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SCHEDULING IRRIGATIONS:

A GUIDE FOR IMPROVED IRRIGATION WATER MANAGEMENT THROUGH PROPER TIMING AND AMOUNT OF WATER APPLICATION

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CHAPTER I. INTRODUCTION

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The targeted user agencies for this publication are the USDA-Soil Conservation Service, the State Soil Conservation Board, the State Engineer's Office, the Water Conservancy Districts, Cooperative Extension and related entities, as well as the technically inclined irrigator. It is a goal of the authors that this manual help increase coordination among the agencies involved in water, energy, soil and other resource management. It is prepared with emphasis on the immediate problems faced by pumped water users in eastern Colorado, but includes information to allow application of the principles throughout the state and in other similar areas. The guide will hopefully serve as a basis for training of user agency personnel and eventually irrigators and as a technical reference for future use.

Although many of the principles of soil-water-plant interactions are discussed, the paper does not delve deeply into the theories or mathematical principles involved. The paper will serve as a source of several brief publications covering various aspects of irrigation. These following publications, in the form of extension bulletins, CSU *Service in Action* sheets, or similar, are expected to be published within a few months. It is these latter, brief publications that are intended to be distributed to the individual irrigator.

PURPOSE

There have been many books, articles, and monographs published addressing when and how much to irrigate. Many of these irrigation scheduling guides have appeared as part of more general papers on irrigation water management or irrigation system design. In a detailed scientific paper, it may be difficult for the practitioner to translate the theory into a method. The purpose of this guide is to present a discussion of soil-water-plant relations as they concern irrigation scheduling, with terminology and procedures that are understandable and can be implemented by user agency personnel.

The guide will serve as a reference for technical representatives to determine which methods of irrigation scheduling and irrigation strategies are most appropriate for a given client. We have attempted to describe the relevant soil-water relationships and the relation of climatic variables to crop water use in such a manner as to give the reader an appreciation for the complex interactions involved in irrigation and irrigation scheduling, without becoming overly involved with technical details.

Several agencies have been involved in promotion of irrigation scheduling in eastern Colorado for as long as 15 years. The Agricultural Research Service, U. S. Bureau of Reclamation, CSU Extension Service, CSU Experiment Station, USDA Soil Conservation Service, several competent consultants and some farmers have used one or more of the procedures described in this paper. Because the different procedures will give somewhat different results, and because the particular situation determines the most appropriate procedure to use, the results being disseminated were not always consistent. Therefore, one of the intents of this guide is to provide a basis for reasonable selection of irrigation scheduling techniques for a given irrigator or area, and to provide for consistent application of procedures that are agreed upon by most of the agencies involved.

HISTORY OF WATER DEVELOPMENT

The history of water development for irrigation in Colorado is one of the most significant and colorful aspects of the state's development. Gravity irrigation dates more than 100 years, and irrigation systems range from small, privately constructed systems to large, federally financed projects such as the Colorado-Big Thompson. Pumped irrigation does not, of course, have such a long history. Some water was pumped to supplement river water in the river valleys as soon as power sources were available, probably little before the 1930's. Irrigation in the Colorado High Plains developed more slowly than further south in Kansas, New Mexico and Texas. Development reached a peak in the "hard lands" in the late 1950's and early 1960's. With the popularity of the center pivot sprinkler irrigation system, many of the "sandy lands" were brought under irrigation in the late 1960's and 1970's.

With the growing demand for irrigation water and the growing population of the state, the competition for water was inevitable. In recent years, we have seen the high cost of energy and low commodity prices force some farmers to cease irrigation. We have seen the major metropolitan areas and water using industries purchase high-mountain meadows and irrigated plains farmland for the water rights it carries. The competition for water will undoubtedly continue, therefore it is important that all water users make the most effective use practical of the available water.

WHY SCHEDULE?

All irrigations can be considered to be "scheduled". Whether the irrigator uses a sophisticated computer controlled irrigation system or several generations of "seat of the pants" experience on a given farm, there is some decision process by which he/she decides when and how much water to apply.

WATER SAVINGS

Studies indicate that, when water is readily available, irrigators in Nebraska and northeastern Colorado apply about 30% more water than the crop requires. In days gone by, the cost of applying this water, even for those who pumped from deep wells, was considered cheap for the "insurance" it provided. Such is no longer the case, however. Regardless of its source, water in eastern Colorado is valuable. Both the pump irrigator at Burlington who pays the power bill every season and the gravity irrigator at Brighton who has to compete with municipal users for water know just how valuable. Thus, making the best use of the water that's available makes good business sense, and its business sense that makes the difference between remaining an irrigator and finding another occupation in today's agricultural economy.

In the southern half of the Colorado high plains, the Arkansas valley, and other areas, the water supply is not necessarily abundant. Nevertheless, careful irrigation water management can make this limited water supply go further. Early in the season, crop water use is small. Only a limited amount of water may be "stockpiled" in the soil for use later in the season. Any excess moves beyond the root zone. With sprinkler systems, applying a partial irrigation leaves some room to store rainfall when it does occur. With surface irrigation systems, accounting for rain that occurs and "holding off" when climatic conditions warrant can make a significant difference in water application during the growing season.

ENERGY SAVINGS

For pump irrigators, water saved means energy saved, whether the pump be powered by electricity (80% or more in Colorado are), natural gas or diesel fuel. Most electric cooperatives in eastern Colorado were faced with demand for electricity for irrigation in the peak water use periods that exceeded the available supply. Many of these suppliers instituted "peak load shedding" programs to temporarily interrupt power to groups of pumps in order to maintain the voltage supplied to remaining users. Studies showed that scientific irrigation scheduling techniques could be used to determine whether the crop in a given field could withstand such shutoffs without reduced yields. The economic incentives for participating in such load shedding programs were as much as 14 percent discount on the power bill, not a small economic factor if yields could be maintained.

FERTILIZER SAVINGS

Even where water is provided by gravity flow from river diversions, there are significant economic reasons to manage irrigation water as judiciously as possible. It is not particularly obvious that water saved means fertilizer saved. Like a bucket, once the soil water reservoir is full, additional water poured in must go somewhere. That somewhere is most often "out the bottom" of the soil root zone. Nitrogen fertilizer is easily dissolved in water and tends to go where the water goes. The studies cited above also showed that every inch of excess water applied carried away 10 to 30 pounds of nitrogen fertilizer. During the average growing season in eastern Colorado, an irrigated corn crop requires about 27 inches of water. In eastern Colorado, about 1/4 of that can be expected from rainfall during the season, leaving some 18 to 22 inches to be applied by irrigation. Overirrigation by 30 percent means 5 to 7 inches excess water application, or easily 50 pounds of nitrogen per acre leached. This represents not only $8.00 to $10.00 per acre loss of fertilizer, but also may mean yield reductions on the order of 1 1/2 bushels per acre for each pound of lost nitrogen unless additional fertilizer is applied.

One can begin to see that the potential for economic loss due to applying too much irrigation water is significant. Of course, the potential for water pollution resulting from this leaching is also significant. Nitrites in drinking water cause methemoglobinemia, or "blue babies" in human infants, and abortion in livestock.

Therefore, whether the objective is to reduce water losses, reduce fertilizer losses, reduce energy consumption, make better use of rainfall or protect the environment, improved water management can pay dividends to the irrigator.

SOIL-WATER-PLANT RELATIONS

Before we can learn to effectively manage irrigation water, we must first understand how and why a plant uses water. Irrigation is not practiced to keep the soil wet. We don't irrigate just because we live in a semiarid climate, because the neighbors irrigate or because our forbearers irrigated. We irrigate for one purpose-- to satisfy the water needs of a crop of economic or aesthetic value.

When we irrigate, the water applied can take many paths on its journey across the field. At one time or another, all our fresh water supplies fell from the sky as precipitation. Figure 1.1 illustrates the "hydrologic cycle", or potential water paths as applied to an irrigated field. Precipitation during the

growing season can be an important part of the water supply for growing a crop in eastern Colorado, although precipitation alone provides meager yields of most crops. Irrigation water may comprise 75 percent or more of the total seasonal water supply to irrigated crops. The intent of irrigation is to store this water applied by man in the soil for use in subsequent days to satisfy the water needs of the plant. However, seldom is all applied water stored where it can subsequently be recovered by the crop. The soil water reservoir can be likened to a bucket. If the amount of water entering the soil is more than the soil (bucket) can hold, then the excess drains beneath the reach of the roots (ie, the bucket

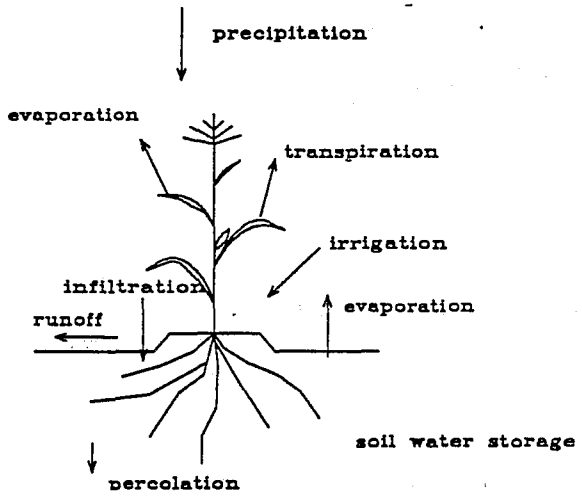

Figure 1.1. Water movement in an irrigated crop environment.

runs over). When water is applied too rapidly, whether by a hard rain, poorly designed sprinkler system or poorly managed furrow irrigation, water may be redistributed or even leave the field as runoff. Particularly when the crop is small and provides little cover on the soil surface, water evaporates from the soil itself. Following a rain, sprinkler irrigation or dew, water collected on the plant surfaces will evaporate.

The most important component of the hydrologic cycle is the water that moves into the roots, up the stem and out the pores, or stomates, of the leaves. This water use is called transpiration. When combined with that free water evaporating from leaf surfaces and the soil, it is referred to as evapotranspiration, or ET for short.

In reality, the amount of water needed by the plant to transport nutrients, support photosynthesis and respiration processes and maintain the rigidity of cells is very small. There is a tremendous amount of heat delivered to every square foot of the earth during a growing season. By far the majority of transpiration occurs to help the plant avoid overheating. Just as evaporation from the surface of a canvas waterbag cools the water inside, so evaporation from a leaf surface cools the leaf. On a calm, cool, overcast day, the needed cooling is small, therefore little water is transpired by the plant. However, when skies are clear, temperatures high and strong dry winds blow, much water must be evaporated to keep the plant cool. This evaporation (transpiration) occurs from within special cell structures in the leaves called stomates. These stomates are capable of opening and closing in response to light and water availability to control the rate of water loss or transpiration by the plant. So long as sufficient water can be

transported to the leaves, transpiration (cooling) can progress as needed to keep the plant cool. On extremely hot days or whenever soil water contents become low, however, the plant is not able to move enough water to the leaves to satisfy the need for cooling. At that point, the leaf cells become susceptible to dehydration and permanent damage. As a defense mechanism, the stomates close to restrict water loss, and leaf temperature begins to rise. Most plants also employ another defense mechanism, wilting or curling of the leaves, to reduce the amount of leaf surface available to absorb the incoming energy, thus reduce the amount of heating. When water is limited to this point, the yield has already been effected. Carried to the extreme, of course, this "water stress" results in permanent injury or death of the plant.

The amount of water available to the plant depends not only on the precipitation and irrigation patterns, but also on the characteristics of the soil. Coarse textured soils generally hold less water than fine textured soils. As the plant grows and sends its roots deeper into the soil, the crop has access to a larger and larger reservoir of water, thus can go for longer times without replenishment of the soil water.

CHAPTER II. SOIL CHARACTERISTICS

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PHYSICAL PROPERTIES AFFECTING SOIL WATER CONTENT

Soil is a porous mixture of inorganic mineral particles, decaying organic matter, air, water and a variety of living organisms. The manner of deposition, along with physical and chemical weathering, cause layering in a soil mass. The arrangement and kind of material in the layers affect root growth and the movement and retention of water in the soil.

Important physical properties of soils are texture and structure. Texture refers to the relative proportion of different particle sizes in the soil mass. Structure refers to the way the particles are arranged in groups or aggregates. Together, texture and structure influence the volume of air and water in the soil mass and the rate at which water moves into and through the soil. Tilth is the physical condition of the soil in relation to plant growth and ease of tillage, and is determined in large part by past cultural practices. Soils in good tilth are crumbly, easily worked, and take water readily when dry. Generally, soils with poor tilth are hard, cloddy, difficult to work, and take water slowly when wetted.

TEXTURE

The size of soil particles is used as a basis for classifying soil types. The range of particle sizes for individual soil fractions corresponding to USDA textural classes is shown in Table 2.1.

TABLE 2.1 Range of particle sizes used to classify soils by texture.

SOIL TEXTURE	PARTICLE SIZE FRACTION
Very coarse sand	1.0 mm to 2.0 mm
Coarse sand	0.5 mm to 1.0 mm
Medium sand	0.25 mm to 0.5 mm
Fine sand	0.1 mm to 0.05 mm
Very fine sand	0.05 mm to 0.1 mm
Silt	0.002 mm to 0.05 mm
Clay	less than 0.002 mm

Textural classification of soils is based on the proportion of sand, silt and clay size particles present, as shown in Figure 2.1. After estimating the percentages of sand, silt and clay in a soil, one may determine the textural class of the soil by drawing a line in the direction of the arrows from the estimated percentages of two of the size fractions. The textural class name at the intersection of these two lines

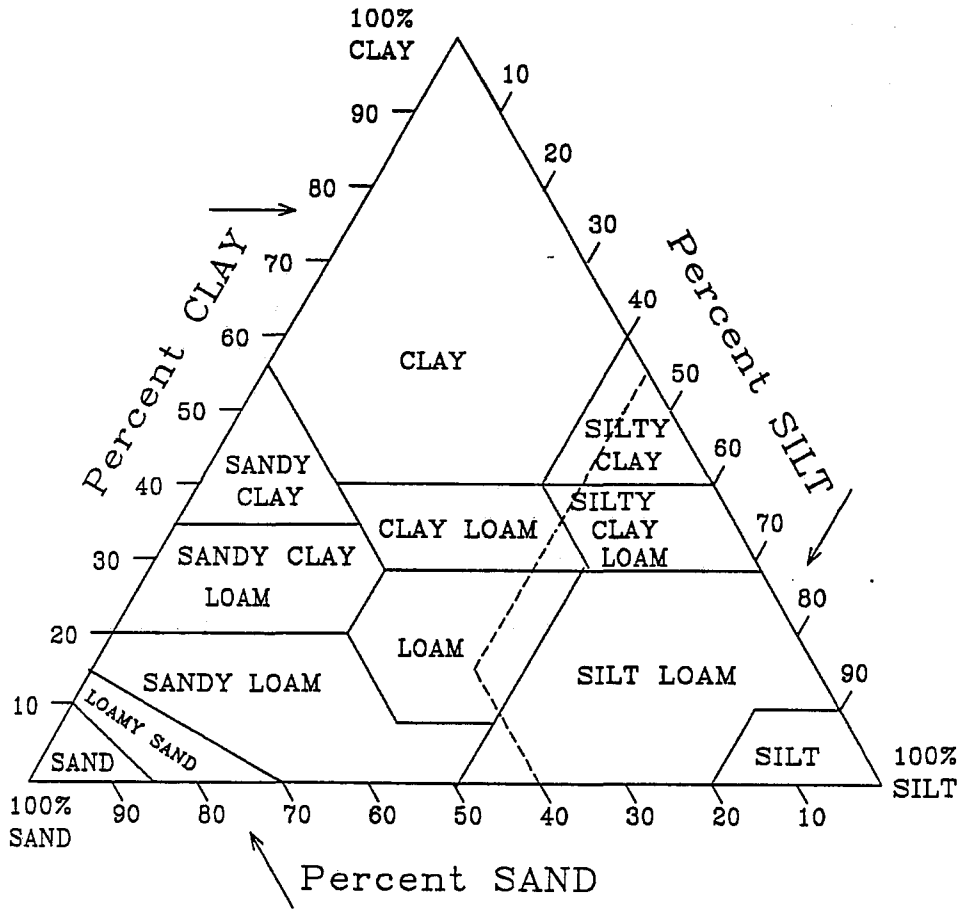


Figure 2.1. Soil textural triangle for determining textural class.

describes the soil in question. For example, a soil with 45 percent silt and 40 percent sand is classified as a loam.

In the field, soil texture can be estimated by feel using the following guidelines:

SAND. Sand is loose and single grained. The individual grains can be seen or felt readily. Squeezed in the hand when dry, sand falls apart when pressure is released. Squeezed when moist, it forms a cast but crumbles when touched.

LOAMY SAND. A loamy sand is a soil containing mostly sand, with insufficient silt or clay to make it cohesive. Like sand, it cannot be formed into a ball except when very moist, when it sticks together slightly, but the ball, if formed, is very weak.

SANDY LOAM. A sandy loam is a soil containing a high percentage of sand but having enough silt and clay to make it somewhat cohesive. The individual sand grains can be readily seen and felt. Squeezed when dry, a sandy loam forms a cast that falls apart readily. If squeezed when moist, a cast can be formed that bears careful handling without breaking.

LOAM. A loam is a soil having a relatively uniform mixture of different grades of sand, silt, and clay. It is mellow, with a somewhat gritty feel but is fairly smooth and slightly plastic when moist. Squeezed when dry, it forms a cast that bears careful handling. The cast formed by squeezing moist soil can be handled freely without breaking.

SILT LOAM. A silt loam is a soil having a moderate amount of fine sand and only a small amount of clay; over half of the particles are of the size called silt. When dry, a silt loam appears cloddy but the lumps can be broken readily. When pulverized, it feels soft and floury. When wet, the soil runs together readily and puddles. Either dry or moist, it forms a cast that can be handled freely without breaking; when moistened and squeezed between thumb and finger, it does not ribbon but has a broken appearance.

CLAY LOAM. Clay loam is fine-textured soil that usually breaks into clods or lumps that are hard when dry. When the moist soil is pinched between the thumb and finger, it forms a thin ribbon that breaks readily, barely sustaining its own weight. The moist soil is plastic and forms a cast that bears much handling. When kneaded in the hand, it does not crumble readily but works into a heavy compact mass.

CLAY. A clay is fine-textured soil that usually forms very hard lumps or clods when dry and is very plastic and usually sticky when wet. When the moist soil is pinched out between the thumb and finger, it forms a long, flexible ribbon. Some clays very high in colloids are friable and lack plasticity at all water contents.

STRUCTURE

Structure refers to the grouping of particles in a soil mass. Structure in many soils differs by soil horizon. Single grained and massive soils are structureless. Principal soil structures are platy, prismatic, blocky and granular. Usually the more favorable water relations are found in soils having prismatic, blocky and granular structure. Water percolates rapidly through granular soils. Platy structure impedes downward movement of water.

Unlike texture, structure of the soil can be changed. Excellent structure develops in soils having high content of organic matter. Cycles of wetting and drying or freezing and thawing improve the structure in plow layers. Cultivation of medium or fine textured soils at high water content destroys structure. Large amounts of sodium in irrigation water disperses soil aggregates causing undesirable lack of structure.

LAYERING

Soil characteristics having the greatest influence on soil water are texture and layers within the profile that impede water flow. Fine grained soils retain more water than coarse soils. Water drains at a significant rate for a longer time from fine grained soils than from coarse soils. A layer interface

inhibits downward water movement, thus restricting vertical redistribution of applied water. Layering can assist in lateral redistribution of water, for example when irrigating alternate furrows in coarse textured soils.

SOIL WATER

A renewable supply of water in the soil is necessary for plant growth. Therefore, how water moves in the soil, how much water the soil can hold, how much of the water is actually available to the plants and how rapidly this supply can be replenished are of concern. The amount of water held by the soil and how it moves in the soil depend on soil texture, on the attraction for water by the soil particles, on the size and distribution of the soil pores (spaces between particles) and on the amount of organic matter in the soil. Generally, the finer the soil particles and the larger the organic content, the more water the soil holds. However, all of that water is not readily available to the plants.

CLASSIFICATION OF SOIL WATER

Soil pores form a network of connected cavities of a variety of sizes and shapes. Water added to a dry soil is held around the soil particles by absorptive forces, displacing air and eventually filling the pores. The soil is saturated when all of the pores are filled with water.

Water in the larger pores moves downward freely under the force of gravity. This gravitational water drains from the soil or is used by the crop within a few days after irrigation. In well-drained soils, gravitational water near the surface usually drains from the larger pores and air is again available to plant roots before crops are damaged.

Water in the smaller pores moves by capillarity. Capillary water moves more slowly than gravitational water and moves toward areas of greatest tension, ie., drier areas. It is this capillary water that is of most importance to the irrigated crop.

Evaporation from the soil surface and absorption of water by growing plants further reduce the amount of water in the soil until water can no longer move in liquid form under capillary forces. The remaining water is held as a thin film around the soil particles and in minute wedges between particle contact points. Plants begin to wilt when forces holding very thin films of water around soil particles exceed the forces the plant is able to exert to pull this water away. Eventually, the soil becomes so dry that plants die unless water is added. At this stage, the remaining water is held on the particle surface so tightly that it does not behave as a liquid, but moves as vapor. This is called hygroscopic water. Only this hygroscopic water is not available to plants. At this water content, water movement continues, but in the form of vapor.

MOVEMENT OF WATER IN SOIL

Intake or infiltration is the movement of water from the surface into the soil. Percolation is the movement of water through the soil mass, chiefly through large pores in the soil. Therefore, percolation depends on the relative number and continuity of the pores.

Water movement in soil is a complex process. It moves freely through large pores in coarse textured soils. It moves less rapidly through fine textured soils because of the resistance to flow in small pores. Also, the small pores may be blocked by swollen colloidal gels and trapped air. Percolation is retarded by slowly permeable layers such as a claypan or plowpan. A sand lens temporarily halts percolation, but once the overlying layer becomes saturated, water penetrates the sand layer and continues to move downward.

Water moves as an unsteady front from saturated layers to unsaturated layers. Water builds up behind the front until large pores are filled, then moves to the next layer of large pores. In moist soils, water moves more uniformly than in dry soils.

Movement of capillary water is affected by soil texture. Forces causing capillary movement in small pores result from tension differences between thick films and thin films of water surrounding soil particles. Water moves from zones of low tension (thick films), to zones of high tension(thin films).

Heat also causes water to move, particularly as a vapor, from warm to cool areas. As vapor diffuses through soil pores near the surface, it either condenses in other soil pores or escapes into the atmosphere. As water evaporates, tension increases and capillary water rises to replace that lost through evaporation. This continues until the upper few inches of soil become sufficiently dry that water can no longer move as a liquid. Water then leaves the soil only by evaporation from the moist areas and diffusion through the overlying dry soil.

INTAKE RATE

Intake rate is the measure of a soil's capacity to absorb water with respect to time. Intake is relatively rapid as water is first applied to a dry soil but decreases to a nearly constant value as the soil becomes saturated. The reduced but nearly constant rate is called the basic intake rate.

Factors affecting intake rate include:

SURFACE SEALING. A thin layer of low permeability is formed on the soil surface as soil structure breaks down under droplet impact or as fine particles carried by flowing water block pores through which water enters the soil.

SOIL COMPACTION. Tillage of wet soils compacts a layer just below the depth of tillage. Compaction also occurs as the weight of the farm equipment is transmitted to the soil through the tires. Compaction reduces the volume of void spaces as the soil particles are consolidated into a smaller space.

SOIL CRACKING. Heavy clay soils crack as they dry. Water rapidly fills these cracks. The wet soil expands, closing the crack and reducing the intake rate because water enters the soil through the smaller remaining pores.

TILLAGE. Plowing, cultivating and other operations loosen the soil surface, creating large voids, through which water enters rapidly. However, these large voids soon close as water settles the soil back to its original density. Conversely, tillage also breaks up root channels, worm holes and other such pores in some soils, reducing the basic intake rate.

CROP ROTATION. Coarse organic matter incorporated into the soil maintains high porosity. Grasses, legumes and residue from previous crops naturally increase organic matter content of the soil.

IRRIGATION METHOD. Sprinkler irrigation has an effect on intake rates similar to that of rainfall. Soils subject to surface sealing under rainfall are likely to seal under sprinkler irrigation. Furrow and corrugation irrigation applies water to only a part of the soil surface. Intake depends on ability of the soil to move water both laterally and vertically and on the size of the wetted area through which water infiltrates into the soil. Flood irrigation completely covers the soil surface allowing water to move only vertically. Depth of flooding has a minor effect on intake rate.

Because these and many other factors affect water intake, it is not surprising that intake rates vary among soil types, from place to place, from irrigation to irrigation, and from season to season. Also, intake rates under sprinkler application differ from those under surface irrigation.

Each soil has its own intake characteristics, but some differences are so minor that it is practical to group several soils. The Soil Conservation Service established eight groups, called intake families. The numeric designation of each intake family is approximately the basic intake rate in inches per hour (Figure 2.2).

USABLE ROOT ZONE RESERVOIR

Soil moisture is at field capacity when capillary forces equal the force of gravity and only a negligible amount of water drains from the voids. Therefore, water applied in excess of field capacity quickly percolates through the soil and is not available for beneficial use of the growing crop after one to three days. Drainage by gravity leaches excess salts from the soil and, therefore, is beneficial to a certain extent, but must be controlled.

Roots of growing plants, exerting a force stronger than gravity or capillary forces, pull water from the voids until the attraction of water to the soil particles exceeds the plant's ability to pull water away. The water content at which this occurs is called the permanent wilting point. With respect to plant growth, the available water holding capacity of the soil is the range between field capacity and permanent wilting point, expressed as a fraction or depth of water per unit depth of soil. The soil water deficit is the amount of water required to restore the soil water content to field capacity.

However, plant growth and crop yield are adversely affected before soil water content approaches the permanent wilting point too closely. Therefore, irrigation should replenish the soil water deficit before the available water is gone. For most crops irrigation should occur when about 50 percent of the available water is gone. Some specialty crops can tolerate only 30 percent depletion and some grain or forage crops tolerate 60 percent depletion without significant yield reduction.

Capillary forces cause water to move within a soil mass. Movement is from zones of high water content to low water content, thus tending to establish a uniform water content throughout the soil. Such movement continues until capillary movement becomes negligible at low water contents. Therefore, the volume of water available to plants is that water stored within the active root zone plus that which moves into the root zone by capillarity. Shallow ground water is a source of capillary water.

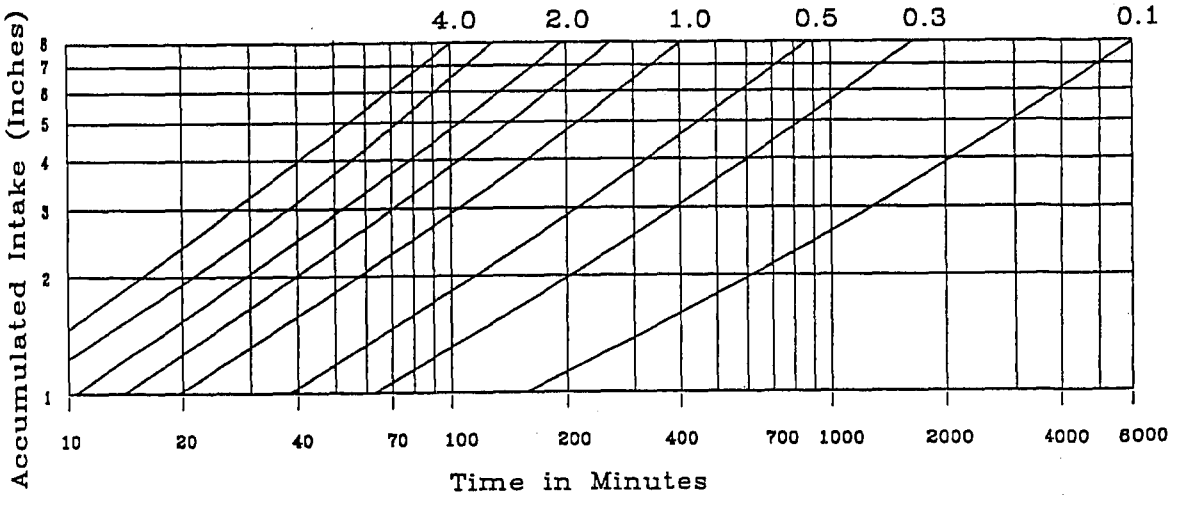


Figure 2.2. USDA-SCS Intake Family grouping for surface irrigation system design.

The growing plant uses only that water coming in contact with its roots. Therefore, the root zone reservoir is the volume of available water retained within the soil mass penetrated by plant roots or from which water can be drawn by capillarity. The root zone reservoir changes as roots grow deeper into the soil until about the time the plant reaches its full size. The amount of water available in the root zone reservoir is determined by multiplying the available water fraction in each soil layer of the root zone by the thickness of that layer.

The magnitude of the usable root zone reservoir can be illustrated by example, using the data presented in the following section. Suppose the soil profile consists of 12 inches of sandy loam overlying a deep silt loam subsoil, and the roots penetrate to an effective depth of 30 inches. The usable reservoir of the upper layer is then (AC) 0.15 inches per inch times 12 inches, or 1.8 inches. For the subsoil, the available water capacity (AC) is 0.23 inches per inch, or .23 (30 -12) = 4.1 inches. Thus, the total usable root zone reservoir is 1.8 + 4.1 or 5.9 inches.

RANGE OF AVAILABLE WATER BY SOIL TEXTURE

Table 2.2 gives ranges for available water capacity by soil texture as determined by USDA-SCS on Colorado soils. Note that the top portion of the table contains data for the top twelve inches of soil. The bottom portion of the table is for soil depths greater than twelve inches.

Figures 2.3a-f also provide descriptive information about available water capacity by soil texture. These figures are more general relationships gathered from nationwide studies, and include several similar soil textures grouped together. The water content can be expressed on either a weight or volume basis. The relationship between percent available water on a volumetric basis and percent water on a dry weight basis is given by the equation

$$P_v = P_w * BD$$

where P_v = percent water on a volume basis,

P_w = percent water on a weight basis, and
BD = average bulk density of soil.

Water depletion, in inches per foot of soil depth, is related directly to percent available water. The water release curve relates available water to soil tension and can be used with tensiometers to convert tension readings to soil water depletion.

These data are averaged from many laboratory tests on soil samples taken for the national soil survey. Some variation from these data should be expected for specific soils, but should not be great.

METHODS FOR MEASURING SOIL WATER

Irrigation water management requires knowing the water content of the soil and the rate and amount of depletion so that irrigations can be scheduled to replenish soil water. However, soil water content needs to be related to field capacity and wilting point of the soil to determine the point at which replenishment is required and how much water is required to refill the soil profile. The relationship between soil water depletion, percent available water and soil water tension for various soil textures is shown in Figures 2.3a-f.

Some methods used to determine soil water content are given in the following paragraphs.

HAND PROBE. This commonly used method is also known as the feel and appearance method of estimating soil water content. No special equipment is needed, but a soil auger or probe will aid in taking samples below the one-foot depth.

Estimating soil water by the hand probe method is not an exact procedure. However, experienced irrigators develop the ability to estimate water content within acceptable limits.

Table 2.3 can be used to estimate the water content of the soil and the amount of water needed to restore it to field capacity.

For row crops, the soil samples should be taken in the plant row. Under sprinkler irrigation, the soil samples should be taken between sprinkler nozzles and ten to fifteen feet from the lateral under stationary systems.

Samples should be taken in the soil from which plant roots extract water, according to the water-extraction pattern of the crop. One sample should be taken from the upper quarter of the root zone and two more samples from lower levels. If the maximum water-extraction depth for a given crop is 48 inches, for example, samples should be taken at depths of 6, 18, and 36 inches. To predict when to irrigate during early stages of root development, the 6-inch sample is sufficient for most crops. As the root system matures, samples from all three depths are needed for a clear picture of the water content throughout the root zone.

GRAVIMETRIC. Perhaps the most precise method for determining water content of the soil is to oven dry a sample of wet soil. Weight of the wet sample is determined as soon as possible after the sample is obtained. The sample is kept in an air tight container in a cool place until the weight has been determined. Then the sample is heated in an oven at 220 degrees F, usually for 24 hours. Weight of the

dry sample is then determined. Water content of the soil, expressed as a percentage of dry soil weight is computed as

$$\frac{\text{(Wet Weight - Dry Weight)}}{\text{Dry Weight}} \times 100 .$$

Accuracy of measurement, commensurate with the precision of procedures and equipment used, is the principal advantage of the gravimetric method.

Disadvantages of this method include cost of equipment needed (although a household oven or microwave may be used if available, the scale is expensive), time and labor required, and degree to which the sample is representative of the soil profile for the field in which the water content is desired. Additionally, the soil sample can be tested only once by this method. Further testing requires new samples taken nearby, thus introducing site variation into the testing procedure.

Variations of this method include using a heat lamp in a Quick-Drying Oven, using a microwave oven (about 15 minutes drying time--be sure not to use a metal container), and burning alcohol that has been poured over the sample to generate heat necessary to evaporate the water.

CARBIDE. This method is based on the amount of gas produced by combining 26 grams of wet soil with a measure of calcium carbide in a closed chamber. The chamber is fitted with a pressure gauge. The water in the soil sample combines with the carbide to produce acetylene gas. The amount of gas produced, depending on the water content, determines the pressure reading, which is converted to soil water content by using a chart provided with the apparatus.

The carbide method enables making complete water content determinations in the field in less than 5 minutes.

Disadvantages of the carbide method include basing conclusions on a small (26 gram) sample of soil, degree to which the soil sample is representative of the soil profile, and cost of the apparatus, including maintaining a supply of calcium carbide.

TENSIOMETERS. The tensiometer is a closed tube with a porous ceramic tip at one end and a vacuum gauge at the other. The tube, filled with water, is placed in the soil with the tip at the desired depth and the gauge extending above ground. Water moves through the porous tip to reach equilibrium with the tension in the surrounding soil, creating a tension in the tube, which is registered on the gauge. Water applied to the soil relieves the tension as water tends to be drawn back into the tube.

Although the gauge readings relate directly to soil water tension, calibration is needed to relate tension to water content. Figure 2.3a-f can be used to convert tensiometer readings to approximate soil water content for various soil types. Readings between 0 and 0.05 bar suggest the soil is too wet for most crops. Readings between 0.15 and 0.3 bar suggest the soil water content is at about field capacity, readings between 0.3 and 0.5 bar represent about ideal water and soil aeration conditions for most crops in coarse textured soils.

Table 2.2. Typical water holding capacity for Colorado soils (FC -- field capacity, WP -- wilting point, AC -- available water holding capacity, %WP -- percent of total water at wilting point; percentages on dry weight basis).

Upper 12 Inch Soil Layer

Soil Texture	Avg Bulk Density	Percent Water				Inches per Foot		
		FC	WP	AC	%WP	FC	WP	AC
Sand	1.60	8.7	3.5	5.2	40	1.67	0.67	1.00
Loamy sand	1.60	11.9	4.5	7.4	38	2.28	0.86	1.42
Sandy loam	1.55	15.4	5.8	9.6	38	2.86	1.08	1.78
Fine sandy loam	1.50	19.5	7.5	12.0	38	3.51	1.35	2.16
Loam	1.45	23.6	9.2	14.4	39	4.11	1.60	2.51
Sandy clay loam	1.40	27.0	13.5	13.5	50	4.54	2.27	2.27
Silt loam	1.40	27.2	10.9	16.3	40	4.57	1.83	2.74
Clay loam	1.40	27.3	15.1	12.2	55	4.59	2.54	2.05
Silty clay loam	1.35	28.8	13.0	15.8	45	4.84	2.18	2.65
Silty clay	1.30	28.7	18.0	10.7	61	4.82	3.02	1.80
Clay	1.25	29.4	20.1	9.3	68	4.94	3.38	1.56

Below 12 Inches

Soil Texture	Avg Bulk Density	Percent Water				Inches per Foot		
		FC	WP	AC	%WP	FC	WP	AC
Sand	1.70	7.0	3.0	4.0	43	1.43	0.61	0.82
Loamy sand	1.70	10.0	4.2	5.8	42	2.65	1.11	1.54
Sandy loam	1.65	13.4	5.6	7.8	42	2.65	1.11	1.54
Fine sandy loam	1.60	18.2	8.0	10.2	44	3.49	1.54	1.96
Loam	1.55	22.6	10.3	12.3	46	4.20	1.92	2.29
Sandy clay loam	1.50	27.6	14.5	13.1	52	4.97	2.61	2.36
Silt loam	1.50	26.8	12.9	13.9	48	4.82	2.32	2.50
Clay loam	1.50	26.3	16.3	10.0	62	4.73	2.93	1.80
Silty clay loam	1.45	27.6	14.5	13.1	52	4.80	2.52	2.28
Silty clay	1.40	27.9	18.8	9.1	67	4.69	3.16	1.53
Clay	1.35	28.8	20.8	8.0	72	4.67	3.37	1.30

Table 2.3. Guide for judging how much water is available in the soil.

	Available Soil Water Remaining	Feel or appearance of soil (soil water deficit)[1/]			
		Loamy Sand Coarse Texture	**Sandy Loam Moderately Coarse Texture**	**Loam and Silt Loam Medium Texture**	**Clay Loam or Silty Clay Loam Fine and Very Fine Texture**
Irrigate Most Crops	0 to 25 percent	Dry, loose, single grained, flows through fingers. (0.7 to 0.9)[2/]	Dry, loose, flows through fingers. (1.0 to 1.3)	Powdery dry, sometimes slightly crusted but easily broken down into powdery condition. (1.5 to 2.0)	Hard baked, cracked sometimes has loose crumbs on surface. (1.6 to 2.2)
	25 to 50 percent	Appears to be dry, will not form a ball with pressure. (0.4 to 0.7)	Appears to be dry, will not form a ball.[1/] (0.6 to 1.0)	Somewhat crumbly but holds together from pressure. (1.0 to 1.5)	Somewhat pliable, will ball under pressure. (1.1 to 1.6)
Irrigate Potatoes	50 to 75 percent	Appears to be dry, will not form a ball with pressure. (0.2 to 0.4)	Tends to ball under pressure but seldom holds together. (0.3 to 0.6)	Forms a ball somewhat plastic, will sometimes slick slightly with pressure. (0.5 to 1.0)	Forms a ball, ribbons out between thumb and forefinger. (0.6 to 1.1)
Delay Irrigating	75 percent to field capacity (100 percent)	Tends to stick together slightly, sometimes forms a very weak ball under pressure. (0 to 0.2)	Forms weak ball, breaks easily, will not slick. (0 to 0.3)	Forms a ball, is very pliable, slicks readily if relatively high in clay. (0 to 0.5)	Easily ribbons out between fingers, has slick feeling. (0 to 0.6)
	At field capacity (100 percent	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand

[1/] Ball is formed by firmly squeezing a handful of soil.
[2/] Parentheses show inches of water deficiency per foot of depth.

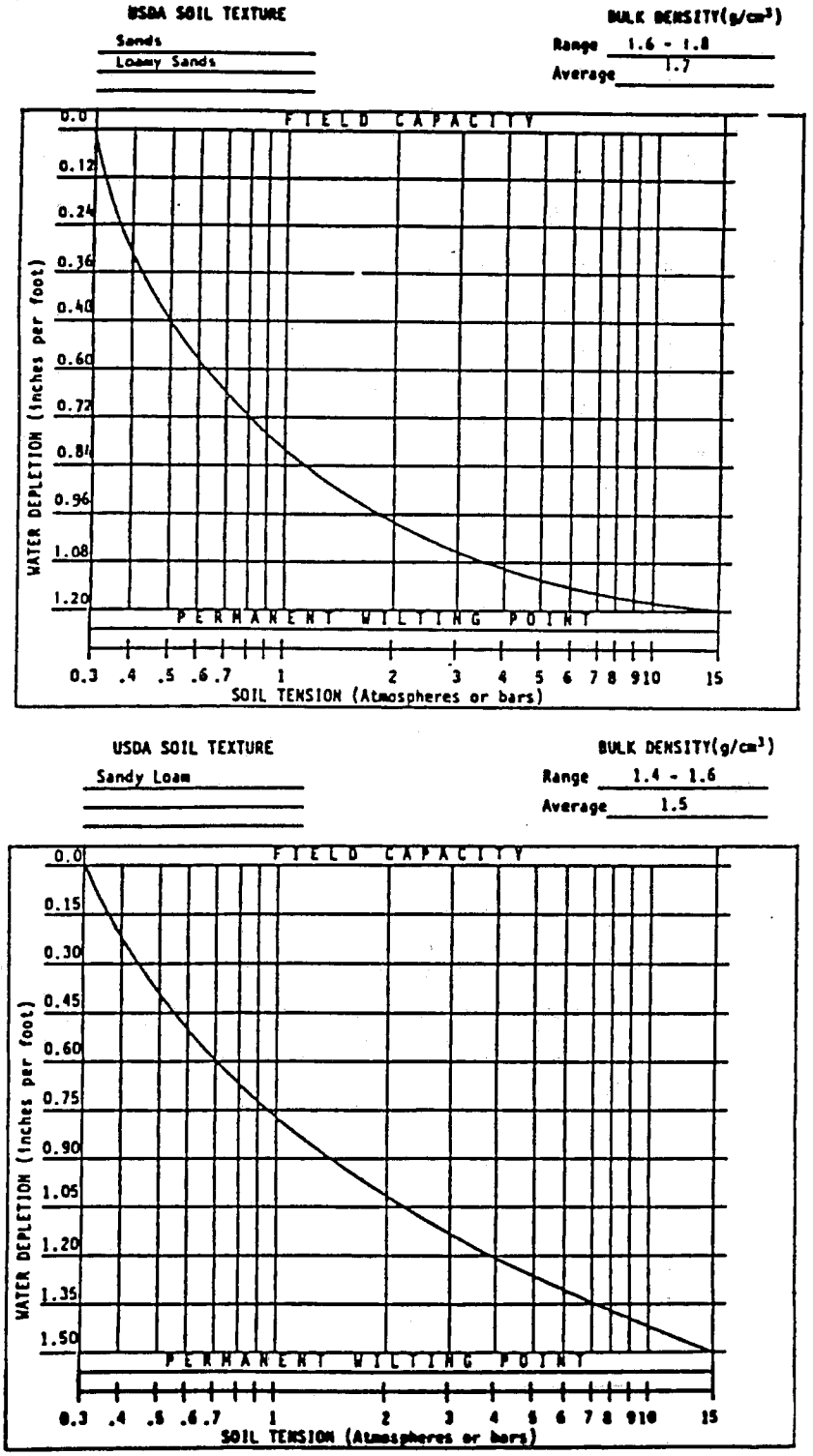
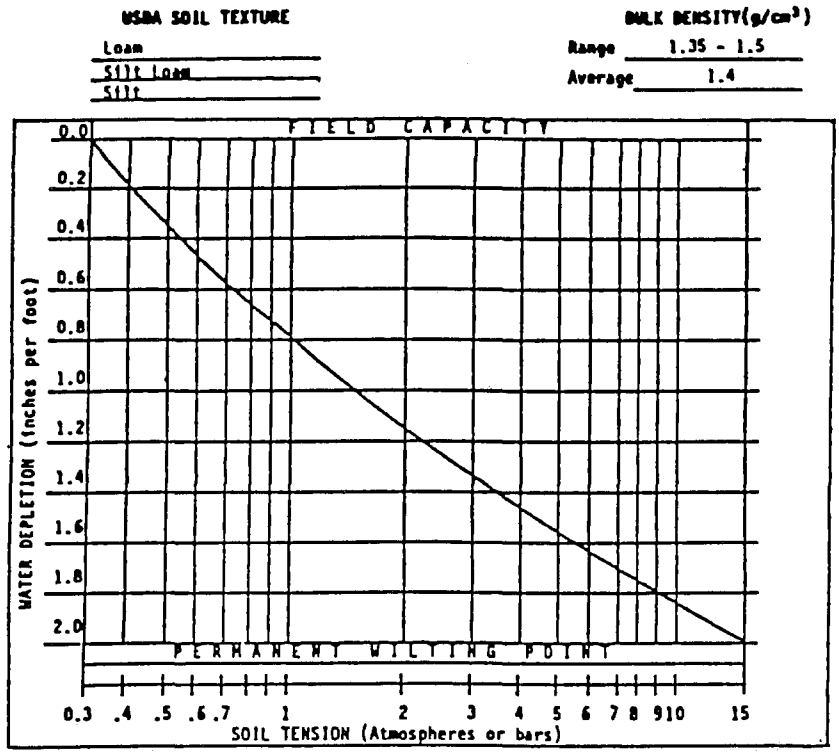


Figure 2.3a,b. Soil water characteristics, sands, loamy sands, sandy loam.



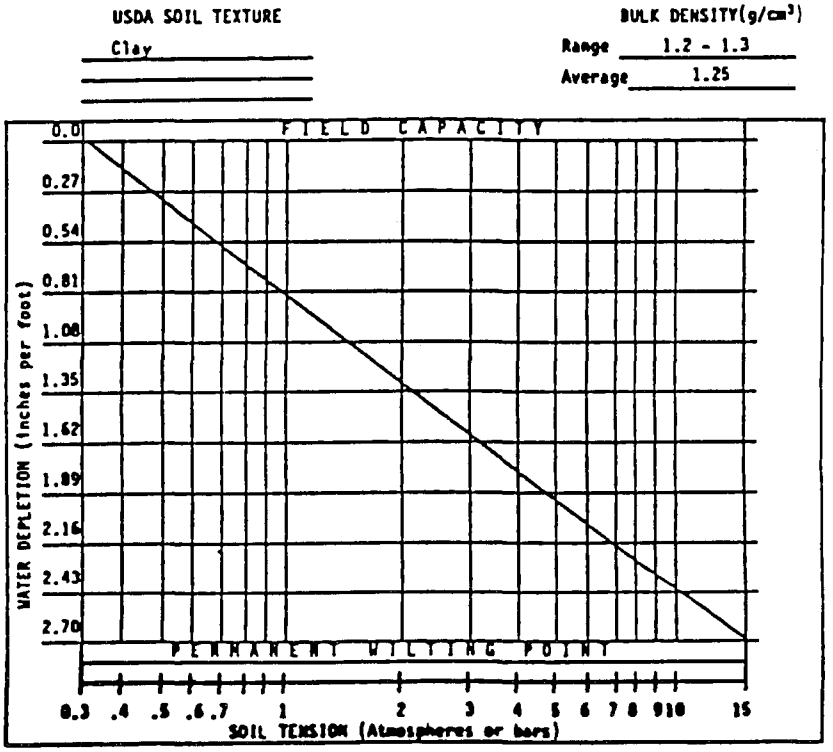


Figure 2.3c,d. Soil water characteristics, loam, silt loam, silt, clay.

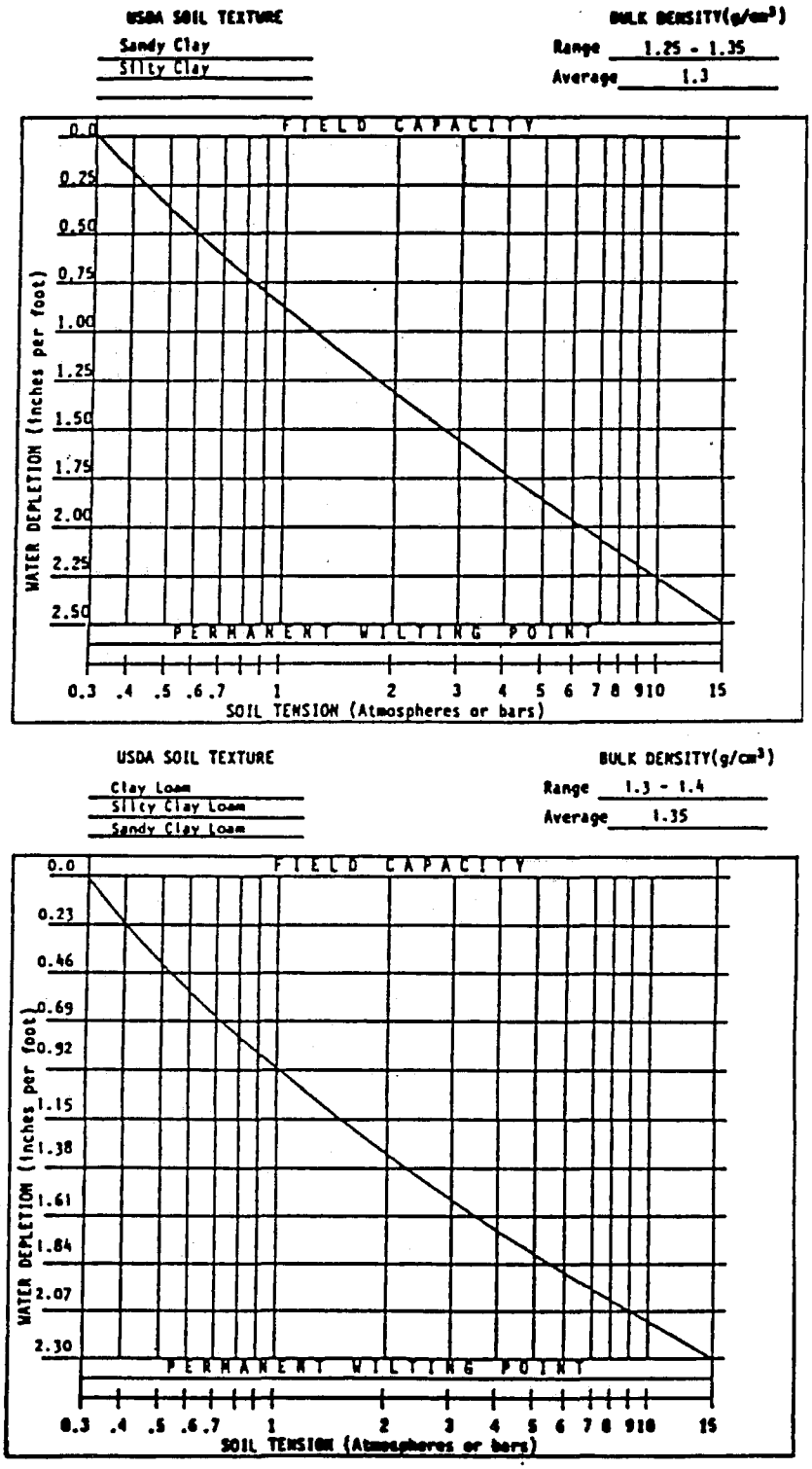


Figure 2.3e,f. Soil water characteristics, sandy clay, silty clay, clay loam, silty clay loam, and sandy clay loam.

Tensiometers work satisfactorily through a tension range from 0 to 0.8 bar. Water in the tube vaporizes at about 0.8 bar tension, rendering the device inoperative. Fine textured soils continue releasing water for plant use beyond the useful range of tensiometers, thus they are most useful for sandier soils (Table 2.4). Wilting point is well beyond the range of the tensiometer, although the lower quarter of the root zone seldom reaches tensions beyond tensiometer range.

RESISTANCE BLOCKS. This method is based on changes of electrical resistance between electrodes embedded within porous blocks. Resistance within the blocks changes as tension within the blocks adjusts to that of the surrounding soil. Therefore, the block indirectly reflects soil water content in a manner similar to tensiometers. The resistance reading is not a direct measurement of soil water content. Calibration is required and may be difficult to achieve because of typical differences in each block and soil type.

Gypsum is the most common material used for making the blocks. Nylon and fiberglass have been used but are sensitive to changes in salinity of the soil water. Gypsum masks the effect of soil salinity because the water within the block is a saturated solution of calcium sulfate. Because the pores in the gypsum are very small, these devices are not useful for measuring water content at soil water tensions less than about 0.2 bar and react very slowly to changes in soil

Table 2.4. Relation between tension and soil water content.

Soil Texture	Water Depletion at 0.8 bar	Soil Water Tension at 50 percent Depletion
Sands, Loamy sands	60%	0.6 bar
Sandy Loam	45%	0.95 bar
Loam, Silt loam, Silt	33%	1.5 bar
Clay	25%	2.1 bar
Sandy clay, Silty clay	29%	1.8 bar
Clay loam, Silty clay loam, Sandy clay loam	33%	1.5 bar

water content. Therefore, they are not recommended for use in sandy soils, where the difference in grain size between the sand and gypsum may also limit water equilibration with the block.

It is not practical to make blocks with identical porosity. Therefore, electrical resistance of individual blocks from a single manufacturer and between manufacturers varies. It is important to use blocks from a single manufacturer's lot. Saturate and test all blocks and group those blocks showing the most nearly equal readings for use in one field. Blocks from a single manufacturer should be read only with the meter provided by that manufacturer. Otherwise erroneous interpretations may be made.

Resistance blocks are inexpensive, usually less than $5.00 each. However, the reading meter can cost as much as $350.00. Normally, a set of blocks is used only one year in fields that are cultivated

annually. Replacing them is easier than retrieving the installed blocks prior to plowing. In alfalfa, pasture or other fields not cultivated annually, the blocks can be read reliably for three to five years before they deteriorate. Deterioration depends on conditions of soil acidity and salinity, quality of irrigation water, and history of wetting and drying. A recently available electronic device is similar to the gypsum block, except that it uses an artificial porous material, treated with gypsum, in which to embed the resistance electrodes. This sensor has an advantage over gypsum blocks in that it is capable of measuring water contents at much lower tension than gypsum blocks, thus is much more useful in sandy soils.

NEUTRON PROBE. The neutron probe uses a small radioactive source (usually Americium) to produce neutrons which move rapidly out into the soil. The neutron probe consists of a source of fast neutrons, a detector for slow neutrons, an instrument that counts the number of slow neutrons reaching the detecting device, and a suitable standard (a plastic shield which also helps protect the user from radiation) for verifying performance of the equipment.

The so-called fast neutrons lose energy when they collide with small atoms. Hydrogen in soil water is the most common such small atom in the soil. These collisions change fast neutrons into slow neutrons that are subject to scatter, reflection and detection by the electronics in the device. A sensitive probe detects and counts the slow neutrons. The count rate is an indication of the soil water content.

For field use, an access tube, usually aluminum, just large enough to accept the probe is placed in a hole drilled into the soil to the desired depth. The probe is lowered in desired increments of depth and readings taken. Readings are converted to water content on a volumetric basis using calibration curves furnished with the probe or determined on site by comparison with gravimetric samples.

With careful, consistent procedures, soil water measurements are relatively precise in uniform soils and measurements can be made repeatedly at one site. However readings at less than twelve inch depths are not precise because some neutrons escape into the atmosphere, and thin lenses in the soil cannot be isolated and measured with the probe.

The neutron probe is expensive, costing about $3500. All radioactive substances are potential health hazards and are controlled. Therefore, the probe must be stored, transported, and handled in conformance with strict regulations. Operators must be trained. USDA operators must wear a radiation detector badge, and submit these badges for regular evaluation to assure no over-exposure to radiation.

HEAT CONDUCTION. This method is based on the principle that heat is conducted faster in water than in dry soil. It uses an electrical heating element embedded in a porous block. Heat generated by passing an electrical current through the element is conducted away from the element. Temperature of the element after a certain time can be related to the water content of the block which is in equilibrium with the surrounding soil. This method is similar to tensiometers in accuracy. Although the method is essentially a research tool, it shows promise for field application. Units are commercially available and have been incorporated into irrigation controllers.

OTHER ELECTRONIC SENSORS. Numerous sensors have been developed recently to utilize state-of-the-art electronics. Inexpensive devices ($10.00 or so) sold at florists and garden shops measure the electrical voltage generated when two dissimilar metals incorporated into the tip are placed in an electrolyte solution, i.e., the soil water. These devices are very sensitive to salt content of the soil water and are not very useful for agricultural applications.

CHAPTER III. EVAPOTRANSPIRATION

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Evapotranspiration, or ET as it is often called, is a term used to describe the water which returns to the atmosphere from a cropped field. ET includes water which is removed from the soil by roots and transported through the plant stem and out through the leaves, called "transpiration"; water which evaporates from the leaves immediately after a dew, rain or sprinkler irrigation; and water which evaporates directly from the soil surface.

Whatever the source of the water vapor, ET is a "heat" or "energy" process. Almost all water taken up by the plant is used for cooling. One may relate ET to boiling a pan of water on the stove. The higher one turns the flame, ie, the more heat made available, the faster the water boils away. So also goes the ET process; the more energy available, the more water the crop "uses" to keep from overheating. This energy may come from several sources, and some is used for processes other than to convert water to vapor (ET). The primary source of energy in the crop environment is from the sun, or "solar radiation". Part of this solar radiation is reflected from the plants or soil and is lost back into space. Some of the energy is absorbed by plants or soil and increases their temperature. Some increases the temperature of the surrounding air, and some is used by the plant to produce materials of growth. The greatest use of energy in the plant environment is for ET. Energy is absorbed by water in the leaves, on the leaves or in the soil and turns that water into vapor. The amount of heat required to evaporate a given quantity of water can be measured very precisely, and is very nearly a constant for the conditions of evaporation from growing plants. Thus, if one can determine the heat available in the field, one can closely determine the amount of water that will be turned to vapor.

Additional energy may be moved into the crop environment by wind (advection). The amount of energy available because of wind movement is dependent on the temperature, humidity of the air surrounding the crop and amount of wind movement.

The irrigator may obtain climatic data and ET information from one of several sources, depending on his location. At the time of this writing, ET data are provided in Colorado by several commercial irrigation scheduling consultants, Colorado State University Cooperative Extension agents, USDA-Soil Conservation Service field offices, Northern Colorado Water Conservancy District and USDA-Agricultural Research Service. The interested individual is invited to contact personnel of any of these agencies for further information.

MEASUREMENT OF ENERGY PARAMETERS

To quantify the energy available for ET, several meteorological or "weather" parameters must be measured. At an agricultural weather station, solar radiation is measured with a pyranometer; total wind movement with an anemometer; and temperature with either a glass or electronic thermometer. Humidity may be measured with any of several instruments ranging from "wet and dry" bulb thermometer readings of a psychrometer to various sophisticated electronic devices. The range of units used to describe the parameters is confusing at best. The reader is advised that consistent units must be used in any ET

calculation procedure. Tables are presented in Appendix B describing the range of each of these parameters which may be expected and giving multipliers to convert from one unit to another.

The reflected portion of the solar energy is estimated with empirical formulas for all but the most sophisticated ET calculation techniques. Likewise, the portion of energy that goes to warm the plants and soil is seldom measured directly. These estimation factors are built into the commonly used techniques.

Whenever ET is to be computed from locally measured weather parameters, the location of the weather station is perhaps more important than the type of sensors used. Trees or buildings may have a significant effect on wind movement (that's why we use windbreaks). Anything that casts a shadow will reduce the measured solar radiation and reflection from buildings, etc., will increase the value. Dry soil or pavement surrounding the temperature sensor will elevate that reading. Thus, it is necessary that the location for the weather station be carefully selected if the data are to be representative of a cropped area. The weather station should be at least ten times the height of obstructions away from those obstructions. For example, locate the station at least 400 feet from a tree 40 feet in height. The anemometer should be mounted 6 1/2 feet (2 meters) above the ground. The temperature and humidity sensors should be mounted 4 1/2 to 6 feet above the ground, and must be sheltered from direct sun, yet allowed free air circulation around the sensors. Most stations use a wooden shelter, made of louvered or slatted materials and painted white to reflect radiation. The station should be located away from roads or buildings, preferably in an irrigated field of grass or alfalfa. Such a location is often difficult to arrange. Location over a non-irrigated but vegetated surface is a satisfactory alternative so long as the area around the site is irrigated. A parking lot or farmstead location is entirely unsatisfactory.

MEASURING EVAPOTRANSPIRATION

There are many techniques for measurement of ET and parameters which can be related to ET. Only a few of those techniques will be discussed here to familiarize the reader with the concepts that can be applied to determine crop water use. Many of the techniques discussed are used to determine the maximum ET, usually called the "reference ET" or "potential ET", that a well irrigated vigorous crop which completely covers the ground would use. This reference ET must be modified as described later to account for the specific crop being grown and its stage of growth.

RESEARCH METHODS

A number of methods are available which, because of the cost and complexity of the equipment required or the labor involved, are suitable only for research purposes. These methods are capable of a high degree of accuracy and are often used to calibrate the techniques used for field scale irrigation scheduling. One such method is called the "Bowen Ratio" method. Precision humidity sensors and anemometers are placed at several heights over the crop and used to measure the change of water vapor content with height above the canopy. These measurements can be related to instantaneous rate of ET. To determine total daily ET, sufficient measurements must be made during the day that the shape of the entire ET curve can be estimated. Thus, determination of actual ET by the Bowen Ratio is practically a full-time job, even for a single field.

LYSIMETERS

Most people who have studied about crop ET have at least heard the term "lysimeter". Although several types of lysimeters have been used over the years, those most applicable to irrigation scheduling over the short term are the weighing type. Essentially, the lysimeter is a large flower pot, of a width equal to one or more crop rows and a comparable length. The "pot" or lysimeter tank, is at least as deep as one would expect the crop to root in the field. This tank is filled with soil, and placed inside a slightly larger tank which contains a weighing mechanism. The weighing mechanism records, on at least a daily basis, the change in weight, which is due almost exclusively to changes in water content in the soil within the tank. Irrigations or rain increase the weight; evaporation and transpiration reduce the weight. The lysimeter is located within a field of the same crop, so that the measured ET is representative of the bulk area of the crop. Sensitive lysimeters may be able to record the depth of water applied or used to less than 0.01 inch.

Several ET computation techniques have been calibrated at several locations using data from crops grown in lysimeters. Lysimeters have been installed near Crook, CO for measuring ET on corn and dry beans. An extensive installation near North Platte, NE has been used to calibrate ET equations for corn, sorghum, and soybeans. Lysimeters at the University of Nebraska Panhandle Station at Scottsbluff have been in use for many years, and are a primary source of the "crop coefficients" used in the central Great Plains. Other lysimeter locations important for irrigation are at Kimberly, ID, Davis, CA and Grand Junction, CO. The lysimeters at Grand Junction as an example, are 44" by 60" and about 48" deep. Each weighs about 7000 pounds and is capable of measuring ET to within about 0.02" equivalent water use. Lysimeters are primarily a research tool, and are not a practical method of on-farm determination of water use.

Many small lysimeters, essentially soil filled buckets, have been used for special studies. Such devices can be removed from the ground and weighed to determine water use. They are not practical for determining ET, except possibly for lawn grass, because great care must be taken in interpreting the results from such a small sample.

EVAPORATION PAN

Perhaps one of the oldest methods of estimating crop water use from an easily measured parameter is the evaporation pan. The same parameters that cause water use by a crop cause evaporation from a free water surface. Thus many attempts have been made to relate pan evaporation to ET. Very precise standards have been developed for building and installing evaporation pans. The US Weather Bureau class "A" pan is 48" diameter, 10" deep and maintained with the water about 2" below the rim of the pan. The pan must be placed on a wooden platform of specific construction, 6" off the ground, and all vegetation kept clipped in the vicinity of the pan.

The evaporation pan maintains an automatic water balance, because any rain (or irrigation if placed under a sprinkler) tends to refill the pan, while evaporation reduces the level. To maintain an accurate pan measurement requires daily servicing, however. Water must be added, or removed following large rains, to maintain the water level near the 2" mark below the rim. Algae growth must be controlled, and the pan protected from animals which find it a convenient place to drink.

Siting of an evaporation pan is especially critical, as the surroundings have a large effect on how much evaporation occurs. The pan must be located in an irrigated area similar to that of the crop of interest. Several researchers have proposed use of a modified evaporation pan, namely a washtub, which is mounted on a wooden platform raised to maintain the washtub at the height of the top of the crop. This washtub can be marked so that the depth of water contained is easily related to the depth of water the soil will hold. Thus, any rain or irrigations refill both washtub and soil profile, and ET depletes the soil water in a similar manner as evaporation depletes the washtub. Direct use of such a pan for irrigation scheduling, however, means that the crop is assumed to use the potential ET regardless of growth stage (see later discussion of crop coefficients).

The evaporation pan is not without its problems as an irrigation scheduling tool, however. The major problem is that ET is a fraction of the measured evaporation. This fraction averages approximately 0.7 over an entire season, but is not a constant during the growing season. Thus, even though a multiplier of 0.7 may be appropriate for one particular time during the season, the multiplier may be 0.6 or 0.8 at other times. Because there is a relatively large volume of water stored in the pan, it tends to average out the incoming energy for several days. Thus, the evaporation pan technique is best suited to ET calculation over periods of the order of 10 days. The technique is best applied in areas where there is little advective energy, ie, where the humidity is high and wind speeds are low. As a result, evaporation pans are not often recommended irrigation scheduling tools for arid and semiarid areas of the western United States.

ATMOMETER

A variation of the evaporation pan which has been used since the early 1900's is the so called "atmometer". The atmometer is a device which supplies water from a calibrated container to a porous surface exposed to evaporation. By changing the color of this surface, one can change the fraction of solar radiation that is reflected, thus control somewhat the absorption of energy for evaporation. Some have covered the evaporating plate with various materials, such as cloth, to try to match the resistance to water vapor flow with the resistance of a plant leaf. The atmometer, like the evaporation pan, is quite sensitive to location, and must be placed within the cropped area and at the crop height to minimize shading or differential exposure to wind.

The atmometer also has significant storage of heat, and is generally recognized as being useful for determining water use over periods of a week or more. The device is quite inexpensive, with manually read models currently available for about $35.00 each. It is easy for the irrigator to relate the atmometer reading to ET, as the change in water volume in the calibrated supply is directly related to reference ET. Because the amount of radiation absorbed is related to the color of the evaporating surface, it is important that the atmometer be kept clean.

SOIL WATER CONTENT

Measurements of soil water content can be used, with some cautions, to estimate water use by a crop. By making measurements, using one of the techniques described in chapter 2, at two different times, one can determine the difference in total soil water storage from one time to the other. If the application (irrigations and rain) can be determined during that period, and if one can reasonably assume that no water was lost to deep percolation beyond the root zone or that water was not supplied from a shallow water table, then the net difference in water content is the use by the crop. The "water balance" method will be discussed in detail later. This method of determining ET has the advantage that it gives a value for

the actual crop ET rather than the reference ET. However, it results in lumping all the errors of measurement (and deep percolation or water table use, if they occur) into the value for ET. To be reliable, several places in the field must be sampled, and samples must be collected each day that an updated ET value is desired.

REMOTELY SENSED MEASUREMENTS

Developments of the space age have filtered into the techniques for determining ET just as in many other aspects of life. The best developed of these techniques, and probably the most nearly practical for on-farm use is the measurement of plant temperature using an infrared thermometer. Transpiration is an evaporation process, and just like evaporation occurring inside a "swamp cooler", transpiration from a leaf surface cools that surface. When the plant can no longer get enough water to satisfy the desired transpiration (ie, when water stress begins) the rate of evaporative cooling decreases and the leaf begins to warm up. The leaves of a well watered plant will be noticeably cool to the touch on a hot day. Those of a plant under water stress, however, will often be warmer than the surrounding air. By measuring the leaf temperature with an infrared thermometer and comparing it with air temperature, one can determine whether and to what degree the plant is short of water. One company has taken this measurement a few steps further, and markets a device which combines temperature with solar radiation and humidity measurements in a computerized "gun" that calculates the crop ET directly in the field.

These infrared temperature devices have been used for several years in ET research. The devices themselves are used extensively in the industrial environment to determine operating and processing temperatures in industrial plants. They range in cost from $2000 to $4000, and may be expected to come down as technology develops and demand increases. Similar sensors are mounted in several of our satellites. If problems of on-time data delivery can be overcome, perhaps wide scale use of such techniques from either satellites or aircraft will become practical in the future.

COMPUTING WATER USE

Many techniques have been developed to allow computation of reference evapotranspiration from measurements of weather (climatic) parameters. These techniques vary in sophistication. Those that require measurement of fewer weather parameters generally also require more restrictive assumptions, which limits their applicability for making daily irrigation decisions.

As discussed earlier in this chapter, evapotranspiration is an energy driven plant cooling process, with the heat or energy to evaporate water coming directly from sunlight or indirectly from wind moving warm, drier air into the area. These two sources are generally referred to as the "energy" and "advective" or wind components of ET. Methods for calculating ET are often classified by the sources of heat considered. All methods result in a value for reference ET (the ET which would occur from a reference crop), which must be modified as described later in this chapter to obtain the actual ET of the crop of interest. Note that the definition of "reference ET" is not universally the same. In California, and many humid areas, grass is used as a reference for comparing the ET of other crops. In most other areas, including Colorado, alfalfa is the common reference. Reference ET is defined as the ET from a well-watered reference crop which fully covers the soil surface (2" clipped turf in the case of grass reference, or 10-12" tall alfalfa). The grass reference does not consume as much water as the alfalfa reference, (in fact only about 85-90 percent as much), therefore, it is important for the person attempting to adapt an

ET computation technique to be certain that the same reference crop is being used consistently. For the remainder of this discussion, it will be assumed that alfalfa is the reference crop.

From the theoretical standpoint, one could write a mathematical equation that would very precisely describe the fate of all the energy available to a crop. This equation would be very complex, however, and probably could not be solved. Many of the parameters in the equation could not be measured, either. Therefore, all the methods for computing ET require some simplification in order to be of practical use. Because of the necessary simplification, all the techniques require calibration to a certain extent before being used in a specific location. The following sections describe the general characteristics of the most used types of ET equations, and their most appropriate use.

COMBINATION EQUATIONS

The combination equations, so called because they combine the effects of the radiation and wind terms, are the most sophisticated class of ET calculation equations. As such, they are least limited by simplifying assumptions, but also require the most weather data for computations. The modified Penman equation, used frequently in Colorado ET computations, is representative of this type of equation.

The Penman equation requires measurement of daily solar radiation, maximum and minimum daily air temperature, total daily wind movement (ie, average wind speed in miles per hour, multiplied by 24 hours per day), and a measure of the average water content or humidity of the air. Humidity may be measured as relative humidity (the percentage of water in the air compared to the maximum amount it will hold at the current temperature), dew point temperature (the temperature at which dew will begin to form with the current amount of water vapor in the air), or the vapor pressure (the pressure of the air that can be attributed to the presence of water molecules). The unit of humidity measurement will depend on the type of sensor used, but by knowing the temperature and corresponding measure of humidity, one measure may be converted to another. The principal point to be made is that the humidity value measured must be consistent with the value required for the computation procedure.

The Penman equation has the advantage that it accounts for the various weather parameters in sufficient detail that it can be used for computation of daily (or even hourly under certain circumstances) ET values. However, this advantage is at the expense of several disadvantages. First, solar radiation is measured at only a few US Weather Service stations. Most stations providing the necessary data for Penman ET calculations are stations set up expressly for that purpose. The equipment for collecting data for Penman ET calculation costs about $3000, depending on the degree of automation desired. This equipment will serve an extended area, although the distance one can stretch the data is probably not as important as the changes in terrain and land use within that distance. In similar terrain, with similar patterns of irrigation, dryland cropping and rangeland, the data have been used for 50 miles surrounding a weather station. If the terrain changes, however, as from the plains to a river valley, or one goes from the fringe of an irrigated area to an intensively irrigated area, stations 5 or 10 miles apart may show significantly different weather parameters.

RADIATION METHODS

As the name implies, the radiation methods make use of measured values of the radiation components of the ET process. The most frequently used of these methods in Colorado is the Jensen-Haise method, which requires measurement of solar radiation and air temperature. The Jensen-Haise

method is calibrated to an area based on the elevation above sea level and the difference between average daily maximum and average daily minimum temperatures during the hottest month of the year (July in eastern Colorado). Thus, humidity is taken into account only as it affects the difference between maximum and minimum temperatures. In humid areas, the temperature cools less during the night than in arid areas, because there is more heat stored in the more moist air and those areas more commonly have nighttime cloud cover which retains heat. The effects of wind on ET are not taken into account by the Jensen-Haise method.

So long as the wind component is not large (ie, wind speeds are low and/or the humidity is high), the Jensen-Haise method can be reasonably applied to calculate reference ET. In recent years, the US Bureau of Reclamation has found that the correction for elevation results in overprediction of ET at higher elevations. Further, the Jensen-Haise method is not recommended for calculating ET on a basis more frequent than five days, which generally limits its usefulness to areas with relatively heavy soils which require irrigation at longer than five day intervals.

Although radiation data are probably the least readily available from established weather stations, that parameter is relatively easy to measure. Commercial electronic instruments are available which automatically measure temperature and solar radiation and use a built-in microcomputer to calculate and display the Jensen-Haise reference ET. These instruments cost in the vicinity of $1200 each, and can probably be placed further apart than Penman ET stations, so long as the restrictions of the technique are recognized. The Jensen-Haise method involves a simple mathematical equation, and values of reference ET can be easily computed with a hand calculator or even longhand.

TEMPERATURE METHODS

One of the first widely used techniques for calculating crop water use was based on correlation of ET with air temperature. The USDA-Soil Conservation Service has long used one such method, the Blaney-Criddle, for long term ET calculations. This technique requires mean air temperature and percent of annual daytime hours during the period of interest to calculate reference ET. Because of its simplified nature, it is useful for ET calculation over periods of a month or longer. The Blaney-Criddle method is more useful for irrigation design and planning than for making daily irrigation decisions. However, because air temperature measurements have been made for many years in all parts of the world, and are often the only weather data available, such techniques are often the only ones which can be used, at least until several years have elapsed since interest in ET calculation began in the area.

OTHER METHODS

Numerous other methods exist to calculate reference ET. In Europe, methods based on humidity are used, although humidity is the most difficult of the common weather parameters to measure. Several investigators, with Hargreaves being a notable example, have developed methods based on statistical correlation of various parameters to local data. Such methods often do a good job of matching historical ET data to which they were fitted, but their accuracy for ET calculation from new data is less certain.

The methods discussed are only a few of the many techniques available. Numerous studies have been conducted to compare the results of one method with another for a given area. The results depend on many factors, and one may no doubt hear that a certain technique works best. Nevertheless, based on several years experience and in-depth studies of the various techniques, the author of this chapter

recommends the modified Penman and Jensen-Haise techniques for use in the High Plains area of eastern Colorado. The Penman is expected to provide the most accurate results, and is the preferred method where data are available. For irrigation of very sandy soils, as in northeastern Colorado, where the soil holds only 3 to 4 days worth of ET, the use of the Penman equation is essential. In heavier soils, with an irrigation frequency of 10 days or more, particularly in areas not exposed to hot, high winds blowing from a large expanse of dry rangeland, the Jensen-Haise method is an acceptable and less costly method to implement. Whichever method is used, the increased attention focused on water management as a result of ET computation will probably result in improved irrigation and increased crop yields.

ACTUAL EVAPOTRANSPIRATION

The previous discussions have concentrated on computation of reference ET. It was mentioned earlier that actual water use by the crop is different from the reference ET. This difference is accounted by increasing ET when a wet soil surface (following a rain or irrigation) will result in increased evaporation; by decreasing ET when the soil is so dry that the crop cannot get as much water as it would like, and by multiplying reference ET by a "crop coefficient" to account for increased water use by the crop as the plant gets larger. The crop coefficient at a given time is the ratio of actual ET to reference ET (ET_a/ET_r).

AVERAGE AND BASAL CROP COEFFICIENTS

Adjustments of reference ET to actual ET must be made in different ways, depending on the expected use of the ET data. When data are published in the newspaper, broadcast on radio or television, or recorded on a telephone answering machine, the person making computations has no way of knowing whether Farmer A's corn field was irrigated yesterday or whether he missed an irrigation. Neither does he know how much it rained on that field last night, nor what kind of soil is in the field. Therefore, for such "regional" ET calculations, computations are made assuming that the crop has adequate water, and that planting and crop development dates follow average values for the area. The crop coefficient used to convert reference ET to actual ET includes a further assumption that the soil surface is wet some "average" amount of time. Thus arises one type of crop coefficient, ie, one based on average conditions for the area.

On the other hand, if the person making computations has the information necessary for a specific field, then he/she can make more precise adjustments to take into account the periods when the soil surface is wet or sufficiently dry to limit crop water use. Under such conditions, it is appropriate to use a different crop coefficient which accounts only for crop water use, and not the excess evaporation that occurs from a wet soil surface. Such a crop coefficient is called a "basal" crop coefficient.

THE CROP COEFFICIENT CURVE

Use of an "average" crop coefficient will result in error, if any, on the side of applying somewhat more water than the crop actually needs, at least during the early growing season. Research on sandy soils in eastern Colorado indicate that reducing water application below crop needs reduced yields about 8 bushels per acre for each inch of water the crop was short. With the price of water in most of Colorado, it is probably better to apply a little too much water (increasing pumping costs and perhaps losing some fertilizer) than to stress the crop by not applying enough water. Thus, for the 1987 irrigation season at

least, the author recommended that "average" crop coefficients be used for all irrigation scheduling in eastern Colorado, even when fields are scheduled on a field-by-field basis. As schedulers and irrigators gain confidence and proficiency, then the water application can be "tightened up" with a more precise crop coefficient.

Perhaps it is appropriate to discuss how and where crop coefficients have been developed, and just how relevant they are expected to be to conditions in eastern Colorado. Figure 3.1 is a typical crop coefficient curve for corn. Note that early in the season, the value of K_c (ie, the ratio of actual ET to reference ET) is low, but not zero. Until emergence, the crop itself uses no appreciable water. However, ET also includes evaporation, and evaporation does occur throughout the season. As the crop begins to grow, the value of K_c increases, slowly at first, then quite rapidly until it reaches a maximum value.

This maximum value occurs at the time the crop reaches "full cover". Full cover is generally defined as the stage of growth at which the crop is intercepting as much incoming energy as it will ever intercept. Full cover may be quantified by the ratio of leaf area to soil area (when leaf area is 3 times the soil area, crop is at "full cover"), by a measure of light interception, or as percent of soil shading. Soil shading is probably the easiest parameter to estimate in the field. For most crops that can be expected to develop "full cover", the soil surface is about 75 percent shaded at full cover. Approximate time or stage of growth at which full cover is expected is shown in Table 3.1 for various crops.

Many of the early crop coefficients were developed from periodic measurements of differences in soil water content and comparing the measured water use with reference ET. Researchers at Davis, CA

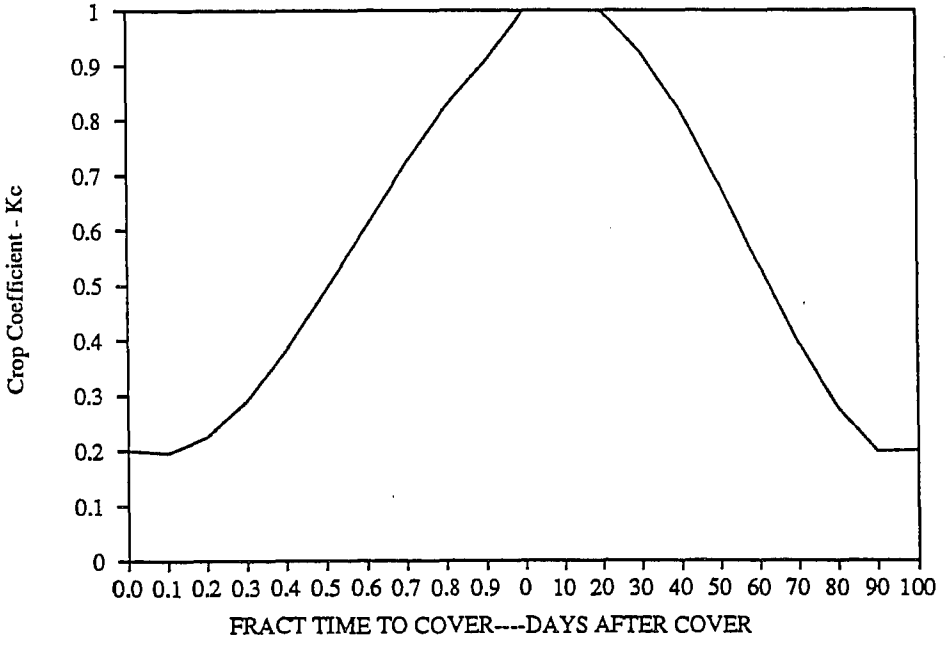

Figure 3.1. Typical crop coefficient curve for corn.

Particularly when ET is calculated using a computer program, it is often desirable to express the crop coefficient as a mathematical equation. Because of the change in shape of the curves near full cover, it is most common to use two equations to describe the crop coefficient; one from planting to full cover, the other from full cover to harvest. These equations are expressed in the form:

$$K_c = Ar^3 + Br^2 + Cr + D$$

where r represents the fraction of time from planting to full cover (today's day-day of planting divided by days from planting to expected full cover) for the period up to full cover. The value of r varies from 0 to 1.0 during this period. After full cover, r is simply the number of days since the crop reached full cover. Typical crop coefficient curves and the corresponding values of A, B, C and D are shown in Appendix D.

ADJUSTING CROP COEFFICIENTS

The crop coefficients shown have been developed over a period of several years, and represent the rate of crop development in an "average" year. Of course, most farmers know that we seldom have an average year. As a result, the crop coefficient curve may not match the actual crop growth very well if one just picks a planting date, a full cover date and blindly proceeds to calculate water use. If the spring is wet and cool, the crop may emerge, then "sit still", growing only very slowly. Obviously, a corn crop that is 4" tall on the day it should be 12" tall will not use as much water as we would have estimated under normal conditions. On the other hand, if conditions are just right, the crop may be 20" tall on the date it would normally be only 12" tall. Thus, we must use some judgement to "adjust" the crop coefficients to account for the actual condition of the crop.

Considerable work has been done to attempt to develop realistic means of determining the actual value of the crop coefficient at a given time. Remote sensing techniques, using aircraft, satellite, or handheld measuring devices promise to allow accurate determination of K_c sometime in the future. Photograph sets have been prepared to allow a visual estimation of the value of K_c for different crops. Perhaps the most used method of adjusting K_c is to artificially adjust the planting and expected full cover dates. Any farmer has a good idea of the stage of growth a given crop should be on any given day, and readily talks about crops being "two weeks behind" or "10 days ahead" of normal. Using such a concept to adjust the planting date 10 days later than the date of actual planting for a crop said to be "10 days behind", or adjusting planting date earlier for crops ahead of schedule, has been quite successful. When one adjusts the planting date in such a manner, he must also consider the effect of the "early" or "late" season on the full cover date. For the grass crops (wheat, corn, sorghum), the full cover date will not be shifted as much as the planting date. As a rule of thumb, the full cover date will occur 1 day earlier for every 3 to 5 days earlier the crop is "planted". With most broadleaf crops, however, the time from planting to full cover is more nearly a constant. That is, if a cool season delays the crop a week in early stages, then the cover date will be delayed a similar length of time if the season is normal following early season delay.

Several researchers have attempted to use other means of "growing" the crop in the crop coefficients. Some use only days from planting. With such a curve, it is easy to determine which value of K_c to use at any time, but this type is restricted in applicability to a range of varieties or locations. Others have tried to use "growing degree days" or "heat units" as a means of better tracking the appropriate value of K_c to use. The results of such studies have been rather inconsistent. This author,

and Kimberly, ID have used precision weighing lysimeters for two decades or more to measure water use by both the reference crop and a variety of other crops to determine the ratio, or crop coefficient.

During the late 1960's and early 1970's, Kincaid and Heermann used lysimeters installed at the University of Nebraska Panhandle Station, Scottsbluff, to determine crop coefficients for major crops grown in the central Great Plains. In the following years, about a dozen lysimeters were used over a 3 to 4 year period near Crook, Logan County, CO to verify the Kincaid-Heermann coefficients for corn and dry beans. Several studies have been conducted throughout the area to compare computed soil water

Table 3.1. Full cover stages for selected crops.

Crop	Stage of Growth or Days From Planting to Full Cover
Alfalfa	30 days after spring greenup and 20 days after each cutting
Corn	10 days after tasseling
Dry beans	mid-bloom or about 50 days
Pasture	30 days after spring greenup
Potatoes	80 days after planting
Sorghum	heading
Soybeans	bloom
Sugar beets	110 days after planting
Winter wheat, other small grains	heading

during the irrigation season with measured soil water. From these studies, a level of confidence has been gained in the crop coefficients in common use. The coefficients of Kincaid and Heermann have found the widest use in eastern Colorado and western Kansas, and are the primary basis for recommendations made to Colorado ET users for the 1987 irrigation season. University of Nebraska researchers have used numerous lysimeters at the North Platte Experiment Station and near Lincoln to measure crop coefficients for corn, sorghum and soybeans. University researchers at Manhattan, KS have used meteorological methods to determine crop coefficients for major crops across Kansas.

Figure 3.1 illustrates the primary method used to "grow" the crop in a crop coefficient curve, and the reason that the full cover date is important. Note that until the time of full cover (near the peak value of K_c), the time (horizontal axis) is expressed as fraction of time from planting to full cover. This means of expressing development compensates, at least partially, for the differences in varieties and differences in time it takes a crop to develop in different areas. Of course, if one can estimate the date of full cover and planting, the fraction of time scale can be readily converted to number of days. After full cover, the crop coefficient is expressed in terms of days. Although many ET computation programs ask the user to estimate the date of crop harvest, this parameter does not effect computed ET values.

while admitting the shortcomings of the method, suggests for the present that the fraction of time to full cover/days after full cover method be used.

CHAPTER IV. WATER APPLICATION

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WATER APPLICATION AND IMPORTANCE OF ITS MEASUREMENT

The water user must be aware of the amount of water needed to replace the soil water depletion at the time and place the irrigation water becomes available. Since each crop type has its own water use characteristics, one must be aware of the soil water depletion status at all times. This is important because of the high cost of water and crop investment and the risk that excess depletion will reduce yields.

PRECIPITATION

The amount, intensity and distribution of precipitation will vary from field to field. Therefore it is very important that the farmer or irrigator obtain his own rain gauge for each field or rely on a close-by gauge so that he can estimate his own water needs as best possible.

Precipitation gauges are available from many companies. Some of the most dependable are the standard 8-inch rain gauge and the tipping bucket rain gauges. Wind screens which minimize the formation of strong wind updrafts are available. There are also rain-snow gauges which are ideal for measuring winter precipitation in remote areas. Precipitation detectors can be obtained also. These utilize gold plated grids to sense the occurrence of precipitation. Rate-of-rainfall gauges can also be obtained. These gauges incorporate a "probe train" which provides input to a translator which records the rate of rainfall.

The farmer or irrigation manager does not need a sophisticated rain gauge to use in his operation but can obtain many excellent varieties of small gauges to fulfill his needs. One of these is the 11-inch "Clear-Vu" rain gauge. These gauges have a rectangular opening and tapered body, are inexpensive and are recommended highly by the National Weather Service. The small diameter glass tube gauges often given as advertising promotionals are not satisfactory.

EFFECTIVE PRECIPITATION

Effective precipitation can be defined as the amount of water occurring in a rainfall event that is intercepted by vegetation, utilized for crop growth, essential for leaching or is stored on the soil surface and evaporates. Therefore, ineffective rainfall is that portion that is lost to surface runoff, unnecessary deep percolation or water removed from the soil after the crop harvest which is not useful for the next season's crop.

There are several methods of determining effective precipitation. These methods include measuring soil moisture changes, use of small portable devices containing soil from the field to weigh changes in water content and lysimeters.

Effective rainfall can also be determined by formula. For practical irrigation scheduling purposes, effective rainfall is usually estimated from observing whether significant runoff occurred, and if so, the estimated fraction that ran off.

FLOW MEASUREMENT TO DETERMINE IRRIGATION APPLICATION

Once the irrigator has determined that he has reached the depletion at which an irrigation is necessary, he must have available sufficient and accurate flow measuring devices to take care of his water needs.

Application of water on a small tract of land or farm does not require large flow measuring devices. There are commercially available flow, pressure or hand held measuring devices to perform the operations needed.

Flumes are widely used and can be purchased commercially. These flumes are usually for low flows and therefore are small. Parshall and cutthroat flumes require significant head drop through the flume to get an accurate measurement. The broad crested flume is an accurate and inexpensive device for measuring flow rate with minimal head loss. One depth measurement is made above the control section. Orifices, short tubes and irrigation siphons can be used to measure flow rates with appropriate calibrations.

Weirs can be used to measure furrow flows, but a large increase of flow results from a small increase of head, causing inaccuracy of measurement. Ninety-degree V-Notch weirs are a practical measuring device for small flows.

Trajectory of a horizontal jet is a simple and practical estimating method when flows from ends of pipes are needed, and accuracy is not of prime importance.

In ditches, current meters, surface floats or moving vertical vanes may be used to determine velocities in several sub-section areas of the cross-section and the product of velocity and area of each section totaled to determine total flow rate.

Specific details of installation and operation of flow measuring devices can be found in the USDA-SCS National Engineering Handbook, Section 15, Chapter 9, and the USDI-Bureau of Reclamation Water Measurement Manual.

DECIDING WHEN AN IRRIGATION IS COMPLETE

The methods presented in later sections of this guide will be directed toward determining when to irrigate and how much water to apply. If one could assume that irrigation were equally effective on all parts of the field, and that all water delivered to the field were effectively stored for the crop, then the methods would be straightforward. Unfortunately, such is the rare exception, and the irrigator must carefully monitor each field to determine when to stop an irrigation.

Under well designed and managed sprinkler irrigation systems, the ideal can be approached. It should be emphasized that periodic testing of both the sprinkler system performance and the pumping plant performance can pay big dividends in controlling irrigation costs. Local CSU Extension or USDA-

Soil Conservation Service personnel have information on availability of such services. Over the period of several irrigations, the efficiency of irrigation application may approach a constant value, and should be in the vicinity of 85 percent. Thus, if the application rate is not too high for the soil type, about 85 percent of the water applied can be assumed to be infiltrated where it falls, without significant runoff. In such a field, one must identify the extent of various soil types, and schedule irrigations to make certain that those areas with the least water holding capacity are neither overirrigated nor allowed to undergo water stress. At the same time, areas with higher water holding capacity (usually those with lower intake rates) must be irrigated at sufficiently low rates that water does not run across the surface from one area to another. Note that little is to be gained by applying more water to soils with high water holding capacity than to areas within the same field and same crop with low water holding capacity. Unless the plant is forced into a stress situation, rate of water use is little influenced by the soil type. Thus, excess water applied to heavier soils is wasted, or crops are stressed on the lighter soils if irrigations are larger than the lighter soils can hold.

Under surface irrigation systems, the decision of when to stop an irrigation is much more complex. All the problems of varying intake rates and varying water holding capacities are present with surface irrigation systems as well as sprinklers. In addition, the surface system depends on this variable soil to move water to the other end of the field, unlike the pipeline with controlled outlet sizes which moves water in a sprinkler system. Typically, larger depths of application (and less frequently) are required, which means that water must infiltrate for a longer period than with a sprinkler. As a result, part of the applied water runs off the end of the field and part may penetrate too deep for the roots to reach.

The best advice we can offer as to when to stop irrigating is to seek assistance to tune the irrigation system design and management to achieve the most uniform application practical, then check the soil at several places to see how deep the irrigation has penetrated. A shovel will not allow an adequate sampling depth, unless the irrigator is especially ambitious. He must sample to the bottom of the root zone (say 4 feet in a deep soil for corn) to adequately determine the adequacy of irrigation. A core-tube type probe, about 3/4" in diameter allows withdrawing about a foot of sample at a time, and brings up a relatively undisturbed sample in which you may find roots and determine a bit about soil structure and tilth. An auger (old 1" wood bit with a 4' extension and "T" handle) may be less expensive but takes a little longer. The auger will recover a sample adequate for determining water content and penetration, but obviously disturbs the sample. Another alternative is to fabricate a penetration probe from a pointed 4' long piece of 3/8" steel rod with a "T" handle. This probe can be pushed into the wet soil by hand. In most soils it easy to tell when the probe encounters a different layer because the force required to push it in increases suddenly. If the soil is uniform, the point of increased resistance may be indicative of the depth the irrigation has penetrated. One must be sure that the change in resistance is not due to plow pans or changes in soil texture, and that assurance will come only with experience and, perhaps, further sampling.

CHARACTERISTICS OF AN ON-FARM IRRIGATION SYSTEM

Some of the types of irrigation systems are furrow, border, drip and sprinkler. These systems apply irrigation water in different ways but they all have one thing in common; they all require sufficient application rate to irrigate the field properly.

If the field is furrow or border irrigated, it is very important that there be sufficient flow rate at the upper end that the water will reach the lower end of the field without excess infiltration. Therefore

it must be stressed that the irrigation system be properly designed in order that the water may be applied both in time and amount needed.

If the irrigation system is improperly designed or managed, there is the possibility of runoff at the ends of the fields, excessive deep percolation and non-uniformity of water application.

After a sprinkler irrigation system has been properly designed, the irrigator must be aware of the set time (or speed of operation for moving systems) necessary to refill the soil water depletion. He also must be aware of drift caused by excessive wind velocities.

Under surface irrigation systems, usually the surface soil water content is at the permanent wilting point or less when the lower profile is at allowable depletion. The soil is increasingly wet with depth. Normally, field capacity is reached just below the effective root zone.

The top 12-inches of the soil under a sprinkler irrigation system is usually kept fairly wet. However, if irrigations are too frequent, water removed from the lower root zone may not be replaced. Such a condition results in reduced root development and reduced yields, particularly if the irrigation system is of marginal capacity to meet subsequent peak demands. One will usually find that the deeper soils will become increasingly drier as the season progresses. This is particularly common when the irrigation system is designed to apply less than the peak ET rate for the crop.

DESIGN CAPACITY

The desired design capacity of the system carrying water to an irrigated field is a function of the peak ET rate. In order to determine peak ET rate, an analysis of average daily ET has to be made. The length of the averaging period is the number of days readily available soil water will last at the peak ET rate. Smaller usable soil water storage will result in a higher design application rate since average peak use is higher for short periods. Larger soil water storage will, conversely, result in lower design application rates because average peak use rate is lower for longer periods.

IRRIGATION EFFICIENCY

Efficiency of irrigation is the fraction of water that is stored in the soil and available for consumptive use by the crop. When the water is measured at the farm headgate it is called farm irrigation efficiency; when measured at the field it is designated application efficiency; and when measured at the point of diversion, it may be called project efficiency.

For purposes of irrigation scheduling, application efficiency is important for estimating the depth of usable soil water storage resulting from an irrigation. Table 4.1 may be used to estimate application efficiency for purposes of irrigation scheduling.

Table 4.1. Typical irrigation application efficiencies.

Method	Efficiency (%)	Comments
Center pivot	70-90	<70% if operated at wind speeds exceeding 6-10 mph, if runoff occurs or low pressure operated on steep terrain. Average 85%.
Drip	75-100	High percolation loss if spaced too far apart. Average 90%.
Level basin	70-90	Requires precision leveling and high flow rates. Average 80%.
Furrow - sandy Furrow - clay	20-60 50-90	Increased by tailwater reuse, reduced furrow length, improved management methods such as surge, cablegation. Decreased by neglect of maintenance, improper leveling, poor irrigation management. Average varies greatly since soil variability is a greater factor than for above systems.

CHAPTER V. MAKING THE IRRIGATION DECISION

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DECIDING WHEN AND HOW MUCH TO IRRIGATE

The irrigation decision can be made in two time frames: long-term and short-term. Long-term irrigation decisions are made at or before the beginning of the season while short-term irrigation decisions are made day-by-day during the irrigation season.

Long-term irrigation decisions include determining the seasonal peak water demands to size and design an irrigation system or to allocate a limited seasonal water volume among candidate crops. Therefore, long-term irrigation decisions must rely on averages of water use based on historical data.

Short-term irrigation decisions are made to determine when and how much to irrigate. These decisions are based on the daily water use. This text emphasizes the short-term irrigation decisions.

The process of making an irrigation decision can be divided into three stages related to specific time frames and which occur at different points in the irrigation development and management process.

The design stage is the initial stage in which the irrigation method and system size is determined. At this stage, long-term irrigation decisions are used in conjunction with soil types, slopes, available water supply and other relevant factors.

The resource allocation stage takes place at the beginning of the season to decide how to allocate the available water supply. Long-term irrigation decisions are needed at this stage to determine seasonal water requirements of different possible crops. Knowing water requirements of candidate crops and available seasonal water quantity a decision can be made regarding areas of different crops that can be grown without exceeding the available water quantities and flow rates. The irrigator may also decide when and how much to stress the various crops to maximize economic return.

The immediate stage is that of short-term irrigation decisions, i.e., the daily decision of when and how much to irrigate. To make the daily irrigation decision, information regarding soil water status and crop status is needed.

FACTORS TO CONSIDER IN THE IRRIGATION DECISION

When making the irrigation decision, several factors need to be considered.

CLIMATE. Climate, or long term weather patterns, effect the expected daily water requirement. Different approaches to making the irrigation decision can be taken in different climates. In arid areas where rainfall is insignificant during the growing season, and in areas where weather conditions are relatively uniform from year to year during the growing season, long-term decisions can be used to construct an irrigation time table at the beginning of the season. In semiarid and humid areas, weather

conditions vary significantly on a daily basis. In these areas, the irrigation time table cannot be determined beforehand. The irrigation decision must be made on a daily basis.

SOILS. Soils act as the water reservoir for the crop. The water-holding capacity and water intake rate of the soil need to be considered in deciding when and how much to irrigate. These factors may limit the amount of water that can be applied in one irrigation and the application rate. The application rate should not exceed the water intake rate of the soil with sprinkler
systems and application depth should not exceed the soil water depletion, except as necessary for leaching of salts.

CHARACTERISTICS OF THE IRRIGATION SYSTEM AND WATER SOURCE. The available water source and capacity of the irrigation system dictate the maximum amount of water that can be applied in a given period of time. If the capacity, or maximum flow rate, of the system is larger than the available flow rate from the source, then the limiting factor is the water source. This maximum flow rate is an important consideration since it determines the time it takes to complete a full irrigation and the area that can be irrigated. A partial irrigation will reduce the time to complete an irrigation, however partial irrigations increase the necessary frequency of irrigations and may impede root development if a dry zone is allowed to develop in the lower soil profile.

CROP GROWTH STAGES. Some crops are more sensitive to water stress at a given stage than others. Table 5.1 describes the growth stages at which several crops are most sensitive to water stress. When making the irrigation decision, the crop growth stage should be considered. Crops that are in a sensitive stage of growth should be irrigated at a lower soil water depletion level than those which can stand to be stressed. If a crop that is last in the irrigation rotation is at a sensitive stage of growth, the recommended strategy may be to apply partial or lighter irrigations in order to reach the end of the field before the sensitive crop is subjected to water stress. Such a strategy used with sprinkler systems, however, may result in trouble. If the soil is repeatedly wetted to only shallow depths, a dry layer tends to develop at shallow depths, which further aggravates the need to provide an irrigation quickly.

THE IRRIGATION DECISION

In an intensive operation where several fields are irrigated from the same system, a situation may arise in which irrigation is needed in different fields at the same time. A measure is needed to determine the relative need for irrigation and an associated level of that need. This measure will be called the irrigation indicator. To decide how much to irrigate, another decision rule is needed.

INDICATORS OF NEED FOR IRRIGATION

The magnitude of the irrigation indicator is the trigger for starting irrigation. Indicators of irrigation need can be crop appearance, soil water status, time or any other measure that has been defined to indicate the need for irrigation. These indicators can be grouped into three main types:

(1) indicators based on time or availability of water,
(2) indicators based on feedback from the field, and
(3) indicators based on economic criteria.

Table 5.1. Growth periods during which crops are most sensitive to water stress (from FAO Irrigation and Drainage Paper No. 33).

Crop	Most Sensitive Stages
Alfalfa	Just after cutting (and for seed production, at flowering)
Beans	Flowering and pod filling; vegetative period not sensitive when followed by ample water supply
Cabbage	During head enlargement and ripening
Carrots	Sensitive during entire season, especially from seeding to emergence
Corn	Tasseling more sensitive than grain filling; tasseling very sensitive if no prior water deficit
Cucumbers	Fruit production more sensitive than flowering, which is more sensitive than vegetative period
Grapes	Vegetative period, particularly shoot elongation and flowering more sensitive than fruit fill
Lettuce	Sensitive during entire season, especially from seeding to emergence
Onions	Bulb enlargement, particularly during rapid bulb growth more sensitive than during vegetative period (flowering sensitive period for onions grown for seed)
Peas	Flowering and pod fill greater than vegetative or ripening for dry peas
Pepper	Throughout, particularly just before and early flowering
Potatoes	Stolonization and tuber initiation, tuber enlargement greater than early vegetative period and ripening
Sorghum	Heading to soft dough greater than vegetative; vegetative period less sensitive when followed by ample water
Soybeans	Flowering and particularly during pod filling
Squash	Fruit production more sensitive than flowering, more sensitive than vegetative period
Sugar beets	First month after emergence
Sunflowers	Flowering greater than seed fill, both greater than vegetative. Particularly sensitive during period of bud development
Sweet corn	Ear formation stage most sensitive, keep well watered from pollination to harvest
Tomatoes	Flowering greater than fruit fill. Least sensitive during vegetative, except transplant period
Watermelon	Flowering, melon enlargement greater than vegetative period, particularly during vine development
Wheat	Heading to soft dough greater than vegetative period; winter wheat less sensitive than spring wheat

IRRIGATION INDICATORS BASED ON TIME OR AVAILABILITY

These are not field indicators but rather a predetermined or dictated irrigation schedule. In some areas, a predetermined time table of irrigation can be used. Such time tables are not practical for Colorado's conditions. A more common situation in Colorado is irrigation timing based on availability. Systems that deliver water on a rotation basis dictate the irrigation timing to the individual farmer. Therefore, instead of using measures to indicate need for irrigation, the farmer will irrigate whenever he gets water from the ditch company. The important question, then, is how much water to apply.

IRRIGATION INDICATORS BASED ON FEEDBACK FROM THE FIELD

Many irrigation indicators are based on feedback from the field. Two types will be discussed here--crop status and soil status.

CROP STATUS. The status of the crop is an indicator of the need for irrigation. Crop appearance has been used as an indicator of the need for irrigation for many years. A crop suffering water stress tends to have a darker color, less "sheen", and may even exhibit curling or wilting. This indicator is inferior for modern agriculture because of its low accuracy. Crop yield can suffer from water stress before any visual signs show up. There are more sophisticated indicators based on crop status that require complicated instrumentation. The main disadvantage of these indicators is the problem of determining how much water to apply. The main advantage is that these indicators provide direct feedback from the plant.

SOIL WATER STATUS. These indicators are based on monitoring the soil water status. Two parameters can be used as indicators of need for irrigation--soil water content or soil water tension. The first determines the amount of soil water existing in the root zone. Soil water content is measured in units of depth of water stored in the soil profile or percentage of field capacity. The second indicator, soil water tension, is based on the fact that the soil water is held to the soil particles by capillary forces and some tension or suction is needed to remove the water from the soil. Soil water tension increases as the soil water content decreases. Soil water content and soil water tension can be measured directly or estimated and provide direct feedback from the soil. The main advantage of using the water content type of indicators is that they provide a quantitative measure of how much water to apply.

ECONOMIC INDICATORS

Economic indicators are based on estimated production costs and returns from crops. An economic indicator can be net return, which is the gross income from the crop less the production costs. Information on income from crop yield is not known during the growing season but must be estimated. Using these indicators is beyond the scope of this publication and they will not be discussed in detail.

IRRIGATION SCHEDULING

ESTIMATING VERSUS MEASURING WATER USE

Two basic approaches can be used to determine the level of irrigation indicators--estimation and measurement. Usually soil water status and crop status indicators are measured directly. Some of these indicators can also be estimated. For example, soil water content can be estimated by using water balance methods and calculating ET (see Chapter 6).

Direct measurement of an irrigation indicator is always more accurate than estimating its magnitude. However, the number of samples required to be representative of the entire field is often prohibitive. An estimated indicator may more accurately represent the overall field condition because of the large variability, particularly in soil parameters, within the field. Measuring certain indicators requires significant labor and time, therefore, oftentimes it is advantageous to estimate these indicators.

Soil water content is a good example of an irrigation indicator that can be measured or estimated. Accurate measurement of soil water content is labor intensive and, therefore, expensive. By using ET calculations, the soil water content can be estimated. By adjusting the estimation procedure to the particular conditions, a reasonable level of accuracy can be achieved. Using ET calculations to estimate soil water content also allows projecting irrigation need into the future by using weather forecasts. The main trade-off between measuring and estimating the irrigation indicator is less accuracy for significantly less labor.

SCHOOLS OF THOUGHT ON IRRIGATION SCHEDULING

Two schools of thought on irrigation scheduling can be found in the literature. The maximum yield school asserts that "irrigation must take place while the soil water content is high enough to meet the crop water requirement without placing the crop under water stress". The irrigation decision is aimed at maximizing crop yield no matter how much it will cost.

On the other hand, the maximum net return school of thought asserts that the primary purpose of irrigation is to supply the crop with the amount of water it needs to achieve the optimum return to the agricultural enterprise. According to this approach, the irrigator will choose to reduce yield if the irrigation cost is higher than the expected return from applying the water. This is invariably the approach used in areas where water is short or pumping costs are high compared to the yield increment expected per unit of water applied.

TYPES OF IRRIGATION SCHEDULING

Irrigation scheduling can be classified into three types according to the irrigator's goal:

(1) Scheduling irrigation to maximize yield,
(2) Scheduling irrigation to maximize yield per unit of water applied, and
(3) Scheduling irrigation to maximize net return.

The first type of irrigation scheduling is associated with the first school of thought--maximum yield; while the other two emerged from the second school of thought--maximum return.

REACTIVE VERSUS PREDICTIVE IRRIGATION DECISIONS

Some scholars prefer to include in the definition of irrigation scheduling only those methods that allow the irrigator to project irrigation into the future. By estimating the indicator of need for irrigation and use of future weather forecasts, the future status of this indicator can be predicted to estimate the timing of the next irrigation. Using estimations and forecasts has the advantage of predicting into the future as compared to just measuring the indicator of need for irrigation and reacting accordingly. The water balance method allows the use of predictions to estimate soil water content in the future. Therefore, this method can be termed predictive irrigation scheduling as opposed to reactive irrigation scheduling where, for example, one uses a hand probe to monitor soil water content and irrigates as soon as the soil water content reaches a predetermined level. The advantages of knowing the need for irrigation in advance are obvious, as irrigations can be integrated with other necessary farming operations.

USING IRRIGATION INDICATORS

DEFINING THE MAGNITUDE OF INDICATORS

The magnitude of the irrigation indicator or the level that an irrigation indicator is allowed to reach before irrigation is applied depends mainly on the irrigator's goal or type of irrigation scheduling. If the irrigator's goal is to maximize yield, water should be applied before any stress develops. In this case, the magnitude of the irrigation indicator is selected to prevent stress. If the irrigator's goal is maximum profit, then the magnitude of the irrigation indicator will be selected to generate a positive return. No explicit rules regarding the selection of the magnitude of an irrigation indicator are available, although much current research is directed toward this goal. Experience and experimentation are two valuable sources of this information.

To illustrate how to determine the magnitude of the irrigation indicator, soil water will be used as an example. Suppose the goal of the irrigator is to maximize yield. A common way to determine the minimum soil water content that should trigger irrigation is to determine a level of soil water content from research recommendations below which the crop suffers from water stress. The depletion from field capacity down to this level is termed allowable depletion. Allowable depletion is expressed as percent of available water holding capacity. For example, 40 percent allowable depletion means that the soil water content may be depleted by 40 percent of its available water holding capacity before irrigation is applied. As an example, the field capacity of a loam soil is about 31 percent by volume, and its wilting point water content about 14 percent. The difference, 17 percent, is the available water holding capacity. If the allowable depletion for a specific crop at a specific stage of growth is 40 percent, then the allowable depletion at that time is 6.8 percent, or 0.068(12) = 0.8 inches of water use per foot of root zone depth.

Recommended allowable depletion levels have been published for several different crops. Table 5.2 summarizes recommended ranges of allowable depletions for crops in Colorado. These allowable depletion levels can be used in any irrigation scheduling scheme that uses soil water content as the irrigation indicator.

DECIDING HOW MUCH WATER TO APPLY

DEVISING A DECISION RULE. To decide how much water to apply in every situation, a decision rule must be devised. Two basic options are available--one is full irrigation to replenish the root zone to field capacity--namely to apply the entire amount that was depleted. The second option is to apply a partial irrigation. Applying a smaller amount than is needed to replenish the root zone to field capacity--for example, returning it to only 80 percent of field capacity, leaves room for storage of some rainfall, should it occur. Such a decision is much more easily applied to sprinkler irrigation systems than to surface irrigation.

RAINFALL CONSIDERATIONS. Expected rainfall is a major consideration in devising the decision rule of how much to irrigate. Possible rain occurrence can be accounted for by considering forecasted rain probabilities and weighing those probabilities against the consequences of no rain and the level of risk the irrigator is willing to incur.

The National Weather Service forecasts probable occurrence of rain, but not the amount. Probabilities near 100 percent mean high chances for rain. Values near 0 mean no chance for rain. No best way exists to consider rain probabilities in the irrigation decision. One possible way is to choose a certain probability, 60 percent for example, and decide to apply full irrigation if rain probability is less than 60 percent and partial irrigation if the probability is higher than 60 percent. By using such a decision rule, part of the root zone reservoir is reserved to store relatively small amounts of possible precipitation.

The final decision of how much water to apply in every situation depends on several factors discussed in preceding sections. All these factors should be considered and accounted for when developing the decision rule, but no explicit method exists. The decision of how much water to apply in every situation is a subjective one that should be made by the irrigator according to his particular needs and goals and is not necessarily the same for every irrigation.

IRRIGATION STRATEGIES FOR LIMITED WATER SUPPLY

Limited water supply is a situation that needs special attention. Limited water supplies can be dealt with in two stages of the agricultural system--at the beginning of the season through crop selection and during the season by optimal water allocation.

SELECTION OF CROPS. If it is known at the beginning of the season that the water supply will be limited, the crops and areas to be grown can be selected so that adequate water will be available to meet the irrigation requirements. The seasonal water use per unit area of each crop can be estimated using ET procedures discussed in Chapter 3. Knowing the seasonal water use per unit area, the crops can be selected to use the available amount of water. In other words, the sum of seasonal water use per unit area multiplied by area of each crop should be smaller than or equal to the amount of water available. If the water source has a limited flow rate, the previous calculation should be done for the period of peak water use. This period is the period in which the ET rate is the highest and, therefore, the crop water use is the highest. The flow rate of the water source should be great enough to meet the average peak water use rate over the time it takes to use the allowable soil water depletion.

ALLOCATION OF WATER DURING THE SEASON. In cases where a water shortage occurs during the season, water should be allocated among crops to minimize water stress damages. One approach is to allocate the water in relation to critical growth stages. The crops that are in a critical growth stage will be irrigated first while other crops will be irrigated later. Critical growth stages for different crops are summarized in Table 5.1. A more detailed recommendation for specific allowable depletions at different stages of growth is given in Table 5.2. The maximum allowable depletion is the greatest depletion that presumably would not stress the crop. Irrigating before a significant amount of depletion is reached may result in percolation of water below the root zone.

OPTIMIZATION MODELS. Irrigation strategies for limited water supply were developed by several researchers. These are mainly complicated models that use optimization techniques to allocate resources before and during the season. Most of these models do not fit the daily needs of the individual irrigator. Furthermore, they are too complicated to be used by most individuals, and require large computers. The best approach for the individual irrigator to handle water shortage situations is to use common sense and available knowledge as presented in this and other resources to make the irrigation decision.

Table 5.2. Suggested maximum allowable depletions for different stages of growth.

Crop	Stage of growth	Maximum Allowable Depletion (inches per inch of soil)
Beans	planting to early bloom	0.70
	early bloom to pod development	0.40
	pod development to maturity	0.50
	after maturity	0.80
Corn	planting to tassel	0.80
	tassel to silk	0.50
	silk to milk	0.40
	milk to maturity	0.50
	after maturity	0.80
Onions	planting to bulb set	0.80
	bulb set to 1/2 bulb's maximum weight	0.50
	1/2 bulb to maximum weight	0.40
	to maturity	0.70
Potatoes	emergence to stolons	0.80
	stolons to beginning tuber formation	0.50
	beginning tuber to 2/3 maximum weight	0.40
	to maturity	0.70
Small grains	planting to boot	0.70
	boot to heading	0.50
	heading to soft dough	0.50
	soft dough to maturity	0.60
Sugar beets	planting to effective cover	0.70
	after effective cover	0.80

CHAPTER VI. APPLICATION OF IRRIGATION SCHEDULING

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Many different methods are employed to schedule irrigations. In general, these methods can be categorized as traditional, reactive, or predictive. Normally, the traditional methods are the most rudimentary, while the more sophisticated methods are predictive.

More sophisticated scheduling techniques are needed when the water holding capacity of the soil is low, when crop yield or quality are readily reduced by water stress and when irrigation costs are high or rainfall must be utilized to its greatest advantage.

TRADITIONAL METHODS

Traditional methods include rotation of fields in sequence, irrigating a predetermined number of days after the last irrigation, working around other farm activities, irrigating when water is available or when neighboring farmers irrigate. These methods generally are not directly influenced by crop water needs. They are often practiced in areas with adequate, relatively inexpensive water supplies. In such cases, excessive irrigation application is common.

REACTIVE METHODS

Reactive methods are used to schedule irrigations when soil or plant indicators show that water is needed. Reactive scheduling methods include both soil and plant based measurements. The soil based methods generally involve measurement of soil water content or water tension. These measurements may be accomplished by hand probing, gypsum blocks, tensiometers, or other methods described in Chapter 2.

SOIL WATER MEASUREMENTS

Use of soil water measurements for scheduling irrigations requires sampling at multiple sites to account for natural variability. At least two sampling sites are required for each field. The potential user must consider the time required to adequately determine soil water content, the interpretive skills necessary to convert the observation or measurement to needed irrigation, and the maintenance and useful service life of the sensors used.

Soil water estimates are used as indicators to determine whether a reduction in plant development is likely to occur soon. Whenever the soil water content reaches a predetermined value (see Tables 2.3 and 5.2), an irrigation is applied.

PLANT BASED MEASUREMENTS

Reactive scheduling methods based on plant measurements include the following:

PLANT APPEARANCE. Detecting visual changes in crop appearance is a simple, common method requiring no equipment. Plants suffering water stress appear darker in color than well watered plants. Changes in leaf appearance from a satin-like sheen to a dull surface indicate water stress. Wilting and curling are indicative of reduced transpiration because the plant is unable to take up enough water. Each of these visual indicators is representative of an extended field area.

Wilting and curling are natural defense mechanisms of the plant and are often evident on hot windy afternoons when the plant cannot transpire rapidly enough, regardless of the ready availability of soil water. However, when the plant does not recover overnight, a shortage of available soil water is indicated. When changes in crop appearance due to water stress are detected, the yield has already been reduced, thus such techniques are not recommended when maximum crop yield is desired.

CANOPY TEMPERATURE. Canopy or leaf temperatures can be measured to determine availability of water over an extended area. Transpiration cools the plant canopy several degrees below ambient air temperature through evaporation, similar to an evaporative cooler or canvas water bag. When canopy temperatures approach air temperatures during periods of high ET demand, a reduction in transpiration is apparent. Infrared thermometers (see Chapter 3) permit accurate remote measurement of canopy temperatures, but are expensive. An inexpensive method is to hold a leaf to your face. A freely transpiring leaf will feel cool to the touch while a water stressed leaf will not.

OTHER METHODS. Other plant based methods more applicable in research efforts include pressure chambers or thermocouple psychrometers to measure leaf water potential (leaf xylem pressure or plant hydration), diffusion porometers to measure leaf transpiration resistance (relative stomatal openings), and acoustic methods to detect the sound of water cavitating in plant vessels. These methods currently require expensive equipment, are time consuming, require sampling skill to select a representative leaf, require training to interpret data, and are subject to large diurnal variations (i.e. sampling must be done at specific times of the day or periodically during the day).

PREDICTIVE METHODS

Predictive methods allow projection of recent crop water use trends into the near future to anticipate water needs and schedule irrigations before water stress influences crop growth. The most widely applicable predictive method of irrigation scheduling is the root zone water balance method. One or more of the reactive methods may be incorporated into a predictive method to assist in determining past crop water use.

ROOT ZONE WATER BALANCE METHOD

The water balance method offers the most effective management technique for irrigation scheduling. It has wide flexibility in application to a variety of management objectives while accommodating multiple operating constraints. It is well suited to forecasting water needs and timing of irrigations.

This method can be relatively simple or quite complex, and may utilize inexpensive equipment or highly technical instruments, depending on the circumstances. However the water balance must be updated at least weekly to be useful for scheduling irrigations.

Estimated crop water use (ET) is an essential input for the water balance method. Crop water use can be obtained from one of several methods described in Chapter 3.

The method utilized for keeping track of the root zone water balance can vary in method and complexity. The following are the principal methods utilized.

GRAPHICAL. A graphical format in which root zone soil water is plotted versus time (days) is shown in Figure 6.1. This method is relatively simple, easy to visualize, and readily permits projection of trends. Each day the soil water content is depleted by the estimated ET for the previous day. On days when water content is measured, that value is plotted directly. Water content is

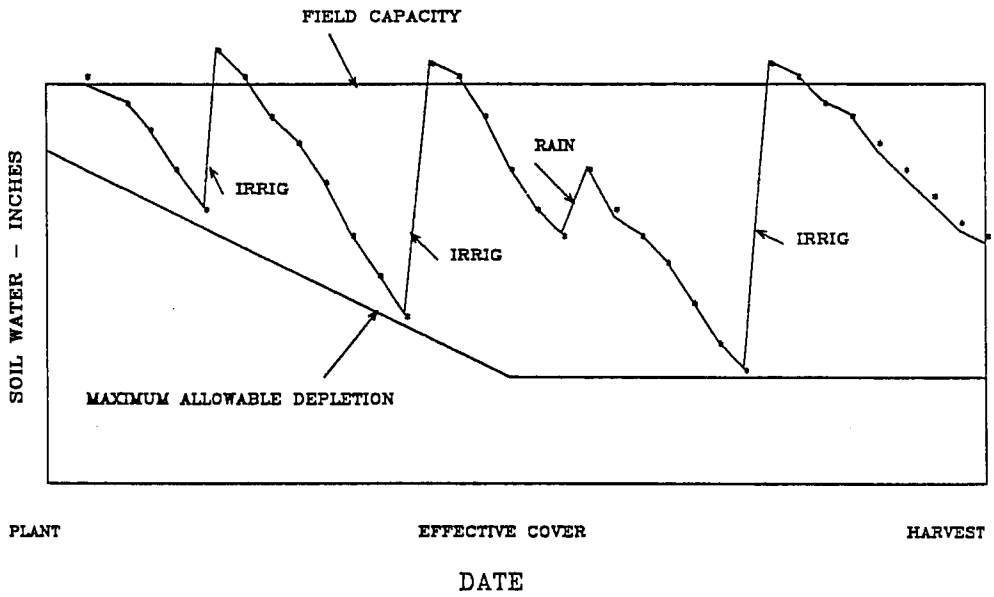

Figure 6.1. Graphical format for irrigation scheduling.

increased on days of irrigation or rain. By extending a line connecting measured points, one can project when water content will reach the maximum allowable depletion and irrigation is required.

TABULAR. A tabular format simplifies computations. Table 6.1 shows a typical tabular water balance for a given field. Each day, the crop ET, effective rainfall, irrigation depth and water table contribution are calculated. The values are then summed to determine the soil water depletion at the end of each day. Whenever the soil water depletion reaches the maximum allowable depletion, then an irrigation must be applied.

COMPUTER PROGRAMS

Computer programs automate the procedure and can automatically adjust for changing parameters such as crop coefficients, root zone growth, increased evaporation from a wet soil surface following a rain or irrigation or decreased evapotranspiration when soil water content gets low enough to reduce ET.

Table 6.1. Tabular accounting of soil water balance.

Date	ET	Irrigation	Rain	Water Table	Depletion
6/21	0.26	4.5	0.00	0.00	0.00
6/22	0.31	0.0	0.00	0.00	0.31
6/23	0.22	0.0	0.21	0.00	0.32
6/24	0.27	0.0	0.00	0.02	0.57
6/25	0.31	0.0	0.00	0.03	0.85
6/26	0.34	0.0	0.00	0.04	1.15
6/27	0.32	0.0	0.00	0.04	1.43
6/28	0.26	0.0	0.17	0.03	1.49
6/29	0.19	0.0	1.76	0.00	0.00
...					

These programs are often available at no cost or minimal cost for personal computers (see Appendix C for examples of programs available).

APPLICATION OF THE ROOT ZONE WATER BALANCE METHOD

Application of the root zone water balance method is accomplished in the following steps:

1. **Estimate initial soil water depletion.** This is usually based on hand probing of the field, however other methods may provide a more accurate estimate. Initial soil water depletion is normally established near the time of planting or crop emergence. In eastern Colorado, beginning season soil water is often near field capacity (zero depletion) except in years of below normal winter precipitation.

2. **Compute the soil water depletion on a daily basis.** Depletion is increased daily by adding estimated ET. Depletion is decreased daily by subtracting the net irrigation, effective precipitation, and water table contribution.

The basic equation is:

$$D = D0 + ET - IR - R - WT$$

where D = soil water depletion (inches) at the end of the given day. Soil water depletion is equal to zero when root zone soil water is at field capacity or above.

D0 = soil water depletion (inches) for the previous day.

ET = evapotranspiration (inches) during the day. Computed from methods described in Chapter 3.

IR = net irrigation depth (inches) during the day. Computed by dividing the measured gross volume applied by the area irrigated, then multiplying the result by the irrigation application efficiency (see Chapter 4).

R = effective precipitation (see Chapter 4) (inches) during the day.

WT = upward movement of water (inches) during the day from water table relatively close to the bottom of the root zone (see following section for computation procedure).

The soil water depletion is set to zero when irrigation or rainfall amounts are equal to or greater than the current depletion. The excess irrigation or rainfall is usually assumed lost to deep percolation.

The root zone soil water content may exceed field capacity temporarily following an irrigation or rain, as excess water drains slowly through the soil. This period of excess water can last from one day on light sandy soils to three days on heavier soils. During this period, or until the excess water is consumed by ET, the soil water depletion should be kept equal to zero.

The purpose of the water balance computations is to determine when the allowable soil water depletion will be reached. The total allowable soil water depletion is determined by multiplying the available water holding capacity of the soil profile by the effective rooting depth of the crop and multiplying the result by the percentage of allowable depletion recommended for the crop and stage of growth (see Table 5.2). The result may be adjusted to account for individual management objectives or field operating constraints.

FIELD VERIFICATION. The success of water balance irrigation scheduling is directly affected by the accuracy of estimating input parameters, by the accuracy of input data, and by the proper interpretation and application of the computations. Common sense and good judgement are essential.

ADJUSTMENTS OR CORRECTIONS. Periodic field checks are required, usually once a week or more often. As discrepancies develop between the calculated and measured soil water depletion, corrections to the depletion and input parameters may be necessary. With experience using a given system and as input parameters are appropriately adjusted, the necessary frequency of field checks will decrease.

Soil water depletion. Soil water depletion is usually verified by hand probing of the field. Tensiometers, electrical resistance blocks, or crop appearance are often used to reduce the need for and/or frequency of hand probing. If the discrepancy is small, the corrected depletion value is simply substituted into the water balance for that day. If the discrepancy is large or repetitive, adjustments to the input parameters are needed.

Allowable depletion. Available water holding capacity of the soil often varies across a field, making it more difficult to determine a representative value for water holding capacity. Soils often vary with depth in their water holding capacity. As the crop root zone increases with root growth, adjustments

are required. As the vegetative growth of the crop increases, so does the crop root zone. Adjustments to allowable total soil water depletion are made periodically during the vegetative growth period. Root growth may be restricted by soil layering or compaction or by dry layers (soil profile was not at field capacity at crop emergence and after).

Effective rooting depth is usually less than maximum root depth. Relatively little water is extracted from the bottom of the root zone because rooting density decreases with depth and because a larger potential gradient is required to move water the longer distances to roots.

Evapotranspiration. Frequent calibration of the instruments at a weather station is essential to assure reliable data. The weather station or evaporation device must be located at a representative site within the irrigated area as described in Chapter 3. Crop coefficients adjust reference ET for the growth stage of the crop and may require adjustment to account for abnormal crop conditions. Most of these coefficients are varied throughout the growing season based on percent of time from planting to effective cover or on days following cover. Until the crop achieves effective cover, further adjustment of the crop coefficient may be required periodically, particularly if crop development is delayed by unusually cool weather or accelerated by unusually favorable weather.

During the early vegetative growth period, little of the field surface is covered by the crop canopy. Evaporation of soil water from a bare, dry soil surface is small. However, evaporation from a wet soil surface (following an irrigation or rain) approaches reference evapotranspiration rates.

Weeds can significantly increase soil water extraction, particularly before the crop reaches effective cover. Disease, pests, or hail can reduce the ability of the crop to extract soil water by transpiration.

Whenever a crop is stressed due to a lack of available water, evapotranspiration is reduced. Stress can be managed in many crops to reduce crop water use without corresponding yield reductions.

Net irrigation. The net irrigation depth is normally obtained by multiplying the gross depth applied by the application efficiency. Typical values of application efficiency are shown in Table 4.1. The uniformity of distribution should also be considered when the net depth of irrigation is less than the current depletion. The crop root zone throughout the field has been returned to field capacity only if the net irrigation is equal to or greater than the current depletion. Completely refilling the profile is not uncommon when the water supply is abundant and relatively inexpensive, particularly under surface irrigation systems.

Irrigation efficiency can vary greatly during the season. High winds can reduce sprinkler system efficiencies. The first irrigation down freshly ditched furrows typically has a lower than normal efficiency because of the high soil intake rate. Furrows choked by weeds, plant leaves, or trash may also result in lower efficiencies.

Effective precipitation. Effective precipitation is equal to measured rainfall when the soil is able to absorb the rain without runoff. If rainfall intensity exceeds the water intake rate of the soil, then runoff is likely to occur. For light summer showers, the effective precipitation is often equal to the measured rainfall. However, heavy downpours normally result in some runoff and adjustments are required to incorporate effective precipitation into the water balance. Little if any rainfall occurring soon after a thorough irrigation will be effective. With sprinkler irrigation systems, a soil water reservoir may be retained for precipitation by intentionally not completely satisfying soil water depletion by irrigation.

Water table effects. Water table contribution to root zone soil water is largely influenced by soil type and by the depth of the water table below the root zone. More water movement to the root zone is possible on heavier soils and less movement from a deep water table. The contribution from a water table to the soil water balance may be approximated from:

$$WT = ET * (100 - AW) * (HC/(DW - RZ))^N / 75$$

where WT = contribution to ET (inches) from a water table near the root zone,
ET = evapotranspiration (inches) during the day,
AW = available soil water in the root zone (percent). When the root zone is at field capacity, water table contribution is zero.
HC = effective height of the capillary fringe above the water table (feet). A capillary fringe of 0.5 feet or less occurs in sandy soils, 3 to 5 feet is common, and up to 10 feet can occur in heavy soils.
DW = depth of the water table below the soil surface (feet),
RZ = effective root zone depth (feet), and
N = a constant for the soil type, ranging from 1 for heavy soils to 3 for sandy soils.

When the water table is less than 3 feet below the root zone, it is not unusual for a majority of the crop water requirements to be supplied from the upward movement of water in a heavy uniform soil. Deep rooted crops such as alfalfa often never need irrigation, once established, when the water table is relatively stable a few feet below the root zone. When the water table is 20 feet or more below the root zone, the upward movement of water can usually be neglected.

Slow draining soils. From the time a thorough irrigation or rainfall ends to the time root zone drainage by gravity becomes negligible, the root zone remains at or above field capacity. During this period, the excess water is available to meet evapotranspiration demands without depleting soil water below field capacity. Crop use of this excess water is accounted by maintaining the soil water depletion at zero until root zone drainage becomes negligible. Drainage time varies by soil properties, initial depth of penetration of the irrigation or rainfall, depth of the root zone and evapotranspiration rates. In general, this time varies from one day in light, sandy soils to three days for deep rooted crops in heavier soils.

Delay from beginning of irrigation to completion. The available water supply for a field is rarely large enough to irrigate the entire field at once. Consequently, some time transpires between the start of an irrigation on a field and the time the irrigation is completed on the last part of the field. It is important that the irrigation begin early enough to allow its completion before the last part of the field experiences undesired stress. This often requires the first part of the field to be irrigated before the soil water depletion reaches the allowable limit. It may be advantageous to maintain a soil water balance at two or more locations in the field so that the first part of the field can be irrigated without overirrigation, while the last part does not exceed the allowable depletion.

FORECASTING FUTURE IRRIGATIONS

The root zone water balance method permits ready prediction of future irrigation depths and timing. The forecast procedure is the same as discussed above except that future inputs must be estimated in order to carry the calculations forward.

Future evapotranspiration may be estimated from the average daily ET for the previous 3 to 5 days, or calculated based on the 2 to 7 day weather forecast. An alternative is to calculate ET from long term average weather conditions for each day of the season and average crop coefficients for the days in question.

Expected rainfall is typically assumed to be zero in arid climates to assure against crop stress. In semi-arid areas like eastern Colorado, one may anticipate a moderate amount of rainfall, and forecast upcoming irrigations with several rainfall values projected to occur before the irrigation.

The expected water table contribution is estimated from the average calculated contribution for the 3 to 5 previous days, adjusted for any expected trends.

The depletion calculations are carried forward using the estimated future inputs until the soil water depletion equals the allowable depletion. The date this occurs will be the predicted date of the next needed irrigation. The scheduler must account for the time delay from beginning of the irrigation to its completion. Also, any needed adjustments for system constraints, such as cultivation, harvest or pesticide application must also be considered.

An example, using the water balance technique to schedule an irrigation, is presented in Appendix J.

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APPENDIX A. GLOSSARY OF IRRIGATION SCHEDULING TERMS.

Actual ET- The water use of a crop, other than the reference, under the existing weather conditions, and at the current stage of growth of that crop.

Available Water- The water stored in the soil which is available to the plant. That water between field capacity and wilting point water contents.

Available Water Holding Capacity- The depth of available water.

Crop Coefficient- A multiplier, which varies with the stage of growth of the particular crop, used to convert reference ET to actual crop ET. As used here, refers to actual ET as a fraction of the ET of a vigorously growing alfalfa crop. Varies from about 0.2 at emergence to 1.0 for crops that fully cover the soil surface.

Decision rule- A predetermined selection of alternatives to dictate when and how much water to apply in response to an observed value of the irrigation indicator.

Effective Cover- That stage of plant growth at which the plant canopy is sufficiently developed to intercept essentially all the incoming solar radiation. Effective cover is achieved at approximately the stage when 75% of the soil surface is shaded at mid-day.

Effective Root Zone- The soil depth penetrated by active roots to such an extent that significant water is drawn from the soil at that depth.

ET- Evapotranspiration.

Evaporation- The conversion of water from liquid to vapor phase as a result of absorption of heat. The amount of heat required to convert a pound of water to vapor is constant at a given temperature.

Evapotranspiration- The sum of liquid to water vapor conversion from evaporation and plant transpiration.

Full Cover- See effective cover.

Irrigation Indicator- Any parameter, such as soil water content, plant appearance, or canopy temperature, which is used to trigger an irrigation.

Jensen-Haise Method- A method for computing reference ET using measured average air temperature and solar radiation. Best applied to scheduling periods exceeding 5 days and in situations where strong, dry winds are not dominant.

Net Irrigation- The depth of water applied which is actually stored in the soil root zone for subsequent plant use. The total application is adjusted for runoff, deep percolation, airborne evaporation, and lack of uniformity of application.

Penman equation- An energy based equation for computing reference ET which considers air temperature, solar radiation, wind movement, and air humidity. One of the most theoretically complete equations. The added difficulty of data collection and computation is warranted when scheduling irrigations in light textured soils or in areas where strong, dry winds are an important factor in increasing ET.

Potential ET- see reference ET.

Predictive Irrigation Scheduling- One of several techniques which uses recent past ET data to allow forecasting of the time and/or amount of the next required irrigation.

Reactive Irrigation Scheduling- A technique which gives an indication that irrigation is required immediately.

Reference Crop- A crop which is assumed to transpire at the maximum rate possible for any crop under the weather conditions existing at the current time. In this guide, alfalfa which is growing vigorously, and at least 8" tall is used as the reference crop.

Reference ET- The evapotranspiration of the reference crop resulting from the weather conditions existing during the period of interest.

Soil Water Deficit, Soil Water Depletion- The amount of water required to restore the soil in the effective root zone depth to field capacity.

Solar Radiation- The energy from the sun, whether coming directly or reflected from sky and clouds, which arrives at the field surface (crop, soil). Part of this energy goes into plant processes, part to convert liquid water to vapor (evaporation and transpiration), part to heat the soil, air and plants, and part is reflected back into the atmosphere.

Transpiration- That part of the liquid-vapor transformation that occurs with respect to water which has moved through the plant roots, stems and leaves into vapor.

Water Balance Method- A method for computing the amount of soil water depletion in the crop root zone based on subtracting irrigations, water table contribution and rainfall; and adding deep percolation, evaporation and transpiration to previously determined soil water content.

APPENDIX B. UNITS AND CONVERSION FACTORS

SOLAR RADIATION: Total daily solar radiation is measured in Langleys (Ly), MegaJoules per square meter (MJ/m^2) or watt-hours per square meter ($w\text{-}hr/m^2$).

MULTIPLY	BY	TO GET
Ly	11.63	$w\text{-}hr/m^2$
MJ/m^2	277.8	$w\text{-}hr/m^2$
Ly	0.04186	MJ/m^2
$w\text{-}hr/m^2$	0.0036	MJ/m^2
MJ/m^2	23.89	Ly
$w\text{-}hr/m^2$	0.086	Ly

EXPECTED RANGE OF DAILY TOTAL VALUES:

Langleys	100 to 750
MJ/m^2	4 to 32
$w\text{-}hr/m^2$	1100 to 8800

TEMPERATURE: Maximum, minimum, average, current and dewpoint temperatures are measured in either Celsius (C) or Fahrenheit (F).

$F = 1.8\ C + 32$

$C = (F - 32)/1.8$

EXPECTED RANGE OF TEMPERATURES (Year round):

F	-20 to 105
C	-29 to 40

DEW POINT TEMPERATURE is measured in the same units as air temperature.
EXPECTED RANGE OF DEWPOINT TEMPERATURE:

0 to 40 F
0 to 25 C less than air temperature (note: may exceed air temperature early in morning when dew is on the ground)

HUMIDITY: Humidity may be expressed as relative humidity, dew point temperature or vapor pressure. RELATIVE HUMIDITY has no units (same value in English or metric).

EXPECTED RANGE OF RELATIVE HUMIDITY:

5% TO 100%

The table at the end of this appendix can be used to convert between values of relative humidity and dewpoint temperature as needed.

VAPOR PRESSURE: Vapor pressure is measured in millibars (mb) or kiloPascals (kPa).

MULTIPLY	BY	TO GET
mb	0.1	kPa
kPa	10.0	mb

EXPECTED RANGE OF VAPOR PRESSURE:

mb	2 to 20
kPa	0.2 to 2.0

Saturation vapor pressure (mb) at any temperature (°F) can be approximated by the equation:

$$SVP\ (mb) = -0.6959 + 0.2946T - 0.005195T^2 + 0.000089T^3$$

WIND RUN: Wind run is the total daily air movement, and is equal to the average wind speed multiplied by the number of time units in the day. Measured as miles per day (mi/d), kilometers per day (km/d), average miles per hour (mph), average kilometers per hour (km/hr), or average meters per second (m/s). Instantaneous or hourly speeds may be several times average daily values.

MULTIPLY	BY	TO GET
km/d	0.622	mi/d
mi/d	1.609	km/d
mph	24	mi/d
km/hr	24	km/d
m/s	86.4	km/d
m/s	53.7	mi/d

EXPECTED VALUES OF WIND:

km/d	80 to 800
mi/d	50 to 500
average mph	2 to 20
average km/hr	3 to 30
average m/s	1 to 10

PRECIPITATION/IRRIGATION DEPTH: Depth of water application, whether from precipitation or irrigation, is measured in either inches (in) or millimeters (mm).

MULTIPLY	BY	TO GET
in	25.4	mm
mm	0.03937	in

EXPECTED VALUES OF WATER DEPTH:

	PRECIPITATION	IRRIGATION
in	0 to 2	0.25 to 8
mm	0 to 50	6 to 200

WATER FLOW RATE: Irrigation water flow rates are measured in many units, including gallons per minute (gpm), cubic feet per second (cfs), miner's inches (MI, different values in different states), liters per second (l/s), or cubic meters per second (m^3/s).

MULTIPLY	BY	TO GET
cfs	448.8	gpm
l/s	15.85	gpm
MI (Colorado)	11.69	gpm
m^3/s	15850.	gpm
gpm	0.002228	cfs
l/s	0.03532	cfs
MI	0.02605	cfs
m^3/s	35.32	cfs
gpm	0.06309	l/s
cfs	28.32	l/s
MI	0.7375	l/s
m^3/s	1000.	l/s
gpm	0.08554	MI
cfs	38.39	MI
l/s	1.358	MI
m^3/s	1358.	MI
gpm	0.00006309	m^3/s
cfs	0.02831	m^3/s
l/s	0.001	m^3/s
MI	0.0007364	m^3/s

DEW POINT TEMPERATURE AT VARIOUS VALUES OF RELATIVE HUMIDITY AND AIR TEMPERATURE

	Relative Humidity- percent																	
T°F	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	100
32	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	32
34	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	34
36	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	32	33	36
38	.	.	.	.	.	.	.	.	.	.	.	.	.	.	32	34	35	38
40	.	.	.	.	.	.	.	.	.	.	.	.	.	32	34	36	37	40
42	.	.	.	.	.	.	.	.	.	.	.	.	32	34	36	38	39	42
44	.	.	.	.	.	.	.	.	.	.	.	32	34	36	38	40	41	44
46	.	.	.	.	.	.	.	.	.	.	32	34	36	38	40	42	43	46
48	.	.	.	.	.	.	.	.	.	32	34	36	38	40	42	44	45	48
50	.	.	.	.	.	.	.	.	.	34	36	38	40	42	44	46	47	50
52	.	.	.	.	.	.	.	.	33	36	38	40	42	44	46	48	49	52
54	.	.	.	.	.	.	.	32	35	38	40	42	44	46	48	50	51	54
56	.	.	.	.	.	.	.	34	37	40	42	44	46	48	50	52	53	56
58	.	.	.	.	.	.	33	36	39	42	44	46	48	50	52	54	55	58
60	.	.	.	.	.	.	35	38	41	44	46	48	50	52	54	56	57	60
62	.	.	.	.	.	33	37	40	43	46	48	50	52	54	56	58	59	62
64	.	.	.	.	.	35	39	42	45	48	50	52	54	56	58	59	61	64
66	.	.	.	.	33	37	41	44	47	49	52	54	56	58	60	61	63	66
68	.	.	.	.	35	39	43	46	49	51	54	56	58	60	62	63	65	68
70	.	.	.	32	37	41	45	48	51	53	56	58	60	62	64	65	67	70
72	.	.	.	34	39	43	47	50	53	55	58	60	62	64	66	67	69	72
74	.	.	.	35	40	45	48	52	55	57	60	62	64	66	68	69	71	74
76	.	.	.	37	42	47	50	54	56	59	61	64	66	68	70	71	73	76
78	.	.	33	39	44	48	52	55	58	61	63	66	68	70	71	73	75	78
80	.	.	35	41	46	50	54	57	60	63	65	67	70	72	73	75	77	80
82	.	.	37	43	48	52	56	59	62	65	67	69	71	73	75	77	79	82
84	.	.	38	45	50	54	58	61	64	66	69	71	73	75	77	79	81	84
86	.	32	40	46	51	56	59	63	66	68	71	73	75	77	79	81	83	86
88	.	34	42	48	53	57	61	64	67	70	73	75	77	79	81	83	85	88
90	.	36	44	50	55	59	63	66	69	72	74	77	79	81	83	85	87	90
92	.	38	46	52	57	61	65	68	71	74	76	79	81	83	85	87	89	92
94	.	39	47	53	58	63	66	70	73	76	78	80	83	85	87	89	91	94
96	.	41	49	55	60	64	68	71	75	77	80	82	85	87	89	91	93	96
98	.	43	51	57	62	66	70	73	76	79	82	84	86	89	91	93	94	98
100	33	44	52	58	63	68	72	75	78	81	83	86	88	90	93	95	96	100
102	35	46	54	60	65	69	73	77	80	83	85	88	90	92	94	96	98	102
104	36	47	55	61	67	71	75	78	81	84	87	90	92	94	96	98	100	104

APPENDIX C. SELECTED SOURCES FOR COMPUTER PROGRAMS TO COMPUTE ET.

Many computer programs have been developed for computation of crop water use, both by public agencies and the private sector. Those presented here are examples of the programs available, and in no way indicate endorsement of specific programs by the authors. The potential user should be aware that there are several sources of technical assistance in application of computerized irrigation scheduling, including many CSU Cooperative Extension agents, USDA-Soil Conservation Service district field offices, and private consultants. All programs listed are available for the IBM-PC or compatible computers using MS-DOS. Some may be a available for other machines/operating systems.

Kansas State University
Attn: Freddie R. Lamm
Rt 2, Box 119
Colby, KS 67701 Templates for spreadsheets, including Lotus 1-2-3, SuperCalc, and MultiPlan to calculate reference and actual crop ET.

Orange Software
PO Box 16046
Fresno, CA 93755 ROY Student, ROY Farmer, ROY Professional; programs for sale from $50.00 and up.

Climate Assessment Technology, Inc.
11550 Fuqua St., Suite 525
Houston, TX 77034 FARM WEATHER CENTER; Programs, including historical weather data for user's area; for sale.

USDA-Agricultural Research Service
CSU-AERC
Ft Collins, CO 80523 SCHED; program to compute field-by-field or regional crop ET using modified Penman or Jensen-Haise method or precalculated ET_r; public domain.

Agricultural Engineering Dept.
Clemson University
Clemson, SC 29631 WEATHER and SCHED; programs to calculate reference and crop ET from weather or pan evaporation data.

APPENDIX D. CONSTANTS FOR USE IN THE CROP COEFFICIENT EQUATION

$$K_c = A R^3 + B R^2 + C R + D$$

BEFORE FULL COVER -- R is fraction of time from planting to full cover (0.0 to 1.0)

Crop	A	B	C	D
Alfalfa	0.0	0.0	1.0870	0.2500
Corn	-1.5830	2.7560	-0.4276	0.2130
Dry beans	-1.3530	2.5620	-0.3532	0.2120
Pasture	0.0	0.0	1.5080	0.2500
Potatoes	-1.3810	2.4560	-0.3710	0.2130
Sorghum	-1.5830	2.7560	-0.4276	0.2130
Soybeans	-1.3530	2.5620	-0.3532	0.2120
Small grains	-2.8930	4.8430	-1.1400	0.2330
Sugar beets	0.1340	0.8782	-0.1899	0.2098

AFTER FULL COVER -- R is days after full cover

Crop	A	B	C	D
Alfalfa	0.0	0.0	2.500E-02	5.000E-01
Corn	2.750E-06	-4.688E-04	1.195E-02	9.150E-01
Dry beans	1.650E-06	-2.644E-04	-1.120E-04	1.050
Pasture	0.0	0.0	0.0	8.700E-01
Potatoes	0.0	0.0	0.0	9.000E-01
Sorghum	2.750E-06	-4.688E-04	1.195E-02	9.150E-01
Soybeans	1.290E-06	-1.559E-04	-1.551E-04	1.080
Small grains	4.440E-06	-7.261E-04	8.532E-03	1.022
Sugar beets	6.255E-07	-1.308E-04	3.427E-03	9.907E-01

APPENDIX E. MONTH-DAY TO DAY OF YEAR CONVERSIONS

(add 1 to all after February 28 during leap year)

DAY	JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29		88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365

APPENDIX F. JENSEN-HAISE COEFFICIENTS FOR COLORADO LOCATIONS.

The Jensen-Haise equation is given by

$$ET_r = (C_t * (T_{avg} - T_x) * SR)/1486$$

where ET_r = reference evapotranspiration (inches)
C_t = coefficient
T_x = temperature coefficient, °F
T_{avg} = mean daily temperature, °F
SR = daily solar radiation (langleys).

The following values for C_t and T_x are calculated from U.S. Weather Service data for selected stations in Colorado. The coefficients are based on the mean maximum and minimum temperatures for the hottest month (July in Colorado) over a 20 year average (except Walsh, only 13 year average available).

Station	Elevation ft	T_{max} (July) °F	T_{min} (July) °F	C_t	T_x °F
Akron	4663	88.2	58.7	0.0135	15.7
Alamosa	7541	82.0	48.0	0.0152	13.5
Burlington	4165	90.3	60.2	0.0135	15.6
Canon City	5332	89.5	61.7	0.0138	15.4
Center	7600	80.8	45.4	0.0151	13.5
Cheyenne Wells	4250	91.5	59.5	0.0138	14.9
Cortez	6201	88.9	54.8	0.0151	13.3
Durango	6523	86.8	49.7	0.0153	13.1
Fruita	4500	93.5	56.5	0.0145	13.5
Ft Collins	5001	85.5	56.9	0.0134	15.9
Grand Junction	4596	94.0	63.8	0.0142	14.3
Greeley	4653	89.6	57.5	0.0139	15.0
Gunnison	7703	81.4	41.9	0.0158	12.7
Holly	3393	94.5	63.3	0.0135	15.2
Holyoke	3746	91.0	59.0	0.0134	15.6
Montrose	5806	89.1	56.4	0.0147	13.9
Palisade	4900	94.8	63.8	0.0145	13.8
Pueblo	4684	92.2	61.5	0.0141	14.6
Rocky Ford	4178	94.0	59.7	0.0142	14.1
Springfield	4575	90.1	60.5	0.0137	15.3
Sterling	3939	89.8	58.8	0.0134	15.8
Walsh	3975	91.6	62.4	0.0134	15.7
Wray	3575	92.4	60.7	0.0135	15.4

APPENDIX G. AVERAGE CROP DEVELOPMENT DATES IN COLORADO (150 day growing season assumed).

Crop	Day of Year (Date)			
	Plant/Greenup	Cover	Maturity	Harvest
Alfalfa	84 (3/27)	114 (4/24)		152 (6/1) 192 (7/11) 237 (8/25)
Beans	161 (6/10)	206 (7/25)	244 (9/1)	263 (9/20)
Corn	118 (4/28)	205 (7/24)	250 (9/7)	288 (10/15)
Wheat	91 (4/1)	147 (5/27)	173 (6/22)	185 (7/4)
Sorghum	152 (6/1)	232 (8/20)	258 (9/15	274 (10/1)
Potatoes	108 (4/18)	202 (7/21)		237 (8/25)
Pasture	91 (4/1)	121 (5/1)		274 (10/1)
Sugar beets	84 (3/25)	185 (7/4)		278 (10/5)
Soybeans	145 (5/25)	222 (8/10)		268 (9/25)

Dates obtained from James Echols and Robert Croissant, Fort Collins and Richard Bartholomay, Grand Junction, Colorado State University Extension.

APPENDIX H. ROOTING DEPTHS IN DEEP SOILS FOR SELECTED IRRIGATED CROPS IN COLORADO (Adapted from Hagan, Haise and Edminster, 1967 and Jensen, 1980).

Crop	Unrestricted Rooting Depth, Feet
Alfalfa	4-6
Beans	2-3
Broccoli	<2
Brussels sprouts, Cauliflower	<2
Cabbage	<2
Carrots	2-4
Cantaloupe	4-6
Corn	2.5-4
Cucumbers	2-4
Fruit trees, deciduous	4-6
Lettuce	<2
Onions	1.5-2
Pasture grasses	3-4
Peas	2-4
Peppers	2-4
Potato	2-3
Pumpkin	4-6
Sorghum	3-4
Soybeans	2-3
Spinach	<2
Squash, summer	2-4
Squash, winter	4-6
Sugar beets	3-4
Tomato	4-6
Watermelon	4-6
Wheat	3-4

APPENDIX J. EXAMPLE CALCULATIONS OF REFERENCE ET, CROP ET AND SOIL WATER BALANCE.

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Most calculations of this nature are done using computer software. Calculations for a seven day period are illustrated here with all computations shown for one day to illustrate the procedure involved using a consistent set of units. We will determine reference crop ET (ET_r) by the Jensen-Haise and Penman methods for a representative seven day period (July 2-8) just prior to full cover using 1986 data from Holyoke, CO. Crop coefficients are calculated from the coefficients in Appendix D and are used to estimate actual ET for corn planted on April 28 and assumed to have emerged May 8.

A soil water balance table is illustrated to show when to apply a 1 inch irrigation to a sandy soil, assuming that the soil water depletion is 0.12" at the beginning of July 2 and that the soil has 0.7 inches per foot available water. Root zone depth is assumed to vary from 3.0 to 3.27 feet over the period, and the expanding portion of the root zone is initially at field capacity. The available soil water is allowed to be depleted up to 50% (0.35 inches per foot) before irrigation.

The equations shown require weather data in English units. The weather data from Holyoke are collected by an automatic data logger, and can be recovered by a computer over the phone lines. The data as collected are in metric units. For the computation period:

Day of Year	Month Day	T_{max} C	T_{min} C	Vapor Press. kPa	Solar Rad. MJ/m^2	Wind Run km/day	Precip mm
183	July 2	36.4	13.2	1.621	29.7	231	0
184	July 3	39.3	14.8	1.119	27.4	359	0
185	July 4	37.9	18.1	1.185	29.8	299	0
186	July 5	26.3	17.1	0.695	18.4	444	0
187	July 6	29.6	15.6	1.034	28.4	228	0
188	July 7	32.6	13.1	1.809	23.9	347	10
189	July 8	32.9	16.4	1.660	25.8	211	0

Unit conversions for DOY 183 (July 2):

Temperature: °F = 1.8 °C + 32

T_{max} = 1.8 (36.4) + 32 = 97.5 °F

T_{min} = 1.8 (13.2) + 32 = 55.8 °F

$T_{avg} = (T_{max} + T_{min})/2$

$= (97.5 + 55.8)/2 = 76.6$ °F

Vapor Pressure: P_{vap} (millibars) = 10 P_{vap} (Kilopascals)

P_{vap} = 10 (1.621) = 16.21 mb

Solar Radiation: SR (Langleys) = 23.89 SR (Megajoules per square meter)
SR = 23.89 (29.7) = 710 ly

Wind run: Wind (miles) = 0.622 Wind (kilometers)
Wind = 0.622 (231) = 144 mi

Rain: Rain (inches) = .0394 Rain (millimeters)
Rain = 0.622 (0) = 0 in

The Holyoke weather data converted to English units are:

Day of Year	Month Day	T_{max} C	T_{min} C	Vapor Press. kPa	Solar Rad. MJ/m^2	Wind Run km/day	Precip mm
183	July 2	98	56	16.21	710	144	0
184	July 3	103	59	11.19	655	223	0
185	July 4	100	65	11.85	712	186	0
186	July 5	79	63	06.95	440	276	0
187	July 6	85	60	10.34	678	142	0
188	July 7	91	56	18.09	571	216	0.39
189	July 8	91	62	16.60	616	131	0

Calculation of reference crop ET using the Jensen-Haise equation:

$$ET_r = (C_t (T_{avg} - T_x) SR)/1486$$

For Holyoke, C_t = 0.0134 and T_x = 15.6 (from Appendix F). For day 183,

$$ET_r = (0.0134 (76.6 - 15.6) 710)/1486$$
$$= 0.391 \text{ inch}$$

Calculation of reference crop ET using the Penman equation:

$$ET_r = 0.000673 [C_1(R_n - G) + 15.36 C_2(1.1 + 0.017W)(e_s - e_d)]$$

where $C_2 = 0.959 - 0.0125 T_{avg} + 0.00004534 T^2_{avg}$
$C_1 = 1 - C_2$
e_s = saturation vapor pressure at mean air temperature
e_d = measured mean vapor pressure for day
W = total wind movement
R_n = daily net radiation
G = daily soil heat movement

For day 183:

$$C_2 = 0.959 - 0.0125(77) + 0.00004534 (77)^2$$
$$= 0.959 - .9625 + .2688$$
$$= 0.2653$$

$C_1 = 1.0 - 0.2653$
$= 0.735$

Saturation vapor pressure can be calculated from:

$$e_s = -0.6959 + 0.2946\ T - 0.005195\ T^2 + 0.000089\ T^3$$
$$= -.6959 + .2969(77) - .005195(77)^2 + .0000089(77)^3$$
$$= -.6959 + 22.684 - 30.801 + 40.6314$$
$$= 31.82 \text{ mb}$$

$e_d = 16.21$ mb

Soil heat movement can be estimated from the equation:

$$G = 5\ (T_{avg} - (T_{avg-1} + T_{avg-2} + T_{avg-3})/3)$$

where T_{avg-1} is the average temperature for one day before, etc.

$T_{avg} = 77\ ^\circ F$

$T_{avg-1} = 74\ ^\circ F$ (DOY 182)
$T_{avg-2} = 70\ ^\circ F$ (DOY 181)
$T_{avg-3} = 80\ ^\circ F$ (DOY 180)

$G = 5\ [77 - (74 + 70 + 80)/3]$
$= 11.67$ ly

Daily net radiation can be estimated from:

$$R_n = 0.77\ R_s - [0.9\ R_s/R_{so} + 0.1]R_{bo}$$

where R_{so} = the maximum solar radiation if the sky is clear on that day,
R_{bo} = the net outgoing longwave radiation on a clear day.

These can be estimated by:

$$R_{so} = 760\ \exp-[(DOY-166)/157]^2$$

$$R_{bo} = [0.37 - 0.044\ (e_d)^{.5}](0.0000001171)(T^*_{avg} + 273.16)^4$$

where T^* is in °C.

For DOY 183:

$R_{so} = 760\ \exp-[(183-166)/157]^2$
$= 760\ \exp-[0.0117]$
$= 760\ (0.988) = 751$ ly

$R_{bo} = [0.37 - 0.044(16.21)^{0.5}](0.0000001171)[(36.4+13.2)/2 + 273.16]^4$
$= 0.1930\ (.0000001171)\ [7881920000]$
$= 178$ ly

$R_s = 710$ ly

and net radiation is

$R_n = 0.77\ (710) - [0.9(710)/751 + 0.1]178$
$= 546.7 - 171.1$
$= 377$ ly.

Now, using the Penman equation, we can calculate ET_r for DOY 183:

$$ET_r = 0.000673\ [C_1\ (R_n-G) + 15.36C_2\ (1.1+0.017W)\ (e_s-e_d)]$$
$$= 0.000673\ [0.735\ (377-11.67) + 15.36\ (0.265)\ (1.1 + 0.017\ (144))\ (31.82-16.21)]$$
$$= 0.000673\ [268.5 + 4.08(3.55)(15.61)$$
$$= 0.000673\ [268.5 + 225.7]$$
$$= 0.333 \text{ inch.}$$

It is evident that the Penman equation is much more difficult to use when calculating ET by hand. That is the reason that calculation of ET by the Penman equation is virtually always done with a computer. In general, the Penman equation is more accurate than more simple equations, therefore is much more useful for irrigation scheduling on sandy soils, or where hot dry winds are a factor during the irrigation season.

The crop coefficient for DOY 183 for corn is calculated from

$$K_c = A\ R^3 + B\ R^2 + C\ R + D.$$

From Appendix D, the constants for the crop coefficient equation before effective cover are:

$$A = -1.583$$
$$B = 2.756$$
$$C = -0.4276$$
$$D = 0.213.$$

For corn planted April 28 (DOY 118), full cover in Colorado (10 days after tasseling) is about July 24 (DOY 205). R is the fraction of time from planting to full cover (0.0 to 1.0) for the day in question, or:

$$R = \frac{183 - 118}{205 - 118} = 0.747$$

then

$$K_c \text{ (DOY 183)} = -1.583(0.747)^3 + 2.756(0.747)^2 - .4276(0.747) + 0.213$$
$$= 0.77.$$

By completing the calculations above for each day of the scheduling period (possibly using an irrigation scheduling computer program or a spreadsheet such as Lotus 1-2-3 or SuperCalc), one can determine the reference ET, daily crop coefficients and daily crop ET as follows:

Day of Year	Month Day	Jensen-Haise ET_r	Penman ET_r	Corn K_c	Crop ET - inches	
					Jensen-Haise	Penman
183	July 2	0.391	0.333	0.77	0.30	0.26
184	July 3	.386	.469	.78	.30	.37
185	July 4	.430	.451	.80	.34	.36
186	July 5	.220	.479	.81	.18	.39
187	July 6	.348	.368	.82	.29	.30
188	July 7	.301	.311	.83	.25	.26
189	July 8	.338	.295	.84	.28	.25
Weekly total		2.41	2.71		1.94	2.19

Note that the Penman equation results in higher computed ET than does the Jensen-Haise during this time of year for every day except two. Relatively high winds and low humidity July 3-6 resulted in higher ET than the temperature and solar radiation alone would indicate. It was humid on July 7, but the wind was high. Even though temperature was high on July 2 & 8, the humidity was also high and winds moderate, therefore Jensen-Haise predicted slightly more ET.

Soil Water Balance. Regardless of the source of ET data, whether calculated directly from local weather data using Jensen-Haise or Penman, whether taken from an automated ET data logger, or from information published in the newspaper or broadcast over radio or television, the calculated crop ET obtained from multiplying ET_r by K_c is used to determine the soil water balance.

The soil water balance may be thought of in very much the same sense as a checkbook balance. When ET occurs (checks are written), the soil water balance (bank balance) is reduced. When the soil water balance approaches maximum allowable depletion (bank balance approaches zero), water must be applied either by rain or irrigation (deposit money to bank account). The penalty for overdraft of soil water is a stressed crop and reduced yields (overdraft charge for bank account). Repeated or excessive water stress (overdraft) may lead to severely reduced yields or crop death (jail!).

The soil water balance table below illustrates how estimated ET values are used to schedule an irrigation to keep soil water depletion at less than 50% of the available soil water. ET estimates based on the Penman equation are used.

Day of Year	Month Day	ET in	Rain in	Irrig-ation in	Root Zone Depth ft	Allowable depletion in	Estimated depletion in
..							
182	July 1						0.13
183	July 2	0.26	-	-	3.00	1.05	.39
184	July 3	.37	-	-	3.04	1.06	.76
185	July 4	.36	-	-	3.09	1.08	1.12*
186	July 5	.39	-	1.0	3.13	1.10	.51
187	July 6	.30	-	-	3.18	1.11	.81
188	July 7	.26	0.39	-	3.22	1.13	.68
189	July 8	.25	-	-	3.27	1.14	.93

*- indicates estimated soil water depletion is approximately equal to the allowable soil water depletion. Irrigation is needed!

Emergence: DOY 128 (May 8)
Root zone depth on DOY 128 assumed 0.5 ft.

Full cover: DOY 205 (July 24)
Root zone depth on DOY 205 assumed 4.0 ft.

Assuming a linear root growth rate from 0.5 to 4.0 ft. from DOY 128 to DOY 205 (77 days), or 3.5/77 = 0.045 ft per day. Then at 55 days (DOY 183 - 128), the root zone depth is the initial depth (0.5 ft) plus 55(0.045) or 3.00 ft. The available soil water increases by 0.7 inches for every foot of root zone increase. The allowable depletion increases by 50% as much, or

$$\text{increase in allowable depletion} = 0.7 \text{ in/ft } (0.045 \text{ ft/day})(0.5)$$
$$= 0.016 \text{ in/day.}$$

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