%, it must be corrected (see below). If it is greater than 80%, try to raise it to 90% or better.

Example: Martha runs 12 emitters for 20 seconds each into a graduated cylinder and records the following volumes of water (in ounces) for each: 8.5, 8, 7, 8, 7.5, 6.5, 7, 7.5, 8, 8, 8.5, and 7.5. The 12 values, arranged from low to high and summed, are

$$6.5 + 7 + 7 + 7.5 + 7.5 + 7.5 + 8 + 8 + 8 + 8 + 8.5 + 8.5 \text{ oz} = 92.0 \text{ oz.}$$

The average output is

$$92 \text{ oz} \div 12 \text{ emitters} = 7.7 \text{ oz/emitter.}$$

The low-quarter amounts (the first three numbers in the series), summed and averaged, are

$$6.5 + 7 + 7 \text{ oz} = 20.5 \text{ oz}$$

$$20.5 \text{ oz} \div 3 \text{ emitters} = 6.8 \text{ oz/emitter.}$$

The low-quarter average divided by the average of all the emitters is the DU:

$$(6.8 \div 7.7) \times 100 = 88.3\%.$$

This irrigation system DU of 88% is not bad, but if the orchard is on flat ground, there should be room for improvement.

Correcting low DU

Poor design may cause an irrigation system to have pressure problems that affect the DU. For example, low DU may be caused by pressure differences among individual emitters in the system; it may be necessary to install pressure regulators or pressure-compensating emitters to equalize the pressures. Or, if there is not enough pressure throughout the system to produce a satisfactory DU, it may be necessary to break the system into two or more irrigation blocks with separate valves. If the system has been properly designed, however, low DU is likely to be caused by poor maintenance—the most common cause of poor DU.

Routine Maintenance

Routine maintenance includes checking for leaks, backwashing filters, periodically flushing lines, injecting chlorination or acids, and cleaning or replacing clogged emitters. Coyotes frequently bite polyethylene tubing to get water. Thus, walking the lines in coyote country to inspect for leaks is critical. Most coyote damage occurs during coyote pup season in spring and in the fall, when surrounding hills have dried out. Putting out water for the coyotes can decrease the damage, but it may be necessary to repair lines before every irrigation. Also, lines and emitters may be damaged during and after harvest.

Clogged emitters can often be identified by reduced flows (a small wetted area) and sometimes by the sound they make (jammed spinners, intermittent spray, etc.). Emitters are designed to operate in a given pressure range, and if the pressure falls below that range, the output of the emitter may be significantly reduced. Clogged filters reduce the system pressure and thus reduce application rates and DU. Filters should be backflushed whenever there is a reduction in outflow pressure by 5 pounds per square inch (psi) or more; the frequency of backflushing depends on the water quality. Automatic backwashing filters are available and are relatively inexpensive; they initiate backwashing as soon as a given pressure differential exists.

Clogged emitters may need to be cleaned or replaced. Before replacing an emitter, identify the cause of clogging. If organic slimes or chemical precipitates are the cause, inject acid or chlorine. If earwigs or other insects enter and damage the emitters, it may be necessary to replace the emitters with insect-proof models. Although some emitters are designed to be disassembled and cleaned, nearly all drip emitters are sealed. Most microsprinkler models clog at the orifice in the head and can be cleaned and reinstalled.

Flushing is key to system maintenance. Periodically flushing lateral lines by opening the lines and allowing them to run clear is essential. Filters trap only the larger sediments; smaller sediments can gradually accumulate in laterals and eventually clog the emitters. For more information on microirrigation maintenance, see Schwankl et al. 2008.

Irrigation Scheduling

Irrigation efficiency requires not only uniform irrigation but also the application of the appropriate amount at the correct intervals. Irrigators must know the system's water application rate in inches per day, inches per hour, or gallons per hour, and they must also know when and how much water to apply. Scheduling irrigation, as opposed to applying a fixed amount at a fixed time, strives to determine the water used by trees and then replace that amount (for detailed information on irrigation scheduling, see Goldhamer and Snyder 1989 and Hanson et al. 1999).

The overall use of water in a field, through transpiration from the tree and evaporation from the ground, is called evapotranspiration (ET). Evapotranspiration varies seasonally and from year to year for a given location. The California Department of Water Resources (DWR) has developed a map of the average daily ET for various zones in California (fig. 11.5). These zones are distinctive because the parameters that drive water loss—total sunlight, wind, relative humidity, and temperature—differ in each zone. The Central Valley is hot and cloudless in the summer, whereas the intensity of the marine layer along the coast and the amount of sunshine differ from year to year. In southern California coastal valleys, the average annual irrigation requirement for citrus is about 2 feet of applied water per year (2 ac-ft per ac, or 651,702 gal per ac). This value varies from as little as 18 inches to as much as 3 feet from year to year; spring and fall conditions contribute the most to the variability in ET. In the Central Valley, on the other hand, a mature tree consistently requires the same amount of water every year (about 4 ft).

One of the most important variables in the quantity of water to be applied is the length of the rainfall season and the effectiveness of the rainfall. Effective rainfall is defined as the amount of rainfall that is retained in the root zone of the tree. For example, assume that a tree has a rooting depth of 2 feet and each foot holds 1 inch of available water. If this tree has just been fully irrigated (or if it rained 2 inches yesterday), and it rains 2 inches today, none of today's rain is effective since the soil was already moist before the rain (although the rain was useful, since it leached salts out of the soil). Also, rainfall of less than 0.25 inch is not considered to be effective.

The amount of water to apply at each irrigation depends on the amount of water remaining in the root zone. A loamy soil in which a microsprinkler with a 20-foot diameter throw has wetted the soil 2 feet deep holds about 200 gallons of water at 50% water-holding capacity. Exceeding this amount of water will help leach salts, but exceeding it too far only pushes existing water out of the root zone.

It is best to observe one or two irrigation cycles to determine how long to run the system to achieve a certain depth of infiltration. This can be done with a shovel or, more easily, with a pointed rod or tensiometers. Water moves in a wetting front, and the wetted soil allows a rod to be pushed into the depth of dry soil. Run the system to find out how long it takes water to infiltrate to a depth of 2 to 3 feet. That information will indicate how long to run the system when irrigating. Applying water 2 to 3 feet deep may take several hours. If runoff occurs, turn the system off for a few hours, then turn it on again to obtain the total run time required to wet the required depth. If runoff is severe, use emitters with a smaller flow rate.

Irrigation schedules may be plant based, soil based, or weather based. Many of the technologies used to create these schedules are proven and have been in use for years; others are more experimental and have not been fully tested. In several cases improved electronics and digitalization have added features to older technologies. Growers should be familiar with all types of irrigation scheduling, because a combination of types is often the most effective.

Plant-Based Scheduling

The plant is the ideal subject for measuring water use, as it integrates all the factors driving water loss, soil moisture, and stresses such as soil salinity. To be useful tools in irrigation scheduling, plant-based measuring devices must provide indicators of stress before it harms current or potential yield. Methods for measuring plant water use include the following:

- Pressure chambers (pressure bombs or Scholander pressure chambers) measure plant water tension by applying a comparable air pressure to a leaf or stem. The amount of pressure required to create equilibrium with the plant sap indicates the level of plant water stress.
- Trunk diameter fluctuations (shrinkage or swelling), measured continuously with linear variable displacement transducers (LVDTs), can be used to calculate parameters that are directly related to tree stress (see Goldhamer and Fereres 2001).
- Stem flow gauges can estimate transpiration by placing a heat source on the trunk of the tree and measuring the temperature differential along the trunk.

Figure 11.5 Evapotranspiration zones as determined by the California Department of Water Resources. For a more detailed version of this map, see the CIMIS website, http://wwwcimis.water.ca.gov/cimis/cimiSatEtoZones.jsp. *Source:* California Department of Water Resources.

- Porometers measure the ability of a leaf to transpire; if a leaf is under water stress, it transpires less water.
- Infrared thermometry measures the canopy temperature as affected by the rate of transpiration; as the tree experiences water stress, the leaves get warmer.
- Visual symptoms such as wilting and leaf curling are the cheapest method, but they are the most expensive in the long run as they do not produce reliable measurements.

The pressure chamber is currently the state-of-the-art in measuring citrus tree water stress. While the other techniques can be valuable for scientific use, they have not been frequently adopted in commercial agriculture. Part of the problem is logistical; for example, stem flow gauges do not adapt well to the uneven surface of the citrus tree trunk. Also, porometers and infrared thermometry do not provide enough lead time for a grower to irrigate. Recent research indicates that LVDTs show promise for automating irrigation scheduling.

Soil-Based Scheduling

A rule of thumb is that irrigation should be done when about 50% of the water has been depleted from the soil in the plant's root zone. This 50% figure, however, allows a buffer of water in the soil in case the weather suddenly turns hot and windy. Sandy soils hold less water than clay soils and must be irrigated more frequently. A common misperception is that it takes more water to grow plants in sandy soil than in clay soil; however, the total amount required for the whole year is the same for both soil types. The amount of sunlight, wind, temperature, and humidity control how much water a plant needs, and the soil is only the reservoir.

Determining water content by soil texture

To check the water content in the soil based on the soil texture, dig 8 to 16 inches down into the soil with a trowel, shovel, or soil tube and feel the soil. At about 50% available water:

- coarse soil appears almost dry and forms a ball that does not hold shape
- loamy soil forms a dark ball that is somewhat moldable and can form a weak ribbon when squeezed between the fingers
- clayey soil forms a good, dark ball, makes a ribbon an inch or so long, and slightly sticky

This method, however, gives only an approximate water content; instruments can give more precise readings.

Using tensiometers and other instruments

Irrigation timing can be determined more precisely using a tensiometer. These water-filled tubes with a pressure gauge accurately reflect the amount of energy a plant needs to extract water from the soil. The pressure gauge measures tension values in centibar units (cbars). For citrus, when the gauge reads 30 centibars, it is a good time to irrigate. Tensiometers must be placed in the root zone between the emitter and the tree trunk. Having two tensiometers next to each other can be helpful in deciding when to turn the system on and off. For example, a tensiometer at a depth of 1 foot would indicate when to turn the water on, and a second at 3 feet would indicate when to turn the water off. Prevent tensiometers from being damaged during harvesting and other orchard operations by placing a plastic milk crate or some other structure over each device.

Other devices can also be used to measure soil moisture. Gypsum blocks are very effective; the part in the ground is inexpensive but the reading device costs about $250, so a relatively large acreage is required to spread out the cost of the system. Portable meters rely on an electrical current carried by water in the soil. Even $10 meters can give a rough estimate of the soil water content, but they are not very effective in rocky ground, because their sensitive tips break easily.

Soil-based methods monitor an aspect of soil moisture that, depending on the method, requires a correlation to plant water use. Some methods are well understood and inexpensive, others are expensive, inaccurate, inappropriate, or not well researched. Some methods allow multiple site readings, while others require a device to be left in place. Some measure soil-water directly (e.g., oven-drying), and others measure another parameter, such as electrical conductance. Some methods are affected by salts or soil iron content, and others have limited value in the desired soil moisture range. Some, like tensiometers and gypsum blocks, give a reading from a porous material that comes to equilibrium with soil moisture, while many others use the soil directly as the measured medium—an important distinction, since discontinuities in the soil caused by rocks or gopher holes can affect readings. Also, some of the older techniques have been improved. For example, gravimetric oven-drying can now be done by microwave, considerably speeding up the process, and tensiometers and gypsum blocks can now be found with digital readouts and connections to data loggers that make data easier to manage. Many types of monitoring devices are available; table 11.1 describes their characteristics. As with any tool, the value of these devices increases with use and familiarity. Even though several are stationary devices, by placing them in representative positions in the orchard, they can accurately reflect the entire orchard. Some types of device can be stationary or portable, depending on the model. "Ease of use" in table 11.1 indicates the ease of reading the device as well as the maintenance.

Weather-Based Scheduling

Another scheduling technique that has become popular is the use of weather data that have been converted to a crop water-use value. This value is the estimated amount of water an orchard would use. The value is often referred to as the evapotranspiration (ET) of the crop. Evapotranspiration is the amount of water that is lost from a well-watered crop through the leaves (transpiration) and through evaporation from the surface of the soil. Applying the ET amount at an irrigation keeps trees at their optimal moisture content. This technique is often called the water budget method or checkbook scheduling.

The information required for water budget scheduling is available in many areas of California from newspapers, irrigation districts, and over the California Irrigation Management Information System (CIMIS, http://wwwcimis.water.ca.gov/cimis/welcome.jsp; 800-922-4647). The CIMIS network of over 50 weather stations calculates reference evapotranspiration (ET_o). Reference evapotranspiration values are available from many irrigation districts, CIMIS, and certain weekly journals and magazines. Other sources include the County Flood Control in Ventura County and the resource conservation districts in San Diego County. These values are an estimate of the amount of water lost from a well-watered field of grass, the standard reference for all other crops. ET_o is modified for the specific crop with a crop coefficient (K_c). The formula for converting ET_o to crop ET is

$$ET_o \times K_c = ET_{crop}.$$

For a full-grown citrus orchard, a crop coefficient of 0.65 is used in most of the state, but 0.56 is used in the desert growing areas. When trees are young and intercept little energy to drive water loss, a coefficient of 0.05 works well. As the trees increase in size to where their shade covers about 65% of the soil surface of the orchard, the coefficient is gradually increased each year. With rapidly growing trees, the increase is usually about 10 % each year, until about year 8, when the 65% figure is reached. A correction factor must be incorporated for the irrigation system distribution uniformity. If the orchard is cover cropped for part or all of the year, the period during which the cover is present must be incorporated into the water-use calculation. If a young orchard is covered by a perennial cover crop, a coefficient of 0.65 is used regardless of tree size. A winter annual cover, which uses only rainfall for its growth, does not require a correction in a high-rainfall year, but it may require one in a low-rainfall year.

One of the drawbacks of centralized weather stations is the station values can be quite different from those at your citrus orchard. When using evapotranspiration figures it is always important to back up the estimates with field checks in your orchard. An alternative to using centralized weather stations is establishing your own. An electronic station costs about $5,000 and requires regular maintenance. A simpler weather station can be developed with an evaporation pan or an atmometer (atmosphere meter). An atmometer is a closed system with a ceramic head, much like a tensiometer. As water is drawn out of a reservoir, a sight tube shows how

Table 11.1. Characteristics of selected soil monitoring devices

Method	Cost	Ease of use	Accuracy	Reliability	Salt-affected	Stationary
gypsum block	L	H	H	H	L	yes
tensiometer	L	M	H	M	L	yes
portable tensiometer	M	M	H	M	L	no
solid-state tensiometer	M	H	H	H	L	yes
time domain reflectometer	H	M	H	H	M	both
neutron probe	H	L	H	H	L	yes
feel (soil probe)	L	H	H	H	L	no
gravimetric (oven)	L	M	H	H	L	no
conductance	L	H	M	M	H	both
capacitance	M	H	M	H	M	both

Key:
H = high; M = medium; L = low.

much water has been evaporated. Since the physics of evaporation and transpiration are very similar, the values can easily be used in a water budget. The major drawback to the evaporation pan is the maintenance required to keep birds, coyotes, and bees from causing inaccurate readings. Algae also must be kept out of the pan. The atmometer is more expensive (about $300) than a pan, but it is much easier to maintain.

Regardless of the scheduling technique or equipment used, a thorough evaluation of the irrigation system must be performed so that a known amount of water is being applied. Until the volume and distribution of water are known, it makes little sense to schedule applications.

Calculating Water Requirements

Determining the application rate of low-flow systems can be confusing because irrigation scheduling and water-use information is often presented in inches per day, while discharge from low-flow emitters is in gallons per hour. Inches per day can be converted to gallons per day by the following formula:

$$\text{Water use (gal/day)} = \text{tree spacing (ft}^2\text{)} \times \text{tree water use (in/day)} \times 0.623 \text{ (gal/in-ft}^2\text{)}.$$

For example, an orchard has fully grown trees at a spacing of 20 by 20 feet (400 ft^2). The tree water use is 0.1 inch per day.

$$\text{Water use} = 400 \times 0.1 \times 0.623 = 25 \text{ gal/day.}$$

With smaller trees, the area of the canopy should be used instead of the plant spacing. Also, extra operating time must be factored in when distribution uniformity is low. With a DU of 80%, allow 25% more operating time to ensure that all trees receive the minimum amount of water required.

A grower can use a device such as a tensiometer to signal when to initiate irrigations and use the CIMIS values since the last irrigation to determine how much to apply. By using soil moisture depletion, once a threshold is found, the same amount of water can often be applied at an irrigation event. Or, if irrigation is done on the same day of the week, the CIMIS values can be accumulated from the previous irrigation and that amount can be applied, taking into account DU and an amount required for leaching.

Regulated Deficit Irrigation

Irrigation is required in virtually all California citrus orchards to produce top yields of high-quality fruit. This is because citrus ET_c far exceeds the effective rainfall that occurs during the summer. However, increased competition for California's water supply from a growing population and environmental protection suggests that growers will be increasingly accountable for their water use and that future water costs will likely be higher. Thus, knowledge of tree response to water stress is important in irrigation management.

What is water stress? As the leaf stomata, the small openings on the underside of citrus leaves, open in the early morning in response to sunlight, water vapor moves from the interior of the leaf through the stomata and into the atmosphere. This process, known as transpiration, causes the leaves to become slightly deficient in water and creates an energy gradient between the leaves and the shoots, trunk, and roots of the plant. At the root-soil interface, this gradient causes water to be extracted from the soil. The transpiration rate depends primarily on weather conditions. As the soil-water becomes limited, the transpiration rate exceeds the extraction rate. Plant water deficits, or water stress, are the result. Without some type of regulation, the leaves would dehydrate, resulting in damage or death. The stomata provide this regulation; they begin to close in response to water stress, thus maintaining a favorable internal water balance in the plant. However, it comes at a price.

The leaf stomata are the conduits not only for transpiration but also for carbon assimilation. Carbon dioxide diffuses from the atmosphere through the stomata and into the leaf, where photosynthesis converts it into sugars, the building blocks necessary for plant and fruit growth and the fuel that powers important plant processes. In essence, the plant trades water for carbon, since both water and carbon dioxide use the same plumbing system at the leaf surface. Maximum transpiration and thus maximum photosynthesis occur when trees are fully irrigated. Reducing carbon uptake (and thus photosynthesis) negatively affects one or more tree organs—roots, shoots, branches, leaves, or fruit. With citrus, water stress usually results in smaller fruit size at harvest. Thus, we normally recommend that citrus growers avoid water stress by careful irrigation management.

However, recent work (Goldhamer and Salinas 2000) has shown that mature navel orange trees can be stressed during certain periods of the season without negative effects on fruit yield. In fact, carefully imposed water stress can significantly reduce peel creasing and thus improve grower profit. Regulated deficit irrigation (RDI) is the controlled imposition of water stress. The goal of RDI in citrus is to reduce the amount of seasonal applied water while maintaining or possibly improving fruit yield and quality. The success of RDI depends on whether the beneficial aspects of water stress can be achieved without concomitant negative impacts on tree processes and other important fruit yield and quality components.

It has been reported (Goldhamer and Salinas 2000) that creasing can occur when the growth rate of the outer layer of the peel (albedo) is exceeded by the enlargement of edible, internal parts of the fruit (endocarp). This apparently results in the formation of weak sites (cracks) in the outer layer and subsequent creasing. By imposing water stress early in the season with Frost nucellar on Troyer rootstock, the occurrence of creasing, and thus fruit considered "juice," in the harvest fruit was significantly reduced. The RDI regime that was most successful in this research, which occurred in Kern County on a moderately shallow soil, applied water at 25% of potential ET_c from mid-May through mid-July. This resulted in a maximum pressure chamber reading of 19.5 bars (1.95 MPa) during this period. It is likely that water stress during this critical, specific period of fruit development slowed the growth rate of the internal fruit segments more than the peel cell enlargement rate, reducing the formation of weak sites in the peel. Fruit size was lower than that of fully irrigated trees at the end of the RDI period, but it recovered within 6 weeks of the reintroduction of full irrigation in mid- July (fig. 11.6).

While navel orange growers, especially those with a severe creasing problem, can improve their profit using RDI, its use in citrus must be carefully managed. Successful implementation of this technique depends on the timely imposition of tree water stress. The approach used in the research described earlier (Goldhamer and Salinas 2000)—irrigating at a fraction of potential ET_c for a given period of the season—is not directly transferable to areas with different soils, soil profiles, and weather conditions. Weather influences ET_c as well as fruit growth, potentially affecting the beneficial RDI effect observed on creasing. Measurements of tree water status must be made with a pressure chamber to improve the precision of RDI management achievable by irrigating at fractions of potential ET_c. For further information, see Ballester et al. 2011.

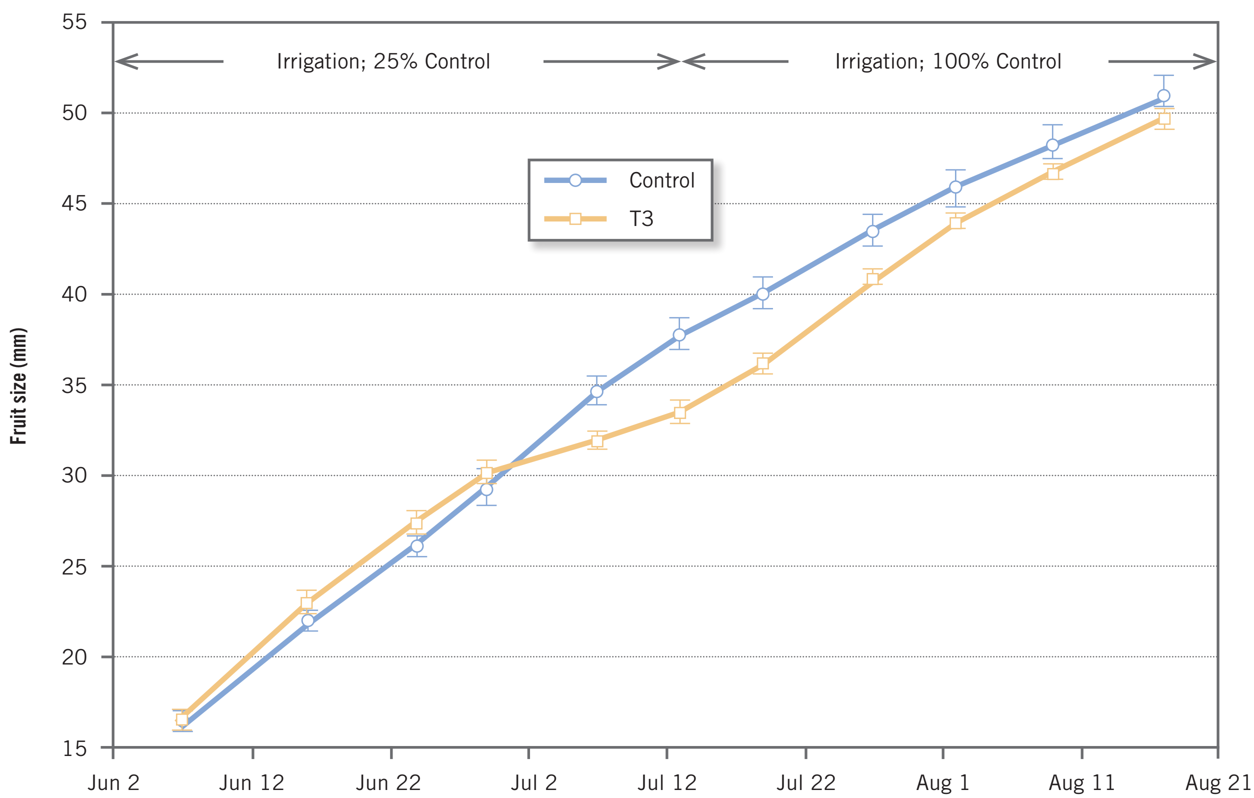

Figure 11.6. Fruit size for regulated deficit irrigation (RDI) regime that applied water at 25% of potential ET_c from mid-May through mid-July (T3) compared with fully irrigated control.

Effect of Irrigation on Disease

High soil moisture content and poor drainage are associated with Phytophthora root rots. This root rot can be caused in winter by *Phytophthora citrophthora* or in summer by *Phytophthora parasitica*. Increasing irrigation intervals, irrigating alternate middles, conversion to drip or microsprinklers from furrow, and installing drain lines have helped in controlling these diseases. On heavier soils, planting on berms or mounds can reduce the likelihood of root rot. The orchard floor should be leveled to avoid water accumulation.

Asphyxiation of roots can occur with excessive water or flooding, and the methods used to help prevent root rot also help with inadequate soil aeration. These methods can also help with lime-induced chlorosis, a soil aeration problem that is exacerbated by a high soil lime content in which trees exhibit an iron deficiency that can be corrected only by improving soil aeration. Correcting this problem is most easily accomplished by adjusting irrigation practices and applying soil acidifiers.

Citrus gummosis is caused by *Phytophthora* species and is attributed to conditions that keep the trunks moist. The incidence can be minimized by avoiding wetting the tree trunk, ensuring good aeration around the trunk, and preventing soil accumulation around the trunk.

Citrus fruit are more prone to oleocellosis when tree moisture status is high. Harvesting fruit shortly after irrigation, early in the morning, or in humid, foggy conditions can cause rupturing of the rind oil glands, leading to rind spotting. Minimizing this problem is accomplished by not harvesting during periods that favor high fruit turgor.

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