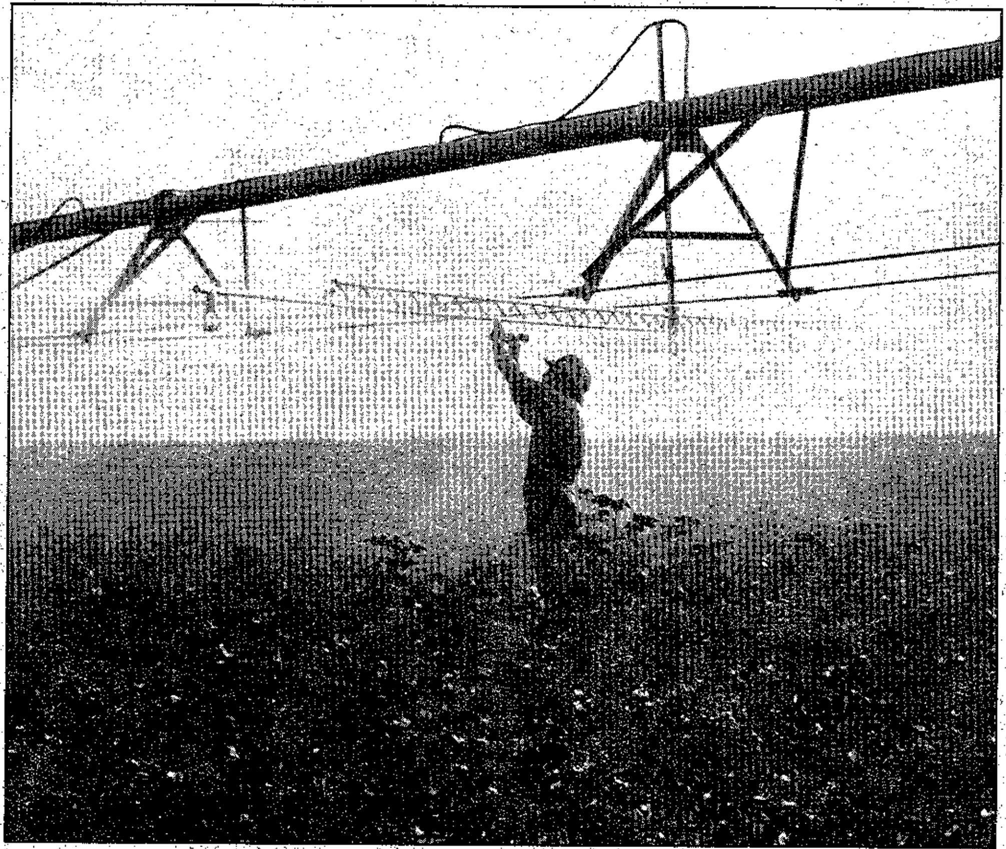
IRRIGATION SCHEDULING

A Guide for Efficient On-Farm Water Management



University of California
Division of Agriculture and Natural Resources
Publication 21454

IRRIGATION SCHEDULING
A Guide for Efficient On-Farm Water Management

Technical Editors:

David A. Goldhamer
Irrigation and Soils Specialist, Cooperative Extension
Department of Land, Air, and Water Resources
University of California, Davis

and

Richard L. Snyder
Bioclimatologist, Cooperative Extension
Department of Land, Air, and Water Resources
University of California, Davis

University of California
Division of Agriculture and Natural Resources
Publication 21454

Publication 21454

For information about ordering this publication, write to:

Publications
Division of Agriculture and Natural Resources
University of California
6701 San Pablo Avenue
Oakland, California 94608-1239

or telephone (415) 642-2431

Printed in the United States of America.

Production:
Jim Coats, Senior Editor
Alfred Smith, Senior Artist

Preface

This publication evolved from a joint meeting of the Department of Land, Air, and Water Resources and the Soil, Water, and Engineering Unit of Cooperative Extension held in Napa in late 1983. These groups meet annually to discuss research and educational activities and to promote communication and coordination of activities. Cooperative Extension and Experiment Station workers recognized the need for a comprehensive, concise source of information on irrigation scheduling methods. Although various scheduling techniques have been utilized in California since the advent of irrigated agriculture, most existing publications focus on a single technique. New developments in assessing evaporative demand and using these measurements to predict crop water use have added significantly to the techniques available to schedule irrigations. It is our position that advances in technology do not necessarily render older scheduling techniques obsolete; in fact, conjunctive use of techniques will likely be the best irrigation management program. In this publication we have tried to assemble the best information available on irrigation scheduling methods in use today.

We gratefully acknowledge the efforts of Diana Nix, Janice Heine, and Gloria Molina, who prepared the many drafts of this publication. Appreciation is expressed to Jim Coats, who edited the manuscript, Alfred Smith, who designed the publication, Arch MacPhail, who assisted in the preparation of the publication, and Jack Kelly Clark for his photography work.

The Authors

Randy Q. Diven, Technical Service Representative, Professional Agriculture Services, Fresno

David A. Goldhamer, Irrigation and Soils Specialist, University of California Cooperative Extension, Department of Land, Air, and Water Resources, Davis, located at the Kearney Agricultural Center, Parlier

Stephen R. Grattan, Plant Water Relations Specialist, University of California Cooperative Extension, Department of Land, Air, and Water Resources, Davis

Donald W. Grimes, Water Scientist, Department of Land, Air, and Water Resources, Davis, located at the Kearney Agricultural Center, Parlier

Robert M. Hagan, Water Specialist (retired), University of California Cooperative Extension, Department of Land, Air, and Water Resources, Davis

Blaine R. Hanson, Irrigation and Drainage Specialist, University of California Cooperative Extension, Department of Land, Air, and Water Resources, Davis

Jerry L. Hatfield, Research Leader, United States Department of Agriculture–Agricultural Research Service, Bushland, Texas

Delbert W. Henderson, Professor of Water Science (retired), Department of Land, Air, and Water Resources, Davis

Theodore C. Hsiao, Professor of Water Science, Department of Land, Air, and Water Resources, Davis

Gordon Lyford, Agricultural Engineer, United States Department of the Interior, Bureau of Reclamation, Sacramento

Jewell L. Meyer, Soil and Water Specialist, University of California Cooperative Extension, Department of Soil and Environmental Sciences, Riverside

James D. Oster, Soil and Water Specialist, University of California Cooperative Extension, Department of Soil and Environmental Sciences, Riverside

Claude J. Phene, Soil Physicist, United States Department of Agriculture–Agricultural Research Service, Fresno

Steven E. C. Post, former Soil and Water Specialist, University of California Cooperative Extension, Department of Soil and Environmental Sciences, Riverside

Terry L. Prichard, Soil and Water Specialist, University of California Cooperative Extension, Department of Land, Air, and Water Resources, located in San Joaquin County

William O. Pruitt, Irrigation Engineer (retired), Department of Land, Air, and Water Resources, Davis

Frank E. Robinson, Water Scientist, Department of Land, Air, and Water Resources, Davis, located at the Imperial Valley Field Station

Herbert Schulbach, Soil and Water Specialist (retired), University of California Cooperative Extension, Colusa County

Michael J. Singer, Professor of Soil Science, Department of Land, Air, and Water Resources, Davis

Richard L. Snyder, Bioclimatologist, University of California Cooperative Extension, Department of Land, Air, and Water Resources, Davis

Ralph A. Strohman, Staff Research Associate, University of California Cooperative Extension, Riverside

Wesley W. Wallender, Associate Professor of Water Science and Agricultural Engineering, Department of Land, Air, and Water Resources, Davis

William E. Wildman, Soil Specialist (retired), University of California Cooperative Extension, Department of Land, Air, and Water Resources, Davis

Contents

Introduction

Agriculture accounts for 85 percent of California's water usage. Increasing competition for the state's water supply from cities and industry, poor prospects for development of significant additional water supplies, and concern about the irrigation-related degradation of surface and groundwater quality have led to increasing emphasis on agricultural water conservation. Agriculture must get the most benefit from each unit of water for sustained crop productivity, and must at the same time maintain the quality of the state's land and water resources. Irrigation scheduling plays an important role in meeting these objectives.

In its simplest terms, irrigation scheduling means deciding when to irrigate and how much water to apply. The goal of an irrigation scheduling program is to supply the plants with adequate water while minimizing the loss of applied water—mainly to deep percolation and runoff. Irrigation scheduling depends upon various soil, atmospheric, crop, and irrigation system and operational factors. As such, no scheduling method is universally applicable. While researchers develop and evaluate different scheduling methods, the best irrigation management program from the grower's point of view is the one that is most profitable.

Some form of irrigation scheduling is practiced by every grower. However, the bases for making irrigation decisions and the levels of sophistication vary widely. They range from irrigation based on experience or on the practices of neighboring growers to techniques based on expensive, computer-aided instruments that assess soil, water, or atmospheric parameters. These more recent methods generally can be grouped into two categories: (1) monitoring water status in the soil or plant, and (2) estimating crop water use based on atmospheric measurements, sometimes referred to as the *water budget* approach. In the past, atmospheric-based irrigation management has been hampered by the joint lack of economical, reliable measurement techniques and of information on water use rates for specific crops. Today, both are available. (For the former, see Chapters 2 and 3; for the latter, see Appendix A.)

Irrigation Scheduling is a book for growers and irrigation professionals. It can also be used as a teaching and technical resource. Its purpose is to provide information on various irrigation scheduling techniques in current use or under evaluation for future use. The publication provides a basic understanding of the soil, water, plant, atmospheric, and operational factors involved in scientific irrigation scheduling, as well as practical considerations in establishing an on-farm water management program. We have attempted to summarize the information, with emphasis on the operational aspects of each method, including strengths and weaknesses. Technical discussions of the methods are limited. The References and Bibliography section lists additional, more technical literature. We have also included chapters that address issues related to irrigation scheduling, including the texture, bulk density, field capacity, and available water of the soil (Chapter 1); as well as shallow water tables and salinity (Chapter 6); and a comprehensive list of historically averaged evapotranspiration figures for 208 California locations (Appendix B).

1

This "Madera" sampler is used to collect a volumetric soil moisture sample. The putty knives are inserted after the sample is withdrawn from the auger hole, and delineate a known volume of soil.

Characterizing the Soil Environment

Soil in a plant's root zone serves many important functions. It acts as a reservoir from which the plant extracts water, an anchor for the plant, and a storehouse and supplier of essential plant nutrients. The water-storage capacity and water-conducting ability of the soil must be considered for scheduling irrigations in surface-irrigated fields.

Soil Water-Holding Properties

You can use any of a variety of methods to determine when to irrigate and how much water to apply to a cropped field, but with the exception of high-frequency (low-volume) irrigation, every method requires that you know the water-holding properties of the soil. These properties help you determine the upper and lower acceptable limits (the *boundary conditions*) for soil water content. Generally, applying more water than is needed to refill the crop's effective root zone to its maximum capacity, control salinity, and account for irrigation system losses (deep percolation and end-of-field runoff) serves no useful purpose and should be avoided. Allowing the water content to fall below the lower limit can reduce crop yield and quality, and should also be avoided.

Soil water content can be expressed as the percentage of the soil volume occupied by water. Because the percentage by volume does not depend on any standard of measure, it applies equally well to metric and English measurements. It can also convert easily to the depth units often used for irrigation scheduling. For example, a soil with 20 percent water by volume has

0.2×12 in/ft $= 2.4$ in/ft

or

0.2×1000 mm/m $= 200$ mm/m

as the depth of water per unit depth of soil.

The usual way to determine soil water content is to weigh the soil wet, dry the soil, weigh it again, and calculate the change in weight. You then take the ratio of that change to the soil's dry weight, and multiply it by the soil density (*bulk density*) to obtain the water content on a volume basis. Soil bulk density is also the primary indicator of soil structure. One of the first steps in identifying the water-holding characteristics of a soil, then, is determining the soil's bulk density.

When you irrigate a field, the water flows into the soil through the holes within the soil aggregates or through holes or cracks between the aggregates. Soil aggregates consist of individual soil mineral grains held together by various "glues," mostly organic matter, iron and aluminum oxides, and clay minerals. The holes and cracks within and between these aggregates are also referred to as *pores*, or *voids*. The number of pores, their sizes, and their shapes help determine how rapidly water will enter and spread through a soil.

Measuring the pores directly is difficult, but it is relatively simple to measure the solid portion of the soil and thus, indirectly, its pores. This is where bulk density fits in the irrigation plan.

Each soil particle has weight and volume. The weight of a single grain of sand, silt, or clay per unit volume is the specific gravity, or particle density, of the mineral grain. In soils, the average mineral particle has a density of 2.65 grams per cubic centimeter (g/cm^3).

If a soil had no pore space and all the individual particles were packed together, the bulk density of the soil would be 2.65 g/cm^3. Most soils have bulk densities between 1.2 and 1.8 g/cm^3. A few soils have bulk densities of less than 1.0 g/cm^3. Such soils usually contain high amounts of organic matter. For example, organic soils of California's Sacramento–San Joaquin Delta region often have bulk densities lower than 1.0 g/cm^3 and can float on water.

In addition to the pores within and between aggregates, the roots, insects, rodents, earthworms, and other living organisms that tunnel through the soil create pores and reduce the density of the soil. Soils with high clay contents shrink and swell, and these processes also create pores. Sometimes, the large cracks found in a dry clay soil provide the soil's only avenue for water entry.

In most soils, roots grow and water moves with little problem. Where the bulk density is low (1.0 to 1.4 g/cm^3), the roots have a fairly easy time of exploration and water will move rapidly through the soil. As bulk density increases, ease of root growth and water movement decreases. Knowing the bulk density of a soil is important to crop production and water management.

Determining Bulk Density

The three methods commonly used to measure bulk density all require that you measure both the volume and the weight of a soil sample. Gravel and stones should be excluded from samples.

Soil core method. You will need a special tool for the soil core technique. Soil core samplers are commercially available, although any rigid, open cylinder of known volume can be used. Drive the cylinder into the soil profile, being careful not to compress the sample. Carefully remove the cylinder and trim excess soil from the top and bottom ends. If you want to measure soil water content, take care to avoid evaporative water loss from the sample. Usually, the soil core is transferred from the cylinder to an airtight container for later analysis, which involves weighing the sample, drying it in an oven for 24 hours at 105°C, and reweighing the dried sample. The difference between the first and second weights is the weight of the water in the soil at the time you took the sample. This value, divided by the oven-dry weight of the soil, yields the soil water content on a dry-weight basis. To determine the bulk density, divide the oven-dry soil weight by the volume of the sampling cylinder.

Waxed clod method. Take a clod of soil about the size of your fist from the soil. Dry the clod in an oven for 24 hours at 105°C, and then weigh it. Then, dip the clod into hot wax to coat it, and suspend it from a scale to measure its weight. Finally, immerse the wax-coated clod, still suspended from the scale, in water, and again record its weight. The cubic-centimeter volume of the clod is calculated as the difference between the wax-covered weights measured in air and water, when the weights are expressed in grams. The difference equals the weight of the water displaced by the clod, as one gram of water occupies one cubic centimeter. The bulk density is calculated as the oven-dry weight, in grams, divided by the volume of the clod, in cubic centimeters.

Irregular hole method. The irregular hole method is probably the simplest method. With a spoon or small garden shovel, you dig a hole about the size of your fist and save all the soil in a container. Line the hole with thin plastic wrap, and then carefully fill it with water. The amount of water added is equal to the volume of the soil that was removed. Dry the soil in an oven and weigh it. That weight, divided by the volume of the hole, yields the soil's bulk density.

Taking more than one sample from each layer in the soil and averaging the values of bulk density is a good idea. Soils are highly variable, and a single sample will not give a reliable measure of bulk density.

Available Water

The next step in characterizing the soil environment is to identify the upper limit of soil water-holding capacity (field capacity) and the lower soil water limit below which plants cannot effectively extract water (permanent wilting point). The quantity of water held in a soil between the two limits is called *available water,* and provides a measure of how much water a crop can extract from the soil. Only a portion of the available water is extracted between most irrigations, the specific amount depending on crop characteristics, soil type, and weather.

Field capacity and permanent wilting point relate to the tightness with which the soil holds onto the water (soil water tension). The criteria for determining field capacity and permanent wilting are somewhat arbitrary; both terms are more accurately defined as concepts than as hard and fast values. Nevertheless, these concepts provide acceptable guidelines for scheduling irrigations.

Field capacity. The concept of field capacity (FC) helps schedulers evaluate the upper limit of a soil's capacity to store water for plants' use. Most available field capacity data are based on laboratory measurements, so schedulers must adjust the data to account for variable conditions encountered in the field.

The idealized concept applies directly only to soils with unrestricted drainage—soils with few physical or textural changes over depth and with water tables well below the measured depth. Stratification and shallow water tables retard or prevent free drainage, increasing soil water storage capability appreciably over the laboratory-measured field capacity.

Field capacity is best understood as the water content beyond which further water movement slows as a result of the soil's reduced ability to conduct water. Movement never stops completely, so the soil represents a full but leaky storage vessel if the entire root zone depth is wetted. The drainage rate slows more abruptly in coarse-textured than in fine-textured soils, so field capacity is better defined in sandy soils, at least in terms of absolute water content. In some finer soils, drainage rates decrease so slowly as to render their field capacities indefinite.

Even in unlayered soils, you must consider the storage characteristics of the entire root zone. If the full depth is wetted or if excess water is applied, the water content at lower depths may increase for several days after irrigation. In this way, drainage from the overall profile can continue over a long time. The drainage lag may increase the amount of usable water, particularly if the interval between irrigations is short. At the same time, drainage usually will continue for some time at the bottom of the root zone. If appreciably less water is applied than is required to re-wet the whole root zone, the water will redistribute within the root zone, but essentially no water will be lost to drainage.

Layers can differ in texture and permeability, and such variations can retard or completely disrupt the drainage process. Less-permeable layers such as claypans and cemented hardpans slow the drainage of overlying soil to varying degrees, depending on how impervious the subsoil layer is. With an impervious subsoil, drainage can be so gradual that the field capacity cannot be determined. Sandy or gravelly layers effectively stop the drainage of overlying soil because they are dewatered early, and can no longer conduct water downward at a significant rate. Such layering thus increases storage for indefinite periods.

Soil water tension levels associated with field capacity range from about 0.1 to 0.3 bar for different soils, so the water table must be from 1 to 3 meters below the measured point if the soil is to drain to field capacity. Water tables or sand or gravel interfaces above that level prevent the soil from reaching field capacity by drainage alone, and the shallower the water table is, the higher the water content must be to stop drainage following the full wetting of the soil profile.

Field capacity (or, more precisely, an approximate upper limit of water storage in the root zone) can be measured in the field by thoroughly wetting soil with no actively transpiring plants, covering the soil surface with plastic film to minimize evaporation (preferably with straw or other residue), and measuring the soil water content frequently at appropriate depths until it stabilizes. As a rule of thumb, the upper parts of the soil attain field capacity 3 to 5 days after irrigation. Longer times are required for lower depths, since water from upper layers drains through these zones. You can also derive values where soil water content is monitored for other purposes by carefully examining the data, especially those from early in the growing season when evapotranspiration is slow. Stable soil water content values following several irrigations often prove consistent, and can serve as reasonable and practical measures of field capacity.

Most available estimates of field capacity are based on laboratory procedures. Nearly all use samples that have been ground and sieved for convenient handling and homogeneous subsampling. The usual effect of such disruption of the natural structure is to increase water retention.

The first procedure to be used widely involved centrifugation of small soil samples; the resulting water content (weight basis) was termed the *moisture equivalent* (ME). The ME correlated well with field measurements of field capacity for intermediate- and fine-textured soils, but underestimated field measurements of coarse-textured soils (ME 10). When the pressure plate procedure for measuring soil water retention was developed, scientists adopted a 0.33 bar value for ground, sieved samples for estimating FC, since that pressure produced water contents that correlated best with ME. Laboratory measurements of FC using 0.33 bar soil water tension are sometimes inaccurate because removal of the soil samples from the field to the laboratory can cause an increase in soil water retention. A 0.33 bar water tension will often underestimate the FC of a coarse-textured soil, and 0.1 bar values are occasionally used with sandy soils.

Laboratory estimates of FC give soil water contents under the free drainage conditions, and must be adjusted upward to account for field conditions that restrict water flow. In some cases, the difference is substantial. For example, field retention of water by a loam soil containing several thin sand layers can be more than twice that estimated for a homogenized sample.

The field capacities of most mineral soils range from about 10 to 40 percent volumetric water content, equivalent to 10 to 40 cm per meter of soil depth or 1.2 to 4.8 inches of water per foot of soil depth.

Field capacity data for specific soil types may be included in soil survey reports. Soil Conservation Service programs sometimes include field capacity in their soil classification criteria. In the late 1950s, Cooperative Extension specialists measured and compiled the moisture equivalents of 2,500 samples from about 220 soil series in California. The field capacities varied considerably within a given soil type, but such data are more accurate than estimates based entirely on one characteristic, such as texture.

Field capacity is not a precise value, even under idealized free drainage, and cannot be defined, standardized, or measured with 100 percent accuracy. Nevertheless, the concept of soil water storage is essential to irrigation management. Field capacity information should be used with a full understanding of its limitations.

Permanent wilting point. The conventional lower limit of available water is the *permanent wilting point* (PWP), the soil water content at which the lower, older leaves of indicator plants wilt. To differentiate between temporary and permanent wilting, place the container-grown indicator plants in a dark, humid atmosphere for several hours or overnight. If the plants do not recover turgor during such a period of low transpiration, the plant is at permanent wilting and the soil moisture content is considered to be the PWP. The water content of the soil in confined contact with the roots of such a plant has been found to be reproducible, for the most part independent of the test environment (prior to placement in humid darkness), and similar for different indicator plants, provided that the wilting symptoms of all the plants are easily visible.

In the field, many crop plants do not wilt or are sufficiently hardened that they wilt only with onset of severe water stress. The PWP, however, has the same general significance with respect to water extraction and growth whether or not plants actually wilt readily and visibly.

If the entire root system is confined to a soil of nearly uniform water content (containerized soil or soil overlying a shallow, unfractured hardpan), the plant may keep extracting water slowly, bringing the soil to water levels appreciably below the PWP. However, such a plant would be severely water stressed and would not be productive during that period. Growth generally ceases well before permanent wilting, but PWP is a definitive lower limit for growth.

A plant with a portion of its root system in moist soil tends to absorb most of its water from that wet zone and to halt water extraction from a drier soil area at or slightly above the dry zone's PWP. The drier soil's water content then changes little until the soil is rewetted. One field example is the water extraction pattern outside the area wetted by localized irrigation (drip or low-volume sprinklers).

Most PWP estimates are based on the water content of a disturbed soil sample that is subjected to 15 bar pressure in a pressure membrane apparatus. This value was initially established by correlation with PWP measured on an indicator plant, although the moisture content corresponding to the mean 15 bar pressure was slightly less than that for the average indicator plant measurement of PWP for the soils used. Coarse grinding and sieving have only minor effects on water retention in this range, and disturbed samples generally give reliable results.

You can express available water on different bases and in different units. Relevant bases are per-unit weight, volume, and depth of soil, and the depth or volume of the entire root zone. In irrigation scheduling, most water balance calculations are based on depth units. Since most reported FC and PWP values are given on a dry soil weight basis, they usually have to be converted.

To convert, you must know the bulk density (BD) of the soil, the density of water (DW), and the depth of soil. The first step is to convert the units of soil water content based on weight (θ_w) to volume basis units (θ_v):

$$(\theta_w)(BD) = (\theta_v)(DW) \qquad [1.1]$$

$$\text{(g } H_2O\text{/g soil) (g soil/cm}^3\text{ soil)} = \text{(g } H_2O\text{/cm}^3\text{ soil)}$$
$$\text{(1 cm}^3\ H_2O\text{/g } H_2O\text{)}$$
$$= \text{cm}^3\ H_2O\text{/cm}^3\text{ soil}$$

The depth of water per unit depth of soil is numerically equal to θ_v if soil and water depths are expressed in the same units. For example, given that 1/3 bar and 15 bar values for the 0 to 1 foot depth are, respectively, 22.2 and 10.3 percent by volume and bulk density is 1.37 g/cm^3:

$$\text{available water (vol \%)} = (0.222 - 0.103) \qquad [1.2]$$
$$\text{cm}^3\ H_2O\text{/cm}^3\text{ soil}$$
$$= 0.163\text{ cm } H_2O\text{/cm soil}$$
$$\text{available water} = 0.163\text{ in } H_2O\text{/in soil}$$
$$= 0.163 \times 12\text{ in/ft}$$
$$= 1.96\text{ in } H_2O\text{/ft soil}$$

Obtain the available water storage capacity of the entire root zone by summing the depths of water for all soil depth increments or by multiplying a weighted average by the root zone depth. Figure 1.1 illustrates the concept of available water and shows typical soil water contents for a sandy loam soil expressed both as the volumetric percentage and the depth of water per depth of soil.

Laboratory estimates of FC, PWP, and available water for specific soil types are included in some soil survey reports. Available water storage capacities vary appreciably within a soil type, but other data are seldom available.

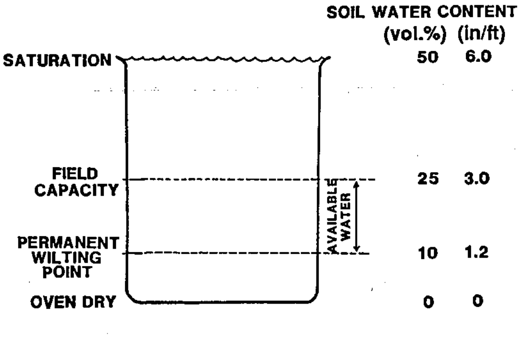


Fig. 1.1. Conceptual representation of key soil water-storage indexes and typical values for a sandy loam soil.

Table 1.1. Ranges of available water for three soil textural groups

Textural group	Available water
	inches of water per foot of soil
Coarse (sand, loamy sand, sandy loam)	½ to 1¼
Medium (fine sandy loam, loam, silt loam)	1 to 2
Fine (clay loam, silty clay loam, clay)	1½ to 3

In many cases, no data can be found on available water storage capacity, and you will need to make an estimate, usually based on soil texture. Available water is not clearly related to texture alone, so such estimates are very rough. Root zone totals differ widely in different soils, but such estimates are still useful. Estimates of available moisture should be reduced for saline soils.

Several moisture tables have been published, but they imply greater accuracy than they can deliver by giving too much detail and characterizing soils as discrete groups. The information in table 1.1, although it characterizes available water in broad groupings, is more realistic.

Soil Texture

Determining soil texture in the field generally starts by using the "feel" method. This method has the primary advantage of being quick, and with practice, can aid in estimating the available water-holding capacity of the soil.

With the feel method, you remove a small handful of soil from the chosen location and depth using a shovel, soil tube, or auger. Add water to the soil in the palm of your hand, and work the soil and water together with your fingers until it gains a moist consistency. The resultant soil mass should be easy to form into a moist soil ball, but not so wet that it glistens or that free water runs out. It takes a little practice to get the right combination, but you can add additional soil or water as you experiment.

Work the moist ball between your thumb and forefinger. The purpose here is twofold: (1) to feel the combination of particle sizes and (2) to try to form a "ribbon." Table 1.2 lists some representative soil textures and describes their characteristic "feels" and ribbon-forming abilities. To better understand the characteristics, learn these three terms:

1. Gritty—Rough, coarse to the touch, you can feel individual particles.
2. Sticky—The soil adheres to the fingers and to other objects, and coheres to itself.
3. Plastic—Will change shape continuously under the influence of applied stress, and retain that shape upon removal of the stress. A plastic soil will ribbon, but a sticky plastic soil will make a longer, stronger ribbon than a nonsticky plastic soil.

Table 1.2. Characteristics of soil textures

Soil textural class	Feel method characteristics
Sand and loamy sand	Crumbles very easily when dry. Feels gritty; single-grained when moist. A cast will form when moist soil is squeezed in the hand. The cast cannot be handled without breaking. No ribbon can be formed.
Sandy loam	Feels gritty, but moist soil holds together more than loamy sand. Fine sandy loam holds together better than coarse sandy loam. You can tell that particles finer than sand are present but the sand still predominates. No ribbon can be formed.
Loam	A loam can be ¼ to ½ sand, but most of the grittiness is masked by the silt and clay contents. A moist loam is fairly smooth, not gritty, not sticky, and somewhat plastic. A short ribbon can be formed, but it will split readily and will break off when about ½ inch long.
Silt loam	Dry silt loam feels like talcum powder when crushed. Moist, it is very smooth and slick. It is not sticky and will not cohere to itself enough to make a good ribbon.
Clay loam	Moist clay loam is definitely sticky and plastic. A moderately strong ribbon is easily formed, but will break away when about ¾ inch long.
Clay	Moist clay is very plastic and coheres to itself very well. Ribbons longer than 1 inch can be formed. It is often difficult to moisten a hard lump of dry clay in your hand to get a plastic mass. It must be soaked or ground first.

Three textural classes shown on the soil textural triangle (fig. 1.2) are not included in table 1.2 because they are more difficult to differentiate. With much practice, you can differentiate the silty from the sandy clay loams, and the silty from the sandy clays. Silts are very uncommon in California.

Particle Size Analysis

You can confirm feel texturing by collecting approximately 1 cup of soil, placing it in a strong plastic bag or cardboard carton, and sending it to a soil testing laboratory. Make sure the sample is from the location and soil horizon of interest and is well identified. The laboratory will send back the percentages of sand, silt, and clay for each sample. You can plot the percentages on the soil textural triangle.

Soil Textural Triangle

The soil textural triangle (fig. 1.2) was developed to establish quantitative boundaries to soil textural classes that had originally been determined by the feel method. The classes on the chart are based on the knowledge gained from years of experience and much testing of soils that had been defined by feel. The chart is now the standard for determining textural classes from laboratory particle size analyses. These analyses and the chart are used to verify our estimates of soil texture made by the feel method.

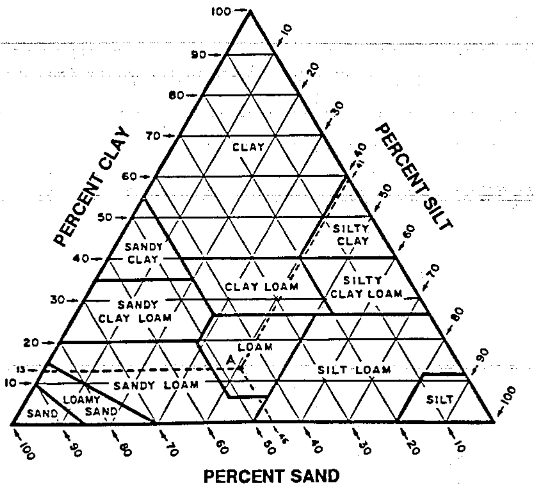


Fig. 1.2. Soil textural triangle. The percentages of sand, silt, and clay in any soil can be plotted on this diagram to determine the soil's textural class.

The textural triangle seems confusing at first, but with a little study you can see that any soil will fit somewhere in the triangle if you know its sand, silt, and clay percentages. First, look at the sand percentages along the bottom of the chart. At the left corner is 100 percent sand. As you go toward the right, each 10 percent decrease in sand content is marked by an arrow and a number. A thin line extends from each arrow through the triangle. Every place on that line has the same sand percentage, given by the number next to the arrow. So for a soil containing 46 percent sand, you follow along the sand line, measure or estimate where 46 should fall between 50 and 40, and draw a line across the chart parallel to the arrows on the sand base line. Next, you follow the same procedure with the clay percentage, but now you start at the top of the chart and go down the left side of the triangle until you come to the clay content, 13 percent in this example. Again, draw a line parallel to the arrows on the clay base line. Use the same process for the silt percentage (41 percent) along the right side of the triangle, and your lines should meet in the box marked "loam."

We can make a few useful generalizations about the triangular chart. First, notice that a soil containing equal proportions of sand, silt, and clay is not a loam, but rather a clay loam. This is because clay expresses its stickiness and plasticity more strongly than sand expresses its grittiness or silt its smoothness. For the same reason, clay soils can have as little as 40 percent of the clay particle size. Above 40 percent clay, all clay soils feel pretty much the same. Sandy loams can contain from 0 to 50 percent silt, 45 to 85 percent sand, and 1 to 20 percent clay. That covers a wide range in itself. When you consider that the sand itself can vary from coarse to very fine, the range of soils within the sandy loam class is broad indeed.

2

Estimating soil moisture using the feel method. When squeezed between the thumb and forefinger, this sandy loam forms a ball and short ribbon, indicating that the soil is near field capacity.

Soil-Based Monitoring

There are three fundamentally different approaches to determining when to irrigate and how much water to apply: (1) monitoring plant water status, (2) monitoring soil water status, and (3) the water budget approach. The soil-based methods include estimating soil water content using the feel method and gravimetric sampling, tensiometers, gypsum blocks, neutron probes, and thermal dissipation sensors. Each technique involves determining either the soil water content or its potential, but to use these data successfully in scheduling irrigation, you must be able to relate the soil-based measurements to the well-being of the plants.

Soil Moisture Sampling

Feel and appearance. Probably the oldest, simplest method of estimating soil moisture is based on the feel and appearance of the soil. Just as you can determine soil texture based on how the soil sample feels when squeezed and manipulated in your hand, you can estimate the soil water content for a particular soil type by a similar technique. The only piece of equipment required is a soil tube or an auger for collecting samples from the plant root zone.

The accuracy of the feel method, again, depends primarily on your experience and judgment in evaluating the appearance and behavior of a handful of soil. Researchers have developed standard descriptions to aid in the process (Hanson, Israelsen, and Stringham 1980; Merriam, 1960). In practice, you estimate soil moisture by comparing field samples to these descriptions after first identifying soil textural class. Table 2.1 classifies soil water levels into six available water categories that range from a level in excess of the field capacity to the permanent wilting point. Approximate soil water contents are given in inches of water per foot of soil depth. You can compute the soil water status for the whole root zone by adding estimated values from each profile increment.

Several types of equipment are available to collect the soil samples. Bucket and spiral type soil augers are commonly used: the bucket auger is a small metal cylinder equipped with teeth that bite into the soil as the auger advances, and the spiral auger is essentially a carpenter's wood bit with the screw point end removed. The primary difference between auger types is that soil obtained with the spiral bit at a particular depth is contaminated somewhat with other soil as the auger is withdrawn from the bore hole. This can be a problem for researchers but not for on-farm samplers. Bucket augers, with their enclosed sides, can extract uncontaminated soil, but removing fine-textured, wet soil from the bucket is sometimes difficult. However, bucket augers with slotted sides are available to facilitate soil removal.

Another sampling device is the soil tube, a small-diameter pipe with a special tip that can be pushed into the profile with a minimum of effort. Part of the tube side is usually cut out to allow inspection and removal of the sample. Many probe tubes are swedged on the tip end to provide for easy soil removal.

Using the feel method to determine soil water is tedious, labor intensive, and time consuming. Because it is a somewhat subjective practice, different people examining the same soil sample may obtain different estimates. The feel method is not the most accurate technique for measuring soil moisture; experience and judgment play important roles. However, with practice, consistent estimates within 10 to 15 percent of the actual soil water content are possible. Depending on the sophistication and needs of the grower, greater accuracy may not be needed or economically justified.

Table 2.1. Soil moisture, appearance, and description chart

Available water*	Feel or appearance of soil†			
	Sand	Sandy loam	Loam/Silt loam	Clay loam/Clay
Above field capacity	Free water appears when soil is bounced in hand.	Free water is released with kneading.	Free water can be squeezed out.	Puddles; free water forms on surface.
100% (field capacity)	Upon squeezing, no free water appears on soil, but wet outline of ball is left on hand. (1.0)	Appears very dark. Upon squeezing, no free water appears on soil, but wet outline of ball is left on hand. Makes short ribbon. (1.5)	Appears very dark. Upon squeezing, no free water appears on soil, but wet outline of ball is left on hand. Will ribbon about 1 inch. (2.0)	Appears very dark. Upon squeezing, no free water appears on soil, but wet outline of ball is left on hand. Will ribbon about 2 inches. (2.5)
75-100%	Tends to stick together slightly, sometimes forms a weak ball with pressure. (0.8 to 1.0)	Quite dark. Forms weak ball, breaks easily. Will not slick. (1.2 to 1.5)	Dark color. Forms a ball, is very pliable, slicks readily if high in clay. (1.5 to 2.0)	Dark color. Easily ribbons out between fingers, has slick feeling. (1.9 to 2.5)
50-75%	Appears to be dry, will not form a ball with pressure. (0.5 to 0.8)	Fairly dark. Tends to ball with pressure but seldom holds together. (0.8 to 1.2)	Fairly dark. Forms a ball, somewhat plastic, will sometimes slick slightly with pressure. (1.0 to 1.5)	Fairly dark. Forms a ball, ribbons out between thumb and forefinger. (1.2 to 1.9)
25-50%	Appears to be dry, will not form a ball with pressure. (0.2 to 0.5)	Light colored. Appears to be dry, will not form a ball. (0.4 to 0.8)	Light colored. Somewhat crumbly, but holds together with pressure. (0.5 to 1.0)	Slightly dark. Somewhat pliable, will ball under pressure. (0.6 to 1.2)
0-25% (0% is permanent wilting)	Dry, loose, single-grained, flows through fingers. (0 to 0.2)	Very slight color. Dry, loose, flows through fingers. (0 to 0.4)	Slight color. Powdery, dry, sometimes slightly crusted, but easily broken down into powdery condition. (0 to 0.5)	Slight color. Hard, baked, cracked, sometimes has loose crumbs on surface. (0 to 0.6)

Source: Adapted from Merriam (1960) and Hansen, Israelsen, and Stringham (1980).
*Available water is the difference between field capacity and permanent wilting point.
†Numbers in parentheses are available water contents expressed as inches of water per foot of soil depth.

Gravimetric. The gravimetric method is a direct, absolute technique for estimating the water content of soils. It is the procedure most commonly used to calibrate such indirect methods as the neutron probe or resistance blocks. The method involves drying the soil in an oven and determining the amount of water in the soil by subtracting the oven-dry weight from the initial soil weight. The amount of water is then divided by the oven-dry soil weight to obtain the percentage water content by weight (θ_w).

The gravimetric method of determining soil water content has many advantages:

1. The full range of soil water contents can be measured.
2. It is inexpensive when some form of a drying oven and an accurate scale are available.
3. Drying is rapid (usually 1 day).
4. It is a direct method requiring no calibration.

A number of disadvantages must also be considered when comparing this method to other soil-water determination techniques:

1. The total time required to use this method may be longer than desired, including sampling, travel, drying, and weighing time.
2. It is impossible to sample the same location over time because the specific location is destroyed when the sample is taken. Due to the spatial variability of soils, the relationship between the initial and subsequent samples may lead to considerable error.
3. Errors can occur in soils high in organic matter when oxidation or combustion takes place while drying at 105°C. High organic soils should be dried at 50 to 70°C.
4. Sampling and handling of samples can lead to errors. When exposed, water may evaporate from the sample.

The feel and gravimetric methods of estimating soil moisture, while tedious and time-consuming, can provide the information necessary to schedule irrigations. The difference between the field capacity and the soil water content estimated by the feel method or determined by gravimetric sampling indicates the amount of water required to refill the soil, the *net irrigation requirement.*

Tensiometers

Using a tensiometer, you can characterize the soil matric potential, which you can then use as an indicator to determine when to irrigate. Soil matric potential is usually negative over the range encountered in production agriculture, so for clarity, we will refer to it as soil water *tension*. Although tensiometers are used extensively in fields with perennial crops, they have also been used successfully to irrigate annual crops. When properly installed and maintained, tensiometers provide good, reproducible measurements. Tensiometers are available in various sizes and at relatively low prices.

Principles of operation. The tensiometer is a cylindrical tube with a device to measure suction (negative pressure), such as a vacuum gauge, attached to the top, and a porous ceramic cup attached to the bottom. The ceramic cup can be viewed as a membrane that acts as a channel for water and solutes but a barrier for soil and air. The tensiometer body is filled with water and the ceramic cup becomes initially saturated with water. When properly placed into an unsaturated soil, water within the cup is drawn out into the surrounding soil. This process creates a partial vacuum inside the sealed tensiometer body, and that registers on the vacuum gauge. As the soil becomes drier, more water is drawn from the cup and the reading on the gauge increases. When the soil surrounding the cup is rewetted by rainfall or an irrigation, water will re-enter the cup, and the reading on the gauge will decrease.

The units of measurement of most tensiometers are centibars (cb). One cb is 1/100 of a bar, and the highest reading obtainable in theory is 100 cb (1 atmosphere). In practice, the operation range of most

Tensiometers on a young peach tree irrigated with low-volume sprinklers. The two instruments, installed to depths of 18 and 36 inches, indicate soil matric potential levels.

tensiometers is from 0 to 85 cb. Zero indicates saturation or free water. Field capacity is usually between 10 and 30 cb, depending on the soil texture. Most plants will not show signs of wilting within the limits of the tensiometer. In contrast to field capacity, yield threshold depletion values may or may not fall within the range of the tensiometer. Under surface irrigation, tensiometers are better suited for use on sandy soils, where they monitor most of the available moisture range. In heavy soils, large amounts of available moisture occur outside the detection limits of the tensiometer. When the soil water tension exceeds 100 cb (the permanent wilting point is usually described as 15 bars), the pores of the ceramic cups lose their water. This allows air to enter the tensiometer, breaking the vacuum, and the gauge readings go to zero. Since the working range of tensiometers is at relatively wet soil water levels, tensiometers are ideally suited for use in high-frequency systems (e.g., drip or microsprinkler), where high soil moisture in the subsurface wetted zone allows the tensiometer to operate throughout the season.

Installation. When installing a tensiometer, take care to ensure the direct and continuous contact of the soil with the ceramic cup. Generally, you auger or punch a hole with a special tool to a specified depth. The diameter of the hole should not exceed the diameter of the tensiometer body. Water is poured around the base of the tensiometer to facilitate soil/cup contact.

The depth of installation is very critical. The purpose of a tensiometer is to characterize soil-water tension in the active root zone. Consequently, several tensiometers are necessary in most situations. However, when 90 percent of the active root zone is within the top 1.5 feet of the profile (e.g., for lettuce, celery, or potato), only one tensiometer is necessary. For deeper-rooted crops, at least two tensiometers are suggested, and three tensiometers may be desirable for some deep-rooted tree crops. Correction of the gauge reading is usually required to account for the gravitational potential due to the depth of placement of the tensiometer. Some tensiometer gauges have calibration screws that allow for this adjustment, but most do not. Three cb should be subtracted from the reading for every foot of depth, determined as the distance from the ceramic cup to the gauge. Thus, a 4-foot tensiometer would require that 12 cb (4 ft×3 cb/ft) be subtracted from the gauge to determine soil matric potential (i.e., a gauge reading of 40 cb would actually indicate 28 cb of soil matric potential).

The recommended placement of tensiometers in a field depends on the crop and the irrigation method. These factors influence the spatial distribution of active roots. In new orchards, the cup of the tensiometer should be placed in the root ball. Such a tensiometer will have to be moved, or additional tensiometers added, to accommodate spatial changes in root distribution over time as the plants grow. For most annual row crops that are furrow irrigated, place tensiometers in the plant row. With perennial crops, place the tensiometers in the wetted soil zone adjacent to the tree or vine. With drip irrigation, place tensiometers 1 or 2 feet from the emitter. With sprinkler irrigation, place tensiometers where they will not be shielded from water.

The number of tensiometers recommended for a given area depends upon the crop, the variability of soil in that area, and the degree of characterization desired. When a field contains different soil textures, the tensiometers should be placed so as to characterize the field adequately.

Instruments' function in the field. The rate of change of soil matric potential depends upon plant, soil, and climatic factors. The values you obtain over time from tensiometers placed in various locations and depths within a field will reflect a combination of these factors.

Soil water tension changes over time with plant water extraction and irrigation (fig. 2.1). Plant water extraction, as evidenced by large changes in the readings, is greater at the 18-inch depth than the 36-inch depth. After an irrigation, tensiometer readings at the shallow location increase faster than at the deep location. Furthermore, it takes longer for the tensiometer reading at 36 inches to reach a maximum value after irrigation. The time it takes for the soil water tension to drop to a given value decreases as the evaporative demand increases. Figure 2.1 shows that water from the third irrigation did not satisfy the soil water deficit at the 18-inch depth. This could indicate (1) poor infiltration or (2) insufficient irrigation.

The soil, plant, atmosphere, irrigation system, and farming operation make it impossible to define universally applicable threshold tensiometer readings for irrigation scheduling. Without considerable ex-

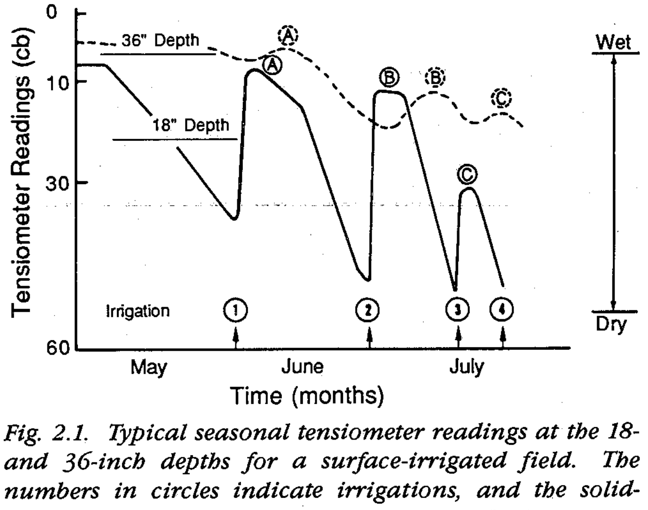


Fig. 2.1. Typical seasonal tensiometer readings at the 18- and 36-inch depths for a surface-irrigated field. The numbers in circles indicate irrigations, and the solid-circled and dashed-circled letters indicate the lowest tensiometer values after each irrigation at the 18- and 36-inch depths, respectively.

perience and knowledge of a given cropping situation, you are best advised to use tensiometer readings to indicate the trend in soil water tension—whether it is increasing or decreasing at a given depth, and at what rate. For example, gradually increasing readings at the 18-inch depth in the wetted zone of a drip-irrigated tree indicate that more water is required. If the 36-inch tensiometer in a furrow-irrigated, deep soil profile orchard reads 10 cb at the beginning of the season and never exceeds 20 or 25 cb throughout the season, you are probably applying too much water.

Maintenance. Tensiometers must be maintained properly to ensure reliable readings. Since freezing temperatures can damage tensiometers, they should be insulated or removed during the winter, or at the least, the water should be drained from them before the freezes start. Occasionally, tensiometers need to be refilled with water, especially if they are exposed to dry soil for extended periods. Tensiometers should be refilled (when needed) after an irrigation. A hand vacuum pump is required to withdraw air bubbles in the tensiometer body.

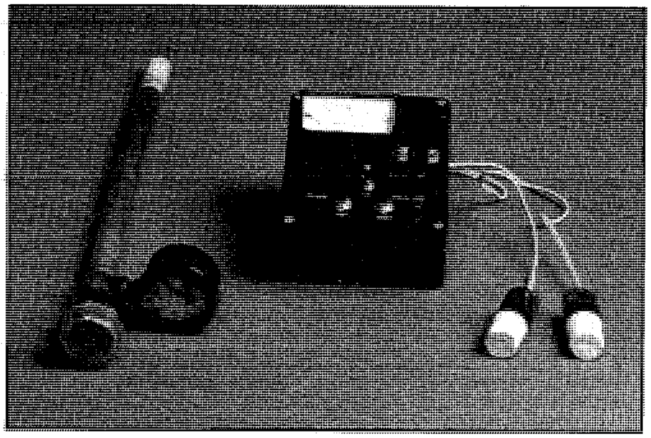
The ceramic tip of a tensiometer may need replacement over time, especially in calcareous and saline soils. If the porosity of the cup has been reduced, sanding the cup with sandpaper may partially restore the porosity. Occasionally, tensiometers develop leaks. Leaks in the bottom of the tensiometer are indicated by large bubbles that rise while you apply suction with the hand pump. Other leaks may occur in the gauge or stopper. These leaks must be repaired before the tensiometers will function.

Tensiometers can be very useful for irrigation scheduling, especially in shallow-rooted, water stress sensitive, and frequently irrigated crops. However, with heavier soils, shallow-placed instruments, or infrequently irrigated crops, the soil water tension may exceed the measurement limits of a tensiometer, and an alternative instrument may be appropriate.

Gypsum Blocks

The gypsum electrical resistance block is a simple, reliable, and inexpensive tool for monitoring soil water tension. You can use it to estimate whether irrigation is needed, but it will not tell you how much water to apply.

Gypsum blocks evaluate soil moisture indirectly by measuring the electrical resistance between two electrodes attached to a small cast block of gypsum buried in the soil. Some electrical resistance devices have electrodes mounted in fiberglass or other materials, but gypsum blocks are most popular. The electrical resistance is read with a portable resistance meter. Prices for meters and blocks vary with the manufacturer, the quantity purchased, and the length of the electrode leads. In an orchard, a block can last 2 to 3 years, but elsewhere it may require annual replacement.



The tensiometer and gypsum block are used to measure soil water status. Tensiometers (left) *monitor soil water matric potential (tension), while gypsum blocks* (right) *use electrical resistance as an indicator of soil moisture.*

You can interpret the resistance readings with charts provided by the manufacturer for the particular meter and blocks. Meter readings can be converted readily to soil water tension values, or they can be correlated directly to plant response if the annual climate changes little.

Gypsum blocks may be placed at several soil depths depending upon the crop, rooting depth, and the soil conditions. Wires from the blocks are brought to the soil surface to facilitate periodic readings. The matric potential of the blocks is assumed to be in equilibrium with the surrounding soil, so the blocks act much like the surrounding soil—taking up and releasing water as the soil wets and dries. The electrical resistance between the electrodes varies according to the water content of the block. The higher the water content, the lower the electrical resistance.

Since gypsum is soluble, blocks slowly dissolve. In orchard or other permanent crops, the life of a block can be extended by 1 or 2 years by the addition of a small quantity of gypsum to the back-fill soil. A small quantity of lime ($CaCO_3$) may likewise be useful in an acid soil to prolong the life of a block.

Gypsum blocks operate more effectively in the drier range of soil water tensions (in excess of 0.33 bar). Consequently, blocks are more useful in the medium to heavy textured soils, which tend to retain more available water as soil tension increases. Sands and coarse-textured soils tend to release much of their water at low tensions, where the accuracy of blocks is questionable. Blocks are also considered inaccurate in highly saline-alkali soils, where salts may affect electrical resistance.

Test each block by soaking it in water and hooking it up to a resistance meter before installation to ensure that the block is functioning properly. Only one block should be installed per hole, so no air pockets will result when you fill the hole. The installation hole should be only slightly wider than the block, and can be made using a soil probe, a solid metal rod, or a small auger. The hole should be about 1 inch deeper than you wish the block to penetrate. Before inserting the block, put a small quantity of loose, moist soil (to which you can add small quantities of gypsum and lime) into the hole. About 2 fluid ounces of water will help the soil seal around the block.

To place the block in the hole, run the wire leads through a length of pipe (1/2-in diameter PVC is best) and pull the wire to hold the block on the end of the pipe. Push the block firmly into the loose soil at the bottom of the hole. Remove the PVC pipe, and fill the hole with soil or a soil-gypsum-lime mixture for several inches, and pack firmly. In some coarse, sandy soils, you may want to add a little loam to help maintain good contact with the soil. Then fill the hole, tamping firmly while avoiding damage to wires and blocks. Packing is important to accurate readings. Water and roots should not penetrate the filled hole more easily than the original soil.

The guidelines used for determining where to place tensiometers in the plant root zone also apply to gypsum blocks. When burying the blocks between the borders in traffic rows or cultivated areas, you can bury the lead wires to prevent damage. Identify the blocks by knotting the wire or by color coding, or tagging for the various depths. Protect the leads by trenching if necessary, but be sure to identify the block location.

Neutron Probes

The neutron probe gives a relatively fast and easy measurement of soil moisture. Once used primarily by researchers, this instrument is coming more and more into use by consultants, growers, and state and federal agencies.

The neutron probe contains a radioactive source, a detector tube, and an electronic indicator unit. The source and detector tube form a single unit that you lower into the ground through an access tube. The fast neutrons emitted by the source become slow neutrons by losing energy when they collide with hydrogen atoms in the soil. The slow neutrons are counted by the detector over a set time interval. Because each water molecule has two hydrogen atoms, wet soils cause more fast neutrons to become slow neutrons. Thus, wet soils have more slow neutrons, shown as the "raw count" on the instrument display.

Calibration. Reliable results depend upon calibrating the neutron probe for the particular soil. A *calibration curve* relates the ratio of the raw count and a standard count (the *count ratio* [CR]) to the soil water content on a volume basis. To calibrate a neutron probe, you must collect data over a wide range of soil water contents.

Neutron probe measurements show the water distribution in the soil profile.

You can use either of two approaches to collect data for a calibration curve. The first approach involves taking volumetric soil samples while installing the access tubes, and analyzing those samples for soil water content. After you install the access tube, take replicated neutron probe readings at the depth of each sampling.

The second approach involves installing an access tube with the sole purpose of calibration, not for in-season monitoring. After installing tubes and taking replicated probe readings at the chosen depth, remove soil samples in the sphere of influence of the probe (about the size of a basketball in most soils and water contents). You can usually remove four to eight samples at various points of the compass around the access tube. This procedure results in replicated soil water measurements associated with one probe reading for the given soil. If taken both when the soil is wet and when it is dry, the data can yield an accurate calibration curve.

The relationship between soil moisture and the CR is normally a straight line, described by

$$\theta_v = a + b\ (\mathrm{CR}), \qquad [2.1]$$

where

θ_v = volumetric soil water content
a = value of θ_v when the CR is equal to zero
b = slope of the θ_v vs. CR curve

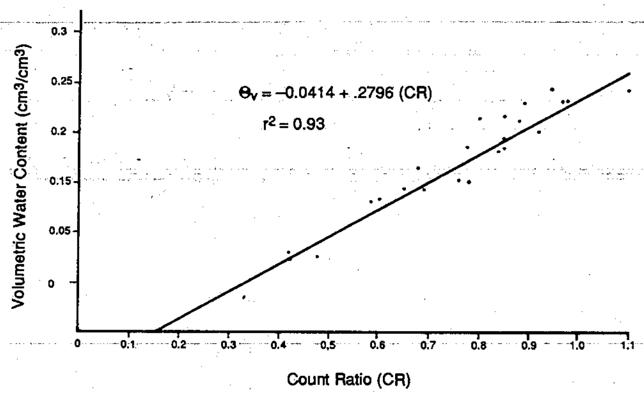


Fig. 2.2. A neutron probe calibration curve developed using soil samples that were collected during installation of access tubes.

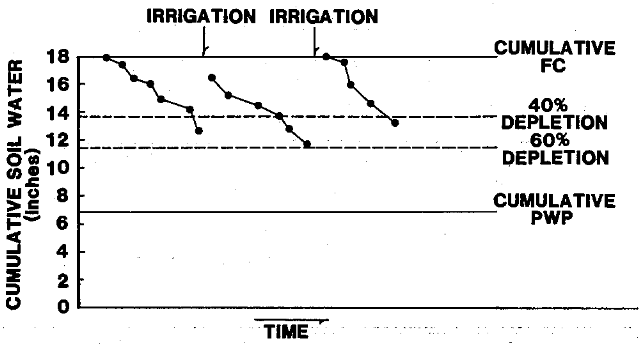


Fig. 2.3. Diagram representing the use of neutron probe measurements of soil water content to determine when to irrigate an orchard, based on depletion of available water. Cumulative values are determined by summing measurements over the root zone.

You can calculate the constants *a* and *b* by using linear regression on a calculator or simply by plotting θ_v and CR on graph paper and measuring the slope and *y* intercept of the best-fit straight line. Figure 2.2 shows a calibration curve developed using the first sampling approach. Because soils of different textures and chemical contents can have appreciably different calibration curves, you should calibrate probes for the different sites being monitored.

The neutron probe provides accurate soil water content data over the entire root zone, and this can be used to evaluate the status of the soil water reservoir. When used with field capacity and permanent wilting point values, neutron probe data allows the irrigation scheduler to irrigate when the root zone has been depleted to a given percentage of available water. Figure 2.3 illustrates this concept. The neutron probe can also be used where large changes in soil moisture between irrigation are not desirable, as with drip irrigation. Cumulative soil water content measurements over the root zone help the irrigation scheduler maintain relatively constant soil water levels over the season.

Considerations. Aluminum, steel, and PVC are materials commonly used for access tubes. Each material affects the count rate differently. The highest count rates will occur in aluminum tubing, while the lowest will occur in PVC. Apparently, the chloride in the PVC absorbs slow neutrons. The decreased count rate in PVC reduces the probe's sensitivity to changes in soil moisture. However, accurate measurements can be obtained with all three tube types. Selection usually depends on the rigidity required during installation, the cost, and the application.

Standard counts are measured with the source and detector locked inside the instrument shielding. The counts can be affected by external factors, such as a wet surface upon which the probe is set or a person standing near the instrument. During a standard count, the probe should be at least 2 feet from any surface or object that might affect the count rate. The distance from other neutron probes in the vicinity should be at least 16 feet.

Since probes differ in their emission and detection characteristics, the calibration curves developed using one probe may not apply to another, even from the same manufacturer. You can check the relative performance of different probes by evaluating the count ratios at a given soil depth and site. Probes should be recalibrated after repair.

The counting time for a neutron probe is 30 or more seconds for the most accurate measurements. A counting time of 15 or fewer seconds can yield data that are too variable, and a counting time beyond 30 seconds will not substantially reduce variability. Normally, one count per depth is adequate.

Access tubes should generally fit as tightly as possible into the soil. An air gap of up to $^1/_{10}$ inch between the access tube and the soil will not affect the count rate, but a loose-fitting tube indicates that the soil adjacent to the tube has been disturbed from its native condition, and that can result in different water flow and rooting patterns around the tube, leading to erroneous conclusions about the soil water content of the field. A rigid-walled material can be driven into an auger hole somewhat smaller than the outside diameter of the tube. You can then use an auger to remove soil that shears off into the advancing tube. A small amount of bentonite placed around the tube at the soil surface will prevent water from channelling down the walls of the tube.

If you measure too near the surface, generally 6 or fewer inches deep, you can underestimate soil water content because you lose neutrons at the soil-air interface. Minimize interface effects by taking the first measurement at or below the 9-inch depth. If you need water content data for shallower depths, use a different method of measurement, such as gravimetric sampling. A calibration curve can be developed for shallow depths, but shallow measurements should be interpreted with caution.

The neutron probe can be an excellent tool for monitoring soil water content if properly used. Some of its limitations are that (1) obtaining enough measurements to characterize a field requires considerable labor, (2) use requires a trained and licensed operator and safety precautions, and (3) the instrument is expensive ($2,000 to $3,000).

Thermal Dissipation Sensors

A new soil-based instrument, the thermal dissipation sensor, measures soil matric potential. This device monitors the dissipation of heat in a porous ceramic block or disk in contact with the soil. The thermal dissipation sensor is well suited to high-frequency irrigation, and can be used for automated irrigation control based on frequent soil measurements.

A porous body like ceramic is a good heat conductor when wet and a poor heat conductor when dry. Assuming good contact between the soil and the ceramic, water will flow in and out of the ceramic to maintain an equilibrium with the surrounding soil. An electrical circuit is used to quantify heat conduction in the ceramic. The voltage output of the sensor increases proportionally with the dryness of the soil.

Under high-frequency irrigation, the soil around a thermal sensor (usually midway in the root zone) is never allowed to dry much beyond a threshold soil matric potential value. The sensor can detect these small drying trends and can be used to trigger irrigation with almost any computer equipment. Once the sensor is calibrated, its measurement is independent of soil texture, temperature, and salinity; hence, the instrument can be used in any soil to monitor soil water status and to control irrigation automatically.

Equipment needed. To monitor soil matric potential manually you will need a regulated battery power supply (+10 – 12 vdc), a precision 10 K resistor, a $4^1/_2$ digit voltmeter with 0 to 10 mv range capable of measuring microvolts, and a timer. For automatic control of an irrigation system, you will need electronics capable of (1) automatically sampling several sensors in sequence, (2) comparing each sensor's output to the threshold soil matric potential at which irrigation is to start, and (3) starting a pump, opening electric valves, and performing other electrical functions as needed.

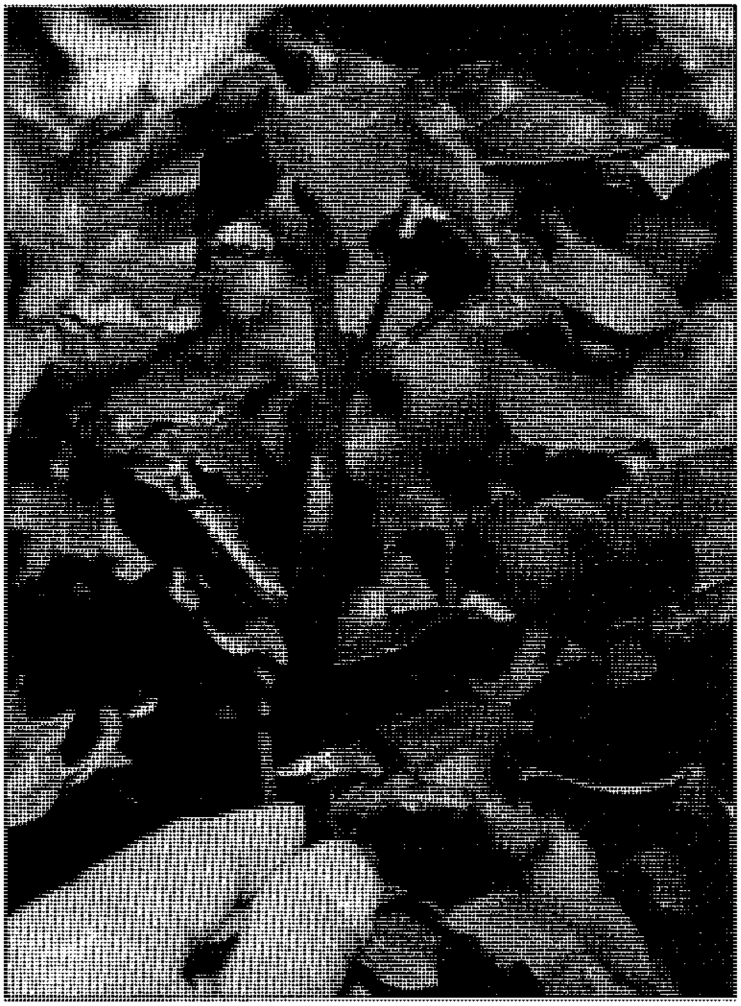
Applications. Soil matric potential sensor feedback technology may find use in agricultural water management that favors automated irrigation. In areas where labor is in short supply and other cost-effective operations require automation, the soil sensor feedback technique can provide a simple means for fully automating the irrigation control systems and for remote monitoring.

Strengths and weaknesses. The range of the sensor can be changed to fit the soil texture and measurement requirements by using ceramic disks with different pore size distributions. For most applications in irrigation scheduling, a ceramic with a maximum range of 0 to –1.0 bar will suffice. Lack of uniformity in the ceramic's pore size distribution and in the physical characteristics of the electronic components requires that each sensor be calibrated in a pressure plate or against some known standard.

The intrument can provide precise measurements (±25 mb) of the soil matric potential with sufficient sensitivity and speed to detect small diurnal variations of the soil matric potential. No maintenance is required after calibration and installation. The sensor can operate for many months, perhaps a few years, without interruption. In case of failure, the sensor can generate a warning signal.

At the date of this publication, sensors and manual readout are available commercially for $115 and $950, respectively. The computer controller and interface cost from $7,000 to $15,000, depending on the size of the system and the software used.

3



The extent of dark (red-brown) pigment coloration on the uppermost internode of cotton plants can be used as an indicator for irrigation scheduling. As vegetative growth slows in response to plant water stress, darkening approaches the terminal, signalling the need for an irrigation.

Plant-Based Monitoring

The plant is the truest indicator of its own well-being with respect to irrigation, so we would like to irrigate according to some plant-based index. The first and most obvious plant-based index is plant appearance. A second is the pressure chamber (pressure bomb), which measures the water status in plant leaves. The third is the infrared thermometer, which measures crop canopy temperature and indicates relative rates of transpiration.

Visible Symptoms

Observing visible plant symptoms as a basis for irrigation scheduling is fast and requires no equipment. The plant integrates the effects of soil water content and other factors, such as low root density, atmospheric evaporative demand, and soil salinity that affect plant water status.

Given the great diversity in crop plants and their environments, it is difficult to generalize about which visible symptoms should trigger irrigations. However, experience indicates that two basic considerations usually apply:

1. Most visible symptoms are associated with the retardation of foliar growth. Such indicators are useful only if the plant tolerates the growth reduction without yield or quality losses or makes up the lost growth by prolonging the growing season.
2. Water stress must develop neither too rapidly nor too slowly. If stress develops rapidly, a potential loss in yield may occur before irrigation can be applied, although a few very brief periods of stress are unlikely to reduce production. Slow-developing symptoms make early visual detection difficult or impossible, and cumulative stress may reduce yield before the change becomes evident.

Some plants can undergo appreciable reduction in foliar growth, especially after achieving full ground cover, without loss of economic yield. The best examples of this are cotton and alfalfa seed in the San Joaquin Valley. Some grain sorghum cultivars react this way to stress, but others do not. Common beans tend to maintain the same ratio of seed weight to vegetative weight under different irrigation regimes, yet experiments show that irrigation can be timed successfully based on visible symptoms.

You can only determine whether a particular crop can tolerate foliar growth reduction without losing yield by experimentation, although it is obvious that irrigation scheduling based on visual symptoms cannot be used with crops whose marketable product is vegetative material.

Barring marked changes in evaporative demand, the rate at which stress symptoms develop depends on the water storage characteristics of the soil, the distribution of water within the root zone, and the pattern of water extraction. Water uptake in general is slower in the lower portions of the root zone, and mild water stress can relate to the need to obtain most of the water absorbed from deep subsoil. If the full depth of rooting is wetted at the beginning of the current depletion cycle, onset of stress will be gradual, more so if the root system is still developing into previously unexplored depths. If only the upper part of the root zone supplies water because of dry subsoils, drought stress will develop abruptly, especially in soils with little water storage capacity or where furrow or drip irrigation localizes the wetting pattern.

Plants can show a number of different symptoms of water stress. Stress during vegetative growth causes young leaves to lose any distinctive appearance and to resemble older leaves, except for their size. They darken, turn grayish, or become dull. Leaf blade orientation can change: grass leaves twist or roll. Symptoms can be more apparent in the overall canopy or canopy surface than in individual plants or leaves.

Wilting in field-grown plants is uncommon, even in sunflower, the classic indicator plant used to determine the PWP of greenhouse soils. An exception is the sugarbeet, which wilts so readily that afternoon wilting ("temporary" wilt) may be a usable symptom. However, afternoon wilting can occur under hot, dry, windy conditions at relatively high soil water levels, when irrigation would be premature.

Experiments and experience show that irrigation of beans, cotton, seed alfalfa, and some grain sorghum cultivars can be safely scheduled by water stress symptoms. Common beans manifest water stress as foliar darkening. Upper, rapidly growing young leaves are normally light green, but when their growth rate slows, their color darkens almost to that of mature leaves. The darkening is rapidly reversible —the change is often visible within a few hours of irrigation.

In San Joaquin Valley cotton, you can use two or more symptoms. When foliar growth slows, open flowers appear nearer to the top of the plant, so scattered blooms at the top of the canopy indicate that irrigation is advisable. A second symptom is the degree to which the uppermost internode is covered with spots of red-brown pigment. In fast-growing plants, only the lower part of the internode is reddened, whereas if growth has slowed for some time or has stopped, the entire internode may be pigmented.

In grain sorghums, water stress decreases the angle between the leaf blades and the stem, while the leaves become more upright and their outer ends twist. In viewing a field canopy surface, the sharp leaf tips in stressed plants give a different appearance than the flatter surfaces predominant in well-watered plants. The symptom is not entirely reversed on rewatering, so it cannot be used repeatedly.

Fruit and nut trees display a wide range of visual responses to water stress. Almond leaves, for example, take on a duller appearance and the leaves begin to roll or "boat." As the intensity of the stress increases, the trees will start to defoliate. These visual symptoms occur only under moderate to severe stress levels that usually result in reductions in sustained tree productivity. Some trees (e.g., pistachio and olive) can be severely stressed in midsummer without showing appreciable changes in leaf color, configuration, or retention.

Vegetative growth in grapevines relates directly to plant water stress. A reduction in the rate of cane elongation usually indicates mild to moderate stress. Since timely, controlled stress can improve winegrape quality, observations of the rate of vegetative growth commonly guide irrigation decisions in winegrape vineyards. However, stress can reduce yield and quality in table and raisin grapes.

Many farmers use plant appearance, whether alone or as an adjunct to other procedures or criteria, for scheduling irrigations, primarily in field and row crops. Often, a grower can describe the critical appearance only very vaguely and subjectively. Such criteria are usually too much a result of personal experience under site-specific conditions to be suitable for general use, but plant appearance can play a major role in many farm management decisions, including irrigation.

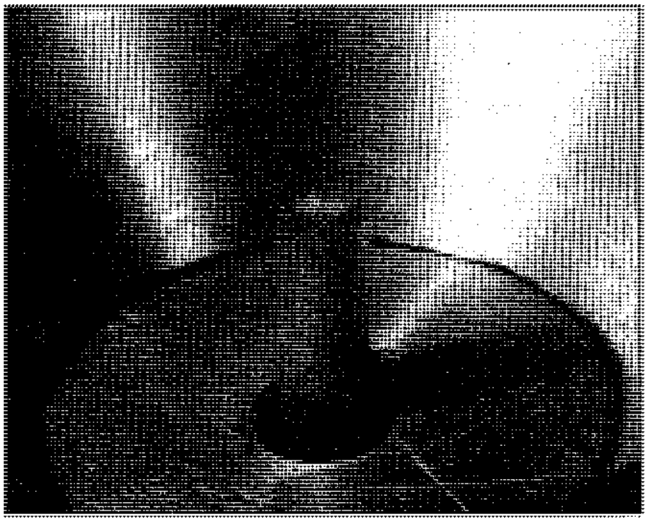
The biggest problem in using plant appearance to schedule irrigation is that by the time visual stress symptoms show, many plants have suffered stress that will hurt productivity. In most cases, when a crop appears to need water, it should already have been irrigated.

Pressure Bombs

Researchers in soil-water-plant relations recognized early on that an accurate description of soil water status is difficult and, moreover, that measurements of bulk soil water status cannot give reliable estimates of the moisture of the soil in contact with the absorbing portion of the roots. Holmes and Robertson (1959) wrote that "the plant is the only true indicator of this factor (soil moisture) and at the present time it is not possible to measure plant moisture stress, per se." This situation changed in the early 1960s with the introduction of the pressure chamber, or pressure bomb.

The primary advantage of plant-based measurement for irrigation scheduling is that plant growth relates directly to plant water status and only indirectly to soil water and atmospheric conditions. The plant essentially integrates its soil and atmospheric environments and reflects the prevailing conditions in growth processes. Because the rates of many of these expansive growth processes relate to plant water status, its measurement can yield valuable data indicative of plant growth and development. The pressure bomb is commercially available at a reasonable cost and is appropriate for measuring the leaf or plant water potential of many vascular plants. Plant-based pressure bomb readings are especially helpful on compact soils that restrict root growth and extension or where shallow water tables in or near the crop root zone may contribute substantial water to meet crop requirements. In either case, soil-based observations may be misleading. One disadvantage to the pressure bomb is that it can take more time than some other plant-based measurements (e.g., infrared thermometer measurements of canopy temperature).

The pressure bomb measures leaf water potential, an index that can be used to set irrigation times for certain crops. The instrument consists of a nitrogen tank, a pressure chamber, and a gauge.



Xylem fluid (sap) is exuded from the cut end of this petiole of a leaf in the pressure chamber. A gauge reading is taken just as the sap appears.

Furthermore, pressure bomb readings may reflect, to some degree, the operator's technique. As with other plant-based methods, the pressure bomb can indicate when to irrigate, but not how much water to apply.

The main components of the pressure bomb are the chamber, the pressure gauge, the control valve, and a small tank of compressed nitrogen gas that serves as a pressure source. To take a measurement, cut a petiole and attached leaf from the plant, leaving sufficient petiole length on the leaf to extend through the sealing stopper. Leaf petioles are unusable in certain tree species because phloem exudate interferes with the measurement process. In such cases, you can use small spurs if you remove the bark within approximately 1/2 inch of the cut surface. Once you have severed the petiole or spur, water withdraws within the xylem vessels, because the pressure outside the plant is several times that inside the conducting tissue. After the initial cut, avoid any further trimming, since it will cause measurement errors. Also, any leaf drying that occurs between leaf removal and the actual measurement will result in low readings. The leaf should be placed in a small, thin plastic bag or wrapped in moist cheesecloth or some other material to suppress evaporation.

Seal the leaf inside the testing chamber with the petiole cut surface extending upward through a pressure-sealed rubber stopper or O ring. Nitrogen gas then flows into the chamber until water in the xylem is forced back, exactly to the cut petiole surface. At this point, pressurization stops and the reading is recorded; the positive chamber pressure now matches the negative potential of the xylem fluid. Xylem potential is essentially the sum of the pressure, matric, and osmotic potentials, but since the latter two are considered relatively insignificant, the gauge reading shows the xylem pressure potential. Because the xylem and leaf water potential are in most cases nearly equivalent, the gauge reading is commonly referred to as leaf water potential. A higher gauge reading indicates a lower leaf water potential, a sign of increasing plant water stress. While the number of measurements needed depends on plant and soil variability, usually the average of three to five readings will characterize a sampling location, and several locations may be necessary to characterize a field.

Pressure bomb readings change drastically during the day. Readings are lowest just before sunrise. Typical curves for two different stress levels in cotton are shown in figure 3.1. After sunrise, the increased light prompts stomata to open, and transpiration begins. Readings increase rapidly until about solar noon. With cotton, readings are stable for the next 2 1/2 to 3 hours; then they fall progressively, reflecting plant water recovery, until they approach the level of the previous day late in the evening or early next morning.

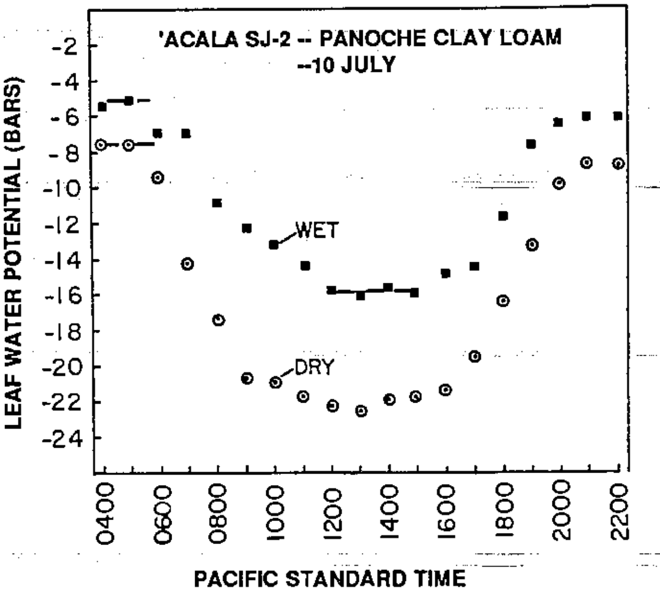


Fig. 3.1. Diurnal measurements of leaf water potential for well-watered and water-stressed cotton.

Some crops, like cotton, undergo a stress conditioning that allows stomata to remain open even under moderate water stress. For these crops, take midday readings for irrigation scheduling. For crops that respond differently to such conditions, midday readings may be erratic as stomata close in response to water stress. In such a situation, use predawn readings of crop water status to schedule irrigation. You must develop water status–plant performance (usually growth) relationships for both predawn and midday values of individual crops in order to make this method a success. Values are available for some crops, and are being developed for others.

After irrigation, pressure bomb readings tend to decline in linear fashion in response to plant water extraction over a period of several days, as shown in figure 3.2. If a soil retains a large amount of available water in the root zone, the decline will be gradual. Sandy soils, on the other hand, will show rapid decline. Variations above and below a straight-line decline usually reflect climatic differences on the day of measurement. In general, pressure bomb readings on cotton in the San Joaquin Valley will increase (or decrease) by 1 bar for every 6°F (3°C) in deviation from normal midday temperatures (D. W. Grimes, unpublished data). For example, a −15 bar midday reading when the temperature is 85°F (29°C) should be adjusted to −17 bar if the normal, or long-term average air temperature is 97°F (36°C). You can extrapolate the straight-line decline in readings over time to predict when a critical reading will occur to signal the need for an irrigation. Lead time will be greatest for high water retention soils and proportionately less as soil water retention decreases or the rooting volume or density decreases.

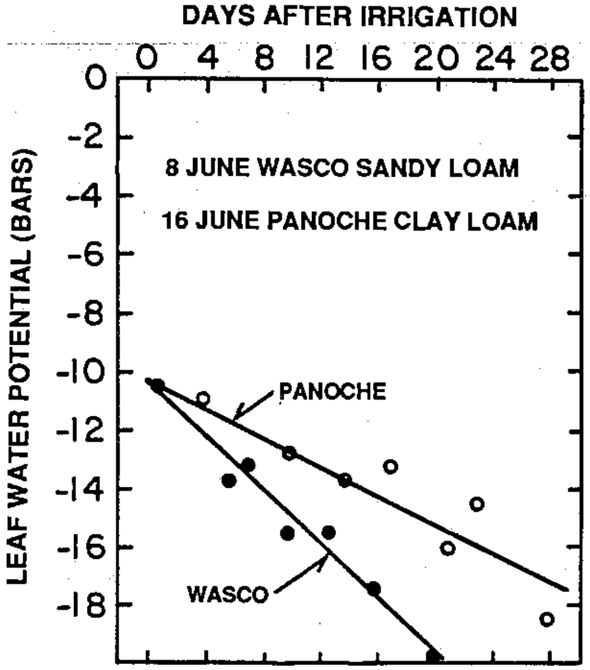
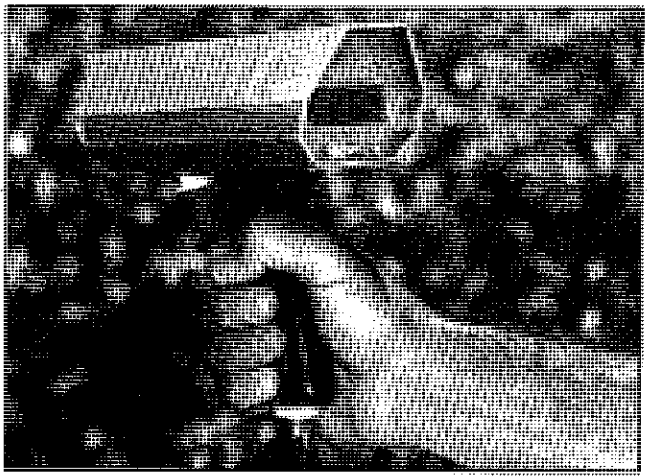


Fig. 3.2. Leaf water potential readings with time for two soil types.

Critical midday pressure bomb readings have been established for effective irrigation scheduling of cotton and some other crops. To make this technique useful in a general way, researchers will have to establish critical values for additional crops, either predawn, midday, or both, that signal the need for an irrigation. Though considerable effort is going into this work, the diurnal behavior of leaf water potential of some crops precludes effective use of midday pressure bomb measurements.

Infrared Thermometers

An infrared thermometer measures the surface temperature of a crop canopy without making direct physical contact. Measurements are based on the principle that an object emits radiation in proportion to its surface temperature. The infrared thermometer can measure this radiated energy in the thermal infrared waveband (8 to 14 μm), and from that you can electronically compute the equivalent temperature. One example of using temperature to identify stress is found in human body temperature. The "normal" human body temperature is 98.6°F (37°C), and a departure from this norm can indicate sickness. Although a plant does not have a "normal" temperature, the plant canopy temperature does respond to air temperature and the form of this response can be used to assess plant water status.



The canopy temperature can be measured remotely with a hand-held infrared thermometer. For some crops, canopy temperature can be used to time irrigations.

Under nonlimiting soil water levels, the canopy temperature responds to net radiation, vapor pressure deficit, and wind speed. Research shows that canopy temperatures range from about 22°F (12°C) below to about 11°F (6°C) above air temperature depending on the plant water status and evaporative demand. This relationship is depicted in figure 3.3. The lower baseline represents the difference between canopy and air temperatures of a well-watered grain sorghum crop over a range of vapor pressure deficits, and is the lowest value a canopy could attain. Vapor pressure deficit (VPD) is the difference between the saturation vapor pressure at the air temperature and the actual vapor pressure of the air. The upper baseline indicates severe, damaging stress with no water loss by the plant. You can calculate the "crop water stress index" (CWSI) as the ratio of the distance the actual canopy temperature is displaced above the lower baseline, compared to the difference between the two

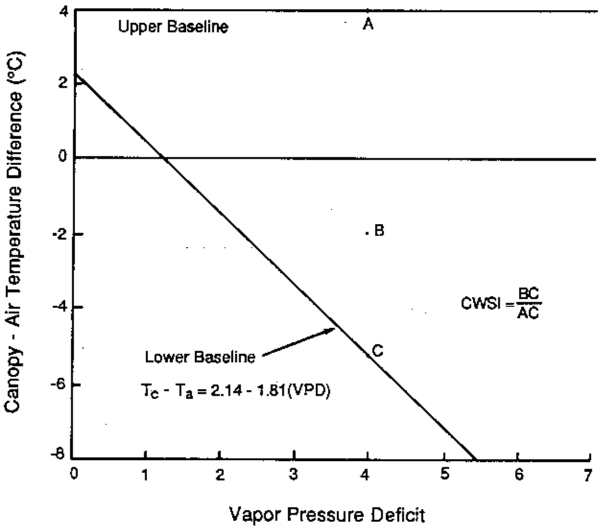


Fig. 3.3. Canopy-air temperature difference presented as a function of the vapor pressure deficit of the air, for grain sorghum.

baselines at a given VPD. This index is sensitive to soil moisture stress and salinity and is based on the relationship between reductions in transpiration that result from partial stomatal closure and rises in the canopy temperature. As such, anything that affects transpiration, such as insect damage, plant disease, or even a nutritional disorder, will affect the crop water stress index value.

In one application of the crop water stress index (fig. 3.4), the summation of the crop water stress is related to the available water in the soil profile. This curve is specific to the crop and soil. An alternative approach assigns an index level that should signal the need for irrigation. Both techniques may be useful, since common baselines appear to fit a variety of crops.

The crop water stress index technique is only one way to use canopy temperatures for stress detection. Others include (1) comparing a field to a well-watered reference, and (2) comparing the variations in canopy temperatures within a field. Canopy temperature variations within a field increase as a soil dries because of spatial variability in soils. This variability might be useful in assessing distribution problems within a field, as well as salinity problems, and in scheduling irrigation for crops that tolerate stress well. Both applications need further study, but both show promise.

Infrared thermometry is a new approach to assessing plant stress. Because the technique requires that the crop be able to sustain sufficient water stress to close stomata without causing yield losses, it may be inappropriate for stress-sensitive crops. However, more research may make this a useful technique for irrigation scheduling in stress-tolerant crops. The crop water stress index agrees well with other approaches such as the neutron probe and pressure bomb and is simpler to use and less labor intensive than these methods. Only a few samples are necessary to quantify a field using a hand-held infrared thermometer, and they can be collected at random throughout the field.

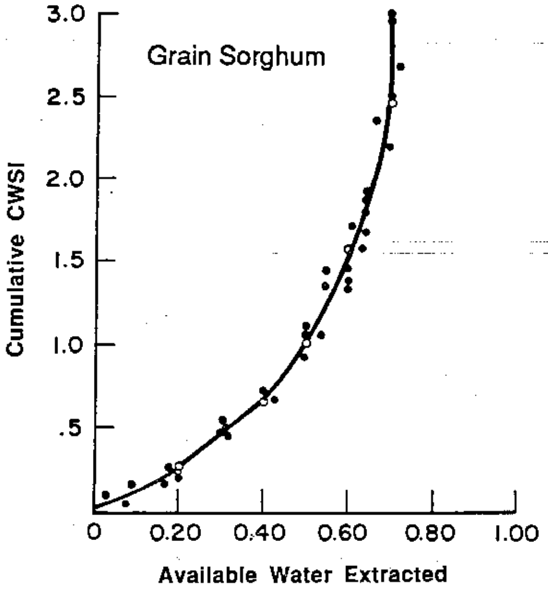
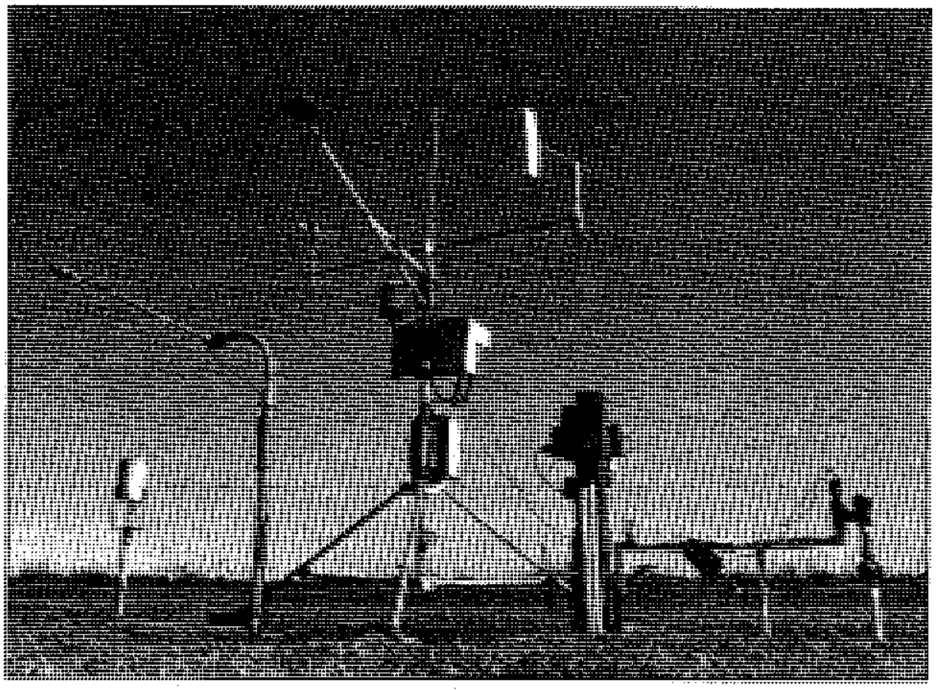


Fig. 3.4. Available soil water remaining in the soil profile, as related to the summation of the crop water stress index (CWSI) for grain sorghum.

4



One of approximately 50 CIMIS (California Irrigation Management Information System) automated weather stations located throughout the state. The instruments measure temperature, solar radiation, humidity, wind speed and direction, and rainfall. The data are used to calculate reference crop water use (ETo).

The Water Budget Approach

One of the more widely promoted procedures for irrigation scheduling is the water budget. The method involves monitoring all of the additions to and losses of a field's water and is based on maintaining a favorable soil water level. Often referred to as ET scheduling, the most important component of the water budget is an accurate estimate of crop water use. The water budget method can be especially useful with high-frequency irrigation where known amounts of water are applied. Because many of the components are estimated, you should employ a good field check program with water budget scheduling to ensure that your calculations are correct.

Reference Evapotranspiration

Evaporation occurs when liquid water changes to water vapor in a process known as vaporization. The process requires energy, and the rate of evaporation relates closely to the amount of energy available. Sunlight (solar radiation) provides most of the energy used to evaporate water on Earth, and is the primary component of several equations used to estimate evaporation.

The rate at which a crop uses water depends mostly on the amount of energy available for evaporation, but wind speed, air temperature, and humidity also affect the rate. *Transpiration* is the evaporation that occurs within plant leaves. After the liquid water is converted to water vapor, the vapor diffuses out of stomata (leaf pores) in response to the difference in water vapor concentration inside and outside of the leaf. The rate of transpiration depends mostly on the amount of energy available, unless stomata close in response to insufficient soil water or other factors.

The rate of evaporation from the soil depends on energy available for evaporation, the area of the soil that is wet, and soil characteristics. The combination of soil evaporation (E) and transpiration (T) make up the total water use of a crop. This sum is commonly referred to as evapotranspiration (ET). You can estimate ET accurately for a fully developed crop canopy if the soil water content is adequate, as it is for a properly irrigated crop.

Modified versions of an equation developed by Dr. H. L. Penman are most commonly used to estimate ET from weather data, including one developed by J. Doorenbos and W. O. Pruitt. The weather components used in estimating ET are radiation, wind, temperature, and humidity.

Radiation

Solar radiation is the major source of energy for ET. Some energy is lost through reflectance and longwave radiation emission from the crop and soil surface. The total radiative energy at the surface is called net radiation (R_n) and it can be estimated from (1) the solar radiation (R_s) in langleys per day, (2) the average of maximum and minimum air temperatures (T) in degrees Celsius, (3) the vapor pressure (ed) of the air in millibars, and (4) the ratio of hours of actual sunshine to the maximum possible (n/N).

$$R_n = (1-0.25)\text{R}_s/59 - f(T)f(\text{ed})f(n/N) \quad (\text{mm/day}) \qquad [4.1]$$

R_n = net radiation expressed in equivalent mm/day of ET

$$f(T) = (2.0\times10^{-9})(T+273.16)^4 \qquad [4.2]$$

$$f(\text{ed}) = 0.34 - 0.044 \quad \text{ed} \qquad [4.3]$$

where $\text{ed} = (\frac{\text{RH}}{100})[6.108 \exp (\frac{17.27T}{T+237.3})]$

and RH = mean daily relative humidity (%)

$$f(n/N) = 1.8(\text{R}_s/\text{R}_a) - 0.35, \text{ where } 0.1 \leq f(n/N) \leq 1.0 \qquad [4.4]$$

and R_a = extraterrestrial radiation in langleys per day from table 4.1.

Wind

You must consider siting factors when evaluating whether you can use available wind data in ET prediction equations. First, situate your wind sensor (anemometer) so that nothing obstructs the wind flow, especially from the direction of the prevailing wind. No crop taller than 1 meter should grow within 50 meters of the anemometer. Again, this is especially important toward the source of the prevailing wind. An optimum site would have an extensive flat surface in all directions from the anemometer. A large pasture is a good location.

Wind data are frequently collected at heights other than the 2-meter standard accepted for agricultural weather stations. Wind speeds measured at heights other than 2 meters should be adjusted to estimate 2-meter wind speeds by using equation 4.5, which employs the so-called log-law wind profile.

$$U_2 = U_1 \times \frac{\ln(Z_2 - d) - \ln Z_0}{\ln(Z_1 - d) - \ln Z_0} \qquad [4.5]$$

where

U_1 = wind speed at measured height Z_1 (m/sec)

U_2 = estimated wind speed at 2 m (m/sec)

Table 4.1. Mean extraterrestrial radiation (R_a) in langleys per day

	North latitude					
Month	**32°**	**34°**	**36°**	**38°**	**40°**	**42°**
	langleys/day					
Jan.	490	466	437	407	378	348
Feb.	602	578	555	531	507	478
Mar.	755	732	714	696	673	649
Apr.	885	873	867	856	844	826
May	974	974	968	968	968	956
June	1,003	1,009	1,015	1,015	1,021	1,021
July	991	991	985	985	985	985
Aug.	920	915	909	903	897	885
Sept.	802	791	773	755	738	720
Oct.	661	637	625	590	566	537
Nov.	531	502	472	443	413	384
Dec.	460	425	389	360	336	307

Z_1 = height of the wind sensor above the soil surface (m)
Z_2 = 2-m standard height
Z_0 = roughness height to account for effects of surrounding vegetation (m)
$= 0.15 \times Z_v$ (approximated for grass)
Z_v = height of crop (m)
d = zero-plane displacement height (m)
$= 0.75 \times Z_v$ (approximated for grass)

Wind effects are included in the Penman equation as a wind function:

$$f(U) = 0.27\ [1 + (U_2/\mathrm{DIV})] \qquad [4.6]$$

where

$f(U)$ = wind function in mm/mb
DIV = divisor
DIV = 100 for U_2 in km/day
DIV = 62.14 for U_2 in miles/day
DIV = 1.157 for average U_2 in m/sec
DIV = 2.589 for average U_2 in miles/hr

Temperature and Humidity

Air temperature and humidity are important factors in determining evapotranspiration. Generally, a higher temperature and a lower humidity will mean a greater ET. A change in air temperature affects the potential loss of water from crops by altering (1) the vapor pressure gradient from the crop surface to air and (2) the relative importance of radiation versus a combination of humidity and wind.

The vapor pressure gradient at any given instant can be approximated by calculating the vapor pressure deficit (VPD) of the air above the crop as

$$\mathrm{VPD} = \mathrm{ea} - \mathrm{ed} \qquad [4.7]$$

where

ea = saturation vapor pressure (mb), taken at air temperature
ed = actual vapor pressure (mb)

A rise in temperature increases the saturation vapor pressure almost exponentially, dramatically increasing the vapor pressure deficit.

Because greater vapor pressure deficits indicate larger gradients of water vapor concentration from the crop surface to the air above the crop, ET increases in proportion to the wind speed. Vapor pressure deficit can also be calculated from the daily mean temperature and percentage relative humidity using equations 4.8 and 4.9.

$$\mathrm{ed} = 6.108 \exp\left(\frac{17.27T}{T + 237.3}\right) \quad \text{(mb)} \qquad [4.8]$$

$$\mathrm{ed} = \mathrm{ea}(\mathrm{RH}/100) \quad \text{(mb)} \qquad [4.9]$$

where

$$T = \frac{T_{\max} + T_{\min}}{2} \quad (^\circ\mathrm{C})$$

and

$$\mathrm{RH} = \frac{\mathrm{RH}_{\max} + \mathrm{RH}_{\min}}{2} \quad (\%)$$

The term "ed" might also be obtained from one or more psychrometric or dewpoint temperature measurements. For the latter, you can obtain ed by substituting the dewpoint temperature for T in equation 4.8.

When evaluating the effect of temperature in weighting the relative effects of radiation versus humidity and wind, the Penman equation (eq. 4.10) is very helpful. The factor W and its complement $1 - W$ vary with temperature.

$$\mathrm{ET}_0 = W(R_n + G) + (1 - W)(\mathrm{VPD})f(u) \qquad [4.10]$$

where

ET_0 = the reference evapotranspiration (mm/day)
R_n = net radiation (mm/day)
G = soil heat flux (normally neglected on a 24-hour basis)
W = a dimensionless function of air temperature
$f(u)$ = wind function (mm/mb)
VPD = vapor pressure deficit (mb)

At sea level, for example, with an air temperature of approximately 7 °C, both W and $1 - W$ equal 0.5. At 40 °C, the factor W reaches 0.85 and $1 - W$ is 0.15. It is clear, then, that warmer weather requires that greater weight be given to the first half (radiation term) of equation 4.10. Also, the effect on ET of greater VPDs, often associated with hot, dry weather, is clearly muted by the low values of the weighting factor $1 - W$ in the second half (the aerodynamic term) of the equation.

The weighting function (W) can be calculated from the psychrometric constant (Δ) and the rate of change in ed (λ) with changing temperature as

$$W = \frac{\Delta}{\Delta + \lambda} \qquad [4.11]$$

where

$\Delta = (\mathrm{ea}/TK)[(6790.5/TK) - 5.028]$ (mb/°C)
$\lambda = 0.0006595\ P$ (mb/°C)
P = barometric pressure (mb)
TK = daily mean air temperature in Kelvin ($= T$ in $^\circ\mathrm{C} + 273.16$)

Barometric pressure (P) can be estimated from altitude (A) in meters above sea level as

$$P = 1{,}013 - 0.1152\ A + 5.44 \times 10^{-6}\ A^2 \qquad [4.12]$$

Calculating Evapotranspiration

The combined effects of temperature, humidity, wind, and radiation are best discerned by considering the modified form of the 1948 Penman energy balance–aerodynamic equation as presented by J. Doorenbos and W. O. Pruitt in 1977 (eq. 4.10). Reference evapotranspiration (ETo) approximates the ET of a 4- to 7-inch-tall, unstressed, cool-season grass.

Correction Factors

In spite of the relative soundness of the Penman equation, Doorenbos and Pruitt suggested correction factors (C_1) to account for diurnal variations of, and interactions among, wind, humidity, and radiation level. Such adjustment is required in part by the stomata (typically closed at night), although some suggest that ET equations should be weighted heavily toward daytime weather conditions. Separate daytime and nighttime calculations of ET would be best.

Values for C_1 were originally in tabular form and required difficult interpolation procedures. An expression for C_1 (eq. 4.13) provides close estimates of original values.

$$\begin{aligned} C_1 = {} & 0.682 + 0.002786\ \mathrm{RH}_{max} + 0.0182\ R_s/59 \\ & - 0.06825\ U_{day} + 0.01265\ (U_{day}/U_{night}) \\ & + 0.00973\ U_{day}\ (U_{day}/U_{night}) \\ & + 0.432 \times 10^{-4}\ \mathrm{RH}_{max}\ R_s U_{day} \end{aligned} \qquad [4.13]$$

where R_s is in langleys/day, U_{day} is average wind from 0700 to 1900 hours in m/sec, and U_{night} is average wind from 1900 to 0700 hours in m/sec.

Even with adjustment, experience has shown that the ETo values need further correction for climatic differences within California. These correction factors (C_2) relate to calculated ETo when the weather data were collected by typical National Weather Service weather stations (noncropped, dry underlying surface). If weather data (temperature and humidity) come from an agroclimate station with a frequently irrigated underlying cropped surface and with 100 meters or more of similar upwind fetch conditions, use somewhat higher C_2 values. Experimental data suggest that C_2 values 15 to 20 percent higher than those in table 4.2 are needed for Central Valley locations where weather data originate in an agroclimate environment. This adjustment does not appear necessary for agroclimate stations in the Imperial Valley. No adjustments for agroclimate stations are currently known for coastal locations in California, but any that exist are likely to be small.

Ideally, hourly weather data would be used to calculate ETo. Such frequent, regular readings would account for climatic variations and daytime-nighttime effects. The CIMIS project is designed to develop improved ETo estimates and disseminate them to growers around the state. The research and development components of the CIMIS project were completed in June 1985, and the California Department of Water Resources now provides ETo estimates for California growers from the CIMIS network.

Equation 4.14 is recommended for use in California. It includes the adjustments suggested by Doorenbos and Pruitt (C_1) and regional calibration coefficients (C_2) developed for typical, nonagroclimatic weather stations within California.

$$\mathrm{ETo} = C_1 C_2 \{ W(R + G) + (1 - W)(\mathrm{VPD})[f(u)] \} \qquad [4.14]$$

The values of C_2 based on calibrations within California are given in table 4.2. The data condense the regional calibration coefficients used by Pruitt in developing ETo maps for California. Figure 4.1 delineates the zones listed in table 4.2.

A sample of the monthly long-term historical ETo maps for California developed by Pruitt is shown as figure 4.2, and data for all 12 months are given in Appendix B. This information is based on the best data available.

Sources of Data

Within California, the best source of solar radiation, temperature, humidity, and wind data is the CIMIS network. Access to CIMIS data can be obtained by contacting the California State Department of Water Resources—Office of Water Conservation, located in Sacramento.

Table 4.2. Recommended correction factors (C_2) for use in various zones delineated in figure 4.1

	Zone								
Month	1	2	3	4	5	6	7	8	9
Jan.	.68	.80	.90	.82	.74	.62	.65	.70	.85
Feb.	.76	.86	.95	.84	.74	.67	.70	.75	.85
Mar.	.84	.92	.99	.86	.74	.72	.70	.80	.91
Apr.	.92	.98	1.03	.89	.74	.74	.70	.80	.91
May	.92	.98	1.03	.89	.74	.74	.70	.80	.91
June	.92	.98	1.03	.89	.74	.74	.70	.80	.91
July	.92	.98	1.03	.89	.76	.74	.70	.80	.95
Aug.	.86	.94	1.03	.89	.79	.74	.70	.80	.95
Sept.	.82	.93	1.03	.89	.79	.74	.70	.80	.95
Oct.	.76	.90	1.03	.89	.77	.70	.70	.78	.95
Nov.	.64	.82	1.00	.89	.75	.66	.65	.70	.90
Dec.	.60	.70	.86	.78	.70	.60	.65	.70	.90

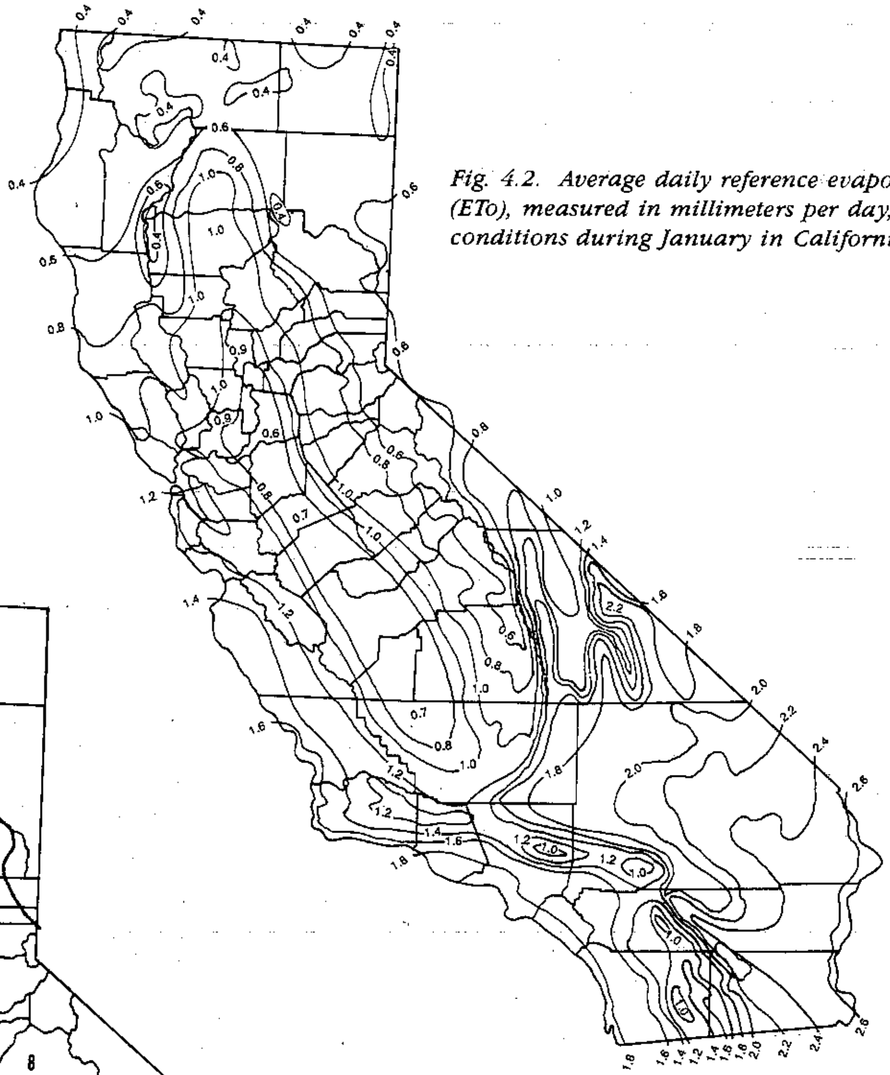


Fig. 4.2. *Average daily reference evapotranspiration (ETo), measured in millimeters per day, for normal conditions during January in California.*

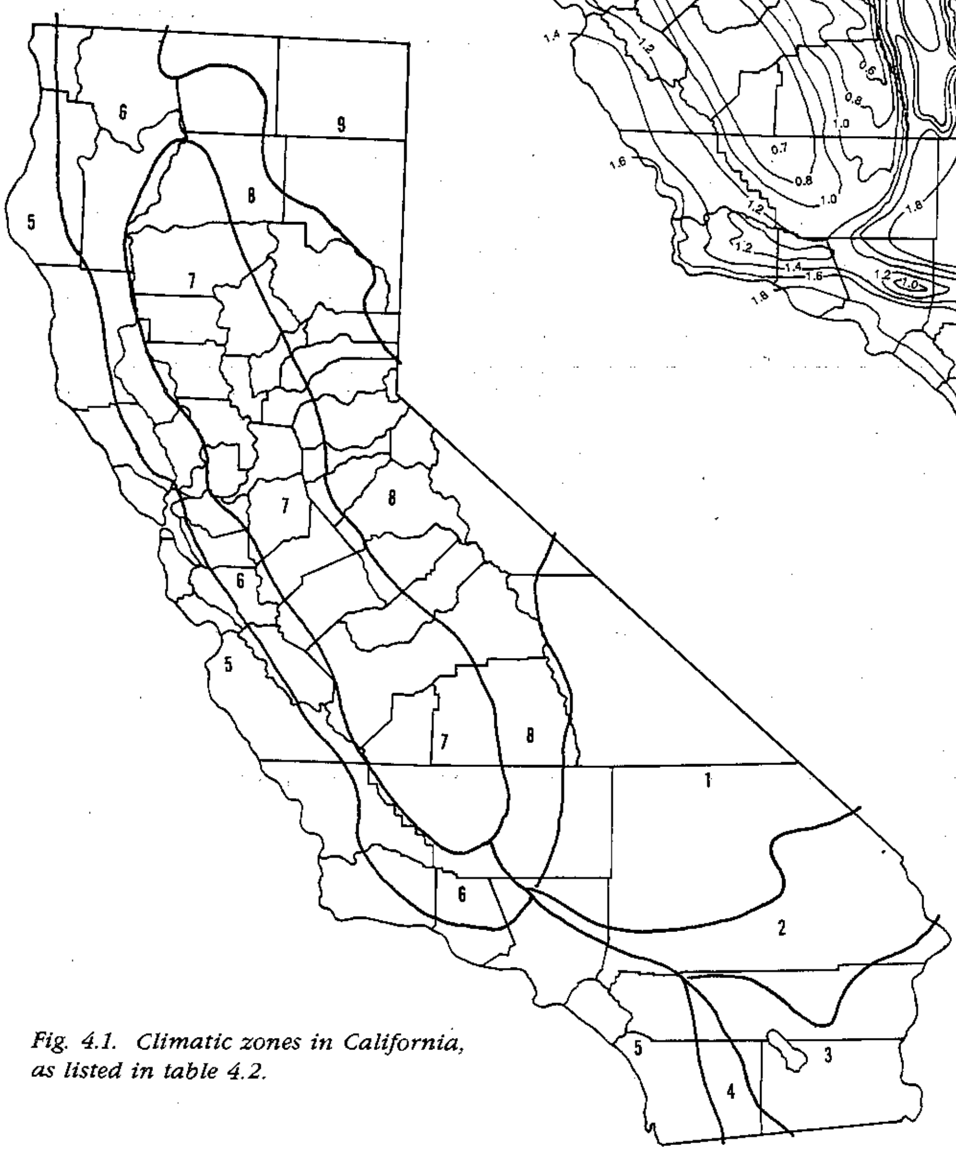


Fig. 4.1. Climatic zones in California, as listed in table 4.2.

Effective Rainfall

One of the more difficult components to estimate in an irrigation water budget is effective rainfall, the portion of rainfall that contributes to evapotranspiration. You can use the method presented here to estimate rainfall contributions to a crop water budget when the rain occurs during the growing season. Do not use it to estimate preseason soil water storage of winter rainfall—preseason soil water levels should be measured rather than estimated.

When rainfall begins, it first coats vegetation and wets the soil surface. As the rainfall continues, the vegetation surfaces become saturated and any additional rainfall reaches the soil where it infiltrates into the soil or contributes to runoff. Soil infiltration rates usually are fast when rainfall first wets the soil, but they slow to a steady state with time.

The components of rainfall that are important in determining effective rainfall are

P	total rainfall
F	infiltrated water
Ia	initial abstraction
S	maximum potential abstraction
D	deep percolation
Q	surface runoff
SW	rootzone water content
FC	rootzone field capacity
R	effective rainfall

Total daily rainfall equals the sum of effective rainfall, runoff, and deep percolation:

$$P = R + Q + D$$

and, therefore, the effective rainfall is

$$R = P - Q - D$$

However, runoff also equals the total rainfall minus the sum of the initial abstraction, the water that coats the surface vegetation, and the water that infiltrates into the soil:

$$Q = P - Ia - F$$

By combining the two previous equations and simplifying, we get

$$R = Ia + F - D$$

If the infiltrated water is greater than the depletion below field capacity, we can substitute $F-(FC-SW)$ for D in the previous equation and simplify it to

$$R = Ia + FC - SW$$

If the infiltrated water is less than the depletion below field capacity, then the deep percolation is equal to zero, and the runoff is

$$R = Ia + F$$

Thus, effective rainfall is calculated using one of the last two equations depending on whether the infiltrated water is greater than or less than the depletion from field capacity. The only parameters needed are the initial abstraction, infiltrated water, field capacity, and the soil water content before the rainfall. Field capacity and the soil water content can be measured or estimated using a water budget. Initial abstraction and infiltrated water can be estimated using the USDA-SCS curve number method.

Figure 4.3 shows the relationship between parameters used in the SCS curve number method to calculate runoff from small basins. The maximum potential abstraction (S) of rainfall before runoff occurs is equal to the sum of initial abstraction and water that infiltrates into the soil. It is calculated using a curve number (CN) in the following equation:

$$S = (1000/\mathrm{CN}) - 10$$

Initial abstraction is often given the value 0.2 times the potential abstraction and, therefore, the infiltrated water is approximately equal to 0.8 times the potential abstraction. Thus, after calculating S using the previous equation, the following two equations are used to determine Ia and F for estimation of effective rainfall:

$$Ia = 0.2 \times S$$

$$F = 0.8 \times S$$

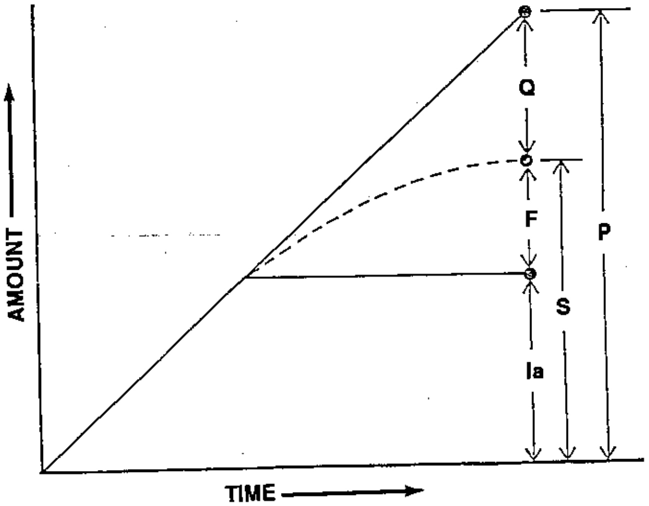


Fig. 4.3. A hypothetical diagram showing how the infiltration rate (F), surface runoff (Q), initial abstraction (Ia), maximum possible abstraction (S), and total possible rainfall (P) vary over time.

The curve number used in the equation to calculate S is extracted from table 4.3 and is adjusted for antecedent soil moisture conditions using table 4.4. Curve numbers depend on the land use or cover, the type of treatment or practice (e.g., row crop or terrace), the hydrologic condition of the land (good or poor, which depends on the field slope and cultural practices), and the hydrological soil group (A, B, C, or D). Type A soils have high infiltration rates even when thoroughly wetted, type B soils have moderate infiltration rates when thoroughly wetted, type C soils have slow infiltration rates when thoroughly wetted, and type D soils have slow infiltration rates and consist mainly of clay soils with high swelling potential or an impervious layer near the surface. Soil Conservation Service soil surveys give hydrologic soil group categories for most soils.

A CN from table 4.3 is correct for average antecedent moisture conditions (AMC II). If the antecedent moisture conditions are higher or lower than average, adjust the CN. Table 4.4 lists the curve numbers for the three categories of antecedent moisture conditions. For below-average conditions, locate the CN from table 4.3 in the AMC II column of table 4.4 and select the corresponding CN from the AMC I column. Similarly, for above-average conditions, select the corresponding CN from the AMC III column. An AMC I condition exists when the soil is dry. If the soil can be cultivated, it is probably in an AMC I condition. If a heavy or light rainfall over several days or an irrigation precedes the rainfall, the soil is probably in an AMC III condition.

Table 4.3. Runoff curve numbers for hydrologic soil-cover complexes (antecedent moisture condition II, and $I_a = 0.2S$)

Land use or cover	Cover		Hydrologic Soil Group			
	Treatment or practice	Hydrologic condition	A	B	C	D
Fallow	Straight row	—	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Contoured & terraced	Poor	66	74	80	82
	Contoured & terraced	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Contoured & terraced	Poor	61	72	79	82
	Contoured & terraced	Good	59	70	78	81
Close-seeded legumes* or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured & terraced	Poor	63	73	80	83
	Contoured & terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		—	59	74	82	86
Roads (dirt)†		—	72	82	87	89
(hard surface)†		—	74	84	90	92

Source: "Hydrology," Suppl. A to Sec. 4, *Engineering Handbook,* U.S. Department of Agriculture, Soil Conservation Service, 1968.
*Close-drilled or broadcast.
†Including right of way.

Table 4.4. Curve numbers (CN) for wet and dry antecedent moisture conditions (AMC) corresponding to an average antecedent moisture condition

Curve number (AMC II)	Corresponding curve number AMC I	AMC III
100	100	100
95	87	98
90	78	96
85	70	94
80	63	91
75	57	88
70	51	85
65	45	82
60	40	78
55	35	74
50	31	70
45	26	65
40	22	60
35	18	55
30	15	50
25	12	43
20	9	37
15	6	30
10	4	22
5	2	13

Source: After "Hydrology," Suppl. A to Sec. 4, *Engineering Handbook*, U.S. Department of Agriculture, Soil Conservation Service, 1968.

AMC I = Lowest runoff potential. Soils in the watershed are dry enough for satisfactory plowing or cultivation.

AMC II = The average condition.

AMC III = Highest runoff potential. Soils in the watershed are practically saturated from antecedent rains.

Example

Consider a nearly level Yolo silty clay loam soil planted to tomatoes in straight rows with 2.0 inches of rainfall during the previous 5 days. Total precipitation is 2.0 inches, cumulative field capacity (ΣFC) is 20 inches, and the root zone soil water content (ΣSW) is 19.5 inches. The Yolo County soil survey puts the soil in a type B hydrologic soil group. The hydrologic condition is good because the field is level. A CN of 78 is selected from table 4.3 for an AMC II antecedent moisture condition. The occurrence of heavy rainfall before the precipitation, however, places the antecedent moisture condition in AMC III with an estimated corresponding CN of 90 from table 4.4. The maximum potential abstraction (S) is$(1000/90)-10=1.1$ inches. The initial abstraction (Ia) and the infiltrated water (F) are $0.2\times1.1=0.2$ and $0.8\times1.1=0.9$, respectively. Since D is $20.0-19.5=0.5$ and F is greater than D, the effective rainfall is

$$R=Ia+\Sigma FC-\Sigma SW=0.2+20-19.5=0.7$$

If the cumulative soil water content before the rainfall was 17.0 inches instead of 19.5 as in the previous example, the depletion below field capacity would have been $2.0-17.0=3.0$ and F would have been less than D. In this case, the effective rainfall would be calculated as

$$R=Ia+F=0.2+0.9=1.1$$

Effective rainfall and the water budget

In many situations, effective rainfall during the season can be an important contributor to the water budget. Surface runoff is easy to estimate. The difficult part is estimating deep percolation, which depends on soil water content. Maintaining a balance of soil water content without soil-based measurements requires the accurate estimation of crop evapotranspiration. To estimate crop evapotranspiration, you must calculate reference evapotranspiration and use crop coefficients.

Crop Coefficients

Reference evapotranspiration (ETo) approximates the evapotranspiration of an extensive field of 4- to 6-inch-tall, cool-season grass that is not water stressed. However, ETo can be used to estimate the ET of a different crop (ETc) by multiplying the ETo values by crop coefficients (Kc values) that account for the ET difference between the crop and the cool-season grass.

The Kc value on any given day is equal to the ratio of ETc to ETo. A crop coefficient actually varies from day to day depending on many factors, but is mainly a function of crop growth and development. Thus, Kc values change as foliage develops and as the crop ages. Crop growth and development rates change, but the crop coefficient corresponding to a particular stage is assumed to be constant from year to year. Daily variations in ETc reflect changes in ETo in response to evaporative demand. The equation to calculate crop evapotranspiration is $ETc=ETo\times Kc$.

You determine the annual crop Kc values on any day by separating the growth and development into four periods, as shown in figure 4.4: (1) initial growth, (2) rapid growth, (3) midseason, and (4) late season. Perennial crops are similar, as shown in figure 4.5, but have no initial growth period. For our purposes, the letters A, B, C, D, and E represent the date preceding the beginning of initial growth, rapid growth,

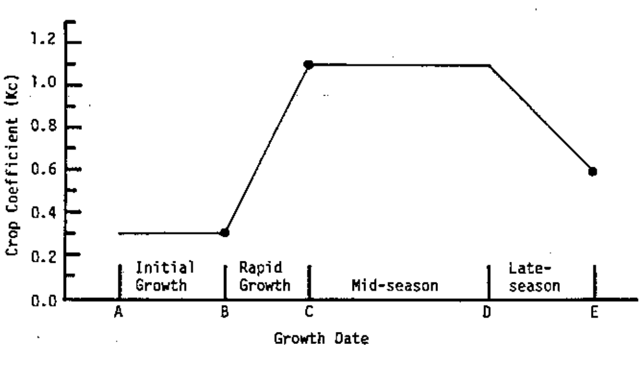


Fig. 4.4. Relationship between crop coefficients and growth and development periods for a hypothetical annual crop. Crop coefficients are entered for dates B, C, and E.

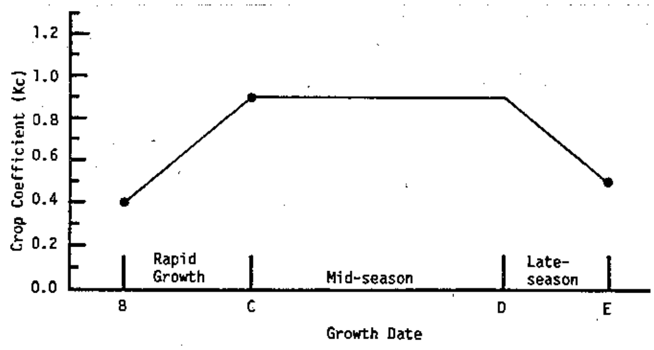


Fig. 4.5. Relationship between crop coefficients and growth and development periods for a hypothetical perennial crop. Crop coefficients are entered for dates B, C, and E.

midseason, late season, and the end of the season, respectively.

Growth is reflected by the percentage of the ground surface shaded by a crop at midday. For annual crops, the crop coefficient dates correspond to these parameters:

A: planting
B: 10 percent ground shading
C: 75 percent (or peak) ground shading
D: leaf aging effects on transpiration
E: end of season

Alfalfa is treated as an annual crop, with date A corresponding to green-up in the spring or to cutting. Broccoli is also treated as an annual crop, and its Kc values depend on spring cutting. Grass pasture is equivalent to ETo, with a Kc equal to 1.0 all year.

Perennial crops do not share the initial growth period, and their dates correspond to these parameters:

B: leaf out
C: full leaf growth
D: leaf aging effects on transpiration
E: end of season

Percentage ground shading does not include shading by cover crops that grow between the rows of trees or vines. Plantings with cover crops transpire more water and their crop coefficients are higher, especially during the rapid growth period. No attempt is made to estimate the water budget of deciduous crops before leafout or after the transpiration ceases. Citrus actually has slightly higher crop coefficients in the winter than in the spring, but ETo rates are much lower in winter, and a constant annual Kc value can be assumed for citrus with little loss of accuracy.

The most difficult growth and development date to identify is date D, when aging begins to affect transpiration rates. There is no easy way to visualize or measure achievement of date D. The actual timing of date D depends on climate, fertility, pests, and other factors, and it is impossible to predict exactly when it will occur. However, you must make an estimate to determine the Kc values during late season. The percentage of a growing season for a particular crop from the beginning to date D tends to be fairly constant regardless of where the crop is grown, so information on the percentage of a season to date D from research at one location can be used in other locations with reasonable accuracy. Information on percentages of the season to date D for a variety of crops grown in California appear in Appendix A.

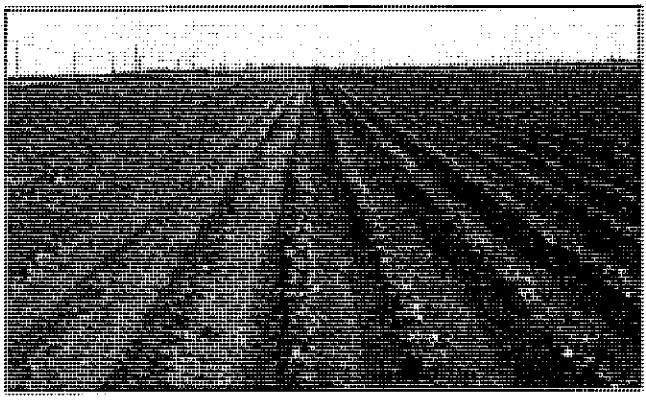
Appendix A contains crop coefficient and growth date information for several crops and California locations. Estimates of crop coefficients and growth dates using a similar method are also available in Doorenbos and Pruitt (1977). You must know or estimate each growth date except date D, and you determine date D using the percentage of the season shown as the last two digits in the code column as shown in Appendix A. Multiply the number of days in the growing season by the percentage to date D, and add the resulting number of days to the date at the beginning of the season (date A for annuals or date B for perennials) to determine date D.

The general shape of a seasonal Kc curve is similar to those shown in figures 4.3 and 4.4. You can plot crop coefficients on dates B, C, and D on graph paper or enter them into a computer program. Before date B, you assume that the crop coefficient is equal to that on date B. The crop coefficient is also assumed constant during midseason. During rapid growth and late season, changes in daily Kc are assumed to be linear between the lettered growth and development dates. With these assumptions, you can determine the Kc values with a graph or a computer.

Values for initial growth crop coefficients in Appendix A are for normal California conditions. During initial growth, ETc can be affected by the frequency of rainfall or irrigation because evaporation at the soil surface is greater when the surface is wet than when dry. Equation 4.16 was derived using least squares regression from information in Doorenbos and Pruitt (1977). The equation can calculate a Kc value for an initial growth period with inputs of rainfall or irrigation recurrence interval (R) and the average ETo during the period.

$$\begin{aligned} \mathrm{Kc} = {} & (1.28 - 0.07515\,R + 0.001848\,R^2) \\ & + (-0.0493 - 0.0109\,R \\ & + 0.0004684\,R^2)\,(\mathrm{Eto}) \\ & + (0.0015 + 0.00075\,R \\ & - 0.0000302\,R^2)\,(\mathrm{ETo}) \end{aligned} \qquad [4.16]$$

Because equation 4.16 is based on regression analysis, the upper limits of 20 days' recurrence interval and an ETo of 10 mm per day cannot be exceeded.



Crop coefficient values vary over the season, depending primarily on the plant growth stage. Early season values change rapidly as the canopy develops.

Immature deciduous trees use less water than mature trees, and you can determine the reduced ETc rates as

$$P = 3.050 + 2.558\ G - 0.016\ G^2 \qquad [4.17]$$

where P is the percentage of mature tree ETc, and G is the percent of ground shading. Equation 4.17 calculates to 100 percent of ETc when the trees have shaded 61 percent of the ground and no further increase in ETc is expected with greater shading. Deviation from a one-to-one relationship between orchard floor shading and tree ETc is due to (1) the tree canopies intercepting more sunlight than they reflect, and (2) advective energy transfer from the sunlit, bare soil to the tree canopies enhancing transpiration. No adjustment is known for vine crops, but it is probably similar to equation 4.17. Likewise, no correction for immature citrus or olive is known, but it is likely to be similar.

Yield Threshold Soil Water Depletion

Using the components of the water balance (initial soil moisture, effective rainfall, and crop water use), you can determine the amount of water needed to bring the soil to field capacity. This amount is the *net irrigation requirement*, and with an estimate of irrigation efficiency it can be used to estimate how much water you need to apply. Water balance calculations can also show the maximum time allowable between irrigations, if the yield threshold depletion (YTD) is known. The YTD is the amount of water that can be depleted from the soil before there is an effect on yield or quality of the crop being grown. By extrapolating ETc estimates, you can predict the time when YTD will be reached and, thus, the final date before water stress will begin to affect yield. Usually, a crop should be irrigated before reaching the YTD level.

Selecting a YTD value is an integral part of determining when to irrigate with surface irrigation methods. Allowable soil water depletion (sometimes called ***management allowable depletion,*** or simply ***allowable depletion***) is the actual value selected for irrigation scheduling. Ideally, the allowable depletion should not exceed the YTD, except as needed to maintain or manipulate plant quality or to preserve a limited water supply. Although simple in concept, confidence in the selected YTD value can be low since the actual YTD depends upon soil, plant, and climatic factors. To complicate matters further, these factors change in space and time. Consequently, most of the allowable depletion values used currently are based on experience with a particular crop and adjusted for management considerations (distribution uniformity, delivery schedules, infiltration, salinity, disease problems, etc.). Fereres and Puech (1980) provided a table of allowable depletion estimates for numerous crops, but use caution when selecting these values since the authors made gross assumptions to obtain many of these values and ignored climatic and plant factors on others. These estimates apply to crops grown under optimal conditions (well-drained, well-aerated, fertile, nonsaline soil free of disease or other pathogens). Unfortunately, few values for sub-optimal conditions have been established.

Water-Yield Relations

In general, yield is directly related to the cumulative seasonal transpiration (T) of a crop. Plants are said to be deficit irrigated when the ETc is not met and, thus, plant growth, crop yield, or quality declines as soil water falls below a critical level. Transpiration, therefore, must be maintained at its maximum rate to optimize yield for most crops. Transpiration is related mostly to two factors: (1) the difference between soil-water potential (SWP) and leaf-water potential (LWP), and (2) the total resistance of water movement in the soil (r_s) and in the plant (r_p). Algebraically, the relationship may be expressed as follows:

$$T = \frac{\mathrm{LWP} - \mathrm{SWP}}{r_s + r_p} \qquad [4.18]$$

Soil water tension and soil resistance to water flow increase with decreases in soil water content. Without plant compensation, both factors can reduce transpiration and hence yield.

Soil Factors

Available soil water, discussed in Chapter 1 as the difference between field capacity and the permanent wilting point, is an integral component of the YTD concept. The total amount of available water depends on soil texture and structure, so it varies among

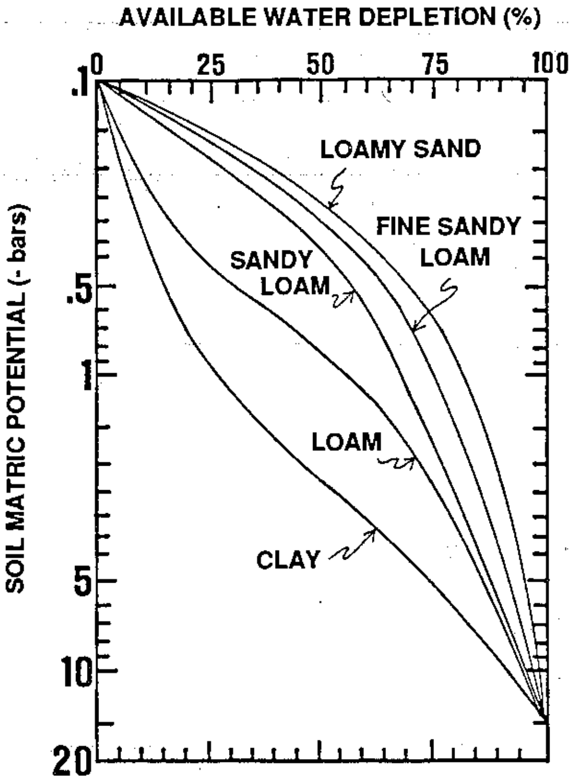


Fig. 4.6. Influence of available soil water on relative evapotranspiration (actual ET÷ET field capacity) under conditions of low, medium, and high evaporative demand.

soil types. One prevalent misconception is that all available water is equally available to the plant. In reality, soil water is most available near field capacity. Soil water tension in the active root zone increases as plants extract water, and the remaining water becomes less available. Figure 4.6 shows soil-water release curves expressing SWP on a logarithmic scale and available water depletion as a percentage.

Soil water release curves differ from soil to soil because each soil has a unique pore size distribution. Most of the available water in sandy loams is held at less than 1.0 bar (1.0 atmosphere) of tension, while most of the available water in clay soils is held at more than 1.0 bar of tension (fig. 4.6). If, for example, the soil throughout the active root zone were uniform in texture and the allowable depletion value were selected not to exceed a root zone average of 1.0 bar tension, the allowable depletion for the sandy loam, loam, and clay would be approximately 65, 55, and 25 percent of available water, respectively. Therefore, the percentage of allowable depletion decreases as the soil texture becomes finer.

A soil's resistance to water flow increases exponentially as the soil water content decreases. As plant roots extract water, soil water levels at the root surfaces and in the large water-conducting soil pores decrease. Thus, water travels through small soil pores and as thin films of water along the walls of larger, mostly drained pores. As extraction progresses, more pores lose their water and the conducting films become thinner. Soon, even with strong hydraulic gradients between the root surfaces and the bulk soil, water cannot easily move to the roots. ~~The~~ rate at which water flows from the surrounding soil to the roots depends mostly upon soil texture and water content.

Plant Factors

Several plant factors are important in selecting an allowable depletion value. These include the plant's sensitivity to water stress, developmental growth stage, and rooting characteristics.

Crops differ in their sensitivity to water stress (table 4.5). Larger differences occur among plant families than among varieties or species. Yield threshold depletions are often less for vegetable crops than for field crops. Certain crops require frequent irrigations to maintain plant quality (leafy vegetables), while a water deficit may be valuable to the management of others (e.g., to control vegetative growth in cotton and seed alfalfa, or increase the soluble solids in tomatoes, or the rubber concentration in guayule). Sensitivity to water stress may change depending upon the crop's development stage. Many crops are more sensitive to water stress during reproductive growth than during vegetative growth. This is especially true when the reproductive organ is the harvested product. This, however, does not mean

Table 4.5. Relative differences in the ability to maintain crop yield and quality under drought conditions

SENSITIVE	<					>	**TOLERANT**
			Grains				
			<maize wheat		<pearl millet sorghum	<sunflower	
			Legumes				
			<bean	<soybean	<peanut		<cowpea
			Fruits and vegetables				
strawberry	<lettuce		<tomato onion melon pea carrot broccoli pepper cauliflower	<cabbage	<cucumber		
			Field				
	potato			<sugarbeet	<alfalfa		<safflower
			Trees and vines				
	cherry	<peach avocado citrus apricot		<almond pistachio walnut	<grape	<olive	<jojoba

Source: Taylor (1965), Haise and Hagan (1967), Fereres and Puech (1980), and personal communication.

that more water must be applied during reproductive growth—only that the soil water content should not drop below the YTD.

The root depth and density within the soil profile are valuable clues to the YTD. Unfortunately, root measurement is difficult and tedious. In general, deeper-rooted crops have lower average allowable depletion values over the entire rooting depth. Root depth for an annual crop increases as the plant matures, and varies with plant and soil conditions. Root distribution is affected by irrigation frequency. Frequent irrigation favors a high root density in the upper portion of the profile.

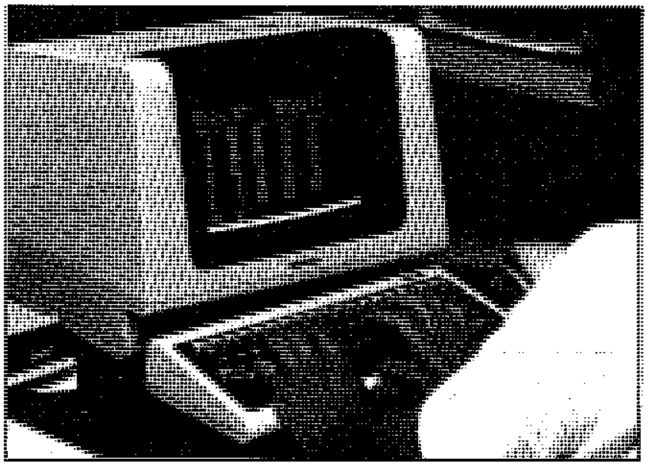
If irrigations are infrequent, certain plants (e.g., trees, vines, cowpea, groundnut, or safflower) can extract deeper water with their extensive root systems. This increases their reservoir of available water. Other crops (e.g., vegetables) are unable to do this. This explains, in part, differences in the drought tolerance of crops.

Root length density (root length per unit volume of soil) differs with crops and with growth and development for a specific crop. The roots of species with a fiberous root system can be denser toward the top of the profile than those with a tap root. For example, the root length density of rice can be 10 times that of cowpea at the 2-foot depth. Also, the root length density of a young seedling is less than that of a mature plant, and nematodes or other root-damaging organisms can significantly reduce effective root length density. As root length density increases, plants are generally able to extend their YTD because the mean distance water travels from soil to root is shorter. The water uptake required to maintain the transpiration rate is less per unit of root length for plants with greater root length densities. Therefore, a plant growing in a relatively dry soil (with a low hydraulic conductivity) will be more likely to transpire at the maximum rate if its root length density is sufficiently high.

The only time you really need to determine precise YTD values is when you want to minimize the irrigation frequency (and maximize the time between irrigations). A conservative estimate of YTD may result in an additional irrigation or two over the season, with smaller amounts of water applied to each irrigation. Indeed, most growers will not risk the possibility of having yield-injurious stress by overestimating YTD. In addition, the irrigation efficiency usually relates to the soil moisture deficit (SMD) in the root zone. When uniformity is good, under-irrigation can improve irrigation efficiency.

Scheduling Irrigation

There are several ways to schedule irrigations, including (1) monitoring the soil water content, (2) measuring the soil water tension, (3) observing plant stress symptoms, (4) monitoring plant water stress, and (5) using evapotranspiration (ET) and the water budget. Each method has advantages and disadvantages, and the best choice depends on crop, soil, and irrigation practices. In most situations, you can use the water budget to schedule irrigations with a reasonable degree of accuracy, especially when you have a soil- or plant-based measurement to verify irrigation timing, and ET and irrigation system performance estimates to tell you how much water to apply. Water budget scheduling involves the use of ET estimates to determine how much and when to irrigate.



Computer programs can speed the calculations necessary for irrigation scheduling, whether based on the water budget method or on soil monitoring.

The main requirement for scheduling irrigations with the water budget method is that you have accurate estimates of daily ETc. Reference evapotranspiration (ETo) values can be calculated from weather data or obtained from the California Irrigation Management Information System (CIMIS). Monthly average historical reference ETo values are given in Appendix B. Current (realtime) reference evapotranspiration data are available through the CIMIS computer dial-up service operated by the California Department of Water Resources. For more information on this service, write to

California Department of Water Resources
Office of Water Conservation
P. O. Box 942836
Sacramento, California 94236-0001

You will receive a user identification number and password when you request access to the service, along with documentation on how to use the CIMIS computer. Reference evapotranspiration (ETo) is adjusted to the ETc of your crop by multiplying it by a crop coefficient (Kc) value.

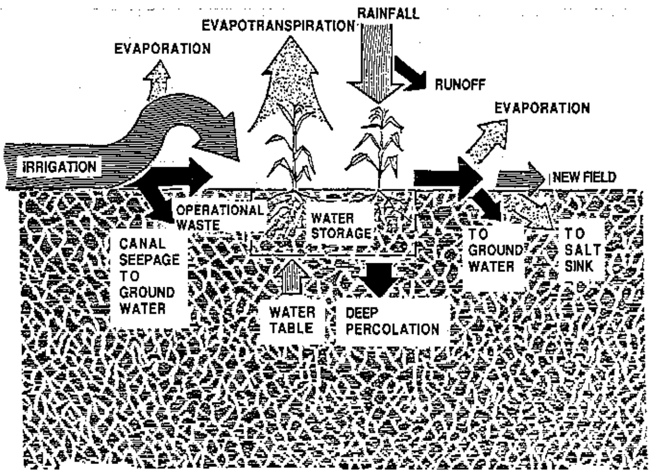


Fig. 4.7. A schematic diagram showing the sources and sinks of water for an irrigated field.

The water used by a crop comes from three main sources: irrigation, rainfall, and shallow water tables (fig. 4.7). During winter in interior valleys and year round in coastal regions, intercepted fog and dew may also contribute significantly to evapotranspiration. Little is known on how to account for the contributions of water tables, fog, and dew to crop water use. Using a water budget to schedule a crop grown on soil with a contributing water table, fog, or appreciable dew can lead you to overestimate the irrigation requirements, so a site-specific calibration is advisable. You can estimate the rainfall contributions to a water budget by determining effective rainfall, which was discussed earlier.

Assuming that there is no unknown water source (e.g., water table, fog, or dew) and that the initial soil water content is known, you can subtract daily evapotranspiration estimates for the crop (ETc) from the soil water content of the previous day to obtain a current estimate of soil water status. Irrigation timing depends on the irrigation system's limitations, the crop's water stress level, the timing of other cultural practices, and the grower's convenience. With these limitations, the timing of irrigations can be characterized as (1) a standard calendar, (2) a fixed set time, or (3) a flexible schedule.

With a standard calendar schedule, the crop is irrigated at a specified interval of days, and only the irrigation amount is changed. A fixed set time schedule maintains a constant set time (amount of applied water) for each irrigation, though the date of irrigation may vary. With a flexible schedule, both the timing (frequency) and application amount (duration) can vary. The water budget method can be used for each type of schedule.

For calendar schedules, ETc accumulates until the desired irrigation date arrives and the accumulated ETc equals the required net application. The net application amount is always less than the gross amount of water that needs to be applied, since losses to deep percolation and runoff are generally unavoidable.

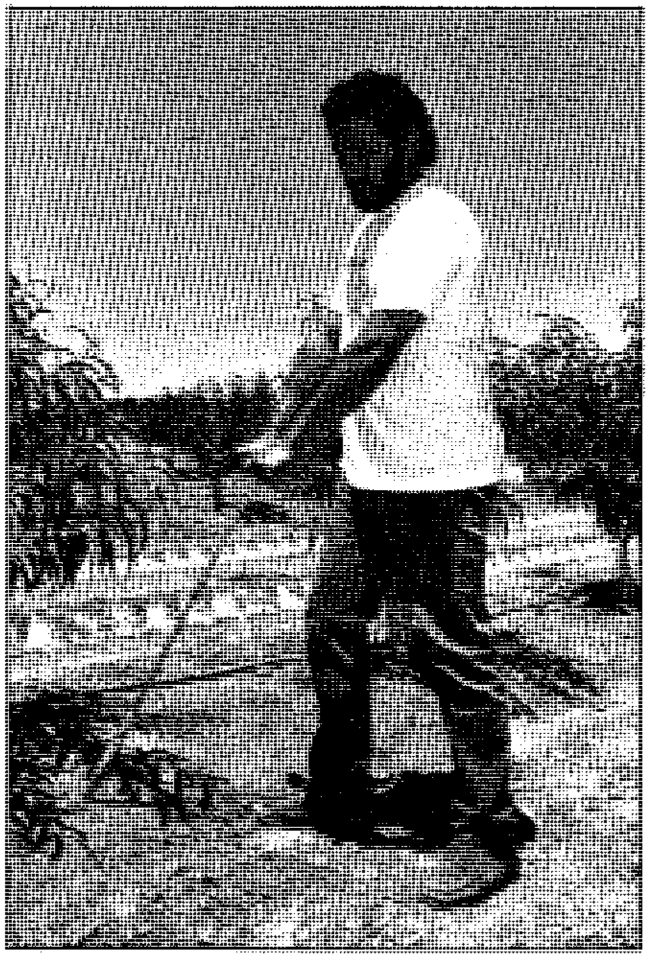
The timing of fixed set time irrigations depends on the net application (the fraction of that applied water that will be used by the crop). The amount to be replaced, or ***net application*** (NA), is

$$NA = WA \times E_a \qquad [4.19]$$

where

WA = gross water applied
E_a = application efficiency, expressed as a fraction

Whenever the soil water depletion exceeds the required net application, the grower schedules an irrigation. The amount applied is always the same. Application efficiency (E_a) is the fraction of applied water that is stored in the root zone of the plant, tak-



A soil tube is used to verify the accuracy of water budget irrigation scheduling in this young peach orchard. The practice is a valuable part of a complete water management program, and is especially useful in an immature orchard or vineyard.

ing into account losses to end-of-field runoff, deep percolation, and spray evaporation.

The timing of flexible schedules can be based on any of a number of factors, but the ultimate limiting factor is plant water stress. The maximum amount of water to deplete between irrigations is the yield threshold depletion (YTD), as discussed earlier. In some cases, an irrigation will be scheduled because of some other limiting factor (cultivation or pesticide application, for example), before water stress becomes imminent.

You can use evapotranspiration to schedule irrigations if (1) the ETc information is available, (2) the irrigation application efficiency is known, and (3) the contributions of other sources of water are either known or insignificant. The advantages of water budget scheduling over other methods are its less labor-intensive nature, its greater accuracy, and its adaptability to all three irrigation scheduling practices (calendar, fixed set time, and flexible).

The following examples show the development of irrigation schedules for a mature pistachio orchard under conventional surface irrigation using flexible, calendar, and fixed set time schedules, and high-frequency irrigation with low-volume sprinklers. While these examples show that, conceptually, water budget irrigation scheduling is quite simple, computerized programs are available to facilitate the calculations and provide information such as graphs or tables.

Crop: Mature pistachio trees
Location: Kettleman City
Soil: Sandy loam
Rooting depth: 6 ft
Tree spacing: 17×17 ft

Furrow, Flood, or Border Irrigation

Assume: Available water-holding capacity (AWC): 1.5 in/ft
Yield threshold depletion (YTD): 50% of total AW
Application efficiency: 80%
Application rate: 0.25 ac-in/ac/hr

Case 1: Flexible schedule (variable frequency and duration).

Step 1: Estimate the amount of available moisture in the root zone. Table 1.1 gives estimated available water (AW) contents for different soil types. Additional AW estimates for California soils are included in newer Soil Conservation Service soil survey reports. Total AW is determined by multiplying the appropriate AW value by the rooting depth.

$$\begin{aligned}\text{total AW} &= \text{AW (in/ft)} \times \text{rooting depth (ft)}\\ &= 1.5\ \text{in/ft} \times 6\ \text{ft}\\ &= 9.0\ \text{in}\end{aligned}$$

Step 2: Calculate the allowable depletion (AD) between irrigations.

$$\begin{aligned}\text{AD} &= \text{total AW} \times \text{YTD}\\ &= 9.0\ \text{in} \times 0.50\\ &= 4.5\ \text{in}\end{aligned}$$

Step 3: Estimate the rate of normal crop water use. Historical long-term average ETo data (Appendix B) and pistachio Kc values (Appendix A, Table A.1) are used to calculate orchard water use (ETc). Real time ETo from the CIMIS network could be used if available. Cumulative ETc vs. time is plotted in figure 4.8.

Step 4: Decide when to irrigate. Assuming that the soil water reservoir is full as the season begins from a combination of winter rainfall and previous year carryover, deciding when to irrigate is simply a matter of periodically determining when the cumulative ETc equals the AD (from Step 2). This procedure is illustrated in figure 4.8. NOTE: If the root zone is only partially wet at the beginning of the season, the initial total AW can be estimated by soil probing.

Step 5: Calculate the irrigation amount.

$$\begin{aligned}\text{Amount to apply} &= \frac{\text{AD}}{\text{Application efficiency}}\\ &= \frac{4.5\ \text{in}}{0.80}\\ &= 5.6\ \text{in}\end{aligned}$$

Case 2: Calendar schedule (fixed frequency, variable duration).

Step 1: Determine the cumulative ETc between each irrigation date. For example, if the orchard was last irrigated on June 12 and the irrigation frequency was every 18 days, cumulative ETc by June 30 would be 5.9 inches based on ETo and Kc data.

Step 2: Calculate the irrigation amount. For the June 30 irrigation:

$$\begin{aligned}\text{Amount to apply} &= \frac{\text{Cumulative ETc}}{\text{Application efficiency}}\\ &= \frac{5.9\ \text{in}}{0.80}\\ &= 7.4\ \text{in}\end{aligned}$$

Case 3: Fixed set time schedule (fixed duration, variable frequency).

Step 1: Determine gross water applied during fixed set time. The water application rate and the set time determine this value. Assuming a fixed set time of 24 hrs:

$$\begin{aligned}\text{gross water applied} &= \text{application rate} \times \text{duration}\\ &= 0.25\ \text{ac-in/ac/hr} \times 24\ \text{hr}\\ &= 6\ \text{in}\end{aligned}$$

Step 2: Calculate net water applied during fixed set time.

net water applied = gross water applied
× application efficiency
= 6 in × 0.80
= 4.8 in

Step 3: Decide when to irrigate. Irrigation should occur when the cumulative ETc equals 4.8 in. For example, if the orchard was last irrigated on July 1, the next irrigation would be scheduled on July 16 based on the ETc data used to develop figure 4.8

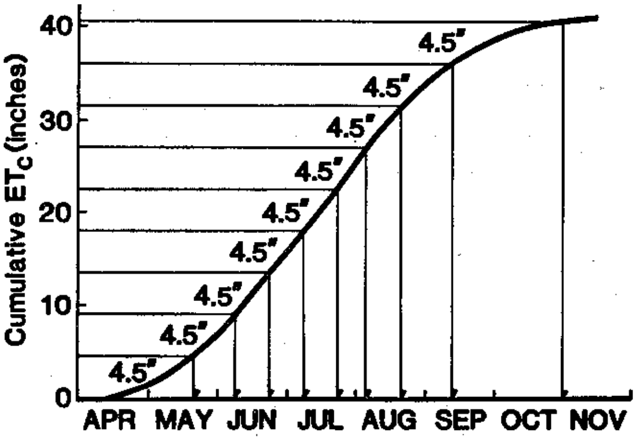


Fig. 4.8. A graphic aid for estimating irrigation dates for a mature pistachio orchard in the San Joaquin Valley, using the water budget approach with a flexible-frequency, flexible-duration schedule.

High-frequency Low-volume Sprinklers

Assume: application efficiency: 90%
application rate: 11 gals/tree/hr
irrigation frequency: twice per week

Step 1: Calculate the crop water use rate. For example, during July 1-15:

orchard ETc = Kc × ETo
= 1.19 × 0.28 in/day
= 0.33 in/day

individual tree ETc = orchard ETc × tree spacing
× conversion factor
= 0.33 in/day × 17 × 17 ft
× 0.622 gal/in · ft^2
≅ 59 gal/tree/day

Step 2: Calculate the irrigation amount.

$$\text{Amount to apply} = \frac{\text{ETc}}{\text{Application efficiency}}$$

$$= \frac{59 \text{ gal/tree/day}}{0.90}$$

≅ 66 gal/tree/day

≅ 462 gal/tree/week

≅ 231 gal/twice weekly irrigations

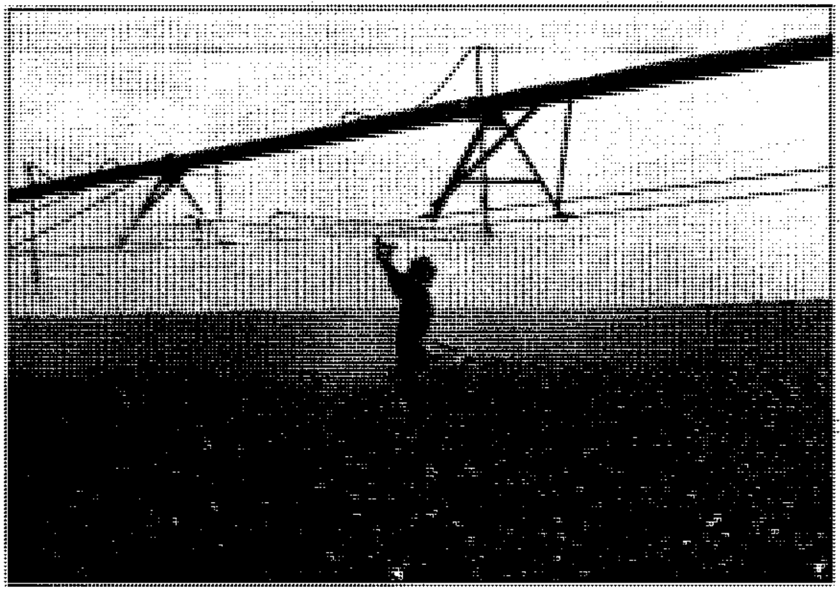
Step 3: Calculate the set time (duration of water application).

$$\text{set time} = \frac{\text{amount to apply}}{\text{application rate}}$$

$$= \frac{\text{231 gal twice per week}}{\text{11 gal/hr}}$$

= 21 hrs twice per week

5



By measuring the operating pressure at the sprinkler nozzles, you can determine the theoretical distribution uniformity of water applied from a traveling sprinkler. The actual distribution uniformity will also depend on the discontinuous travel of the spans as they move across the field.

Irrigation Effectiveness

In order to determine how much irrigation water to apply, you need to estimate your irrigation efficiency. Reference crop ET and crop coefficients give you the net irrigation requirement for your crop, but knowledge of irrigation effectiveness is required before you can determine the gross application amount. Losses to deep percolation and end-of-field runoff are unavoidable with most surface systems. Deep percolation results from the nonuniformity of infiltrated water and overirrigation (infiltration in excess of the soil moisture deficit). End-of-field runoff is actually necessary for good furrow irrigation management, but must be taken into account when you decide how much water to apply to the field.

Once you develop an irrigation schedule that includes application efficiency estimates, you can manage water well. One additional consideration, however, is the field check that ensures that you have determined the components of the water budget procedure accurately. A field check usually involves using a soil- or plant-based technique to verify the accuracy of one method against another in order to see whether they are consistent.

Efficiency and Uniformity

Efficient irrigation replenishes the soil moisture depletion with minimum losses. Efficiency requires good water management and good irrigation system design and maintenance, as reflected in the uniformity of the water application.

Performance of Irrigation Systems

The performance characteristics of irrigation systems reflect system design and maintenance, and include the following:

1. *Application efficiency*—the ratio of the water stored in the root zone to the water applied. Losses that affect application efficiency are surface runoff and subsurface drainage. Sprinkler systems are also subject to losses from evaporation and wind drift.
2. *Uniformity*—a measure of how uniformly the water is applied throughout the field. A uniformity of 100 percent indicates that the same amount of water infiltrated throughout the field. Indexes of uniformity include the coefficient of uniformity (CU) and the distribution uniformity (DU) for surface and sprinkler irrigation, and the emission uniformity (EU) for low-volume systems.

High uniformity and proper water management are the keys to efficient irrigation. The uniformity of an irrigation system depends on design and maintenance, and the application efficiency depends on both the uniformity and the system management. Management includes the timing and duration of water applications. The more uniform the system is, the higher the potential to reduce subsurface drainage losses attributable to nonuniform water infiltration. With poor uniformity, you can only reduce subsurface drainage by underirrigating some areas of the field.

Uniformity and management effects on subsurface drainage are illustrated in figure 5.1, which shows the cumulative water distribution of an irrigation system (the percentage of the irrigated field that receives a given depth of water). For example, 100 percent of the field in figure 5.1 received at least 8 inches of water, substantially more than the desired depth of 3 inches (the soil moisture depletion used in this example). The field was overirrigated by an amount represented by the crosshatched area. Improvements in management, such as reducing the set time, reduce subsurface drainage and surface runoff losses from overirrigation.

Nonuniformity causes some areas of a field to receive more water than others. Figure 5.1 shows that about 10 percent of the area received at least 15 inches of water, considerably more than that applied elsewhere. You can increase uniformity by improving system design and maintenance or by changing irrigation systems.

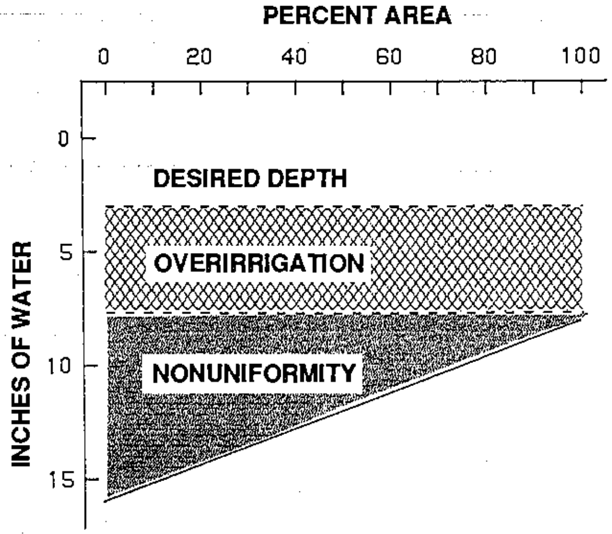


Fig. 5.1. Distribution of infiltrated water, expressed as percentages of a field that received a given depth of water.

Factors Affecting Performance

Surface irrigation. Uniformity of a surface irrigation system depends on the time required for water to advance (advance time) and recede (recession time) across the field, and on the variability of the soil's infiltration rate. Because of differences in advance and recession times, infiltration differs at the upper and lower ends of the field. This causes nonuniformity in the depth of water infiltrated, with more water infiltrated at the upper end than at the lower end. You can decrease these differences by increasing the furrow inflow rate during the advance time, reducing the length of the run, and improving the slope of the field. Better uniformity may help decrease subsurface drainage losses, but reduced set times are needed to prevent overirrigation.

While you can reduce differences in infiltration time, the maximum uniformity of a surface irrigation system is controlled by soil variability. Studies of spatial variability of infiltration revealed a fieldwide distribution uniformity (DU) of about 80 percent. This DU may represent an upper limit, since these fields are relatively uniform in soil texture. Some evidence suggests that the DU, as determined by infiltration time differences, should be adjusted downward by 5 to 10 percentage points to account for soil variability.

Losses in surface irrigation systems (subsurface drainage and surface runoff) are competitive; that is, by reducing one type of loss, you increase the other. By decreasing the length of the run to improve uniformity and reduce subsurface drainage, you will increase surface runoff. Reduced runoff losses are achieved with cutback irrigation (reduced inflow rate after advance is complete) or with runoff recovery

Low application efficiencies result when the water application is not uniform over a field, as can be the case with flood irrigation.

systems, commonly called tailwater return systems. Return systems capture the surface runoff in small ponds from which it can be reused.

One recent development in surface irrigation is surge irrigation, applying water in pulses rather than continuously. Surge irrigation reduces the soil's infiltration rate (the impact on the uniformity of the infiltration rate is uncertain), so complete coverage is possible with less water. Studies show that the water required for full field advance using the surge technique is 50 to 70 percent of that required with continuous-flow irrigation. The difference reflects the potential for surge irrigation to reduce drainage losses in areas with relatively high infiltration rates.

Another development is cablegation, an automated surface irrigation system developed in southern Idaho (fig. 5.2). A pipeline runs downhill from the water source, perpendicular to the furrows, with an orifice at each furrow. Inside the pipeline is a plug that can be moved by means of a cable. As the cable feeds into the pipeline, the plug inside the pipeline moves slowly downhill, opening the orifices furrow-by-furrow as it goes. Each furrow, and so each orifice, is a little farther downhill than the preceding one, and the greatest amount of water flows out of the lowest open orifice, and into its furrow. The next lowest orifice delivers a bit less water; the next, less than that, and so on. This system decreases surface runoff. For a cablegation system in southern Idaho, the runoff was less than 50 percent of that of a conventional system.

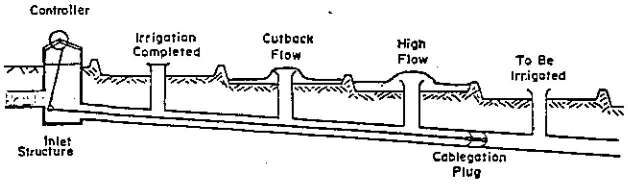


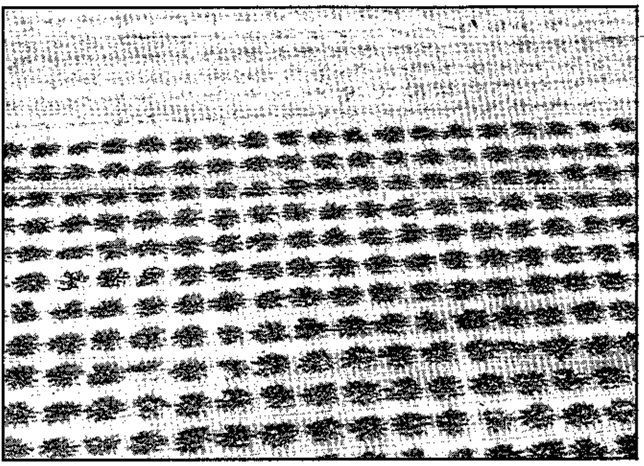
Fig. 5.2. A border cablegation system with four orifices pictured.

Level-basin irrigation has the potential of high uniformity and application efficiency with minimal labor and energy costs. Water flows at a high rate into dead-level basins, achieving irrigation efficiencies as high as 90 percent with no surface runoff. Level-basin systems can be automated. A level-basin system studied in California reduced subsurface drainage with minimal labor and energy costs (160 acres were irrigated in a little more than 24 hours, compared to more than 1 week for conventional graded irrigation). However, the system design must reflect the highest infiltration rate of the season (normally that of the first irrigation), water must flow into the fields at 15 to 20 cubic feet per second, and lengths of run must not exceed $^1/_8$ mile of precisely leveled land. The soil type must be uniform across each basin.

Sprinkler irrigation. The uniformity of a sprinkler irrigation system depends on hydraulic design and system maintenance and on the areal distribution of the applied water. The hydraulic design affects uniformity because pipeline friction and elevation differences result in pressure losses along mainlines and laterals. Poor system maintenance will result in leakage, mixed nozzle sizes, excessive nozzle and sprinkler head wear, and reduced pressure. The greatest pressure loss that will still allow good uniformity is 20 percent of the average pressure. Sprinkler spacing, system pressure, wind velocity, and sprinkler and nozzle type affect the areal uniformity of applied water. Under low-wind and adequate-pressure conditions, DUs of 70 to 80 percent have been measured for solid-set and hand-moved systems. Under high winds and low pressures, DUs are closer to 60 percent.

Linear-move and center-pivot sprinkler machines can give higher uniformity than solid-set or hand-moved systems, particularly under high wind conditions. The uniformity of some linear-move machines with spray nozzles on drop tubes has been measured at 70 to 80 percent. Nonuniformity in these systems resulted from inadequate overlap of the spray patterns (nozzle spacings ranged from 8 to 10 feet) and the start-stop sequence of the machines. These machines, classified as continuous-move, actually move in a series of starts and stops controlled by a guide tower. Better uniformity may come with closer spacings or with boom-mounted nozzles rotated at some angle to the lateral. For one system with nozzles spaced at 40 inches, the DU was nearly 85 percent.

A modification of center-pivot and linear-move machines is the low-energy precision application (LEPA) irrigation system developed in west Texas to reduce irrigation energy costs. The LEPA system is a center-pivot or linear-move sprinkler machine converted so drop tubes discharge water into individual furrows. Furrow dikes or checks spaced along the furrow prevent surface runoff on sloping ground.



A properly designed, maintained, and managed low-volume sprinkler system can deliver water with an application efficiency greater than 90 percent.

The uniformity of LEPA systems due to hydraulic losses has been measured at about 94 percent. However, fieldwide uniformity along the travel path of the apparatus depends on the machine's irregular movement and the soil's variability between dikes. Research shows that machine movement controls the uniformity for close dike spacings, while soil variability controls the uniformity for distant spacings. A maximum uniformity of about 80 percent occurred for check spacings between 10 and 13 feet on level ground for one system. On sloping ground, uniformity is lower because of differences in ponded water depth between checks.

Drip and trickle irrigation. The uniformity of drip and trickle irrigation systems depends on their hydraulic design, variations in the emitters, and system maintenance. Like sprinkler systems, drip and trickle irrigation system uniformity can suffer because of pipeline friction and elevation differences. Variations in the emitters' discharge rates also result from the manufacturing process (the manufacturing coefficient of variation). A good manufacturing coefficient of variation is less than 5 percent.

Manufacturing coefficients of variation for the drip tape and tubing used in subsurface drip and trickle irrigation range from 5 to 7 percent. This corresponds to uniformities of 96 percent and 94 percent, respectively.

While drip and trickle irrigation systems have high theoretical uniformities and efficiencies, measured field uniformities are lower. Of 57 drip irrigation systems evaluated in one survey in California's San Joaquin Valley, 10 had DUs greater than 90 percent, 35 were between 70 to 90 percent, and 12 were less than 70 percent. Lower uniformities were caused by water quality-related plugging problems, poor filtration, and excessive variability in emitters.

Microsprinklers (also referred to as misters, mini- and low-volume sprinklers), a recent development, are small plastic spray nozzles set about 6 inches above the ground. These sprinklers wet an area up to 20 feet in diameter, and discharge up to 40 or 50 gallons per hour, depending on nozzle size. Microsprinklers have some potential advantages over drip emitters: they have fewer plugging problems, they wet larger soil areas, and they can be operated less frequently than drip. However, spiders and salt precipitation can cause performance problems for microsprinklers, especially those with rotating parts.

Since microsprinklers do not overlap, the uniformity of applied water is poor. However, one study showed that although the applied water had poor uniformity, the subsurface soil water had good uniformity as the applied water moved laterally in the soil.

Which Is the Best?

Which irrigation system is the best? Interestingly, many studies comparing uniformities and efficiencies of different types of irrigation systems fail to answer this question. Some studies compare a poorly managed furrow system to a properly managed sprinkler or drip system. Obviously, such a furrow system uses more water than the better-managed system. In other studies, the small plots used for comparison may have had performance characteristics considerably different from those of a fieldwide system. Extrapolating these research results to a large-scale situation is inappropriate.

One might expect high uniformities from drip or microsprinkler systems and continuous-move sprinkler systems such as center-pivot and linear-move machines. Realistic potential uniformities, however, are only moderately different for all irrigation methods. Also, for adequate and efficient irrigation, realistic potential application efficiencies are about equal to the distribution uniformities (this is true for surface systems only if surface runoff is recirculated). The uniformities and application efficiencies attainable for various irrigation methods are listed in table 5.1.

Table 5.1. Attainable potential irrigation uniformities and application efficiencies, assuming adequate irrigation

System	Distribution uniformity	Application efficiency
Sprinkler	——————— %	———————
Periodic move	70-80	65-80
Continuous move	70-90*	75-85
Solid set	90-95	85-90
Drip or trickle	80-90	75-90
Surface		
Furrow	80-90†	60-90‡
Border	70-85†	65-80‡
Basin	90-95†	75-90

*Spray nozzles on booms or impact sprinklers have the higher values.
†Figures do not include nonuniformities resulting from variability of the soil infiltration rate.
‡Tailwater recovery systems and cutback irrigation have the higher values.

While potential uniformity and application efficiency are considerations when you select a system, other considerations include the capital costs of the system, the maintenance costs and labor costs, the topography and soil type, the quality of the irrigation water, and cropping patterns. In some cases, there may be trade-offs. For example, systems with high capital costs may have low labor costs, and vice versa. Table 5.2 provides some guidelines on systems suited to specific conditions.

Field Checks

Irrigation scheduling using the water budget approach is based on sound principles, but uncertainties in some of the input data can undermine predictions of when to irrigate and how much water to apply. Therefore, an important aspect of a complete water management program is the periodic checking of soil moisture in the field. Field checks can verify the accuracy of irrigation scheduling and determine the effectiveness of the most recent irrigation.

You can perform field checks in a number of ways that can involve such instruments as the tensiometer, gypsum block, neutron probe, thermal dissipation sensor, pressure bomb, and infrared thermometer. However, hand probing and using the feel method described in Chapter 1 are the most common field check methods.

For surface and multiple-set sprinkler irrigations, take the field verification samples in the area of the field that is irrigated during the first set. That area is the driest when the irrigation cycle is complete. Because soils and irrigation efficiencies vary, use an average of several sampling sites to estimate soil or plant water status. Samples should reflect the full effective rooting depth of the crop.

Different irrigation methods require different field check strategies. Avoid atypical locations, as indicated by crop appearance or soil conditions. With furrow irrigation, check the head, middle, and tail of several furrows, since infiltration along a furrow varies with length. More samples will result in a more reliable field check.

Table 5.2. Factors to consider in selecting an irrigation system*

	Sprinkler system					Surface system			
Factors to consider	Portable	Wheel roll	Solid set	Center-pivot Linear-move	Boom (giant)	Graded border	Level border	Furrow	Drip system
Slope limitations:									
Direction of irrigation	20%	15%	none	15%	5%	0.5-4.0%	level	3%	none
Cross-slope	20%	15%	none	15%	5%	0.2%	0.2%	10%	none
Soil limitations:									
Intake rate (in/hr)									
Minimum	0.10	0.10	0.05	0.30	0.30	0.30	0.1	0.1	0.02
Maximum	none	none	none	none	none	6.0	6.0	3.0	none
Water-holding capacity in root zone	3.0	3.0	none	2.0	2.0	2.0	2.0	2.0	none
Depth	none	none	none	none	none	deep enough soil to allow required grading			none
Erosion hazard	slight	slight	slight	moderate	severe	moderate	slight	severe	none
Saline-alkali soils	slight	slight	slight	slight	slight	moderate	slight	severe	moderate
Water limitations:									
Quality									
Total dissolved solids (TDS)	severe	severe	severe	severe	severe	slight	slight	moderate	slight
Suspended solids	moderate	moderate	moderate	moderate	moderate	none	none	none	severe
Rate of flow	low	low	low	high	high	moderate	moderate	moderate	low
Climatic factors:									
Temperature control	no	no	yes	no	no	yes	yes	yes	no
Wind-affected	yes	yes	yes	yes	yes	no	no	no	no
Adaptability to all crops:	good	good	good	fair	limited	very good	very good	very good	good
Potential for automation:	poor	very good	very good	very good	moderate	moderate	very good	moderate	very good
System costs (1981 data):									
Capital cost ($/ac)	650-1,000	650-1,000	1,000-1,900	1,100-1,600	1,000-1,100	800-1,000	800-1,000	650-800	800-1,900
Labor cost†	high	moderate	low	low	moderate	moderate	moderate	high	low
Power cost‡	high	high	high	high	high	low	low	low	moderate
Average annual cost§ ($/ac/yr)	150-300	150-300	300-500	300-500	300-500	150-300	150-300	300-500	300-500

Source: Irrigation Water Use in the Central Valley of California (1987).

*Factor limitations in excess of those specified may be used, but an increase in the number of conservation practices will be required along with high level of management.

†Low—less than $30/ac/yr; Moderate—$30/ac/yr; High—over $80/ac/yr.

‡Low—$0-15/ac/yr; Moderate—$15/ac/yr; High—over $40/ac/yr.

§Amortized capital cost plus operation and maintenance cost.

Border irrigation resembles furrow irrigation in that soil water content varies along the length of the border. Relatively minor variations exist across individual borders. Thus, field checks should be made down the length of the border, preferably in a location indicative in infiltration (not the middle of the berm separating borders).

Sprinkler systems have a uniformity pattern different from that shared by furrow and border systems. The soil moisture under a sprinkler system is influenced by the distance from the sprinkler head and by wind speed and direction. When measuring soil moisture under a sprinkler system, take samples at various distances from sprinkler heads.

The soil water content in fields irrigated with low-volume, high-frequency systems such as drip or microsprinklers, varies with depth, distance from the emitter or microsprinkler, soil type, and emitter or microsprinkler discharge rate. Sample the soil water to determine the geometry of the wetting patterns near several emitters—both the depth of wetting and the lateral movement of water. Field measurements of soil water content with low-volume systems should not be taken to characterize the entire potential root zone, as with surface irrigation methods. Rather, measurements should characterize the subsurface wetting pattern, including whether it expands or contracts with time over the season.

Additional field checks immediately after a surface or sprinkler irrigation provide valuable information on the efficiency of the water application and the degree to which the soil moisture reservoir is refilled. Ideally, the soil will be wetted to the depth of the crop root zone over the entire length of the field. If a field is underirrigated, water will infiltrate through only part of the root zone, and the bottom of the root zone will become progressively drier through the season as only the top portion of the profile is wetted. If irrigation is inadequate, the grower must apply more water per irrigation or irrigate more frequently to prevent crop stress. Field monitoring can identify underirrigation of an entire field, which can be caused by (1) underestimated ETc rates, (2) overestimated application efficiencies, or (3) underestimated applied water amounts. Make an effort to identify which component causes the error. If you only detect inadequate irrigation in localized areas of the field, the problem is generally in the distribution uniformity of infiltrated water.

If the input data are reasonably accurate in a water budget program, only a few field checks are necessary throughout the season. Generally, one check each week is adequate. If possible, conduct field checks before and after each irrigation. If irrigation intervals are long, make an additional check a few days before the projected irrigation date to allow time to adjust the schedule.

6

The rising, saline, shallow water table (foreground) at this site on the west side of the San Joaquin Valley prompted the removal of this olive orchard.

Additional Considerations

While irrigation scheduling is based on sound agronomic principles, site-specific factors that can influence the soil, water, and plant should also be considered. Two such factors affecting vast areas of California's San Joaquin Valley are shallow water tables and saline soils. The impact of these problems on crop production depends largely on irrigation management.

Shallow Water Tables

Traditionally, we assume that all of a crop's water comes from moisture stored in the root zone, so evapotranspiration between irrigations should equal soil moisture depletion. This assumption is the basis of the water budget method. A shallow water table, however, invalidates this assumption, because the upward flow of shallow groundwater into the root zone provides another source of water. As a result, the soil moisture depletion between irrigations is less than the evapotranspiration. You can make substantial errors in estimating the amount of irrigation water to be applied if you use the water budget method without adjusting for a shallow water table.

What causes this upward flow? Between irrigations, plants extract water from soil. Where the water table is shallow, the plants' suction can make the soil behave something like a soda straw, inducing an upward flow from the perched water table. Many factors affect this upward flow, including soil texture, depth to the shallow groundwater, crop type and rooting depth, and quality of the groundwater. For a given depth to the water table, upward flow in a sandy soil will be less than in a loamy soil. Upward flow from the water table decreases as the depth to the water table increases. A study on Yolo silt loam showed about 45 inches of upward flow for a water table depth of 0.5 foot, and only about 5 inches for a 5-foot depth.

Upward flow can contribute substantially to the plants' water needs. Researchers in Montana found alfalfa yield to be only about 0.4 tons per acre more with six irrigations than with no irrigations where the water table was about 6 feet deep. Nevada researchers found only slight yield differences between irrigated and nonirrigated alfalfa for water table depths to 8 feet. Studies in California found that where the depth to the water table ranged between 7 and 9 feet, cotton yields ranged from about 2.1 bales per acre (no irrigations) to 2.7 bales per acre (three irrigations).

A detailed study in California's San Joaquin Valley revealed relationships between the percentage of evapotranspiration contributed by the shallow groundwater, the depth to the groundwater, and the salinity of the groundwater. These data (fig. 6.1) illustrate that for a particular groundwater salinity, there is a unique water table depth where the groundwater makes a maximum contribution to evapotranspiration. The depth of this maximum contribution increases as the salinity of the groundwater increases and the percentage of the contribution decreases. For a salinity of about 10 mmhos per cm, typical of many areas on the west side of the San Joaquin Valley, a maximum contribution of nearly 30 percent occurs at a water table depth of about 5 feet.

In a proper irrigation schedule with a shallow water table, you must account for upward flow when you estimate the interval between irrigations and the amount of water to apply.

One way to estimate the irrigation interval for cotton planted over a shallow water table is to measure midday leaf water potential with a pressure bomb. Using this approach, fewer irrigations are usually required and the crop yield can substantially improve, presumably because the root zone is less waterlogged. This approach does not, however, provide information on the amount of soil moisture depletion, which you can estimate using a soil-based technique.

Methods for irrigation scheduling for other crops with shallow water tables include tensiometers, the soil feel method, neutron probes, and other approaches to estimating soil moisture depletions. You might also use figure 6.1 to estimate the groundwater contribution, but take into account that during the early plant development period for annual crops, the contribution from shallow groundwater is minimal.

Salinity

The standard reference in this discipline on the effects of salt on plants and soils, USDA Handbook 60 (*Diagnosis and Improvement of Saline and Alkali Soils*), published in 1954, is out of print, but changing water quality guidelines related to crop-salt tolerances, leaching requirements, and soil permeabilities mean that Handbook 60 is also out of date. You can find more current information in chapters 3 and 7 of *Irrigation with Reclaimed Municipal Wastewater—A Guidance Manual* (Pettygrove and Asano, editors,

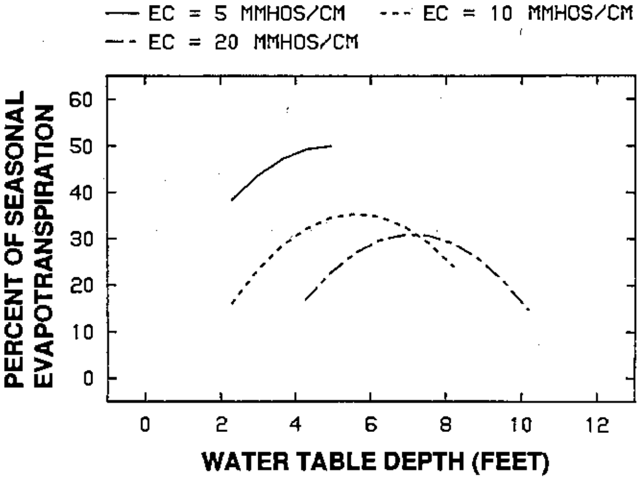


Fig. 6.1. Relationship between water table depth and percentage of seasonal evapotranspiration supplied by three perched water tables of different water qualities (Grimes et al., 1984).

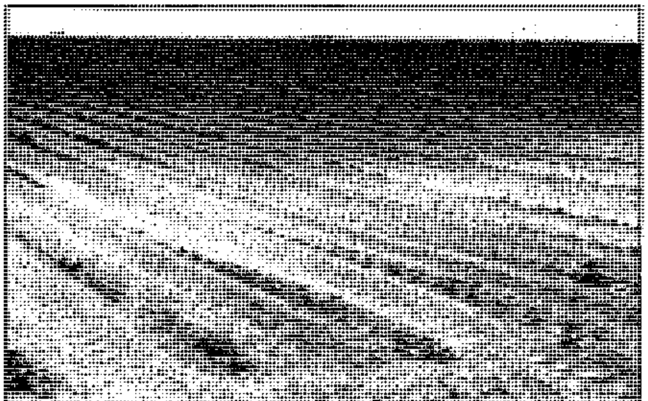
Lewis Publishers, Chelsea, MI), and in United Nations Food and Agriculture Organization (FAO) Handbook 29 (Ayers and Westcot 1985). A special issue of *California Agriculture* entitled "Salinity in California" (volume 38:10, 1984) addressed historical, research, and management issues pertinent to California.

Plant Response to Salinity

Herbaceous crops (vegetables, grains, forages, and fiber crops) growing on saline soils may exhibit barren spots, areas of stunted growth, and deep blue-green foliage. If barren spots are absent, the main characteristic of a salt-stressed crop may be marked variability in plant growth. Unlike herbaceous crops, woody plants often exhibit foliar injury caused by soil salinity, varying in severity from a mild chlorosis along leaf margins to severe leaf necrosis, defoliation, and twig dieback. Excess boron in the leaves of herbaceous and woody plants can also cause leaf tip and marginal burn, chlorosis, rosette spotting, leaf drop, and branch dieback.

Exercise care when using visible injury to diagnose soil salinization. Reduced crop yields and variable crop growth may not be accompanied by any visible injury. Also, variable growth may result from uneven water distribution attributable to compaction, poor leveling, or infiltration variability resulting from soil spatial variability. The irrigation method can also affect injury symptoms. For example, herbaceous plants are not sensitive to chloride or sodium in the soil, but they develop symptoms of leaf burn (foliar necrosis) when sprinkle-irrigated with saline water. In this case, susceptibility to leaf burn is related more to the rate of foliar salt absorption than to the plant's tolerance to soil salinity.

The overall salinity effect on plants is a reduction in growth. Growth may be suppressed by either osmotic or ion-specific effects. Although these mechanisms are not mutually exclusive, we will discuss them independently.



A localized area of high salinity causes poor germination of cotton in this Fresno County field.

Osmotic effects. Plant growth does not reduce appreciably until salinity exceeds some threshold. The threshold and the degree of growth reduction beyond the threshold vary with the plant. We should emphasize that growth reduction accompanies an increased salt concentration, regardless of the type of salts in the root zone. Nutrient salts will suppress plant growth if the total salt concentration exceeds the threshold value. Under saline conditions, the plant expends energy to adjust the osmotic potential within its tissue by either accumulating salts from the soil solution or by synthesizing organic solutes, and less energy is available for plant growth. Variations in energy efficiency may explain differences in growth rate among species or cultivars.

Under field conditions, the salt concentration within the crop root zone varies both spatially and temporally. The influence of salinity on crop growth is related, for the most part, to the root zone salinity averaged over time. Since plants primarily extract pure water from the soil, leaving salts behind, it has generally been recommended that the allowable depletion be reduced to prevent salts from concentrating in the soil water. Therefore, irrigating more frequently would minimize salts from concentrating in the root zone. Some scientists have found that drip irrigation with saline water improved crop performance over that under conventional furrow irrigation because of a reduced time-averaged root zone salinity. Exercise caution, however, since frequent irrigations may lead to phytophthera and other root diseases. Benefits from increased irrigation frequency may not always be evident.

Ion-specific effects. Some ion-specific effects produce visible injuries, and some result in nutritional imbalances. However, these effects are not necessarily exclusive. Certain elements (e.g., chlorine, boron, and sodium) can accumulate in leaf tissue to toxic levels. The mechanism of foliar injury (leaf chlorosis or necrosis) may involve interference with metabolic processes or plant regulatory systems. For example, chloride or sodium ions may accumulate in the leaves and impair stomatal closure, causing excessive water loss and injury that resembles drought damage. Boron, which can interfere with chlorophyll synthesis, is toxic at levels only slightly greater than are required for healthy plant growth. Correlating tissue element concentrations with visible injury is difficult; for example, a plant may contain toxic levels of a particular element in its leaves, and produce no visible injury until the onset of hot, dry weather.

Roots exclude salt as a primary protective mechanism to control salt transport to stems and leaves, and the mechanism varies with species. The differences are important considerations when you select rootstocks for stone fruits, citrus, avocados, and grapes. Differences among cultivars result from genetic differences in the structure and composition of root membranes.

Soil usually contains a mixture of salts that apparently buffer against severe nutritional deficiencies and imbalances within the plant. However, quantifying a plant's response caused by a salinity-induced nutritional imbalance is difficult, since many interactions exist among ions near the roots and within the plant. Furthermore, plant varieties differ in uptake, translocation, and accumulation of many elements required for plant growth. Selective ion transport is the major mechanism the plant uses to buffer against ion imbalances. For example, sodium concentrations in a saline soil solution may exceed potassium concentrations by 100-fold, yet the ratio of the two elements within the plant tissue may be close to one.

Salts have varying effects on plants. Some plants are more sensitive to sulfate than to chloride salinity. In recent laboratory experiments, growth differences occurred in plants subjected to different ratios of calcium to sodium. Although effects are specific to species and cultivar, excess sodium with respect to calcium generally induces a calcium deficiency, and calcium stabilizes the plant's membrane structure. Sustained selective-ion transport requires membrane integrity, and sodium effects and calcium deficiency play important roles in crop growth in sodic soils.

Ion-specific effects may reduce growth by any of several mechanisms. Possibilities include (1) a nutrient deficiency due to competitive uptake or translocation, (2) a metabolic inefficiency, (3) a nutrient deficiency caused by an increased metabolic requirement for the nutrient in the presence of high concentrations of other elements, or (4) a direct toxicity. However, it is still difficult to assess the importance of ion-specific effects under field conditions.

Plant and Soil Analyses

Chemical analyses of soil and plant samples usually are needed to confirm a diagnosis based on visual observations. Analytical methods include measuring soil salinity, electrical conductivity, and specific ion concentrations within the root zone, and analyzing leaf tissue for chloride, sodium, and boron. Salt tolerance tables and tissue compositions for individual crops provide guidelines for interpreting soil and tissue data.

Reclaiming Saline, Sodic, and High-boron Soils

Reclamation is the reduction of soil salts or soil boron to acceptable levels by leaching, or reduction of soil sodicity by both applying soil amendments and leaching. The salinity of the upper 2 feet of soil is of most concern. Applying water in excess of field capacity before planting, when coupled with a second excess irrigation immediately after planting, will usually reclaim this zone. Salinity levels higher than an electrical conductivity (EC) of 10 mmhos per cm may require more leaching than can be provided by one preirrigation. For continuous ponding, leach with a depth of water equivalent to the depth of soil to be reclaimed and you will remove about 70 percent of the soluble salts initially present. Thus, removing 70 percent of the soluble salts from a 2-foot-deep soil profile would require 2 feet of water.

Less than half as much water would be required by intermittent applications of ponded water or sprinkling. Because it adsorbs onto soil particles, excess boron requires more leaching water than other salts, about twice as much.

To reclaim sodic soils you must replace the exchangeable sodium with calcium, and then leach. If a native soil does not contain sufficient soluble calcium, you can add it in the form of a soluble salt. You can make soil lime soluble by adding acid or acid-forming materials. The most common additive is gypsum (calcium sulfate), which you mix into the soil or dissolve in the irrigation water. Acid and acid-forming additives include sulfur, sulfuric acid, iron sulfate, and aluminum sulfate, and are effective only where residual lime is present.

Managing Water for Salt Control

Crop water requirements and irrigation water quality are the main parameters to consider when planning effective irrigation management for salt control. Correct irrigation will restore any soil water deficit while avoiding a wasteful and potentially harmful excess. A small excess, the leaching requirement, may be applied deliberately to control soil salinity by leaching the surface 2 feet of soil.

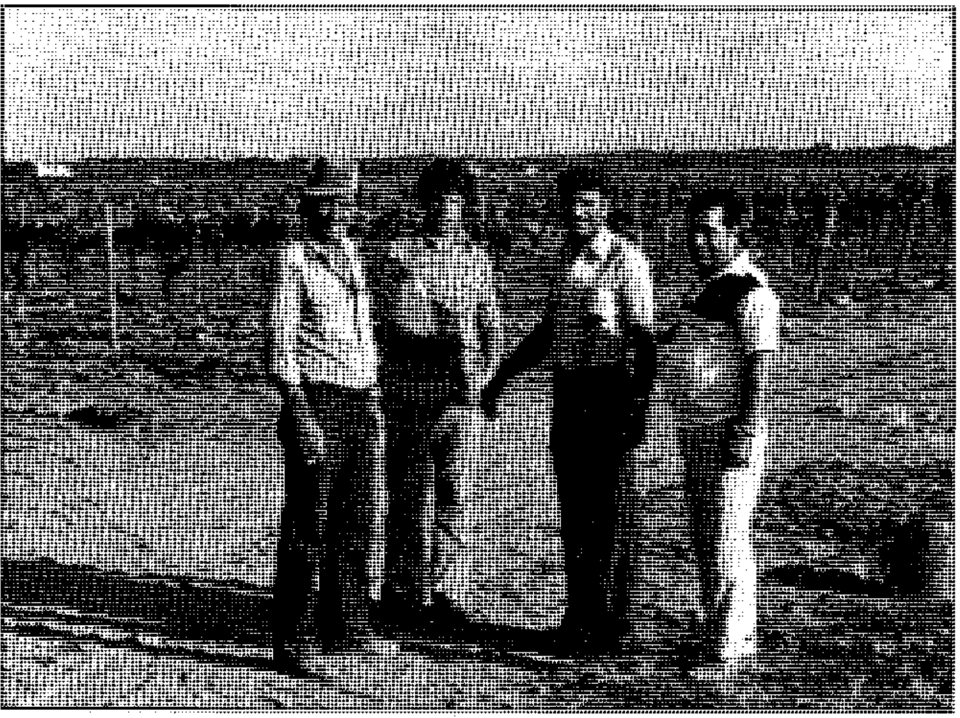
You control soil salinity by leaching to remove the soluble salts left by irrigation water after evapotranspiration. Because soluble salts are transported by water, salinity control depends on the quality of the irrigation water and on the amount and direction of the water flow. Plant water uptake and surface evaporation may cause an upward flow of water, particularly when the water table is within 3 feet of the soil surface. When more water is applied than is used during a crop season, the net water movement is downward, and salts leach from the root zone. The amount of extra water that leaching requires depends on the crop salt tolerance and the irrigation water salinity.

Several studies indicate that the yield in a saline soil correlates with the average salinity in the root zone. Assuming the average salinity depends predictably on the leaching fraction (the fraction of applied water that is not used by the crop and passes through the root zone), you can estimate the leaching requirement for a crop by referring to published salt tolerance tables.

Almost no leaching is required with most of the surface irrigation waters in central and northern California (EC of 0.05 to 0.5 mmhos/cm). Waters from the Colorado River (1.3 mmhos/cm, or 900 ppm), however, require leaching for moderately sensitive and sensitive crops. For example, the leaching requirement for lettuce in the Imperial Valley is about 20 percent. Salt-tolerant crops (e.g., cotton, barley, wheat, and alfalfa) irrigated with Colorado River water have a leaching requirement of 2 to 10 percent.

Growers avoid salt buildup in soils by leaching. But by applying additional water the grower aggravates another problem—drainage. The problem is reduced if you use only the minimum of water for leaching. If no perched water table develops and the salts and drainage water move freely below the root zone, the location has neither a salt nor a drainage problem, but salts and water percolating down from a grower's land may contribute to the drainage problem of a downslope neighbor. They may also degrade the deep water table quality on which a whole area or region may depend. Almost always, salinity and drainage problems are caused jointly by many water users and require regional or districtwide approaches to control.

7



Cooperation and communication on the part of the irrigator, supervisor, grower, and consultant are necessary for a successful irrigation management program.

Implementing an Irrigation Strategy on the Farm

Developing irrigation schedules based on weather, soil, and crop factors is only the first phase of a successful agricultural water management program. Scheduling must also take into account water supply conditions, irrigation system capacity, and irrigator convenience. Successful implementation also requires adjusting schedules to facilitate farm cultural practices such as harvest, cultivation, and pest control.

The basic purpose of irrigation scheduling is to develop a water management strategy that will result in optimum plant performance: crop growth, yield, and quality. At the same time, scheduling helps to minimize the nonbeneficial loss of applied water. Whether you base scheduling on atmospheric, plant, or soil measurements, the same two questions remain: when to apply water (frequency) and how much to apply (duration).

Frequency-Duration Concept

With a well-designed irrigation system and on-demand water, you determine irrigation frequency based on the need to prevent depletion of the soil water reservoir to a level that results in plant-injurious water stress. Climatic conditions affecting evaporation, soil water holding capacities, the distribution of roots, and crop sensitivity to water stress are the main factors that determine irrigation frequency. Since labor is a component of irrigation costs, sound economics requires minimizing the number of irrigations in a season. In practice, one or two more irrigations than the minimum requirement will lessen the impact of any scheduling errors on plant response and act as a safety factor. Once you establish the irrigation frequency, you base the amount of water to be applied on the crop's water requirement and the irrigation system's application efficiency.

Predicting irrigation dates based solely on weather, soil, and crop factors does not yield practical irrigation schedules in most cases. Irrigation frequency and amount usually depend on other factors that are unique to each farm; limited irrigation system capacity, low infiltration rates, fixed delivery dates and amounts of water, multiple harvests, and irrigator convenience can all require flexibility in the irrigation schedule. Taking these factors into account, either the frequency or duration of irrigation must generally be fixed for much of the irrigation season.

In such cases, schedulers must work with only one variable. For example, irrigation methods requiring that equipment be moved by hand (gated pipe, siphons, and sprinklers) usually have set times of approximately 12 or 24 hours for irrigator convenience, so the duration of water application is fixed. In another example, the set time is fixed by "off-peak" electric power rates that restrict pump operation to a set maximum number of hours per day. In both cases, the scheduler has little or no control over the amount of water applied during each irrigation, although the farmer can choose to reduce the quantity pumped. The only alternative possible without altering the system capacity is to manage the frequency of irrigation. A fixed set time is also used when a soil has a poor infiltration rate and when there is a specific time requirement to maximize irrigation efficiency.

Similarly, irrigation frequency can be dictated by cultural practices, such as crop harvest periods, irrigation district water deliveries, or simple grower convenience. With alfalfa, for example, water application must conform to cutting cycles that occur periodically throughout the season. This usually means one to three irrigations will be made between cuttings, so the irrigation frequency is fixed. This limits irrigation scheduling decisions to adjusting the set time (amount of water applied), values that will change during the year depending on the prevailing evaporative demand.

System Capacity Limitations

Another factor that limits the utility of irrigation scheduling based solely on atmospheric, soil, and plant factors is irrigation system capacity. Under most conditions, a farm's system is designed to apply water at rates necessary to satisfy crop needs during peak demand periods. However, where the system capacity fails to meet the irrigation requirement when weather conditions are most severe, the grower must modify the water management program, whenever possible, to minimize the potential water stress damage to the crop. For example, where the crop has an extensive root zone and the soil water holding capacity is high, a common approach is to apply the amount of water necessary to fill as much of the profile as possible just before the peak evaporative demand. While this is the normal irrigation scheduling practice with conventional irrigation methods, it represents a fundamental change of management for high-frequency irrigation (drip, microsprinklers, traveling sprinklers). Under high-frequency irrigation, additional filling of the soil water reservoir provides a safety factor against yield-reducing water stress because, although the rate of evapotranspiration during peak demand would exceed the rate at which water could be applied, the contribution of stored soil water to the crop water needs should lessen the magnitude of plant water stress.

Flexibility

The complexity of modern production agriculture requires that irrigation programs serve purposes other than the strict satisfaction of crop water requirements. As such, irrigation schedules must facilitate such farm cultural practices as planting, harvest, and cultivation, and help overcome problems including slow water penetration and poor seed germination. Modifying basic irrigation programs to accommodate these additional management objectives depends on the knowledge and skill of the irrigation scheduler as well as on water supply and other factors.

Verification

Irrigation decisions based on the water budget method involve estimating atmospheric, soil, and plant parameters. Since these factors are difficult to assess accurately, field verification of soil and plant conditions must be a component of an on-farm irrigation scheduling program. Besides independently verifying that the correct irrigation decisions have been made, field visits foster communication between the grower, the irrigator, and the scheduler. Irrigation scheduling has proven most successful when on-site monitoring is incorporated into the program. Many growers have found that intensive soil water monitoring is inconvenient and costly, and that limited soil water measurements taken for verification purposes are more useful. If soil monitoring indicates an inaccuracy in predicted soil water storage immediately before an irrigation, the irrigation schedule can be adjusted accordingly.

An accurate measure of applied water is critical to good water management. This can be gained either directly or indirectly using meters, flumes, irrigation district delivery information, or pumping plant performance data.

Making Irrigation Decisions

Implementing an irrigation schedule based on atmospheric, soil, and plant measurements constitutes a fundamental change in the approach most growers take toward water management. In the past, water has often been applied according to arbitrary schedules that relied heavily on previous practices and personal judgment. Today, the efficient use of water to maintain high crop productivity requires more precise water use. Irrigation scheduling is an important aspect of farming strategy, along with decisions related to fertilizer, cultivation, pest and disease control, cropping patterns, marketing, and capital expenditures. In fact, many of these other practices are significantly affected by irrigation management. Effective irrigation judgment depends on (1) accurate data and (2) the ability to successfully interpret the data. Scientific irrigation scheduling provides the information necessary for the best possible water management decisions.

Consultants

Irrigation professionals, whether in-house or hired consultants, present a viable option for the grower interested in improved water management. Growers commonly hire consultants to provide information or make decisions regarding cultural practices where the grower lacks knowledge or time, or where the grower recognizes the disastrous consequences that could result from a poor decision. Because of its complexity, few people have a good working knowledge of the soil-water-plant relationship, so the potential damage that "mild" to "moderate" water stress can bring to crop productivity is generally unrecognized. Moreover, the visible indicators of these water stress levels, which vary widely among crops, may not appear until after some crop damage or yield loss has occurred. In addition, the housekeeping aspects of irrigation scheduling can be time consuming, so personnel specialized in the discipline may be desirable.

The acceptance and continued use of scientific irrigation scheduling, whether conducted by the grower or irrigation professionals, depends first on the perception and then on the realization of economic advantages. While the merits of the different approaches to irrigation scheduling are subject to debate, the best method from the grower's point of view is clear: the one that is most profitable.

Water Cost and Availability

Water prices can have a great effect on irrigation management strategies. Where water is inexpensive and plentiful, there is little apparent incentive for efficient irrigation. However, research shows that optimal crop growth is usually impossible with overirrigation or underirrigation. While the idea of irrigation scheduling may suggest simply keeping the plant adequately supplied with water, the practice can also prevent problems associated with excessive irrigation, including increased volumes of drainage water and unnecessary leaching of nutrients.

Crops have a wide range of sensitivities to waterlogging, which can be aggravated by soil and weather conditions. Accurate irrigation scheduling can minimize the root respiration and disease problems associated with high, sustained soil water levels. Scientific water management can promote high crop productivity, conserve water, and minimize drainage requirements.

Appendix A
Crop Coefficients

The following tables list tree and vine crop coefficients (A.1), agronomic crop, vegetable crop, and miscellaneous coefficients (A.2), and coefficients for miscellaneous surfaces (A.3) for date B (Kc1), date C (Kc2), and date E (Kc3), with approximate growth dates. Growth dates correspond to the following: (A) planting (for field and row crops), (B) 10 percent ground shading (for field and row crops) or leaf out (for perennials), (C) peak canopy development, (D) leaf aging effects on transpiration, and (E) end of season.

Table A.1. Tree and vine crop coefficients

	Crop coefficient*			Growth date			
Region and crop	**Kc1**	**Kc2**	**Kc3**	**B**	**C**	**E**	**Code†**
Imperial Valley							
Citrus orchard	0.56	0.56	0.56	—	—	—	399
Guayule	0.55	0.72	0.50	01/01	07/24	12/31	166
Sacramento Valley							
Deciduous orchard‡	0.50	0.90	0.50	02/15	06/01	11/10	175
Deciduous orchard§	0.55	1.00	0.55	02/15	06/01	11/10	175
	0.55	1.00	0.55	04/15	07/07	11/10	190
Grape	0.27	0.82	0.34	03/15	06/15	10/22	170
Kiwifruit	0.31	1.05	1.05	04/15	06/01	10/31	199
San Joaquin Valley							
Citrus	0.65	0.65	0.65	—	—	—	399
Deciduous orchard‡	0.50	0.90	0.50	02/15	06/01	11/10	175
Deciduous orchard§	0.55	1.00	0.55	02/15	06/01	11/10	175
	0.55	1.00	0.55	04/15	07/07	11/10	190
Grape	0.27	0.82	0.34	03/15	06/15	10/22	170
Olive	0.80	0.80	0.80	—	—	—	399
Pistachio	0.43	1.19	0.25	04/23	06/15	11/15	165
Walnut	0.45	1.14	0.15	03/15	07/07	11/15	170

*Crop coefficients were estimated from Fereres et al. (1981), Doorenbos and Pruitt (1977), Letey and Vaux (1984), State of California Department of Water Resources (1986), Goldhamer et al. (1985), Goldhamer (1989), Pruitt and Snyder (1984), and Buchner, Shaw, and Schulbach (1985).

†The first digit of the code identifies the crop type (1 = deciduous; 3 = constant year-round Kc). For deciduous crops, the last two digits are the percentage of the season from leafout (date B) to the start of Kc decline caused by aging (date D). When the crop type is equal to 3, the Kc Values do not decline, and the last two digits of the code are always 99.

‡Includes peaches, apricots, pears, plums, almonds, and pecans without a cover crop. Add 0.35 to Kc1, 0.30 to Kc2, and 0.25 to Kc3 for orchards with a cover crop.

§Includes apples and cherries without a cover crop. Add 0.35 to Kc1, 0.30 to Kc2, and 0.25 to Kc3 for orchards with a cover crop.

Table A.2. Agronomic, vegetable, and miscellaneous crop coefficients

	Crop coefficient*			Growth dates				
Region and crop	**Kc1**	**Kc2**	**Kc3**	**A**	**B**	**C**	**E**	**Code†**
Imperial Valley								
Alfalfa	0.40	1.20	1.20	11/15	11/19	12/09	01/15	274
	0.40	1.20	1.20	01/15	01/20	02/17	03/15	276
	0.40	1.20	1.20	03/15	03/16	04/04	04/14	281
	0.40	1.20	1.20	04/15	04/16	05/20	05/15	277
	0.40	1.20	1.20	05/15	05/16	06/01	06/15	277
	0.40	1.20	1.20	06/15	06/16	07/01	07/15	273
	0.40	1.20	1.20	07/15	07/16	07/31	08/15	277
	0.40	1.20	1.20	08/15	08/16	08/31	09/15	274
	0.40	1.20	1.20	09/15	09/16	10/09	11/15	274
Asparagus	0.30	0.95	0.15	01/01	03/30	05/01	12/31	286
Barley	0.73	1.11	0.01	11/30	12/16	03/06	05/31	273
Barley	0.23	1.04	0.01	11/30	12/16	02/02	05/31	261
Cantaloupe	0.42	0.96	0.90	01/31	03/01	04/15	05/31	291
	0.15	0.97	0.01	07/31	08/08	08/21	11/30	272
Carrots	0.43	1.06	0.75	09/30	10/27	12/21	04/30	269
Cotton	0.40	0.86	0.40	03/31	04/30	08/28	10/31	282
Lettuce	0.17	1.02	0.10	08/31	09/20	10/31	12/31	271
	0.30	0.83	0.30	10/31	11/20	01/15	03/31	264
Onion	0.75	1.03	0.20	12/31	02/15	04/01	05/31	265
Sorghum forage—cut 1	0.14	1.01	0.15	03/31	04/25	05/21	08/31	256
Sorghum forage—cut 2	0.57	1.39	0.30	07/30	08/11	09/07	11/40	243
Sorghum grain	0.10	1.15	0.01	02/28	03/15	04/02	07/31	233
Sorghum	0.09	1.19	0.01	05/31	06/12	07/06	10/31	237
Squash	0.19	0.85	0.80	06/31	09/15	10/27	12/31	296
	0.45	1.30	0.05	12/31	01/21	02/21	04/30	246
Sugarbeet	0.18	1.14	0.70	06/30	07/01	09/27	04/30	262
	0.28	1.10	0.75	09/30	10/17	12/06	06/30	283
Tomato, canning	0.41	1.20	0.48	01/31	03/07	04/18	06/30	279
Tomato, market	0.45	1.12	0.10	12/31	02/15	04/15	05/31	270
Wheat	0.38	1.07	0.15	12/31	01/15	02/13	05/31	279
Northern mountain valleys								
Alfalfa	0.40	1.20	1.20	04/01	04/07	04/30	05/25	280
	0.40	1.20	1.20	05/25	05/26	06/16	07/05	276
	0.40	1.20	1.20	07/05	07/06	07/26	08/15	276
	0.40	1.20	1.20	08/15	08/16	08/28	09/10	273
	0.40	1.20	1.20	04/01	04/07	05/01	05/31	273
	0.40	1.20	1.20	05/31	06/01	06/26	07/15	276
	0.40	1.20	1.20	07/15	07/16	08/06	08/31	274
Barley	0.27	1.15	0.01	04/30	05/01	06/14	08/31	269
Potato	0.08	1.20	0.70	04/30	05/01	08/20	09/30	282
Sacramento Valley								
Alfalfa	0.40	1.20	1.20	02/12	02/23	03/03	03/31	269
	0.40	1.20	1.20	04/01	04/03	04/18	05/15	279
	0.40	1.20	1.20	05/06	05/07	05/20	06/04	283
	0.40	1.20	1.20	06/05	06/06	06/18	07/02	270
	0.40	1.20	1.20	07/03	07/05	07/16	07/31	275
	0.40	1.20	1.20	08/01	08/02	06/16	08/31	273
	0.40	1.20	1.20	09/01	09/02	09/16	10/14	279
Bean, pinto	0.15	1.09	0.22	04/30	05/23	06/06	08/18	275
	0.08	1.08	0.30	06/03	06/11	07/14	09/22	276

*Crop coefficients were estimated from Fereres et al. (1981), Doorenbos and Pruitt (1977), Letey and Vaux (1984), State of California DWR (1986), Phene et al. (1985), and Pruitt and Snyder (1984).

†The first digit of the code identifies the crop type (2=annual crop). The last two digits show the percentage of the growing season from date A to date D. Date D is the date when the Kc values begin to decline because of crop aging.

Continued

Table A.2.—*Continued*

Region and crop	Crop coefficient*			Growth dates				Code†
	Kc1	Kc2	Kc3	A	B	C	E	
Sacramento Valley *(cont.)*								
Corn	0.20	1.15	0.50	04/02	04/25	06/18	08/25	278
	0.20	1.15	0.48	04/30	05/24	07/07	09/08	273
	0.18	1.15	0.55	06/17	07/04	08/05	10/20	274
Milo	0.14	1.10	0.73	05/13	06/15	07/14	09/29	266
	0.13	1.12	0.43	06/17	07/13	08/05	10/27	262
	0.14	1.13	0.62	07/01	07/26	08/21	10/31	268
Rice	0.95	1.24	1.00	05/13	06/12	07/17	10/06	280
Small grains	0.20	1.23	0.09	10/14	11/06	01/10	06/02	273
	0.31	1.23	0.04	11/15	12/16	02/18	07/14	270
	0.25	1.20	0.15	12/16	01/12	03/30	08/04	271
Sugarbeet	0.25	1.10	1.00	02/28	03/19	05/15	08/25	292
	0.20	1.12	0.95	03/01	03/18	05/24	11/01	286
	0.11	1.14	0.83	04/02	04/15	06/29	12/31	287
Tomato	0.26	1.11	0.73	02/26	04/22	06/11	08/11	282
	0.25	1.10	0.63	04/02	05/15	06/24	09/08	277
	0.25	1.14	0.90	04/30	05/25	07/07	09/22	272
	0.20	1.14	0.80	06/03	06/18	07/31	09/29	275
San Joaquin Valley								
Alfalfa	0.40	1.20	1.20	02/12	02/22	03/07	03/21	279
	0.40	1.20	1.20	04/01	04/03	04/18	04/30	285
	0.40	1.20	1.20	05/06	05/07	05/20	06/04	283
	0.40	1.20	1.20	06/05	06/06	06/18	07/02	270
	0.40	1.20	1.20	07/03	07/04	07/15	07/31	275
	0.40	1.20	1.20	08/01	08/02	08/14	08/31	273
Bean	0.14	1.15	0.30	04/01	04/30	05/25	07/31	274
	0.14	1.12	0.35	05/01	05/18	06/08	08/15	268
	0.13	1.07	0.20	06/16	07/01	07/26	09/30	274
Corn	0.19	1.17	0.40	03/16	04/12	05/27	08/15	272
	0.19	1.17	0.40	04/01	04/25	06/14	08/31	268
	0.18	1.10	0.45	04/16	05/07	06/28	09/15	274
	0.19	1.06	0.55	05/16	06/07	07/16	09/30	277
	0.26	1.07	0.15	06/16	06/21	07/25	10/15	269
Cotton	0.12	1.20	0.30	04/01	05/03	07/15	09/30	279
	0.16	1.18	0.40	04/16	05/18	07/06	10/15	269
	0.19	1.15	0.30	05/01	05/24	07/07	10/31	268
Melon	0.14	1.10	0.01	02/15	03/31	04/30	06/30	279
	0.18	1.11	0.08	03/16	04/17	05/23	07/31	275
	0.18	1.10	0.01	04/16	05/09	06/22	08/15	278
Milo	0.16	1.05	0.45	05/01	06/04	07/04	09/30	265
	0.14	1.08	0.30	06/16	07/12	08/10	10/31	263
	0.13	1.06	0.30	07/01	07/29	08/22	11/15	268
Onion	0.30	1.14	0.63	03/01	04/11	05/24	08/31	263
	0.18	1.15	0.78	09/16	10/06	01/01	05/31	272
	0.27	1.11	0.55	11/16	12/12	02/01	07/31	284
Potato	0.51	1.15	0.75	12/01	02/24	03/26	05/15	287
	0.43	1.18	0.25	02/01	02/28	04/12	06/15	275
	0.55	1.21	0.30	03/01	03/21	04/26	06/30	269
Rice	0.95	1.25	0.95	04/01	04/26	05/28	08/31	259

*Crop coefficients were estimated from Fereres et al. (1981), Doorenbos and Pruitt (1977), Letey and Vaux (1984), State of California DWR (1986), Phene et al. (1985), and Pruitt and Snyder (1984).

†The first digit of the code identifies the crop type (2=annual crop). The last two digits show the percentage of the growing season from date A to date D. Date D is the date when the Kc values begin to decline because of crop aging.

Continued

Table A.2.—*Continued*

	Crop coefficient*			Growth dates				
Region and crop	**Kc1**	**Kc2**	**Kc3**	**A**	**B**	**C**	**E**	**Code†**
San Joaquin Valley *(cont.)*								
Small grains	0.30	1.17	0.20	01/01	02/01	03/22	06/30	272
	0.15	1.11	0.95	03/16	04/10	06/07	09/15	263
	0.25	1.20	0.40	11/01	12/14	01/25	05/15	274
	0.22	1.17	0.38	12/01	12/24	03/02	05/31	275
	0.23	1.16	0.40	12/16	12/23	03/01	05/31	272
	0.23	1.18	0.18	12/16	01/20	03/26	06/30	274
Sugarbeet	0.24	1.13	0.90	02/01	03/27	05/13	08/31	270
	0.20	1.07	1.00	05/01	05/20	07/13	12/15	289
	0.23	1.10	0.95	06/16	07/06	08/13	03/15	284
Tomato	0.25	1.16	0.70	03/01	04/28	06/10	08/15	272
	0.24	1.12	0.70	04/01	05/08	06/28	08/31	271
	0.25	1.12	0.68	05/01	05/22	07/18	09/15	269
Tomato	0.06	1.00	0.80	03/23	04/23	05/30	08/02	275

*Crop coefficients were estimated from Fereres et al. (1981), Doorenbos and Pruitt (1977), Letey and Vaux (1984), State of California DWR (1986), Phene et al. (1985), and Pruitt and Snyder (1984).

†The first digit of the code identifies the crop type (2=annual crop). The last two digits show the percentage of the growing season from date A to date D. Date D is the date when the Kc values begin to decline because of crop aging.

Table A.3. Coefficients for miscellaneous surfaces

	Crop coefficient*			Growth dates			
Region and condition or crop	**Kc1**	**Kc2**	**Kc3**	**B**	**C**	**E**	**Code†**
Statewide							
Open water surfaces	1.10	1.10	1.10	01/01	05/01	12/31	375
Wet light soil	1.05	1.05	1.05	01/01	05/01	12/31	375
Wet dark soil	1.10	1.10	1.10	01/01	05/01	12/31	375
Grazed pasture	0.90	0.90	0.90	01/01	05/01	12/31	375
Grass and clover	1.05	1.05	1.05	01/01	05/01	12/31	375
Statewide							
Evergreen shrubbery	1.15	1.15	1.15	01/01	05/01	12/31	375
Evergreen trees	1.20	1.20	1.20	01/01	05/01	12/31	375

*Crop coefficients are estimated from Doorenbos and Pruitt (1977), and Pruitt and Snyder (1984).

†The first digit of the code identifies the crop type (3 = constant year-round Kc). The last two digits are the percentage of the growing season from beginning to date D. When the crop type is equal to 3, the percentage to date D is set to 75 to allow for more flexibility when using the CIMIS irrigation scheduling programs.

Appendix B
Reference Crop Evapotranspiration

Appendix B. Historical average monthly reference crop evapotranspiration (ETo) in California, by county and city in inches per month

County and city	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	ETo total inches per month											
ALAMEDA												
Livermore	1.22	1.54	2.93	4.37	5.86	6.61	7.44	6.35	5.31	3.17	1.54	0.85
Oakland	1.46	1.54	2.81	3.98	5.13	5.31	5.98	5.49	4.84	3.05	1.42	0.85
ALPINE												
Markleeville	0.73	0.88	1.95	3.54	5.00	6.14	7.32	6.35	4.37	2.56	1.18	0.49
AMADOR												
Jackson	1.16	1.54	2.81	4.37	5.98	7.20	7.93	7.20	5.31	3.17	1.42	0.85
BUTTE												
Chico	1.22	1.76	2.93	4.72	6.10	7.38	8.54	7.32	5.43	3.66	1.65	0.98
Gridley	1.22	1.76	2.99	4.72	6.10	7.74	8.54	7.08	5.43	3.66	1.65	0.98
Oroville	1.22	1.65	2.81	4.72	6.10	7.56	8.54	7.32	5.31	3.66	1.65	0.98
CALAVERAS												
San Andreas	1.16	1.54	2.81	4.37	5.98	7.32	7.93	7.02	5.31	3.17	1.42	0.73
COLUSA												
Colusa	1.10	1.65	2.81	4.84	6.59	7.44	8.18	6.96	5.67	3.54	1.65	0.98
Williams	1.22	1.65	2.93	4.49	6.10	7.20	8.54	7.32	5.31	3.42	1.59	1.04
CONTRA COSTA												
Brentwood	0.98	1.54	2.93	4.49	6.10	7.09	7.93	6.71	5.20	3.17	1.42	0.73
Concord	1.10	1.43	2.43	4.02	5.49	5.91	6.96	5.98	4.84	3.17	1.30	0.73
Martinez	1.22	1.43	2.43	3.90	5.25	5.55	6.71	5.61	4.72	3.05	1.18	0.73
Pittsburg	0.98	1.54	2.81	4.13	5.61	6.38	7.44	6.35	4.96	3.17	1.30	0.73
DEL NORTE												
Crescent City	0.49	0.88	1.95	2.95	3.66	3.54	4.27	3.66	2.95	1.95	0.94	0.49
EL DORADO												
Camino	0.98	1.66	2.48	3.90	5.98	7.20	7.75	6.82	5.10	3.10	1.50	0.93
FRESNO												
Clovis	0.98	1.54	3.17	4.84	6.35	7.74	8.54	7.32	5.31	3.42	1.42	0.73
Coalinga	1.22	1.65	3.11	4.61	6.22	7.20	8.54	7.32	5.31	3.42	1.59	0.73
Five Points	0.92	1.65	3.30	4.96	6.59	7.68	8.54	7.32	5.43	3.42	1.48	0.85
Fresno	0.65	1.65	3.30	4.84	6.71	7.80	8.42	7.08	5.20	3.17	1.42	0.61
Friant	1.22	1.54	3.05	4.72	6.35	7.68	8.54	7.32	5.31	3.42	1.42	0.73
Kerman	0.85	1.49	3.23	4.84	6.59	7.74	8.42	7.20	5.31	3.42	1.42	0.73
Kingsburg	0.98	1.54	3.36	4.84	6.59	7.74	8.42	7.20	5.31	3.42	1.42	0.73
Reedley	1.10	1.54	3.17	4.72	6.35	7.68	8.54	7.32	5.31	3.42	1.42	0.73

Continued

Appendix B.—*Continued*

County and city	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	ETo total inches per month											
GLENN												
Orland	1.22	1.65	3.05	4.84	6.71	7.44	8.79	7.32	5.79	3.78	1.65	1.10
Willows	1.22	1.71	2.93	4.72	6.10	7.20	8.54	7.32	5.31	3.60	1.65	1.04
HUMBOLDT												
Eureka	0.49	1.10	1.95	2.95	3.66	3.66	3.66	3.66	2.95	1.95	0.94	0.49
Ferndale	0.49	1.10	1.95	2.95	3.66	3.66	3.66	3.66	2.95	1.95	0.94	0.49
Garberville	0.61	1.18	2.20	3.07	4.52	5.02	5.49	4.88	3.78	2.44	1.00	0.67
Hoopa	0.49	1.10	2.07	2.95	4.39	5.43	6.10	5.13	3.84	2.44	0.94	0.67
IMPERIAL												
Brawley	2.81	3.75	5.86	8.03	10.37	11.46	11.72	10.01	8.39	6.22	3.54	2.07
Calipatria	2.87	3.86	6.10	8.27	10.50	11.81	11.96	10.37	8.62	6.47	3.78	2.26
El Centro	2.69	3.53	5.61	7.91	10.13	11.10	11.59	9.52	8.27	6.10	3.31	1.95
Holtville	2.81	3.75	5.86	7.91	10.37	11.57	11.96	10.01	8.62	6.22	3.54	2.07
Yuma	3.05	4.08	6.59	8.74	10.98	12.40	12.69	10.98	8.86	6.59	3.96	2.56
INYO												
Bishop	1.71	2.65	4.76	6.73	8.18	10.87	9.76	9.64	7.44	4.76	2.48	1.59
Death Valley	2.20	3.31	5.37	7.68	9.76	11.10	11.35	10.13	8.27	5.37	2.89	1.71
Independence	1.71	2.65	3.42	6.61	8.54	9.45	9.76	8.54	7.09	3.91	2.01	1.46
Lower Haiwee Res.	1.83	2.65	4.39	7.09	8.54	9.45	9.76	8.54	7.09	4.15	2.60	1.46
KERN												
Arvin	1.16	1.76	3.48	4.72	6.59	7.44	8.06	7.32	5.31	3.42	1.65	0.98
Bakersfield	1.04	1.76	3.48	4.72	6.59	7.68	8.54	7.32	5.31	3.54	1.59	0.85
Buttonwillow	0.98	1.76	3.17	4.72	6.59	7.68	8.54	7.32	5.43	3.42	1.54	0.85
China Lake	2.07	3.20	5.25	7.68	9.15	10.04	10.98	9.76	7.32	4.88	2.72	1.71
Delano	0.92	1.76	3.42	4.72	6.59	7.68	8.54	7.32	5.43	3.42	1.42	0.73
Grapevine	1.34	1.76	3.05	4.37	5.61	6.79	7.57	6.83	5.91	3.36	1.89	0.98
Inyokern	1.95	3.09	4.88	7.32	8.54	9.69	10.98	9.40	7.09	5.13	2.60	1.71
Isabella Dam	1.16	1.43	2.75	4.37	5.80	7.32	7.93	6.96	4.96	3.23	1.65	0.85
Lost Hills	0.61	1.10	2.56	4.37	6.96	7.68	8.54	7.08	4.96	3.91	0.83	0.37
Shafter	0.98	1.65	3.42	4.96	6.59	7.68	8.30	7.32	5.43	3.42	1.54	0.85
Taft	1.28	1.76	3.11	4.25	6.22	7.32	8.54	7.32	5.37	3.42	1.65	0.98
Tehachapi	1.40	1.76	3.17	4.96	6.10	7.68	7.93	7.32	5.91	3.42	2.07	1.22
KINGS												
Corcoran	0.85	1.54	3.30	5.20	7.20	7.91	8.42	7.32	5.79	3.42	1.42	0.73
Hanford	0.85	1.54	3.42	4.96	6.59	7.68	8.30	7.20	5.43	3.42	1.42	0.73
Kettleman City	0.98	1.76	3.42	5.31	7.20	7.91	8.42	7.44	5.91	3.66	1.65	0.98
Lemoore	0.85	1.54	3.42	4.96	6.59	7.68	8.30	7.32	5.43	3.42	1.42	0.73
LAKE												
Lakeport	1.10	1.32	2.56	3.54	5.13	6.02	7.32	6.10	4.72	2.93	1.24	0.85
Lower Lake	1.22	1.43	2.69	4.49	5.25	6.26	7.44	6.41	4.96	3.05	1.30	0.92
LASSEN												
Ravendale	0.61	1.05	2.32	4.13	5.61	6.73	7.93	7.32	4.72	2.81	1.18	0.49
Susanville	0.73	0.99	2.20	4.13	5.61	6.50	7.81	6.96	4.61	2.81	1.18	0.49
LOS ANGELES												
Burbank	2.07	2.76	3.66	4.72	5.13	6.02	6.59	6.71	5.43	4.03	2.60	1.95
Glendora	1.95	2.54	3.60	4.49	5.37	6.14	7.32	6.83	5.67	4.15	2.60	1.95
Gorman	1.59	2.15	3.42	4.61	5.49	7.38	7.69	7.08	5.91	3.60	2.36	1.10
Lancaster	2.14	2.98	4.64	5.91	8.54	9.69	10.98	9.76	7.32	4.64	2.78	1.71
Long Beach	2.20	2.54	3.42	3.78	4.76	4.96	5.25	4.88	4.49	3.42	2.36	1.95
Los Angeles	2.20	2.65	3.66	4.72	5.49	5.79	6.22	5.86	5.02	3.91	2.60	1.95
Palmdale	1.95	2.65	4.15	5.08	7.57	8.54	9.89	9.76	6.73	4.15	2.60	1.71
Pasadena	2.07	2.65	3.66	4.72	5.13	6.02	7.08	6.71	5.55	4.15	2.60	1.95
Pearblossom	1.71	2.43	3.66	4.72	7.32	7.68	9.89	7.93	6.38	4.03	2.60	1.59
Redondo Beach	2.20	2.43	3.30	3.78	4.52	4.72	5.37	4.76	4.37	2.81	2.36	1.95
San Fernando	1.95	2.65	3.54	4.61	5.49	5.91	7.32	6.71	5.31	3.91	2.60	1.95

Continued

Appendix B.—*Continued*

County and city	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	ETo total inches per month											
MADERA												
Chowchilla	0.98	1.43	3.17	4.72	6.59	7.80	8.54	7.32	5.31	3.42	1.42	0.67
Madera	0.92	1.43	3.17	4.84	6.59	7.80	8.54	7.32	5.31	3.42	1.42	0.73
Raymond	1.22	1.54	2.99	4.61	6.10	7.56	8.42	7.32	5.20	3.42	1.42	0.73
MARIN												
Novato	1.34	1.54	2.43	3.54	4.39	6.02	5.86	5.37	4.37	2.81	1.42	0.73
San Rafael	1.22	1.32	2.44	3.30	4.03	4.84	4.84	4.88	4.25	2.69	1.30	0.73
MARIPOSA												
Coulterville	1.10	1.54	2.81	4.37	5.86	7.32	8.06	6.96	5.31	3.36	1.42	0.73
Mariposa	1.10	1.54	2.81	4.43	5.86	7.38	8.24	7.08	5.02	3.42	1.42	0.73
Yosemite Village	0.73	0.99	2.32	3.66	5.13	6.50	7.08	6.10	4.43	2.87	1.06	0.55
MENDOCINO												
Fort Bragg	0.85	1.27	2.20	2.95	3.66	3.54	3.66	3.66	2.95	2.32	1.18	0.73
Hopland	1.10	1.32	2.56	3.43	5.00	5.91	6.47	5.74	4.49	2.81	1.30	0.73
Point Arena	0.98	1.32	2.32	2.95	3.66	3.90	3.66	3.66	2.95	2.32	1.18	0.73
Ukiah	0.98	1.32	2.56	3.31	5.00	5.79	6.71	5.86	4.49	2.81	1.30	0.73
MERCED												
Los Banos	0.98	1.54	3.17	4.72	6.10	7.38	8.18	7.02	5.31	3.42	1.42	0.73
Merced	0.98	1.54	3.17	4.72	6.59	7.91	8.54	7.20	5.31	3.42	1.42	0.73
MONO												
Bridgeport	0.73	0.88	2.20	3.84	5.49	6.61	7.44	6.71	4.72	2.69	1.18	0.49
MONTEREY												
Castroville	1.59	1.76	2.69	3.54	4.39	4.37	4.52	4.15	3.78	2.81	1.77	1.34
King City	1.71	1.98	3.42	4.37	4.37	5.61	6.14	6.71	6.47	5.20	2.24	1.34
Long Valley	1.53	1.87	3.17	4.13	5.80	6.50	7.32	6.71	5.31	3.60	1.95	1.22
Monterey	1.71	1.76	2.69	3.54	4.03	4.13	4.27	4.15	3.54	2.81	1.89	1.46
Salinas	1.59	1.87	2.72	3.76	4.76	4.72	5.00	4.52	4.02	2.93	1.89	1.34
Soledad	1.71	1.98	3.42	4.37	5.49	5.43	6.47	6.22	5.20	3.66	2.24	1.46
NAPA												
St. Helena	1.22	1.54	2.81	3.90	5.13	6.14	6.96	6.22	4.84	3.05	1.42	0.85
Yountville	1.34	1.65	2.81	3.90	5.13	6.02	7.08	6.10	4.84	3.05	1.54	0.85
NEVADA												
Grass Valley	1.10	1.54	2.56	4.02	5.74	7.09	7.93	7.08	5.31	3.23	1.48	0.92
Nevada City	1.10	1.54	2.56	3.90	5.80	6.85	7.93	6.98	5.31	3.17	1.42	0.85
Soda Springs	0.73	0.66	1.77	2.95	4.27	5.31	6.20	5.49	4.13	2.50	0.71	0.67
Truckee	0.73	0.66	1.71	3.19	4.39	5.43	6.35	5.74	4.13	2.44	0.83	0.61
ORANGE												
Laguna Beach	2.20	2.65	3.42	3.78	4.64	4.61	4.86	4.88	4.37	3.42	2.36	1.95
Santa Ana	2.20	2.65	3.66	4.49	4.64	5.43	6.22	6.10	4.72	3.66	2.48	1.95
PLACER												
Auburn	1.22	1.65	2.81	4.37	6.10	7.38	8.30	7.32	5.43	3.42	1.59	0.98
Blue Canyon	0.73	1.05	2.14	3.43	4.76	6.02	7.20	6.10	4.61	2.87	0.94	0.61
Colfax	1.10	1.54	2.56	4.02	5.80	7.09	7.93	7.02	5.31	3.17	1.42	0.92
Lincoln	1.22	1.65	2.81	4.72	6.10	7.44	8.42	7.32	5.43	3.66	1.89	1.22
Roseville	1.10	1.71	3.05	4.72	6.22	7.68	8.54	7.32	5.55	3.66	1.65	0.98
Tahoe City	0.73	0.66	1.71	2.95	4.27	5.43	6.10	5.61	4.13	2.44	0.83	0.61
PLUMAS												
Portola	0.73	0.86	1.95	3.54	4.88	5.91	7.32	5.86	4.25	2.69	0.94	0.49
Quincy	0.73	0.94	2.20	3.54	4.88	5.91	7.32	5.86	4.37	2.81	1.18	0.49

Continued

Appendix B.—*Continued*

County and city	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	ETo total inches per month											
RIVERSIDE												
Beaumont	1.95	2.31	3.42	4.37	6.10	7.09	7.57	7.93	6.02	3.91	2.60	1.71
Blythe	3.17	4.19	6.71	8.86	11.11	12.40	12.81	11.11	9.09	6.71	4.02	2.69
Coachella	2.93	4.39	6.22	8.39	10.50	11.93	12.33	10.13	8.86	6.22	3.78	2.44
Desert Center	2.93	4.08	6.35	8.50	10.98	12.05	12.20	11.11	8.98	6.35	3.90	2.56
Elsinore	2.07	2.76	3.91	4.43	5.86	7.09	7.63	7.02	5.79	3.91	2.60	1.95
Indio	2.93	3.97	6.22	8.27	10.50	11.93	12.33	10.01	8.86	6.35	3.78	2.44
Oasis	2.69	2.75	5.86	8.03	10.37	11.69	11.59	10.01	8.39	6.22	3.43	2.07
Palm Desert	1.95	3.53	4.88	7.68	8.54	10.63	9.76	9.15	8.39	6.10	2.72	1.77
Palm Springs	1.95	2.87	4.88	7.20	8.30	8.50	11.59	8.30	7.20	5.86	2.72	1.71
Riverside	2.07	2.87	4.03	4.13	6.10	7.09	7.93	7.57	6.14	4.15	2.60	1.95
SACRAMENTO												
Courtland	0.92	1.54	2.93	4.43	6.10	6.85	7.93	6.71	5.31	3.17	1.36	0.73
Sacramento	0.98	1.76	3.17	4.72	6.35	7.68	8.36	7.20	5.43	3.66	1.65	0.92
SAN BENITO												
Hollister	1.46	1.76	3.05	4.25	5.49	5.67	6.35	5.86	4.96	3.54	1.65	1.10
SAN BERNARDINO												
Baker	2.69	3.86	6.10	8.27	10.37	11.81	12.20	10.98	8.86	6.10	3.31	2.07
Barstow	2.56	3.64	5.74	7.91	10.13	11.57	11.96	10.37	8.62	5.74	3.31	2.07
Chino	2.07	2.87	3.91	4.49	5.74	6.50	7.32	7.08	5.91	4.15	2.60	1.95
Crestline	1.46	1.87	3.30	4.37	5.49	6.61	7.81	7.08	5.43	3.54	2.24	1.59
Lucerne Valley	2.20	2.87	5.13	6.50	9.15	10.98	11.35	9.89	7.44	5.00	2.95	1.83
Needles	3.17	4.19	6.59	8.86	10.98	12.40	12.81	10.98	8.86	6.59	4.02	2.69
San Bernardino	1.95	2.65	3.78	4.61	5.74	6.85	7.93	7.44	5.91	4.15	2.60	1.95
Twentynine Palms	2.56	3.64	5.86	7.91	10.13	11.22	11.23	10.25	8.62	5.86	3.43	2.20
Victorville	2.32	3.09	4.88	6.73	9.28	10.04	11.23	9.76	7.44	5.13	2.83	1.83
SAN DIEGO												
Chula Vista	2.20	2.65	3.42	3.78	4.88	4.72	5.49	4.88	4.49	3.42	2.36	1.95
Escondido	2.07	2.76	3.78	4.72	5.49	6.14	6.71	6.47	5.43	3.78	2.48	1.95
Fallbrook	2.07	2.65	3.78	4.72	5.49	6.14	6.84	6.47	5.43	3.78	2.48	1.95
Oceanside	2.20	2.65	3.42	3.78	4.88	4.72	4.88	5.13	4.13	3.30	2.36	1.95
Pine Valley	1.46	1.76	2.93	4.13	5.49	6.85	7.93	7.32	5.91	4.03	2.24	1.47
Ramona	2.07	2.54	3.91	4.72	5.49	6.50	7.32	6.96	5.55	3.91	2.60	1.71
San Diego	2.20	2.65	3.42	3.78	4.88	4.86	5.13	4.88	4.49	3.42	2.36	1.95
Santee	2.07	2.65	3.66	4.49	5.49	6.14	6.84	6.22	5.43	3.78	2.60	1.95
Warner Springs	1.59	2.20	3.66	4.72	5.74	7.56	8.30	7.69	6.26	4.03	2.48	1.47
SAN FRANCISCO												
San Francisco	1.46	1.32	2.44	2.95	3.66	4.61	4.88	4.78	4.13	2.81	1.30	0.73
SAN JOAQUIN												
Farmington	1.46	1.49	2.93	4.72	6.22	7.56	8.08	6.83	5.31	3.30	1.42	0.73
Lodi	0.85	1.54	2.93	5.08	6.47	6.97	7.69	7.69	5.20	3.05	1.30	0.73
Manteca	1.46	1.49	2.99	4.72	6.35	7.56	8.06	6.83	5.31	3.30	1.42	0.61
Stockton	0.79	1.54	2.93	4.72	6.22	7.44	8.06	6.83	5.31	3.23	1.42	0.61
Tracy	0.98	1.54	2.93	4.49	6.10	7.32	7.93	6.71	5.31	3.17	1.30	0.73
SAN LUIS OBISPO												
Arroyo Grande	1.95	2.20	3.17	3.78	4.27	4.72	4.27	4.64	3.78	3.17	2.36	1.71
Atascadero	1.22	1.54	2.81	3.90	4.52	6.02	6.71	6.22	4.96	3.17	1.65	0.98
Morro Bay	1.95	2.20	3.11	3.54	4.27	4.49	4.64	4.58	3.84	3.48	2.13	1.71
Paso Robles	1.59	1.98	3.17	4.25	5.49	6.26	7.32	6.71	5.08	3.66	2.13	1.40
San Luis Obispo	1.95	2.20	3.17	4.13	4.88	5.31	4.64	5.49	4.37	3.54	2.36	1.71
San Miguel	1.59	1.98	3.23	4.25	5.00	6.38	7.44	6.83	5.08	3.66	2.13	1.40
San Simeon	1.95	1.98	2.93	3.54	4.15	4.43	4.58	4.27	3.54	3.05	2.01	1.71
SAN MATEO												
Half Moon Bay	1.46	1.65	2.44	2.95	3.91	4.25	4.27	4.15	3.54	2.81	1.30	0.98
Redwood City	1.46	1.76	2.87	3.84	5.19	5.31	6.22	5.61	4.84	3.11	1.65	0.98

Continued

Appendix B.—*Continued*

County and city	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	ETo total inches per month											
SANTA BARBARA												
Carpenteria	1.95	2.43	3.17	3.90	4.76	5.20	5.49	5.74	4.49	3.42	2.36	1.95
Guadalupe	1.95	2.20	3.17	3.66	4.88	4.61	4.52	4.58	4.13	3.30	2.36	1.71
Lompoc	1.95	2.20	3.17	3.66	4.76	4.61	4.88	4.76	3.90	3.17	2.36	1.71
Los Alamos	1.83	1.98	3.17	4.13	4.88	5.31	5.74	5.49	4.43	3.66	2.36	1.59
Santa Barbara	1.95	2.54	3.17	3.78	4.64	5.08	5.49	4.49	3.42	2.36	1.83	1.83
Santa Maria	1.83	2.20	3.17	4.02	5.00	5.08	5.13	5.13	4.49	3.54	2.36	1.71
Solvang	1.95	1.98	3.30	4.25	5.00	5.55	6.10	5.61	4.37	3.66	2.24	1.59
SANTA CLARA												
Gilroy	1.34	1.76	3.05	4.13	5.25	5.55	6.10	5.49	4.72	3.42	1.65	1.10
Los Gatos	1.46	1.76	2.81	3.90	5.00	5.61	6.22	5.49	4.72	3.17	1.65	1.10
Palo Alto	1.46	1.76	2.81	3.84	5.19	5.31	6.22	5.61	4.96	3.17	1.65	0.98
San Jose	1.46	1.76	3.05	4.13	5.49	5.79	6.47	5.86	5.20	3.30	1.77	0.98
SANTA CRUZ												
Santa Cruz	1.46	1.76	2.56	3.54	4.27	4.37	4.76	4.39	3.78	2.81	1.65	1.22
Watsonville	1.46	1.76	2.69	3.66	4.64	4.49	4.88	4.15	4.02	2.93	1.77	1.22
SHASTA												
Burney	0.73	0.99	2.14	3.54	4.88	5.91	7.44	6.41	4.37	2.93	0.94	0.61
Fall River Mills	0.61	0.99	2.07	3.66	5.00	6.14	7.81	6.71	4.61	2.81	0.94	0.49
Glenburn	0.61	0.99	2.07	3.66	5.00	6.26	7.81	6.71	4.72	2.81	0.94	0.55
Redding	1.22	1.43	2.62	4.13	5.61	7.09	8.54	7.32	5.31	3.23	1.42	0.85
SIERRA												
Downieville	0.73	0.99	2.26	3.54	5.00	6.02	7.44	6.22	4.72	2.81	0.94	0.61
Sierraville	0.73	1.10	2.20	3.19	4.52	5.91	7.32	6.35	4.25	2.62	0.94	0.49
SISKIYOU												
Happy Camp	0.49	0.88	1.95	2.95	4.27	5.20	6.10	5.25	4.13	2.44	0.94	0.49
Mt. Shasta	0.49	0.88	1.95	2.95	4.52	5.31	6.71	5.74	4.02	2.20	0.71	0.49
Tulelake	0.49	0.88	2.07	3.43	5.25	5.91	7.93	6.71	4.37	2.69	0.94	0.49
Weed	0.49	0.88	1.95	2.48	4.52	5.31	6.71	5.49	3.66	1.95	0.94	0.49
Yreka	0.61	0.88	2.14	2.95	4.88	5.79	7.32	6.47	4.25	2.50	0.94	0.49
SOLANO												
Benecia	1.34	1.43	2.69	3.76	4.88	5.02	6.35	5.49	4.43	2.93	1.18	0.73
Fairfield	1.10	1.65	2.81	4.02	5.49	6.14	7.81	5.98	4.84	3.05	1.42	0.85
Rio Vista	0.85	1.65	2.81	4.37	5.86	6.73	7.93	6.47	5.08	3.17	1.30	0.73
SONOMA												
Cloverdale	1.10	1.43	2.56	3.43	5.00	5.91	6.22	5.61	4.49	2.81	1.42	0.73
Fort Ross	1.22	1.43	2.20	2.95	3.66	4.49	4.15	4.27	3.43	2.44	1.18	0.49
Healdsburg	1.22	1.54	2.43	3.54	5.00	5.91	6.10	5.61	4.49	2.81	1.42	0.73
Petaluma	1.22	1.54	2.81	3.66	4.64	5.61	4.64	5.74	4.49	2.93	1.42	0.85
Santa Rosa	1.22	1.65	2.81	3.66	5.00	6.02	6.10	5.86	4.49	2.93	1.54	0.73
STANISLAUS												
La Grange	1.22	1.54	3.11	4.72	6.22	7.68	8.54	7.32	5.31	3.42	1.42	0.73
Modesto	0.85	1.43	3.17	4.72	6.41	7.68	8.06	6.83	5.02	3.42	1.42	0.73
Newman	0.98	1.54	3.17	4.61	6.22	7.44	8.06	6.71	4.96	3.42	1.42	0.73
Oakdale	1.22	1.49	3.17	4.72	6.22	7.68	8.06	7.08	5.08	3.42	1.42	0.73
Turlock	0.85	1.49	3.17	4.72	6.47	7.68	8.18	7.02	5.08	3.42	1.42	0.73
SUTTER												
Yuba City	1.34	2.09	2.81	4.37	5.74	7.20	7.08	6.10	4.72	3.17	1.18	0.85
TEHAMA												
Corning	1.22	1.76	2.93	4.49	6.10	7.26	8.06	7.20	5.31	3.66	1.65	1.10
Red Bluff	1.22	1.76	2.93	4.37	5.86	7.44	8.54	7.32	5.43	3.54	1.65	1.04

Continued

Appendix B.—*Continued*

County and city	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	ETo total inches per month											
TRINITY												
Hayfork	0.49	1.10	2.32	3.54	4.88	5.91	6.96	5.98	4.49	2.75	0.94	0.73
Weaverville	0.61	1.10	2.20	3.31	4.88	5.91	7.32	5.98	4.37	2.69	0.94	0.73
TUOLUMNE												
Groveland	1.10	1.54	2.75	4.13	5.74	7.20	7.93	6.59	5.08	3.30	1.42	0.73
Sonora	1.10	1.54	2.75	4.13	5.80	7.20	7.93	6.71	5.08	3.23	1.42	0.73
TULARE												
Alpaugh	0.85	1.71	3.42	4.84	6.59	7.68	8.18	7.32	5.43	3.42	1.42	0.73
Badger	0.98	1.32	2.69	4.13	5.98	7.32	7.69	6.96	4.84	3.30	1.36	0.73
Dinuba	1.10	1.54	3.17	4.72	6.22	7.68	8.54	7.32	5.31	3.42	1.42	0.73
Porterville	1.22	1.76	3.42	4.72	6.59	7.68	8.54	7.32	5.31	3.42	1.42	0.73
Visalia	0.96	1.76	3.42	5.43	6.96	8.15	8.42	7.20	5.67	3.78	1.65	0.85
VENTURA												
Oxnard	2.20	2.54	3.17	3.66	4.39	4.61	5.37	4.76	4.02	3.30	2.36	1.95
Thousand Oaks	2.20	2.65	3.42	4.49	5.37	5.91	6.71	6.35	5.43	3.91	2.60	1.95
Ventura	2.20	2.65	3.17	3.76	4.64	4.72	5.49	4.88	4.13	3.42	2.48	1.95
YOLO												
Davis	0.98	1.87	3.30	4.96	6.35	7.56	8.18	7.08	5.43	4.03	1.77	0.98
Winters	1.71	1.65	2.93	4.37	5.80	7.09	7.93	6.71	5.31	3.30	1.59	0.98
Woodland	1.04	1.76	3.17	4.72	6.10	7.68	8.18	7.20	5.43	3.66	1.65	1.04
YUBA												
Brownsville	1.10	1.43	2.56	4.02	5.74	6.79	7.93	6.83	5.31	3.36	1.48	0.85

References and Bibliography

Ayers, R. S., and D. W. Westcot. 1985. Water quality for agriculture. Irrigation and drainage paper No. 29. Rome: Food and Agriculture Organization of the United Nations (FAO). 97 pp.

Baver, L. D., W. H. Gardner, and W. R. Gardner. 1972. Soil Physics. New York: J. Wiley and Sons. 488 pp.

Bernstein, Leon. 1975. Effects of salinity and sodicity on plant growth. Am. Rev. Phytopathol. 13:295–311.

Buchner, R. P., D. A. Shaw, and H. Schulbach. 1985. Kiwi irrigation scheduling. Soil and Water Newsletter No. 62. Davis: University of California Cooperative Extension. pp. 1–6.

Campbell, R. E., W. E. Larson, T. S. Ausheim, and P. L. Brown. 1960. Alfalfa response to irrigation frequencies in the presence of a water table. Agron. J. 52:437–41.

Chapman, H. D. 1966. Diagnostic Criteria For Plants and Soils. Berkeley: University of California, Division of Agriculture and Natural Resources. 793 pp.

Clark, R. B. 1983. Plant genotype differences in uptake, translocation, accumulation, and use of mineral elements required for plant growth. Plant Soil 72:175–96.

Clawson, K. L., and Blad, B. L. 1982. Infrared thermometry for scheduling irrigations in corn. Agron. J. 74:311–16.

Doorenbos, J., and W. O. Pruitt. 1977. Crop water requirements. 2d ed. Irrigation and Drainage Paper No. 24. Rome: Food and Agriculture Organization of the United Nations. 144 pp.

Fereres, E., P. M. Kitlas, W. O. Pruitt, and R. M. Hagan. 1980. Development of irrigation management programs. Report prepared for the California Department of Water Resources, Agreement No. B53142.

Fereres, E., and I. Puech. 1980. Irrigation Scheduling Guide. California Department of Water Resources, Office of Water Conservation, Sacramento.

Fereres, E. (ed). 1981. Drip irrigation management. Berkeley: University of California, Division of Agriculture and Natural Resources. Leaflet 21259. 39 pp.

Fereres, E., D. W. Henderson, W. O. Pruitt, W. F. Richardson, and R. S. Ayers. 1981. Basic irrigation scheduling. Berkeley: University of California, Division of Agriculture and Natural Resources. Leaflet 21199. 8 pp.

Fereres, E., D. A. Martinich, T. M. Aldrich, J. R. Castel, E. Holzapfel, and H. Schulbach. 1982. Drip irrigation saves money in young almond orchards. Calif. Agric. 36(9–10):12–13.

Frevert, D. K., R. W. Hill, and B. C. Braaten. 1983. Estimation of FAO evapotranspiration coefficients. New York: Irrigation and Drainage Division, American Society of Civil Engineers.

Gardner, W. R. 1983. Soil properties and efficient water use: An overview. *In* Limitations to Efficient Water Use in Crop Protection. H. M. Taylor, W. Jordan, and T. Sinclair, eds. Madison: American Society of Agronomy Publications. pp. 45–64.

Geiser, D. M., D. C. Clack, E. R. Allred, and K. W. Stange. 1982. Irrigation scheduling using crop canopy temperature difference. Trans. ASAE 25:689–96.

Goldhamer, D. A. 1989. Drought irrigation strategies for deciduous orchards. Oakland: University of California, Division of Agriculture and Natural Resources. Publication 21453. 20 pp.

Goldhamer, D. A., R. K. Kjelgren, L. Williams, and R. Beede. 1985. Water use requirements of pistachio trees and response to water stress. Proceedings of the National Conference on Advances in Evapotranspiration. American Society of Agricultural Engineers. St. Joseph, Missouri. pp. 216–23.

Grimes, D. W., R. L. Sharma, and D. W. Henderson. 1984. Developing the resource potential of a shallow water table. Davis: California Water Resources Center, University of California, Contribution No. 188. 39 pp.

Grimes, D. W., and H. Yamada. 1982. Relation of cotton growth and yield to minimum leaf water potential. Crop Sci. 22:134–39.

Gupta, U. C., Y. W. Jame, C. A. Campbell, A. J. Leyshon, and W. Nicholaichuk. 1985. Boron toxicity and deficiency: A review. Can. J. Soil Sci. 65:381–409.

Haise, H. R., and R. M. Hagan. 1967. Soil, plant, and evaporative measurements as criteria for scheduling irrigation. *In* Irrigation of Agricultural Lands. R. M. Hagan, et al., eds. Madison: American Society of Agronomy Publications. pp. 577–97.

Hanks, R. J. 1983. Yield and water-use relationships: An overview. *In* Limitations to Efficient Water Use in Crop Production. H. M. Taylor, W. Jordan, and T. Sinclair, eds. Madison: American Society of Agronomy Publications. pp. 393–411.

Hansen, V. E., O. W. Israelsen, and G. E. Stringham. 1980. Irrigation Principles and Practices. 4th ed. New York: John Wiley and Sons, Inc. 417 pp.

Hanson, B. R., and S. W. Kite. 1984. Irrigation scheduling under saline conditions. Calif. Agric. 38(1–2):12–14.

Hanson, J. B. 1984. The function of calcium in plant nutrition. *In* Advances in Plant Nutrition. Tinker and Lauchli, eds. New York: Praeger Publishers. pp. 1:149–208.

Hatfield, J. L. 1983. The utilization of thermal infrared radiation measurements from grain sorghum crops as a method of assessing their irrigation requirements. Irrig. Sci. 3:259–68.

Hoffman, G. J., and M. Th. van Genuchten. 1983. Soil properties and efficient water use: Management for salinity control. *In* Limitations to Efficient Water Use in Crop Production. H. M. Taylor, W. Jordan, and T. Sinclair, eds. Madison: American Society of Agronomy Publications. p. 538.

Holmes, R. M., and C. W. Robertson. 1959. A modulated soil moisture budget. Mon. Weather Rev. 97:1–7.

Howell, T. A., J. L. Hatfield, J. D. Rhoades, and M. Meron. 1984a. Response of the crop water stress indicators to soil salinity. Irrig. Sci. 5:25–36.

Howell, T. A., J. L. Hatfield, H. Yamada, and K. R. Davis. 1984b. Evaluation of cotton canopy temperature to crop water stress. Trans. ASAE 27:84–88.

Hsiao, T. C., J. C. O'Toole, and V. S. Tomar. 1980. Water stress as a constraint to crop production in the tropics. *In* Priorities for Alleviating Soil-related Constraints to Food Production in the Tropics. Los Banos, Philippines: International Rice Research Institute.

Idso, S. B., R. D. Jackson, R. D. Pinter, Jr., R. J. Reginato, and J. L. Hatfield. 1981. Normalizing the stress-degree-day parameter for environmental variability. Agric. Meteorol. 24:45–55.

Idso, S. B., D. C. Reicosky, R. J. Reginato, and J. L. Hatfield. 1981. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. Agron. J. 73:826–30.

Ingvalson, R. D., J. D. Rhoades, and A. L. Page. 1976. Correlation of alfalfa yield with various indices of salinity. Soil Sci. 122:145–53.

Jackson, R. D., S. B. Idso, R. J. Reginato, and P. J. Pinter, Jr. 1981. Canopy temperature as a crop water stress indicator. Water Resour. Res. 17:1133–38.

Kozlowski, T. T. 1982. Water supply and tree growth. I. Water deficits. For. Abstr. 43:57–95.

Lauchli, A., and E. Epstein. 1984. Mechanisms of salt tolerance in plants. Calif. Agric. 38:18–20.

Liss, H. J., B. A. Faber, and E. Fereres. 1981. Preliminary evaluation of irrigation scheduling services and farmer practices in selected areas of California. Final Report, Agreement #B54104, State of California Department of Water Resources. 52 pp.

Lovatt, C. J., and L. M. Bates. 1984. Early effects of excess boron on photosynthesis and growth of *Cucurbita pepo*. J. Exp. Bot. 35:297–305.

Letey, J., and H. J. Vaux, Jr. 1984. Water duties for California agriculture. Report prepared for the California State Water Resources Control Board. Sacramento. Agreement No. 2–043–300–0. 110 pp.

Maas, E. V. 1986. Salt tolerance of plants. App. Agric. Res. 1:12–25.

Maas, E. V. 1984. Crop tolerance to saline sprinkling waters. Plant Soil 89:273–84.

Maas, E. V., and R. H. Nieman. 1978. Physiology of plant tolerance to salinity. Chapter 13 *In* Crop Tolerance to Suboptimal Land Conditions. G. A. Jung, ed. Madison: American Society of Agronomy Special Publication 32:277–99.

Marsh, A. W. 1978. Questions and answers about tensiometers. Berkeley: University of California, Division of Agriculture and Natural Resources, Leafet 2264, 12 pp.

Merriam, J. L. 1960. Field method of approximating soil moisture for irrigation. Trans. ASAE 3:31–32.

Nieman, R. H. 1983. Energenetics of salt stressed plants. Proceedings Plant and Soil Conference, California Chapter of American Society of Agronomy. January 26–28, pp. 83–89.

Oster, J. D., G. J. Hoffman, and F. E. Robinson. 1984. Management alternatives: Crop, water, and soil. Calif. Agric. 38(10):29–32.

Oster, J. D., and J. D. Rhoades. 1984. Water management for salinity and sodicity control. Irrigation with reclaimed waste water: A guidance manual. G. Pettygrove and T. Asano, eds. Chelsea, MI: Lewis Publishers. pp. 7.1–7.20.

O'Toole, J. C., and J. L. Hatfield. 1983. Effect of wind on the crop water stress index derived by infrared thermometry. Agron. J. 75:811–17.

Penman, H. L. 1948. Natural evaporation from open water, bare soil, and grass. Proceedings Roy. Soc. (London) A:193:120–146.

Phene, C., D. W. Meek, K. R. Davis, R. L. McCormick, and R. B. Hutmacher. 1985. Real time crop evapotranspiration and determination of crop coefficients. Proceedings American Society of Agricultural Engineers, Publication 14–85, pp. 122–28.

Pruitt, W. O., and R. L. Snyder. 1984. Crop water use. *In* Irrigation with reclaimed municipal waste water: A guidance manual. G. S. Pettygrove and T. Asano, eds. Chelsea, MI: Lewis Publishers. pp. 5.5–5.7.

Rains, D. W. 1984. Metabolic energy cost for plant cells exposed to salinity. Calif. Agric. 38(10):22.

Reuther, W., J. A. Beutel, A. W. Marsh, J. L. Meyer, F. K. Aljibury, R. A. Ayers, and H. Schulbach. 1981. Irrigating Deciduous Orchards. Berkeley: University of California, Division of Agriculture and Natural Resources. Leaflet 21212, 52 pp.

Russell, R. S. 1977. Plant root systems: their function and interaction with the soil. New York: McGraw-Hill, 298 pp.

Scholander, P. F., H. T. Hammel, E. A. Hemmingsen, and E. D. Bradstreet. 1964. Hydrostatic and osmotic potential in leaves of mangroves and some other plants. Proc. Nat. Acad. Sci. 52:119–25.

Second International Drip Irrigation Congress. 1974. Proceedings. Silver Springs: The Irrigation Association, MD 20906. 569 pp.

Shalhevet, J. 1984. Management of irrigation with brackish water. *In* Soil salinity under irrigation. I. Shainberg and J. Shalhevet, eds. New York: Springer Verlag. 8:298–318.

Shaw, R. H., and D. R. Laing. 1981. Moisture stress and plant response. *In* Plant Environment and Efficient Water Use. Pierre et al., eds. Madison: American Society of Agronomy Publications pp. 73–94.

State of California Department of Water Resources. 1986. Crop Water Use in California. Sacramento: DWR. Bulletin 113–4. 116 pp.

Tanner, C. B., and W. L. Pelton. 1960. Potential evapotranspiration estimates by the approximate energy balance of Penman. J. Geophys. Res. 65:3391–3413.

Taylor, S. A. 1965. Managing irrigation water on the farm. Trans. ASAE 8:433–36.

Thorne, M. D., and W. A. Raney. 1956. Soil moisture evaluation. Beltsville, MD: USDA-ARS publication 41–6. 14 pp.

Tovey, R. 1969. Alfalfa water table investigations. J. Irrig. Drain. Div. Proc. Am. Soc. Civ. Eng. IR4:525–35.

Veihmeyer, F. J., and F. A. Brooks. 1954. Measurements of cumulative evaporation from a bare soil. Trans. Am. Geophys. Union 35(4):601–07.

Wallender, W. W., D. W. Grimes, D. W. Henderson, and L. K. Stromberg. 1979. Estimating the contribution of a perched water table to the seasonal evapotranspiration of cotton. Agron. J. 71:1056–60.

Wenkert, W., E. R. Lemon, and T. R. Sinclair. 1978. Changes in water potential during pressure bomb measurements. Agron. J. 70:353–55.

3m-pr-6/89-WJC/ALS