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**Soil
Conservation
Service**

National
Engineering
Handbook

Section 15

Irrigation

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Chapter 1

Soil-Plant-Water Relationships

Chapter 1
Soil-Plant-Water Relationships

Contents

Page

Figures iii
Tables v
Nomenclature vi
Preface vii
Introduction 1-1

Soil 1-3
- Soil Physical Properties 1-3
- Soil Texture 1-3
  - Mineral Soil 1-3
  - Organic Soil 1-5
- Soil Structure 1-5
- Tilth 1-5
- Soil Porosity 1-6
- Soil Compaction 1-7
- Soil Salinity and Sodicity 1-7
- Categories of Salt-Affected Soils 1-7
- Soil Water 1-8
  - Soil Water Potential 1-8
  - Soil Water Characteristic Curves 1-10
  - Water Movement in Soil 1-10
  - Plant Available Water 1-12
  - Soil Water Measurement 1-14
  - Methods Used for Characterizing Soil Water 1-14
    - Gravimetric 1-15
    - Feel and Appearance Method 1-15
    - Tensiometers 1-17
    - Electrical-Resistance Instruments 1-18
    - Neutron Scattering 1-19
    - Heat Dissipation 1-19
  - Sampling Error 1-19
  - Location of Soil Water Measurements 1-20

Water Intake 1-21
- Percolation 1-21
- Factors Affecting Infiltration 1-21
  - Soil Water Content 1-21
  - Soil Sealing 1-21
  - Surging 1-22
  - Compaction 1-22
  - Tillage 1-22
  - Soil Cracking 1-22
  - Organic Material 1-22
  - Salts in Soil 1-22
  - Sediments in Irrigation Water 1-23
  - Soil Erosion 1-23
  - Land Leveling 1-23
  - Temperature 1-23
  - Surface Storage 1-23

Infiltration Stages 1-23
Cumulative Infiltration and Infiltration Rate Relations 1-24
Basic or Steady Infiltration Rate 1-24
Seasonal and Spatial Variation 1-24
Field Infiltration Measurements 1-25
Models 1-27
Plants 1-28
Plant Root Systems 1-28
Crop Species Rooting Characteristics 1-28
Factors Affecting Root Growth 1-30
Water Flow Into Roots 1-30
Water Uptake-Root Profile Relations 1-30
Plant Water Use from Shallow Water Tables 1-31
Design Water-Extraction Depth 1-32
Evapotranspiration (ET) 1-32
Potential ET 1-32
Predicting Crop ET 1-34
Crop Coefficient 1-35
Crop Critical Stress Periods 1-37
Yield-Evapotranspiration Relationships 1-38
Concepts of Production Functions 1-38
Yield-Evapotranspiration Production Functions 1-39
Yield-Applied Water Relationships 1-39
Transferability of Yield-Evapotranspiration Functions 1-40
Salinity Effects 1-41
Plant Factors 1-44
Soil Factors 1-44
Climatic Factors 1-44
Specific Ion Effects 1-44
Acid Soils 1-45
Chemistry of Acid Soils 1-45
Effects of Soil Acidity on Plant Growth 1-45
Crop Response to Liming in the United States 1-45
Determining Lime Requirement 1-46
Scheduling Irrigations 1-49
Water Balance 1-49
Allowable Water Depletion 1-49
Soil Water Extraction Depth 1-50
Net Water Calculations 1-50
Water Balance Accounting Procedures 1-51
Plant Based Concepts 1-52
Pressure Chamber 1-52
Leaf or Canopy Temperature Methods 1-53
Visual Appearance 1-54
Indicator Plants 1-54
Automation in Irrigation Scheduling 1-56

Figures

1-1.—Four climatic areas in the United States: arid, semiarid, subhumid, and humid (AAVIM Planning for an Irrigation System, 2nd edition, 1980) 1-2

1-2.—Proportions of sand, silt, and clay in basic soil textural classes 1-4

1-3.—Types of soil structure and their effect on downward movement of water (U.S. Dept. Agr. and U.S. Dept. of Int. Agr. Inf. Handbook 199. Irrigation on Western Farms, 53 pp., illus. 1959) 1-6

1-4.—Effect of soil bulk density on alfalfa root growth in greenhouse pots at the end of 80 and 110 days (D.W. Grimes, W. R. Sheesley, and P. L. Wiley, 1978. Agron. J. 70:955-958) 1-8

1-5.—Illustrations and example calculations for gravitational, matric, and pressure potential based on weight as specifying the unit of water. Increasing depth below the soil surface is considered to be negative in the illustrations (R. J. Hanks and G. L. Ashcroft, 1980. Applied Soil Physics. Springer-Verlag, Berlin) 1-10

1-6.—Soil water characteristic curves (M. D. Thorne and W. A. Raney. Soil Moisture Evaluation. U.S. Dept. Agr. ARS 41-6, 14 pp., illus. 1956) 1-11

1-7.—Water penetration and movement in sandy and clay loam soils; to achieve complete wetting, furrows have to be closer together on sandy soils 1-13

1-8.—Relation between the water content and the water tension of a soil 1-14

1-9.—General relationship between soil water characteristics and texture (adapted from The Nature and Properties of Soils, Nyle C. Brady, 1984) 1-14

1-10.—Water release curve for three soils (M. D. Thorne and W. A. Raney, 1956. Soil Moisture Evaluation. U.S. Dept. Agr. ARS 41-6, 14 pp.) 1-15

1-11.—Soil water depletion by cotton on a Panoche clay loam (D. W. Grimes, 1986. Texas Agr. Exp. Sta. MP-1616) 1-16

1-12.—Tensiometers are used to measure soil water at a point in the soil profile 1-17

1-13.—Electrical resistance soil water meters 1-18

1-14.—Predicted infiltration rates for a deep Columbia silt loam with different initial water contents (ASAE Monograph, Farm Irrigation Systems, 1980) 1-21

1-15.—Potential runoff for high and low steady water application rates similar to stationary sprinklers (ASAE Monograph, Farm Irrigation Systems, 1980) 1-23

1-16.—Potential runoff for nonstationary sprinkler 1-24

1-17.—Relation of cumulative infiltration to time for three soils 1-25

1-18.—Relation of infiltration rate to time for three soils 1-26

1-19.—Fibrous root system of corn (left) and taproot system of sugar beet (right): both are approximately two months old (R. Scott Russell, 1977. Plant root system. McGraw-Hill, U.K. p. 51 and John E. Weaver and Frederic E. Clements, 1938. Plant Ecology. McGraw-Hill, New York and London, p. 313) 1-28

1-20.—Average water extraction pattern of plants growing in a soil without restrictive layers and with an adequate supply of available water throughout the root zone 1-31

1-21.—Water extraction patterns as determined by available water content in various parts of soil profile. Width of each profile represents total available water; gross area (height and width) of each profile represents total available water in profile; hatched area shows water extraction pattern for each profile [Dale R. Shockley, 1955. Capacity of soil to hold moisture. Agri. Engin. 36(2):109-112] 1-32

1-22.—Upward flux-water table depth relationships for eight North Carolina soils (W. Skaggs, 1980. Drainmod. USDA-SCS Reference Report) 1-33

1-23.—Change in relative rooting depth with relative time for annual crops (H. Borg and D. W. Grimes, 1986. Transactions of the ASAE 29:194-197) 1-34

1-24a through 1-24f.—Monthly reference estimates from several different procedures versus lysimeter-measured ET (ASCE Water Requirements Committee, 1987) 1-36

1-25.—Illustration of a crop coefficient curve (J. Doorenbos and W. O. Pruitt, 1977. Guidelines for predicting crop water requirements. FAO Irrig. and Drain. Paper No. 24, p. 144) 1-38

1-26.—Alfalfa hay yield-ET and yield applied water (AW) functions for the San Joaquin Valley, California (D. W. Grimes, personal communication) 1-39

1-27.—Cotton lint yield-ET and lint yield-applied water (AW) functions for the San Joaquin Valley, California (D. W. Grimes and Kamal Elzik, 1982. Cotton water management. University of California Bull. No. 1904) 1-39

1-28.—Relative yield of Thompson grapes versus relative evapotranspiration (L. E. Williams and D. W. Grimes, 1987. Modeling vine growth-development of a data set for a water balance subroutine. Sixth Australian Wine Industry Tech. Conf., Adelaide) 1-40

1-29.— Nutrient Availability in Acid Soils: the wider the bar, the more available is the nutrient (adapted from Emil Truog, USDA Yearbook of Agriculture, 1943-47) 1-46

1-30.—Components of a field water balance (E. Fereres, D. W. Henderson, W. O. Pruitt, W. F. Richardson, and R. S. Ayers, 1981. Basic irrigation scheduling. Div. of Agricultural Sciences University of California Leaflet 21199, 8 pp.) 1-49

1-31.—Generalized relationship between soil-water retention and crop growth 1-50

1-32.—Diurnal leaf water potential curves for cotton of contrasting water stress levels (D. W. Grimes and H. Yamada, 1982. Relation of cotton growth and yield to minimum leaf water potential. Crop Sci. 22:134-139) 1-53

1-33.—Foliage-air temperature differential versus air vapor pressure deficit for well-watered alfalfa grown at a variety of specific sites and dates (S. B. Idso, R. D. Jackson, R. J. Pinter, Jr., R. S. Reginato, and J. L. Hatfield, 1981. Normalizing the stress-degree day parameter for environmental variability. Agric. Meteorol. 24:24-55) 1-55

Tables

1-1.—Range in particle size by texture 1-3

1-2.—General terms for basic soil textural classes (U.S. Dept. of Agr. Soil Survey Manual, 430-V. June 9, 1981) 1-5

1-3.—Classification of salt-affected soils 1-9

1-4.—Ranges in available water content by soil textural classes 1-13

1-5.—Data source summary of several crop species on the depth development of roots with time and expected maximum rooting depth (RD_m) under favorable environmental conditions (H. Borg and D. W. Grimes, 1986. Depth development of roots with time on empirical description.Transactions of the ASAE. Vol. 29, No. 1, pp. 194-197) 1-28

1-6.—General factors for conversion from one method of estimating crop ET to another (Snyder & Dickey, 1982) 1-35

1-7.—Critical periods for water stress, symptoms, and some other considerations for several important crops 1-37

1-8.—Salt tolerance of herbaceous crops (E. V. Maas, 1986. Applied Agricultural Research 1:12-26) 1-42

1-9.—Tolerance classification of plants to boron (Robert S. Ayers, 1977. Quality of water for irrigation. J. Irrig. Drain. Div. ASCE, IR2, 103:135-154) 1-44

1-10.—Permissible soil pH ranges for various crops growing on mineral soils in Michigan (C.M. Woodruff, 1967. In Soil, Acidity and Liming. Robert W. Pearson and Fred A. Adams, eds. Agronomy Monograph No. 12. Amer. Soc. Agron. Madison, WI, p. 222) 1-47

1-11.— Approximate amounts of finely ground limestone needed to raise the pH of a 7-inch layer of soil 1-48

1-12.—Suggested percentage of available soil water content remaining in the crop root zone when an irrigation should be scheduled for several common crops 1-50

1-13.—Water retention characteristics of a Hinckley loamy sand 1-51

1-14.—Example of water balance accounting procedure 1-52

Nomenclature

AW = Applied water in inches

AWC = Available water capacity of a soil. Water content difference between FC and PWP

B.D. = Bulk density of soil in grams per cubic centimeter

C_{et} = Coefficient to convert ET_p to ET_c

C,S,b = Infiltration function parameters related to soil characteristics

CWSI = Crop water stress index

D = Depth of water in soil in inches

d = Soil depth in inches

dw = Density of water as 1 gram per cubic centimeter

E_{pan} = Evaporation from National Weather Service "class A" evaporation pan

EC_e = Electrical conductivity of soil solution saturation extract in decisiemens per meter

ET = Evapotranspiration in inches

ET_a = Actual crop ET

ET_c = Evapotranspiration of a specified crop

ET_m = Maximum crop ET

ET_o = Reference ET (approximates 4-7 inch tall grass)

ET_p = Potential ET (approximates uncut alfalfa)

F = Cumulative infiltration in inches

f = Infiltration rate in inches per hour

FC = Field capacity, the water content a soil will hold when freely drained (1/10 to 1/3 atmosphere tension).

f_c = Final infiltration rate in inches per hour

f_o = Infiltration rate at time 0 in inches per hour

H = Hydraulic head in feet

K = Hydraulic conductivity in feet per day

k_c = Crop coefficient, unitless

K_c = Coefficient to convert ET_o to ET_c

K_p = Coefficient to convert E_{pan} to ET_c

K_{pan} = Coefficient to convert E_{pan} to Et_o

K_s = Saturated hydraulic conductivity in inches per day

k,a = Infiltration function fitting parameters

L = Distance in feet

Md = Difference between initial and final water content

PWP = Permanent wilting point (the water content of a soil at 15 atmospheres tension)

q = Flux density in volume per unit area per time

R = Universal gas constant

RD_m = Maximum rooting depth

SAR = Sodium absorption ratio, unitless

S_f = Suction or matrix potential at the wetting front in inches

T = Absolute temperature in degrees kelvin

t = Time after irrigation starts in hours

T_a = Air temperature in degrees celsius

T_f = Foliage temperature in degrees celsius

Y_a = Actual crop yield associated with ET_a

Y_m = Maximum crop yield associated with ET_m

Preface

Section 15 of the National Engineering Handbook (NEH), Irrigation, supplies engineers and others with the basic data necessary to plan, design, and maintain efficient conservation irrigation practices. Engineering principles and research findings have been screened to give emphasis to the information needed to provide technical assistance to individual farmers and groups of farmers. Chapter 1, Soil-Plant-Water Relationships, describes those properties of soils and plants that affect the movement, retention, and use of water that are essential to plant growth.

The first edition of this chapter was published in March 1964. This updated second edition was prepared by Dr. Wes Wallender and Dr. Don Grimes of the University of California at Davis under contract to the Soil Conservation Service (SCS). The principal reviewers of this publication for SCS were Paul K. Koluvek, retired, Gylan L. Dickey, Carroll A. Hackbart, and Elwin A. Ross, National Technical Center irrigation engineers, and Swayne F. Scott, national irrigation engineer, retired. Valuable comment also was provided by Bobby Birdwell, assistant director of the Soils Division, retired; Milton W. Meyer, soil characterization specialist; and David L. Schertz, national agronomist. Final review was provided by Richard Van Klaveren, national irrigation engineer.

NEH Section 15, Chapter 1 is written for the employees of the Soil Conservation Service who provide technical assistance to the water user.

October 1990

Chapter 1

Soil-Plant-Water Relationships

Introduction

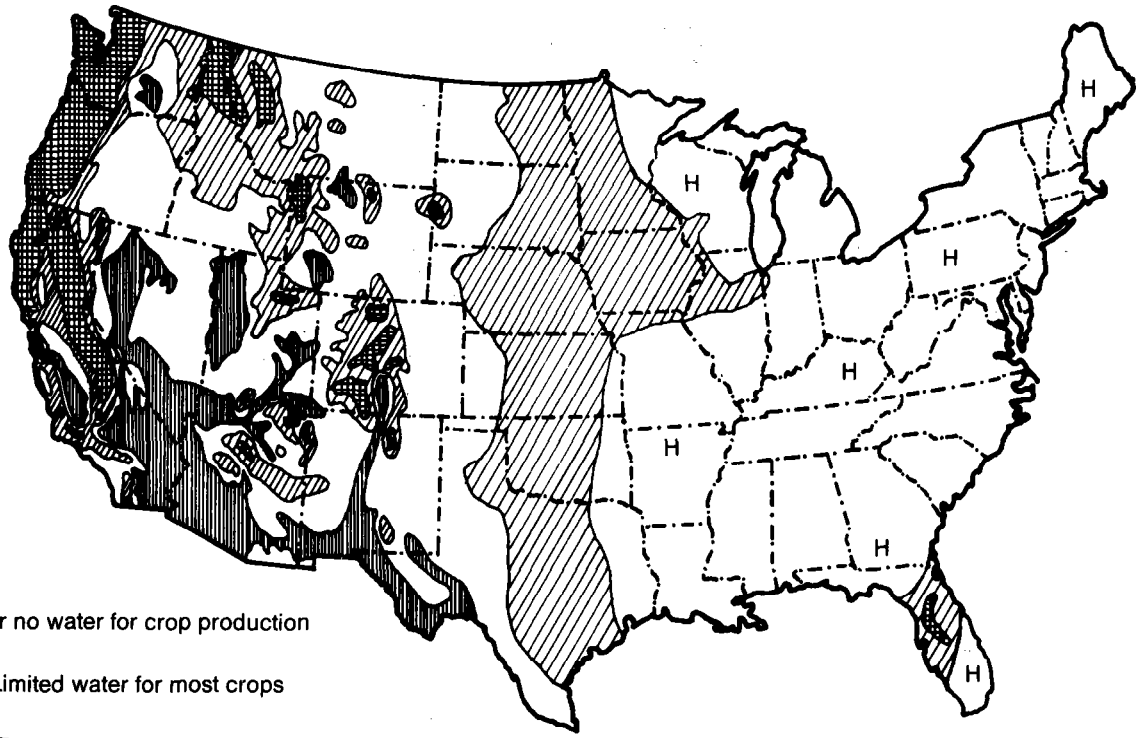
Irrigation is the controlled application of water to arable lands in order to supply crops with the water requirements not satisfied by natural precipitation. In arid climates (fig. 1-1), adequate food and fibers cannot be produced without irrigation. Because of the potential for low crop yields and risk of crop failure due to variations in rainfall, irrigation in semiarid regions is needed most of the time. Furthermore, irrigation in humid and subhumid regions is desirable as insurance against crop losses. Even though summer rainfall ordinarily is sufficient for crop growth, sometime during the year a drought may occur. Production of a profitable crop is generally the objective of agriculture. Irrigation provides the insurance for a profitable agriculture in semiarid, subhumid, and humid areas; it is a necessity in arid regions.

Water is introduced to the soil by an irrigation system, by a regulated water table, or by precipitation. It is stored in the soil matrix and then extracted by plant roots to meet the plant evapotranspirational (ET) needs. This chapter on soil-plant-water relationships treats the physical properties of soils and plants that affect the movement, retention, and use of water and that must be considered in designing and operating systems for conservation irrigation.

In planning and designing an irrigation system, the technician is concerned primarily with the water-holding capacity of a soil, particularly in the root zone of the plant; with the water-intake rate of the soil; with the root system of the crop to be grown; and with the amount of water that the crop uses. In addition, a working knowledge of all soil-plant-water relationships is necessary in order to plan and manage efficiently the irrigation for particular crops grown on particular soils and in order to adjust the design to various conditions.

Figure 1-1.

Four Climatic Areas in the United States: Arid, Semiarid, Subhumid, and Humid



Climatic Area

- Arid - Little or no water for crop production
- Semi-arid - Limited water for most crops
- Subhumid - Requires special farming practices to conserve moisture
- Humid - Enough annual precipitation for most crops, but unevenly distributed

Soil

Soils function as a storehouse for plant nutrients, as habitat for soil organisms and plant roots, and as a reservoir for water to meet the evapotranspirational demands of plant communities. The amount of water that a soil can hold for plant use is determined by its physical and chemical properties. This amount determines the length of time that a plant can be sustained adequately between irrigations or rainfall events. This amount also determines the frequency of irrigation, the amount to be applied, and the capacity of the irrigation system needed for continuous optimum crop growth.

Soil Physical Properties

Mineral soils are porous mixtures of inorganic particles, decaying organic matter, air, and water. They also contain a variety of living organisms. The parent material of mineral soils consists of loose, unconsolidated fragments of weathered rocks or unconsolidated sediments. Physical and chemical weathering, with the translocation and the accumulation of various substances, give rise to a horizontal layering of the soil mass that is frequently visible in trenches and road cuts. Collectively, these horizons or layers are called the soil profile. The characteristics of the layers of the profile affect root growth and the retention and transmission of water in the soil.

Two important physical properties of soils are texture and structure. Soil texture refers to the relative proportion of variously sized groups of mineral particles in a specific soil or horizon. Soil structure refers to the manner in which soil particles are arranged in groups or aggregates. Together, soil texture and soil structure help to determine the supply of water and air in a soil. The inherent characteristics of a soil may be adversely affected by soil compaction. Compaction can extensively modify soil aeration, water retention, transmission properties, root penetration, temperature relations, and the nutritional properties of a soil system.

Soil Texture

Mineral Soil

The variously sized groups of mineral particles in a soil are called separates. The classification of soil separates used by the U.S. Department of Agriculture and their range in diameter size are shown in table 1-1. Coarse fragments, larger than 2 millimeters in diameter, are not included.

Table 1-1.—*Range in particle size by texture*

Soil separate	Particle diameter (millimeters)*
Very coarse sand	2.0 - 1.0
Coarse sand	1.0 - .5
Medium sand	.5 - .25
Fine sand	.25 - .1
Very fine sand	.1 - .05
Silt	.05 - .002
Clay Less than .002	

*millimeters x 0.03937 = inches

Soil textural classes are based on different combinations of sand, silt, and clay. For some purposes it is necessary to make fine distinctions in texture; the basic classes used in terms of size distribution, as determined by mechanical analysis in the laboratory, are shown in figure 1-2.

In places, it is more convenient to speak of texture in general terms; acceptable terms for groups of the basic classes are shown in table 1-2.

In the field, soil texture can be determined by feeling the soil with the fingers. If necessary, this determination can be checked later in the laboratory. The USDA Soil Survey Manual includes the following general definitions of soil textural classes in terms of field experience:

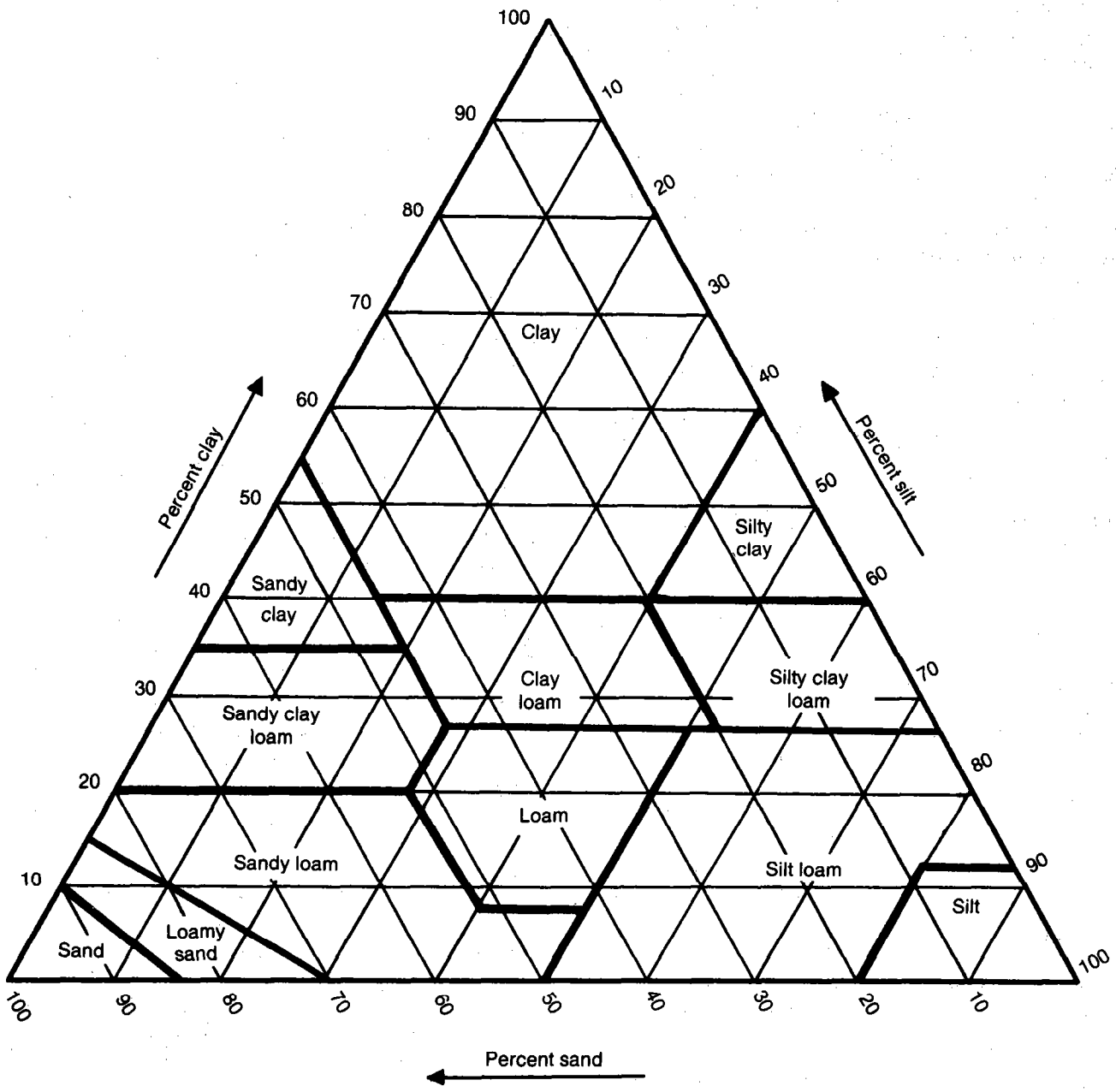
Sand.—Sand is loose and single-grained. The individual grains can be seen or felt readily. Squeezed in the hand when dry, sand falls apart when pressure is released. Squeezed when moist, it forms a cast but crumbles when touched.

Sandy Loam.—A sandy loam is soil containing a high percentage of sand but having enough silt and clay to make it somewhat coherent. 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 soil having a relatively even mixture of different grades of sand, silt, and clay. It is mellow with a somewhat gritty feel but is fairly smooth and slightly plastic. Squeezed when dry, it forms a cast that bears careful handling, and the cast formed by squeezing the moist soil can be handled freely without breaking.

Figure 1-2.

Proportions of Sand, Silt, and Clay in Basic Soil Textural Classes



Silt Loam.—A silt loam is 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, silt loam 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.—A clay loam is a moderately 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, clay loam 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 that are very high in colloids are friable and lack plasticity at all conditions of moisture.

Organic Soil

Organic soils vary in organic matter content from 20 percent to as high as 95 percent. They generally are classified on the basis of degree of decomposition of the organic deposits. The terms peat, muck, and mucky peat are used for organic materials in a manner similar to the way in which mineral textural terms are used. Muck is well-decomposed organic soil material. Peat is raw undecomposed organic materials in which the original fibers constitute almost all of the material. Mucky peat material is intermediate between muck and peat.

Mucky is used to modify mineral soil texture. The term implies the presence of enough organic matter to give the material some properties of organic soil combined with the properties of the mineral material. The material does not, however, have enough organic matter to be "muck." Mucky material is usually dark, friable, and retentive of moisture; it is mineral in basic composition. The organic matter content is commonly more than 10 percent.

Table 1-2.—*General terms for basic soil textural classes (U.S. Dept. of Agr. Soil Survey Manual, 430-V, June 9, 1981).*

General terms	Textural Classes
Sandy soils:	
Coarse-textured	Sands (coarse sand, sand, fine sand, very fine sand), loamy sands (loamy coarse sand, loamy sand, loamy fine sand, loamy very fine sand)
Loamy soils:	
Moderately coarse-textured	Coarse sandy loam, sandy loam, fine sandy loam
Medium-textured	Very fine sandy loam, silt loam, silt
Moderately fine-textured	Clay loam, sandy clay loam, silty clay loam
Clayey soils:	
Fine-textured	Sandy clay, silty clay, clay

Soil Structure

Soil structure is the arrangement and organization of soil particles into natural units of aggregation that soil scientists call peds. Peds are separated from one another by planes of weakness that persist through cycles of wetting and drying in place. Most peds are large enough to be seen without magnification. Structure influences the rate at which water and air enter and move through the soil; it also affects root penetration and the nutrient supply of the soil.

Structure type (fig. 1-3) refers to the particular kind of particle grouping that predominates in a soil horizon. Single-grained and massive soils are structureless. In single-grained soils, such as loose sand, water percolates very rapidly. Water moves very slowly through massive soils such as some clays. The more favorable water relations are usually in soils that have prismatic, blocky, and granular structure; platy structure impedes the downward movement of water.

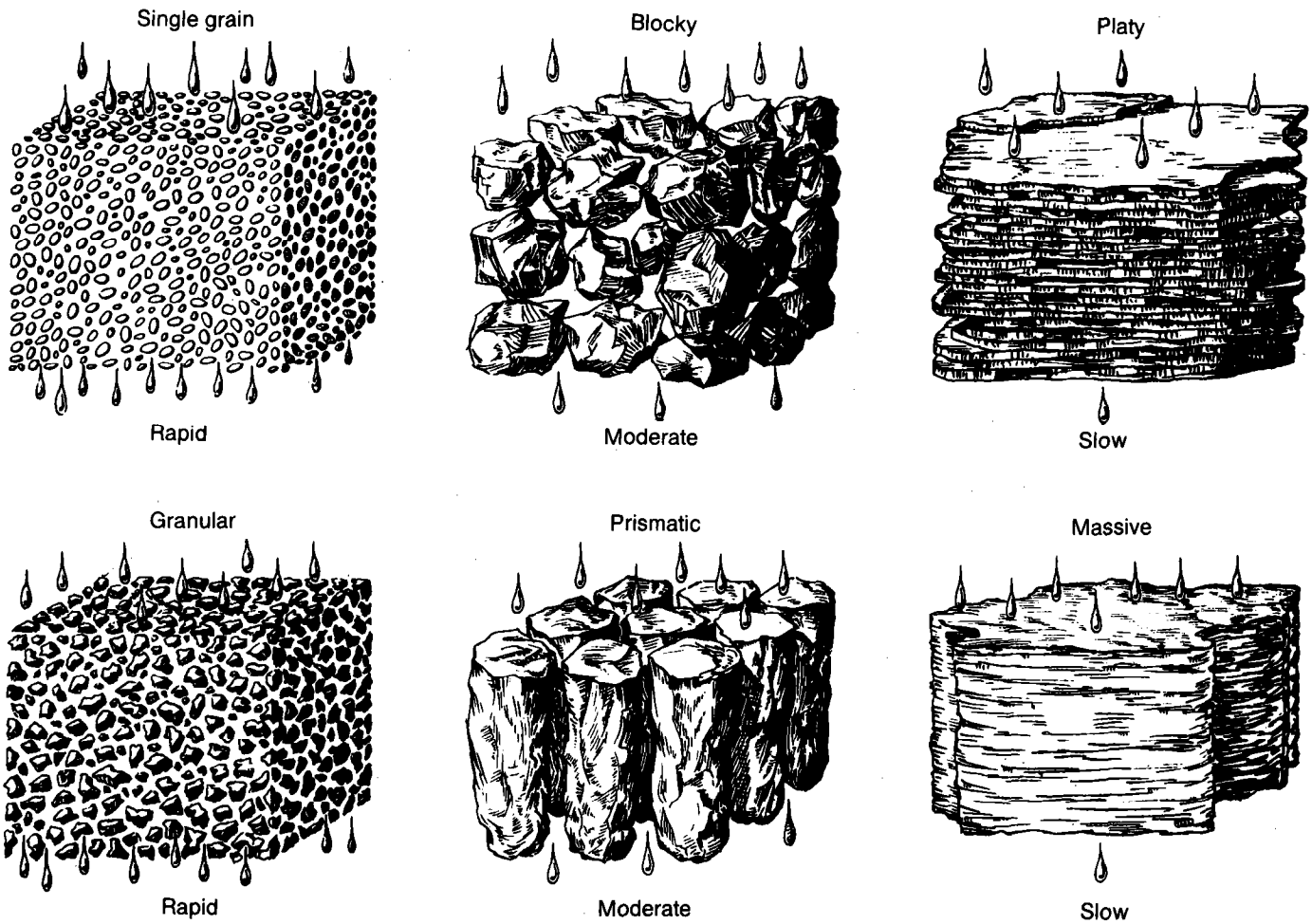
Unlike texture, structure of the soil can be changed to the depth of tillage. Excellent structure develops in the surface layer of soils high in organic matter and on which perennial grass is growing. Cycles of wetting and drying or of freezing and thawing improve structure in the plow layer. On the other hand, cultivation of medium- or fine-textured soils when their moisture content is high tends to destroy structure. Irrigation water that contains large amounts of sodium causes very undesirable structure by dispersing the soil aggregates.

Tilth

The physical condition of the soil in relation to plant growth and ease of tillage is commonly referred to as tilth. It depends on both the degree and stability of soil aggregates. Good, fair, and poor are the common descriptive terms for tilth. They refer to the ease with which a soil can be tilled

Figure 1-3.

Types of Soil Structure and Their Effect on Downward Movement of Water



and the rate it takes in water. Good soil tilth can be achieved on most soils by using good soil management practices.

Soil Porosity

The volume of pore space in mineral soils generally ranges from 30 to 60 percent of the total volume with the average being close to one-half. Soil porosity is affected mostly by soil aggregation, texture, root activity, entrapped gases, and by burrowing insects, worms, and other animals. Coarse-textured soils tend to be less porous than fine-textured soils, but the mean size of individual pores is usually larger in sandy soils. Porosity tends to be more variable in clayey soils because of the potential for swelling and contracting during wetting-drying cycles and the greater ability to either aggregate or disperse.

Pore space in soils can be viewed as a vast interconnecting network of voids extending in all directions. The voids hold liquids and gases and regulate their movement, contain most of the living organisms, and serve as avenues of entry for roots to grow and expand. Total soil porosity can be determined for a soil sample from the equation:

Total porosity = 1 - (bulk density/average particle density)

Bulk density is generally measured by means of a core sampler, of known volume, designed to extract undisturbed samples from various depths in the profile. Using the water displacement technique, soil scientists sometimes determine bulk density from a clod sample. Pore-size distribution can

be measured in the laboratory by desorption methods in which a presaturated sample is subjected to a stepwise series of incremental suctions, and the capillary theory is used to obtain the equivalent pore-size distribution. Where aggregation is quite distinct, it is possible to divide pore-size distribution into macropores and micropores. The macropores are primarily the pore spaces between aggregates that serve as the principal avenues for water infiltration, drainage, and aeration. The micropores are the smaller pores inside aggregates that function mostly for the retention of water and solutes. The demarcation is seldom distinct, and the separation between macropores and micropores is largely arbitrary.

Soil Compaction

Compaction of agricultural soils generally refers to the reduction of soil porosity through the partial collapse of the pores and expulsion of the permeating air. In an agricultural sense, soils are considered to be compact when the air-filled porosity is low enough to restrict aeration which impedes root penetration and drainage.

Soils may become compact naturally as a result of their textural composition, moisture regime, or the manner in which they are formed. Frequently, agricultural soils become compact as a result of mechanical force applied to the soil surface during cultural operations. Trampling by livestock can cause soil compaction; however, the most common cause of soil compaction in contemporary agriculture is that imposed on the soil by wheels, tracks, and soil-engaging tools. Figure 1-4 illustrates the effect of increased compaction (high-bulk density) on the growth and proliferation of alfalfa roots at the end of 80 and 110 days in greenhouse pots. Longer growth periods did not change root length density much beyond that shown for the 110-day period.

Soils of the southeast United States characteristically do not allow crops to develop a deep root system. Many of these soils have a textural class, such as the sandy loams, that is receptive to soil compaction by traffic and excess tillage in seed-bed preparation. Such soils may become increasingly restrictive to rooting.

Soil Salinity and Sodicity

Saline and sodic soils are most common in arid and semiarid regions, because rainfall is inadequate to meet the potential evapotranspiration requirement of plants. These soils occur when salts are not leached and accumulate to levels detrimental to plant growth. Salt problems can develop in subhumid and humid regions, particularly near coastal regions. It is estimated that 5 million hectares of irrigated land in the United States are salt affected, mostly in the 17 Western States. As much as one-third of all irrigated lands in the world (about 70 million hectares) have salt problems.

There are three main natural sources of soil salinity, namely: mineral weathering, atmospheric precipitation, and fossil salts. In addition, salts are added to soils by irrigation and agricultural and industrial wastes. Salts commonly are transported from areas of overirrigation to accumulate in poorly drained areas. As drainage water or irrigation return-flows evaporate, high concentrations of salts remain.

Normal irrigation involves applying water to the soil surface and displacing unused water through the soil during subsequent irrigations. Some drainage water also may pass eventually below the crop root zone. Water is lost through evaporation at the soil surface and through transpiration. Both evaporation and transpiration increase the residual concentration of dissolved salts. Salt concentration normally increases with soil depth in well-drained soil. As the proportion of irrigation water passing through the root zone (the leaching fraction) is increased, salt accumulation in the lower profile decreases.

When soils are irrigated with waters containing large amounts of sodium, the exchangeable sodium levels may become quite high. Such soils frequently crust severely and swell or disperse, which greatly decreases the hydraulic conductivity or permeability of the soils to water.

Categories of Salt-Affected Soils

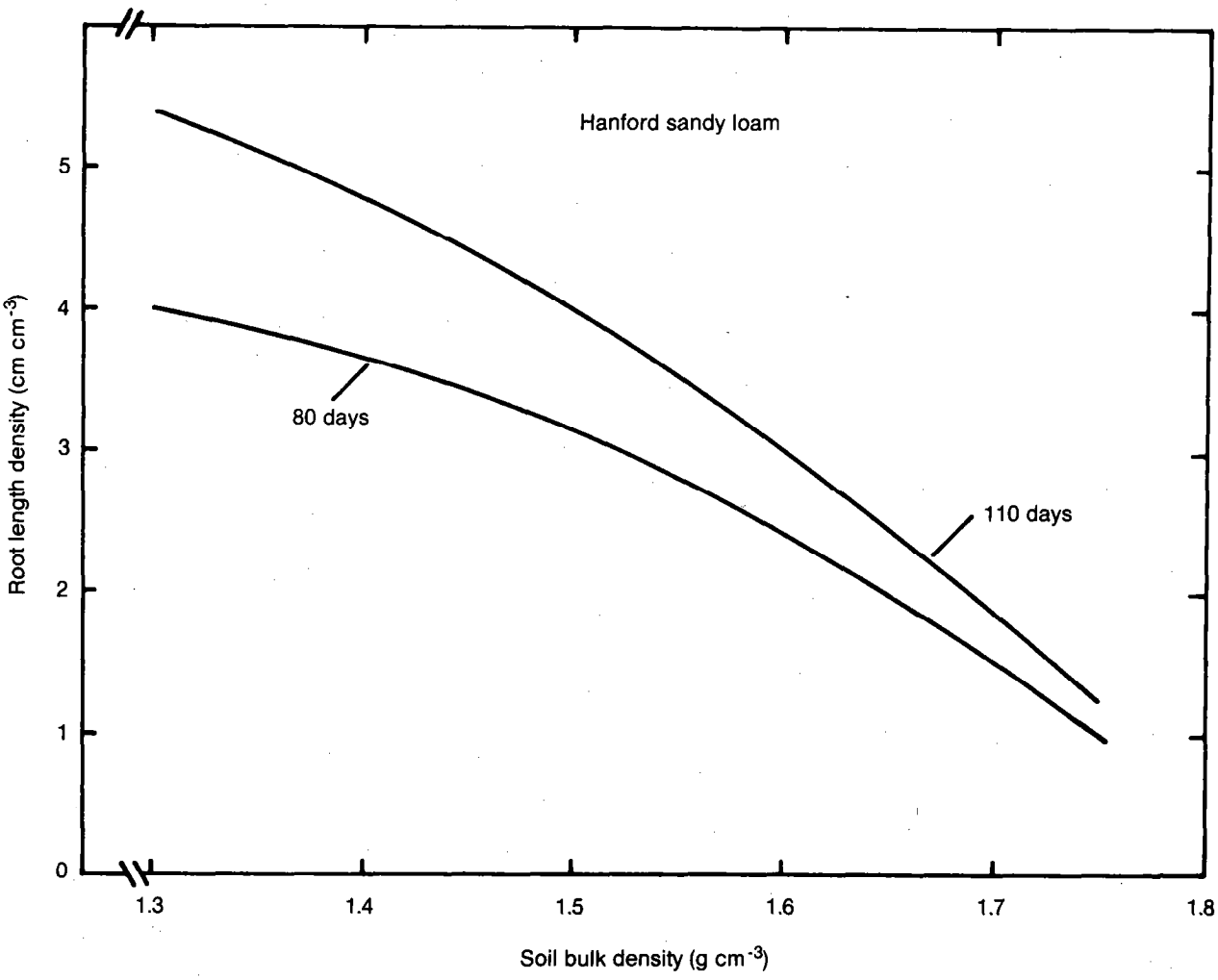
The classification of salt-affected soils is based on the soluble salt concentrations in extracted soil solutions. Electrical conductivity (EC_e) of a saturated extract is the standard measure of salinity. Table 1-3 gives the salinity class associated with electrical conductivity of soil saturation extracts that are in use by the Soil Conservation Service.

The sodium adsorption ratio (SAR) is the standard measure of the sodicity of a soil; it replaces the previously used exchangeable sodium percentage. The sodium adsorption ratio is calculated from the concentrations (in milliequivalents per liter) of sodium, calcium, and magnesium ions in the saturation extract according to the following relationship:

$$SAR = Na/ [(Ca + Mg)/2]^{1/2}$$

Figure 1-4.

Effect of Soil Bulk Density on Alfalfa Root Growth in Greenhouse Pots at the End of 80 and 110 Days



Soil Water

Soil water is frequently described in terms of content in units of gravimetric percent, percent on a volume basis, or equivalent water depth per unit of soil depth. Such descriptions are usually adequate for irrigation considerations when the primary question is one relating to how much irrigation water is required to bring the soil back to a defined water content. A descriptive property is needed, however, to explain why soils treated in similar ways have different water contents; why plants respond differently on contrasting soils even though they have the same water content; and why if a sandy soil and clay soil have the same water content and are placed in intimate contact with one another, water will move from the sandy soil to the finer textured soil. Soil water potential is the property used to describe such a phenomenon.

Soil Water Potential

Total water potential is the amount of work required per unit quantity of pure water to transport, reversibly and isothermally, a small quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water at the point under consideration. Differences in potential energy of water from one point in a soil system to another give rise to the tendency of water to flow within the soil. In the soil, water moves continuously in the direction of decreasing potential energy.

Table 1-3.—*Classification of salt-affected soils.*

Class	Electrical conductivity (EC_e)* Siemens per meter (S/M)	Decisiemens per meter (dS/m)**
Very slightly saline	0 - 0.4	0 - 4
Slightly saline	0.4 - 0.8	4 - 8
Moderately saline	0.8 - 1.6	8 - 16
Strongly saline	>1.6	>16

*Corrected to a temperature of 25 degrees C.
**Decisiemens per meter = millimhos per centimeter.

The concept of soil-water potential is of great fundamental importance. It replaces the arbitrary categorizations (gravitational water, capillary water, hygroscopic water) that were used in the early development stages of soil physics. Water in the soil differs from place to place and from time to time, not in form, but in potential energy. For very practical reasons, however, it is convenient to retain the concepts of "field capacity" and "permanent wilting point," while recognizing the qualitative aspects of such nomenclature.

Total water potential consists of several conponents. It is the sum of matric, solute, gravitational, and pressure potential:

Total = Matric + Solute + Gravitational + Pressure

Units of the potential depend on how a unit quantity of water is specified. Because weight is one of the most convenient ways of specifying the unit of water and conversions between English and SI (International System) are easily done, this will be used in some illustrations.

Gravitational Potential.—Determination of gravitational potential is illustrated in figure 1-5. This component of total potential is independent of soil properties and depends only on the vertical distance between the reference and the point in question. For points above the reference, gravitational potential is positive; points below the reference are negative. In figure 1-5 two points in a soil are located at a specific distance from a reference point Z. Gravitational potential of point A is 6 inches and of point B is 4 inches, thus the difference in gravitational potential between the two points is 6 inches - (-4 inches) = 10 inches.

Matric Potential.—When the unit quantity of water is expressed as weight, then matric potential is the vertical distance between the measured point of the soil (ceramic cup of figure 1-5) and the water surface of a water-filled manometer. Matric potential is a dynamic soil property and will be at a theoretical zero level for a saturated soil. The matric potential of a soil system results from capillary and adsorptive forces due to the soil matrix. These forces attract and bind water in the soil and lower its potential energy below that of bulk water. Capillarity results from the surface tension of water and its contact angle with the solid soil particles. This potential was formerly called capillary potential or capillary water. In figure 1-5 the unglazed ceramic cup that is embedded in soil is connected to a water manometer to form a tensiometer. The weight matric potential of the soil water at the cup is the vertical distance from the center of the cup to the water level in the manometer which is 6 inches.

Pressure Potential.—The pressure potential applies mostly to saturated soils. Where water quantity is expressed as a weight, pressure potential is the vertical distance between the water surface and a specified point. In the field, this component is zero above and at the level of water in the piezometer. Below the water level it is always positive. In figure 1-5 a piezometer tube (tube open at both ends) is installed in the soil to a depth below the water table. Pressure potential at point A is the distance between the point and the water level which is 4 inches.

Solute Potential.—Solute or osmotic potential arises because of soluble materials (generally salts) in the soil solution and the presence of a semipermeable membrane. Two recognized membranes in soil-water systems are the cell wall of plant roots and air-water interfaces. The solute potential can be approximated from the relation:

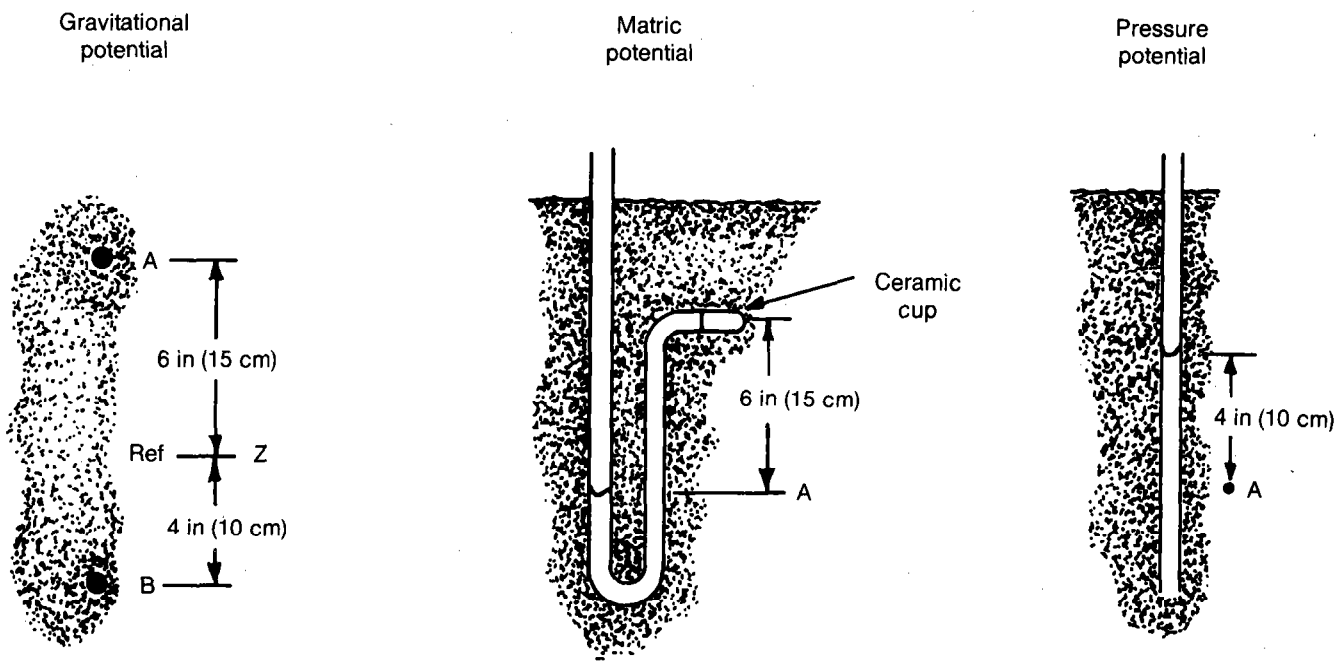
$$\text{Solute potential} = RTC$$

where R is the universal gas constant (82 bars cm^3/mol °k), T is absolute temperature (°k), and C is solute concentration (mol/cm^3). Because of the nature of the universal gas constant (R), it is much easier to use SI units in solving for solute potential. With the units illustrated, as values of temperature and solute concentration are placed in the equation, all units cancel except bars. This unit (bar) is now easily converted to another unit as shown in the following discussion.

Units.—Historically, many units have been used to express suction, tension, stress, or potential. A partial list is: bars, centimeters (cm) of water, centimeters of mercury, inches of water, atmospheres, centibars, millibars, joules per kilogram,

Figure 1-5.

Illustrations and Example Calculations for Gravitational, Matric, and Pressure Potential Based on Weight as Specifying the Unit of Water. Increasing Depth Below the Soil Surface is Considered to be Negative in the Illustrations.



pounds per square inch, ergs per gram, and dynes per square centimeter. The bar unit is in extensive use; some conversions for this unit are:

1 bar = 1020 cm of water
= 75.01 cm of mercury
= 401.5 inches of water
= 0.987 atmospheres
= 100 centibars
= 1000 millibars
= 100 joules/kg
= 10^6 ergs/g
= 10^6 dynes/cm^2

Soil Water Characteristic Curves

When saturated soils are subjected to increasing amounts of suction, progressively smaller pores are drained until, at very high suctions, only the very narrow pores retain water. Also, an increase in soil-water suction is associated with a decreased thickness of the water film that covers the surface of soil particles. The amount of water remaining in the soil at a series of equilibrium steps is related to the size and volume of water-filled pores and is, therefore, a function of the matric suction. Experimentally, pressure is substituted for suction with appropriate equipment and a curve of water content versus soil moisture tension is prepared. Illustrative curves for contrasting soil types are shown in figure 1-6. The relation between matric potential changes and changes in water content is a complex, nonlinear function. This characteristic curve is usually determined for individual soils.

Water Movement in Soil

Under saturated conditions, the rate of water movement in a soil system is governed by the characteristics of the pore space; therefore, the actual geometry and flow pattern of a soil is extremely complex. An equation known as Darcy's law is used to express the flux density (volume of water flowing through a unit cross-sectional area per unit of time). The equation is:

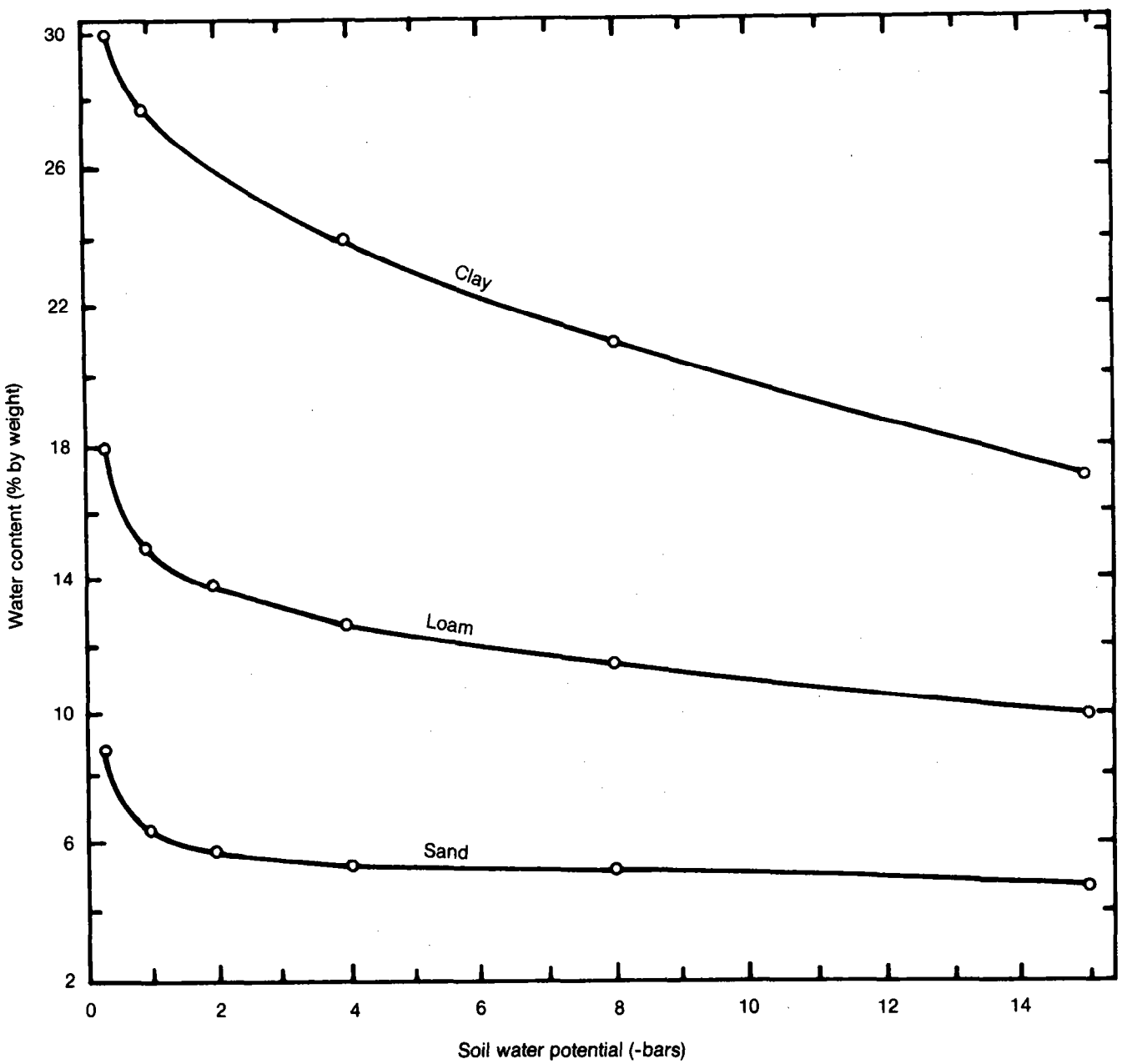
$$q = K \text{ (delta H)}/L$$

where q is the flux density, (delta H)/L is the hydraulic gradient (head drop or change in head per unit distance in the direction of flow), and K is the proportionality factor generally designated as the hydraulic conductivity. The K factor reflects the complexities of individual soil systems. This law indicates that the flow of water through the soil is in the direction of, and at a rate proportional to, the driving force acting on the system.

Many processes involving water movement or flow in the crop root zone occur under unsaturated conditions. In

Figure 1-6.

Soil Water Characteristic Curves



comparison to saturated flow, water movement under unsaturated conditions is considerably more complex and difficult to describe quantitatively; however, many excellent quantitative reviews on this subject are available for definitive information. An overview of practical unsaturated flow characteristics will be considered here.

Under unsaturated conditions water in soils is subject to subatmospheric pressure that is equivalent to a negative pressure potential. A gradient of this potential constitutes a driving force. Matric suction, as pointed out earlier, is due to the affinity of water to the soil-particle surfaces and capillary pores. Water is drawn from a region where hydration films are thicker to where they are thinner and from a zone where capillary menisci are less curved to where they are more highly curved. In other words, water flows from a region of higher to a region of lower matric potential (low to high suctions).

For saturated flow, the hydraulic conductivity (K) of a given soil will remain constant. Under unsaturated conditions, K changes drastically with water content. Large, more highly conductive pores are drained first; therefore, K decreases dramatically as a given soil dries. Because different soils have varying pore space characteristics, K values also are markedly different; contrasting textural soil classes influence unsaturated hydraulic conductivity in a very pronounced way. Generally, a saturated sandy soil will conduct water more rapidly than a saturated clay soil. As the soils drain, the very opposite conditions prevail; the small pores of the clay soil will retain and conduct water even at appreciably low potentials. Under unsaturated field conditions, flow is much more pronounced with fine-textured soils than with sandy soils.

From this discussion it is evident that water moves in soils in any direction in relation to potential energy gradients. The rate and magnitude of movement is determined by the many and complex relations that exist in soil systems. Some practical implications of textural class are illustrated in figure 1-7.

Plant Available Water

In designing an irrigation system, information is needed on how much of the water in soils is available to plants; the soil functions as a reservoir that has a limited capacity. Traditionally, plant available water has been considered to be the amount of water held by the soil between field capacity (FC) and permanent wilting point (PWP). These two points provide only qualitative information on soil water retention properties; nevertheless, their usage continues and useful planning information can be obtained from these concepts. It is important, however, to understand the limitations that are imposed.

By definition, FC is the amount of water a well-drained soil holds after "free" water has drained off. For coarse-textured soils drainoff occurs soon after irrigation because of their relatively large pores. In fine-textured soils drainage takes much longer because of their small pore size. Soil properties that affect field capacity materially are texture and strata within the profile that restrict water movement. Fine-textured soils hold more water than coarse-textured soils. Field capacity for sandy soils is defined as –1/10 bar, for silty soils, –1/5 bar; and for clayey soils, –1/3 bar. Restricted flow in stratified soils slows redistribution, but may increase the amount of water used by the plant. The effect of contrasting soil texture on the soil-water potential is illustrated in figure 1-8 by the broken line near the left vertical axis. Field capacity can be determined in the field after a soil has been thoroughly wetted by irrigation or rain or estimated in the laboratory from water-characteristic relations.

The permanent wilting point (PWP) is the soil-water content at which plants can no longer obtain enough water to meet minimal transpiration requirements; at which time, they wilt and if watered will not recover. Plants will wilt if they are not able to take up soil water fast enough to meet the climatic ET demand.

Plants continue to absorb water when wilted, but not at a sufficient rate to regain turgor.

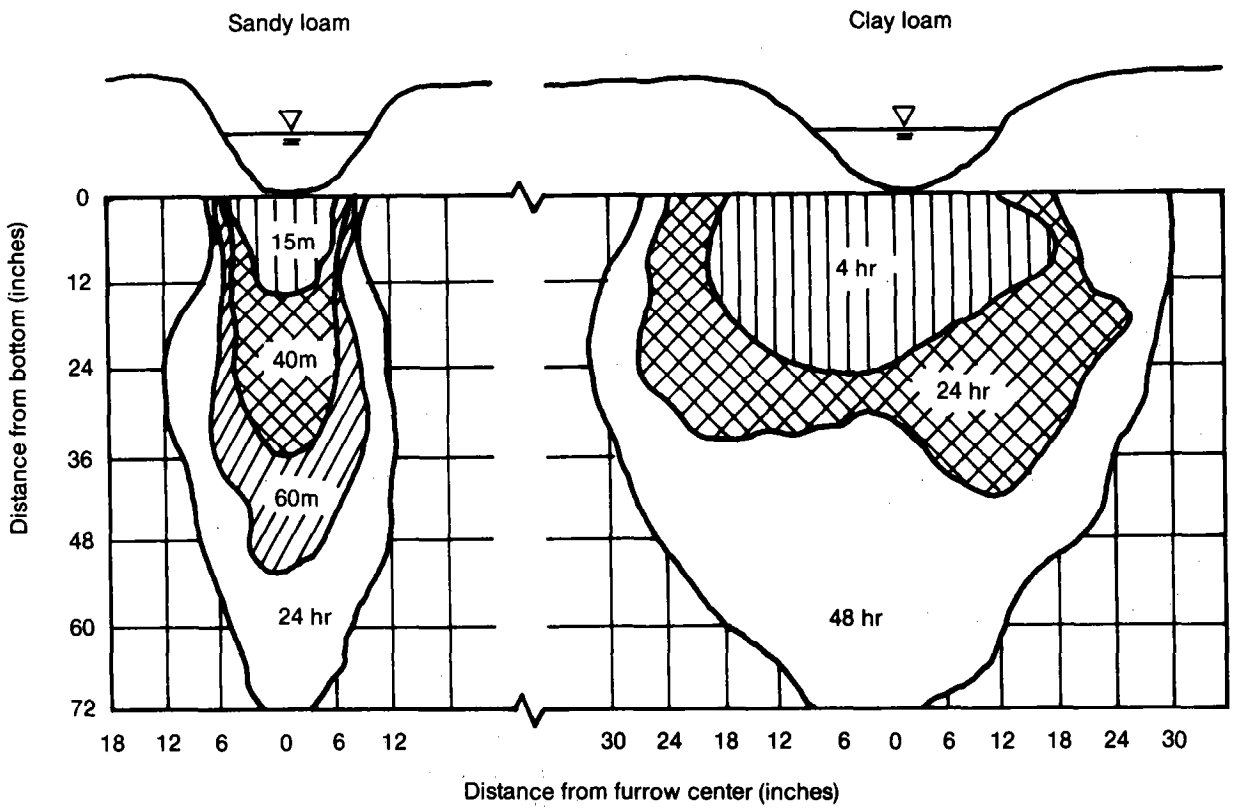
The water potential commonly used for PWP is -15 bars, which was first established with sunflowers over a wide range of soils. This parameter is shown as the right vertical line of figure 1-8. Some plants can extract soil water to potentials below -15 bars before they wilt and some will wilt above -15 bars.

Soil water considered to be available for plant growth lies at a potential energy level between FC and PWP. It should be pointed out, however, that these determined values represent only the matric potential of the soil water system. The presence of salts may contribute a substantial osmotic component to the total soil water potential. It is the total potential that determines soil water availability to plants. Nevertheless, it is helpful to examine some effects of soil texture on the water held between FC and PWP. For soils low in soluble salts, the finer the texture the greater the available water capacity (AWC).

Figure 1-9 shows the variation in FC and PWP water content by texture. Soil water content in percent by dry weight of soil is shown on the left margin and soil water content in inches of water per foot of soil is shown on the right margin for various soil bulk densities. The figure may be used as a general guide for estimating the AWC of soils based on texture until local curves can be developed. It applies generally to uniform soil profiles with low salt content.

Figure 1-7.

Water Penetration and Movement in Sandy and Clay Loam Soils; to Achieve Complete Wetting, Furrows Have to be Closer Together on Sandy Soils.



Generally, well-drained sandy soils have a low available water capacity. Silty soils have a good available water holding capacity, as do clay loams and clays. Table 1-4 provides a general guide of available water ranges for given soil textural classes.

While FC is considered to be the upper limit of available water, it should be pointed out that this is not strictly true. Water moving downward in the soil following an irrigation or rainfall can be effectively used by growing plants. Because this is a transitory stage, this water is generally not considered in calculations to determine the available water retaining capability of a soil but may affect irrigation scheduling.

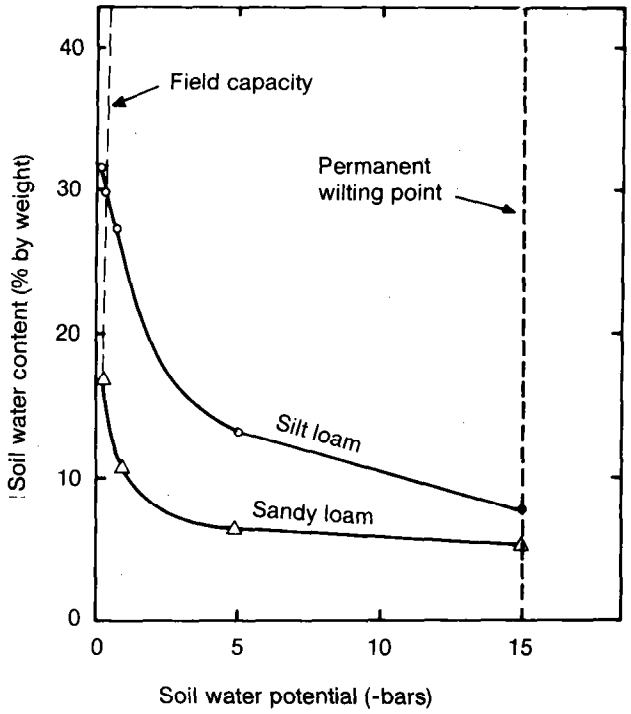
Water held between FC and PWP is frequently considered to represent 100 percent of the available water supply. The water release characteristic curve of figure 1-6 is replotted in figure 1-10 to illustrate this concept. From figure 1-10 it is clear that a given level of allowable depletion, for example,

Table 1-4.—*Ranges in available water content by soil textural classes.*

Textural class	Inches of water per inch of soil depth or cm of water per cm of soil depth		
Very coarse sand	0.03	-	0.06
Coarse sand—loamy sand	0.06	-	0.10
Sandy loam—fine sandy loam	0.10	-	0.14
Very fine sandy loam—silt loam	0.12	-	0.19
Sandy clay loam—clay loam	0.14	-	0.21
Sandy clay—clay	0.13	-	0.21
Peat and muck	0.17	-	0.25

Figure 1-8.

Relation Between the Water Content and the Water Tension of a Soil



the 50 percent level, will represent very different soil water potentials when water has been used by plants to that extent. This point is discussed further in the irrigation scheduling section. Calculations relating to plant available water are presented under water balance.

The dynamic nature of how plant roots extract soil water is shown in figure 1-11. Cotton was planted on April 16 in the San Joaquin Valley, California, and the soil water content of the profile at that time can be taken to represent FC. No rainfall occurred during the growing season, and the crop was not irrigated. By harvest, some soil water was extracted at total water potential lower than PWP at depths shallower than 160 centimeters. Limited root growth in the lower parts of the profile, however, resulted in some water that was held at greater than -15 bars being unused by harvest time.

Soil Water Measurement

The measurement of water stored in soils and the capacity of soils to store water are important. That some soils in the humid climates produce crops despite the lapse of many days, and sometimes weeks, between periods of rainfall is evidence of their capacity to store available water, because all growing plants require water daily. In irrigated regions, the depth of water to apply in each irrigation and the interval between irrigations are both influenced by storage capacity of the soil; therefore, the capacity of soils to store available water for use by growing crops is of special importance and interest. Irrigated soils that have large water-storage capacity may produce profitable crops in places where there is a shortage of irrigation water.

Knowledge of the capacity of soils to retain available irrigation water is essential for efficient irrigation. If the irrigator applies more water than the root-zone soil reservoir can retain at a single irrigation, the excess is wasted. If less is applied than the soil will retain, the plants may wilt from lack of water before the next irrigation unless water is applied more frequently. Irrigations are scheduled in humid areas in order to make efficient use of rain. Water losses which result from deep percolation below the root zone of crops cannot be seen. Losses can be determined or approximated by subtracting the storage capacity of the various soils from the amount of water applied in single irrigations, less the runoff.

Methods Used for Characterizing Soil Water

The best and most effective way of determining when to irrigate is to measure or to estimate the water level in the soil. By knowing the amount of water that is available, the irrigator who has knowledge of and experience with a particular crop on a particular soil can accurately determine

Figure 1-9.

General Relationship Between Soil Water Characteristics and Texture

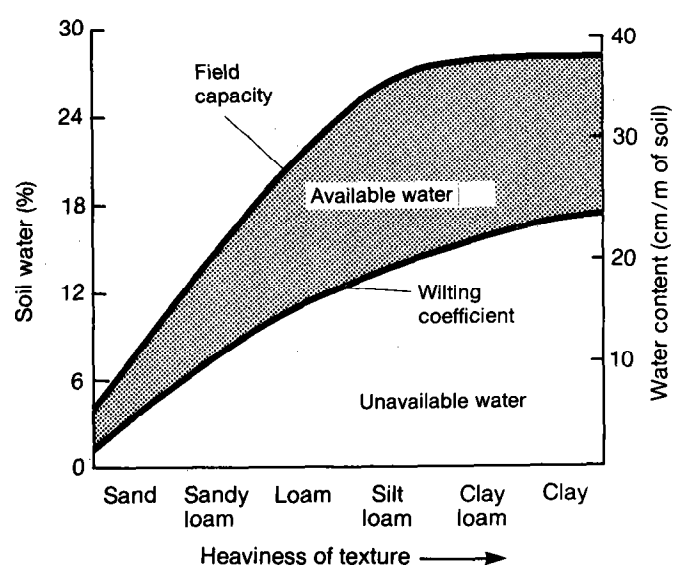
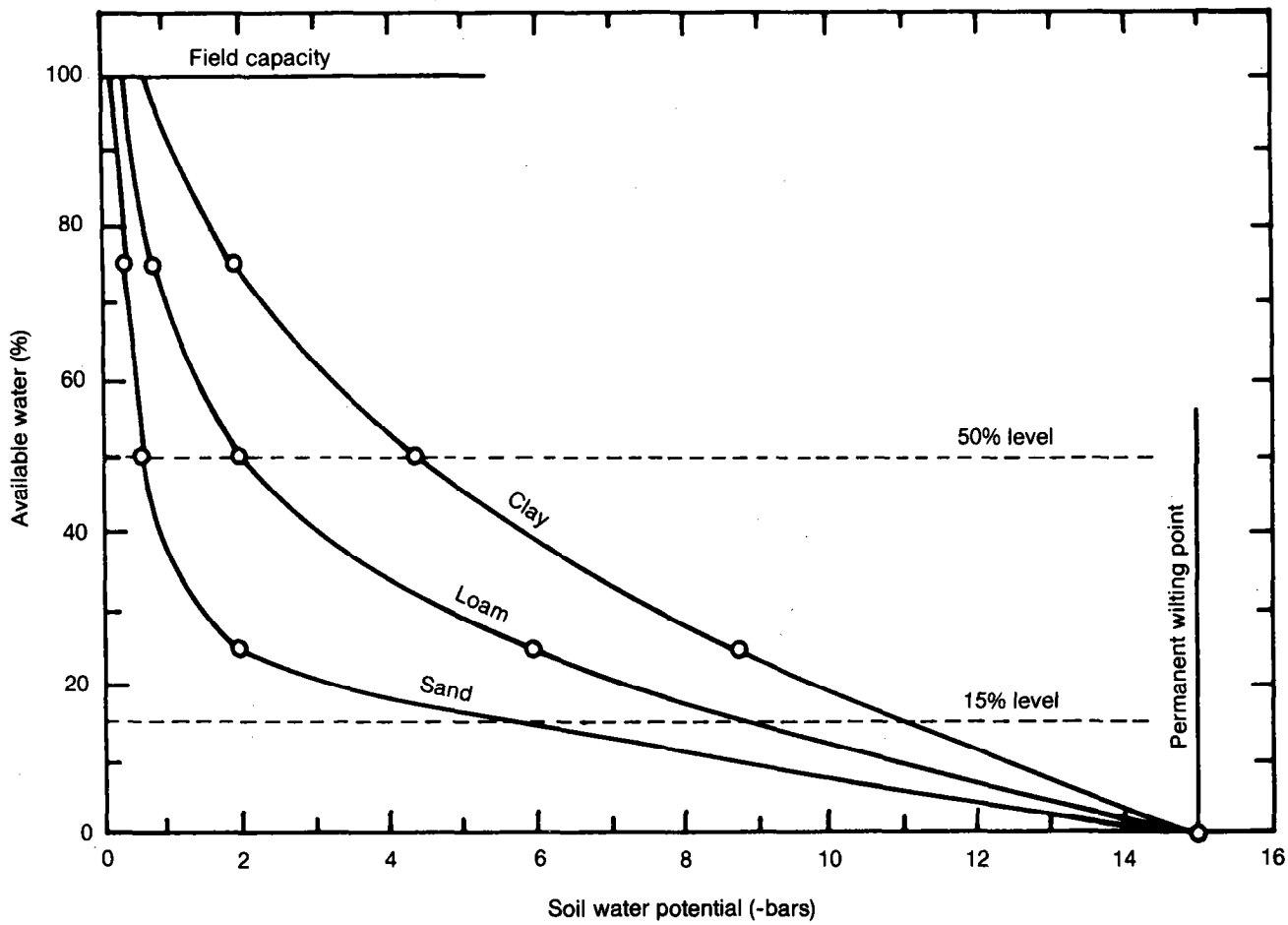


Figure 1-10.

Water Release Curve for Three Soils



when irrigation is needed. Of the numerous methods that can be used to measure and estimate soil water, many are not suited to field use. But several methods are now being used by irrigators and others are being developed that show promise as methods of determining when to irrigate. Some of these methods are discussed in the following pages.

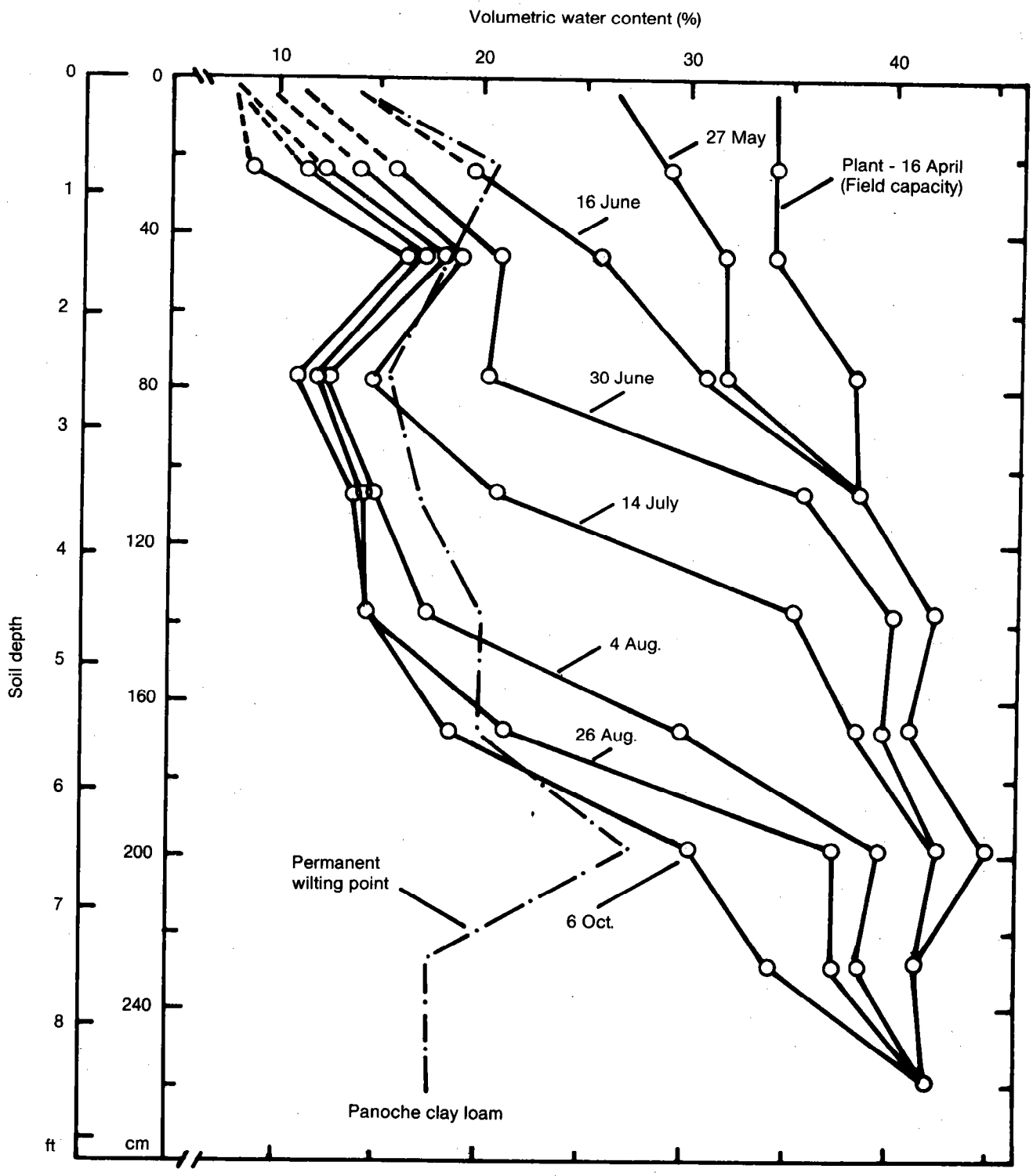
Gravimetric—The gravimetric method is the accepted standard for soil water measurement. Soil samples are taken from a desired depth at several locations in a field for each soil type. Samples are weighed, dried in an oven for 24 hours at 105 to 110 degrees centigrade, and then weighed again. The difference in weight is the amount of water, dry weight basis, in the soil, which can be converted to inches or centimeters of water remaining in the soil.

Although this method gives good results, it is not used generally by growers. Its accuracy depends on the number of samples taken and on the skill used in obtaining and handling the samples. It requires using facilities not ordinarily owned by growers and requires much time and labor. The method is used principally in experimental work and is a standard against which other methods of soil water determination can be compared.

Feel and Appearance Method—How soil samples taken in the field from appropriate locations and depths feel and look gives some indication of water content. A shovel can be used to get samples, but for some soils a soil auger or a sampling tube is better. The reaction of the soil to three field tests are recorded and compared to locally developed feel and water

Figure 1-11.

Soil Water Depletion by Cotton on a Panoche Clay Loam



content. These three tests are as follows: the ball test where the soil is squeezed several times into a firm ball, and then dropped from several heights and the effects are recorded; the rod test where the soil is rolled to form a 0.10-inch (3 mm) diameter rod and then it is held out vertically and the effect on the length is measured and recorded; and the ribbon test where the soil material is smeared out between the thumb and first finger and the length of the resulting ribbon is recorded. Although gauging water conditions by feel and appearance is not the most accurate method, with experience the irrigator should be able to estimate the soil water content level within 10 to 15 percent. This method is inexpensive, but acquiring the soil samples is a lot of work.

Tensiometers—Tensiometers (fig. 1-12) work on the principle that a partial vacuum is created in a closed chamber when water moves out through a porous ceramic cup to the surrounding soil. Tension is measured by a water manometer, a mercury manometer, or a vacuum gauge. The scales are generally calibrated in either hundredths of an atmosphere or in centimeters of water. Tensiometers that utilize a mercury manometer are usually preferred as research tools because they afford great precision. Because of their simplicity, tensiometers equipped with Bourdon vacuum gauges are better suited to practical use and to irrigation control on particular soils.

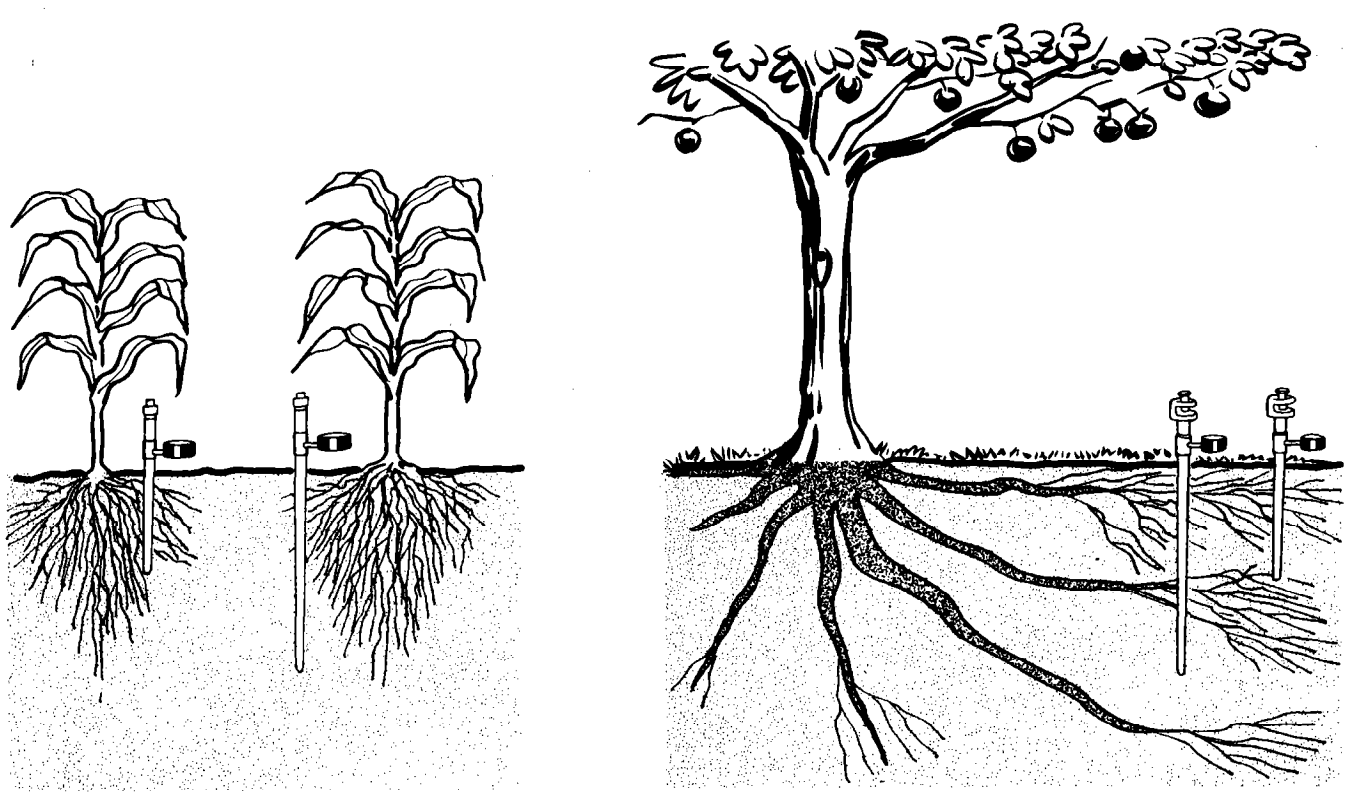
The cup of the tensiometer is placed in the soil at the desired depth, after which the instrument must be filled with water. Water moves through the porous cup until water in the cup and the water in the soil reach equilibrium. Any increase in tension that occurs as the soil dries causes the above ground vacuum-gauge reading to increase. Conversely, an increase in soil-water content reduces tension and lowers the gauge reading. The tensiometer continues to record fluctuations in soil-water content unless the tension exceeds 0.85 atmosphere; at which point, air enters the system and the instrument ceases to function. If this occurs, the instrument must again be filled with water before it can operate after an irrigation or rain.

Some experience is required to use a tensiometer. If air enters the unit through any leaks at the rubber connections, measurements are not reliable. Air leaks can also result from faulty cups as well as at the contact points of the setscrews used to secure the porous cup to the metal support. Some manufacturers provide a test pump that can be used to test the gauge and to remove air from the instrument.

Tensiometer readings reflect soil water tension only; that is, they indicate the relative wetness of the soil surrounding the porous tip. They do not provide direct information on the amount of water held in the soil. Tension measurements are useful in deciding when to irrigate, but they do not indicate how much water should be applied. A special water-characteristic curve for the particular soil site is needed to convert

Figure 1-12

Tensiometers Are Used to Measure Soil Water



water-tension measurements into available water percentages.

Tensiometers do not satisfactorily measure the entire range of available water in all soil types. But they probably are the best field instruments to use to determine water conditions in medium to coarse textured soil in the wet range. They are best suited to use in sandy soils because in these soils a large part of the water available to plants is held at a tension of less than 1 atmosphere. Tensiometers are less well suited to use in fine-textured soils in which only a small part of the available water is held at a tension of less than 1 atmosphere. Tensiometers are usually installed in the lower half of the root zone in finer textured soils in order that the readings are within the gauge range even though appreciable water has been extracted.

Electrical-Resistance Instruments—These instruments use the principle that a change in water content produces a change in some electrical property of the soil or of an instrument in the soil (fig. 1-13). They consist of two electrodes permanently mounted in conductivity units, usually blocks of plaster of Paris, nylon, fiber glass, gypsum, or combinations of these materials. Electrodes in the blocks are attached by wires to a resistance or conductance meter that measures changes in electrical resistance in the blocks. When the units are buried in the soil, they become almost a part of the soil and respond to changes in the water content of the soil. The amount of water in the blocks determines electrical resistance; thereby, measurement of any change in resistance is an indirect measure of soil water if the block is calibrated for a particular soil.

Nylon and fiber-glass blocks are more sensitive in the higher ranges of soil water than plaster of Paris blocks, but often their contact with soil that is alternately wet and dry is not very good. Nylon blocks are most sensitive at a tension of less than 2 atmospheres. Plaster of Paris blocks function most effectively at a tension between 1 and 15 atmospheres; fiber-glass blocks operate satisfactorily over the entire range of available water. A combination of fiber glass and plaster of Paris provides sensitivity in both the wet and dry ranges and provides good contact between the soil and the unit.

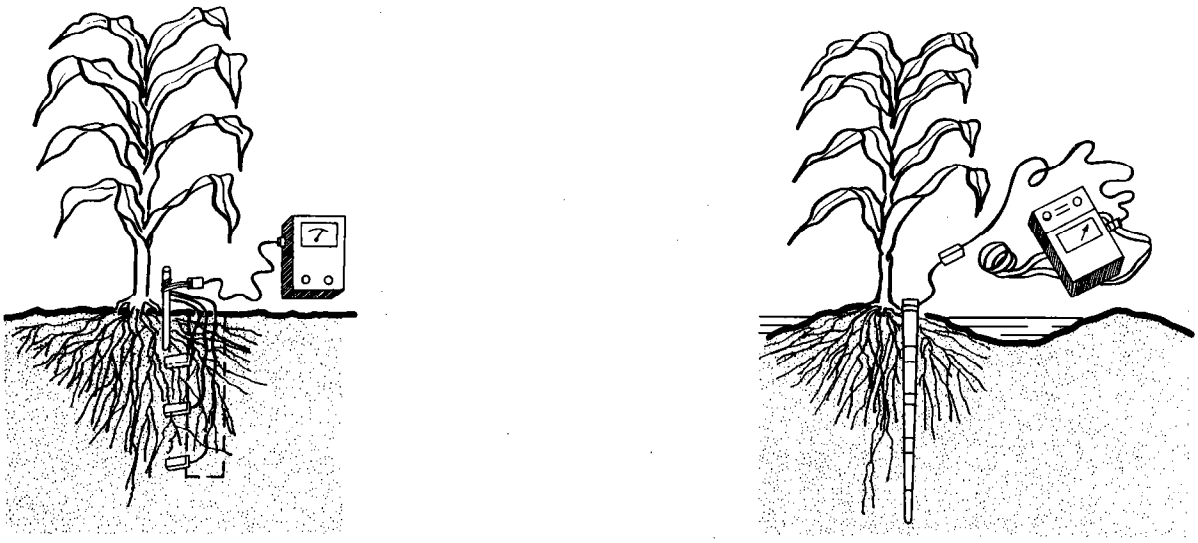
There may be a lag between the soil water change and that in the block, especially in sandy textured soils. This is particularly true with gypsum blocks. Lag times of 1 to 3 days have been measured.

Electrical-resistance instruments are sensitive to salts in the soil; fiber-glass blocks are more sensitive than plaster of Paris. Electrical resistance readings, therefore, are also affected by concentrations of fertilizer. Where fertilizer is spread in bands, electrical-resistance instruments should be placed well to one side of the bands. Temperature affects readings in all units.

In some units calibration drift has caused changes of as much as 1 atmosphere of tension in a single season. The magnitude of a change depends on the number of drying intervals and the number of days between each. Readings

Figure 1-13.

Electrical Resistance Soil Water Meters



also vary with soil type. The same reading may indicate different amounts of available water for different soil textures; therefore, the instrument must be calibrated for the soil in which it is to be used.

If readings are to be representative of an area, the blocks must be properly installed. Individual blocks must be placed in a hole, which disturbs the soil. If the soil is not replaced in the hole at the same density and in the same way as in the rest of the profile, the root development and moisture pattern may not be representative. A good method is to force the blocks into undisturbed soil along the sides of the hole dug. For placement of the blocks, see figure 1-13. In one type, the blocks are cast in a tapered stake. A tapered hole, the same size as the stake, is bored into the ground with a special auger. The stake is saturated with water and then pushed into the hole so that close contact is made between the stake and the soil.

Most of the commercial instruments give good indications of soil water content if they are used according to the manufacturers' instructions. For good results, however, the blocks must to be calibrated in the field for each job. Experience and careful interpretation of instrument readings are needed to get a good estimate of soil-water conditions.

Neutron Scattering—The neutron scattering procedure to estimate soil-water content has gained wide acceptance. It has some advantages over the gravimetric method because repeated measurements may be made at the same location and depth, thus minimizing the effect of soil variability on successive measurements. It also determines water content on a volume basis, the volume of soil involved being influenced by soil type and wetness by the particular instrument used. Disadvantages are the initial high investment in equipment, Federal operating regulations, and the time required per site to install access tubes.

A source of high energy, or fast neutrons, is lowered to the desired depth into a previously installed access tube. The fast neutrons are emitted into the soil from an americium-beryllium or radium-beryllium source and gradually lose energy by collision with various atomic nuclei. Hydrogen, present almost entirely in soil water, is the most effective element in the soil to slow down the neutrons. Thus, the degree of the slowing down of neutrons is a measure of the soil-water content. The slowed, or thermalized, neutrons form a cloud around the source and some of these randomly return to the detector, which causes an electrical pulse on a charged wire. The number of such pulses is measured over a given interval of time with a scalar, or the rate of pulsation can be measured with a ratemeter. The count rate is approximately linearly related to the water content.

When not in use, the radiation source is housed in a shield that contains a high hydrogen material, such as polyethylene or paraffin wax. This material serves as a standard by which proper operation of the instrument can be verified. Inasmuch as instrument variations and source decay take place, it is more satisfactory to use the count ratio method rather than just a count. The ratio of sample count to standard count is plotted versus water content. This eliminates any systematic errors that the instruments may introduce from day to day. The volume of soil measured depends upon the energy of the initial fast neutrons and upon the wetness of the soil. With the radium-beryllium source the volume of soil measured is a sphere of about 6 inches (15 centimeters) in diameter in a wet soil and up to 20 inches (50 centimeters) or more in a dry soil. Measurements near the surface may not be accurate because neutrons may be lost through the surface. It is difficult to accurately detect any sharp change in soil water with depth caused by a wetting because the sphere of influence integrates individual layers.

The manufacturer usually supplies a calibration curve, but one should verify whether it can be used for a given soil. Standard procedures have been developed by SCS for calibrating neutron gauges for a specific soil site.

Heat Dissipation—Heat conductivity can be used as an index to water content using the principle that heat is conducted much faster in water than in dry soil. A constant current may be passed through a heating element imbedded in a porous block for a given time. The resulting heat is conducted away from the element, and the temperature of the element can be related to the water content of the porous block. Temperatures can be measured with a linear diode temperature sensor which eliminates the need to correct for ambient temperature changes. This system is being used to control irrigation in order to maintain soil matric potential within a narrow range. The combination of the heating element and temperature sensor is referred to as a soil water potential sensor. These sensors have essentially been a research tool, although on a limited basis they are being used for field applications. They are available commercially and are being incorporated into irrigation controllers.

Sampling Error

Error of sampling has long plagued irrigators as they seek to determine the amount of water in the soil. Obtaining representative samples is a major problem. Uneven growing of plants and nonuniform root penetration must be considered, because they cause variations of soil water content. Texture and structure variations of soils alter the intake, transmission, and retention of moisture. Variations in land-surface configuration affect the opportunity for intake of

rainfall and irrigation water, and the shapes and sizes of furrows alter the rate of intake of irrigation water. All of these factors cause the water content to vary from point to point in a field. To obtain a representative soil water sample requires that several samples be taken, unless the method determining soil water inherently integrates a large volume of soil. The number of samples required to obtain a representative sample increases as the soil water variation increases.

Another factor which adds to the complexity of measuring soil water is that essentially all methods of soil water determination are based upon small samples. Individual samples can be expected to vary at least 20 percent, plus or minus, from the mean of a large number of samples.

Location of Soil Water Measurements

The location of any soil water measurements is highly important. Selection of places that will give a good estimate of the soil water level over a field generally is a matter of knowing the soil, previous experience, and good judgement. Locating the places for examination is not so difficult in fields of the same soil type as in fields of different soils.

It is generally recommended that one location be near the side of the field where irrigation is to be started as a reference point for starting the irrigation cycle. At least one location should be at the opposite end of the field to determine if the field is being covered fast enough to maintain an adequate soil water level there. Measurements should be made at other locations as indicated by any critical condition in the soil, such as an area that dries out first or stays wet longest. It is good practice to have at least two measurement stations in each critical area and possibly two or three stations in areas that are typical of most of the field. An adequate system of soil water measurement provides the irrigator with enough data to manage the system so that the soil water level is controlled over the entire field. This kind of information serves as a guide in varying both the amount and the frequency of irrigation for different locations in the field or for different periods in the growing season.

In sprinkler irrigation, the measuring stations should be between the sprinkler heads and 10 to 15 feet away from the lateral line. For row crops, measurements should be made in the row or near the plant but not in the bottom of the furrow. For trees, measurements generally are made 4 to 6 feet from the trunk and inside the drip line.

Measurements should be made in that part of the soil from which plant roots extract their water and according to the water-extraction pattern of the particular crop. In uniformly textured soils, one measurement should be made in the upper quarter of the root zone, and one to three more measurements should be made at lower levels. If the maximum water-extraction depth for a given crop is 24 inches, for example, measurements probably should be made at about 6, 12, and 18 inches. For stratified soils, measurements should be taken from the various textural strata. To predict when to irrigate during the early stages of root development, the 6-inch measurement is all that is needed for most crops. As the root system reaches maturity, measurements from all three locations are needed for a clear picture of the water content throughout the water-extraction zone. Sum the water for each measurement to obtain the total soil water content for the profile.

By definition, movement of water from the surface into the soil is infiltration. Water enters the soil through pores, cracks, worm and decayed root holes, and through cavities introduced by tillage. Infiltrated water may evaporate from the soil surface or may be transpired by the plants or may percolate downward beyond the plant roots and contribute to the ground water.

Water applied to the soil by precipitation (natural or man-made, such as sprinkling systems) infiltrates; and some of the water may be stored temporarily on the soil surface if the soil is unable to absorb it. Thus, if the rate of application exceeds the infiltration rate, water collects on the surface, and either ponding takes place or the water runs off. The infiltration rate governs the amount of water entering the soil and the amount that can be stored in the soil profile to be available for crops. In addition, the infiltration rate governs the amount of potential runoff and its associated soil erosion threat. As an example, surface sealing or crusting can reduce infiltration, increase erosion, and limit the available water for plants.

Percolation

The infiltration rate is limited by the ability of the soil to transmit water away from the soil surface through the soil profile when the surface is ponded. This movement of water through the soil profile is known as percolation. Percolation rate is governed by the permeability of the soil or its hydraulic conductivity. Both terms describe the ease with which soil transmits water.

Because water percolates chiefly through large pores in a soil, percolation depends on the relative number and continuity of these pores. Soil with high porosity and coarse open texture has high hydraulic conductivity. For two soils of the same total porosity, the soil with small pores has lower conductivity than the soil with large pores because resistance to flow is greater in small pores. Soil with pores of many sizes conducts water faster if large pores form continuous paths through the profile. In fine-textured soils, conductivity depends almost entirely on the pore space between structural units. In some soils, particles are cemented together to form nearly impermeable layers commonly called hardpans. In other soils very finely divided or colloidal material expands on absorbing water to form an impervious gelatinous mass that restricts water movement.

Quality of water transmitted, particularly its salinity and alkalinity, may have a marked effect on hydraulic conductivity. Change in the viscosity of water has an effect. Chemical change in water may affect hydraulic conductivity greatly without changing viscosity. The addition of even small amounts of sodium chloride to the soil water, insufficient to make any noticeable difference in viscosity, may affect soil structure so much that hydraulic conductivity is greatly reduced.

Factors Affecting Infiltration

Soil Water Content

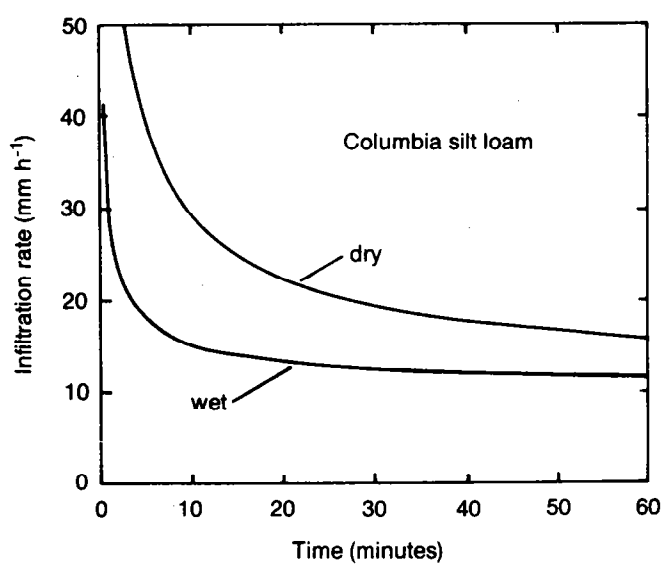
Residual soil water content influences the rate water enters the soil under ponded conditions (fig. 1-14). In dry soils, large differences in matric potential drive water into the soil profile and soil is able to store more water than if the soil were initially wet. The surface soil, however, gradually becomes saturated as irrigation continues and the intake rate decreases to the steady infiltration rate, whether the soil was initially wet or dry.

Soil Sealing

Infiltration may be limited by any restriction to flow that is caused by a change in hydraulic conductivity or a restriction at the soil water interface. Formation of a thin compact layer on the soil surface rapidly reduces the rate of water entry through the surface. This layer results from a breakdown in soil structure that is caused by the beating action of raindrops or the drops from sprinkling systems and by the

Figure 1-14.

Predicted Infiltration Rates for a Deep Columbia Silt Loam With Different Initial Water Contents



action of water flowing over the soil surface. Fine particles, fitted around larger particles, form a relatively impervious seal. Light cultivation before irrigation can help break the seal and increase infiltration. Sealing can be partly prevented by protecting the soil surface with a mulch or some other permeable material. Grasses or other close-growing vegetation intercept droplets, dissipate their energy, and reduce surface sealing.

Surging

During surge irrigation, the intermittent wetting of the soil surface by cycling of flow reduces infiltration. Several mechanisms to explain the reduction in infiltration have been suggested. Wetting and drying allows water to soak and dissolve clods and thereby settle and compact the soil on dewatering. In conjunction with dissolving, a seal may also form as water flows along the surface. Thus, both compaction and sealing reduce infiltration. Air entrapped during dewatering has also been suggested as a reason for reduced infiltration. Water traps air bubbles that block small pores of the soil surface and reduces infiltration. Soil swelling, because of the hydration of clays and the reduction in hydraulic gradient as wetting of the soil progresses, have been suggested as mechanisms for reducing infiltration.

Compaction

Tillage operations may cause compaction and formation of plowpans below cultivation depth if soils are tilled when too wet. A plowpan impedes water movement and thus reduces the infiltration rate. For some soils, infiltration rate is reduced in furrows where tractor wheels travel. Deep tilling, or subsoiling, helps improve water movement for a time by breaking up the impermeable sublayer. The enlarged openings improve water movement. If there are no changes in cultural practices, such as reduced tillage, addition of crop residues, reduced tillage operations, or proper timing of tillage operations, compaction will be reestablished.

Tillage

The infiltration rate may be temporarily increased by plowing, cultivation, or any other stirring that increases pore size in the soil. The beneficial effect of cultivation on soil porosity and intake lasts only until subsequent precipitation or flooding or compaction settles the soil to its former condition. The infiltration rate of loose, porous sand is not likely to increase by tillage operations. Cultivation may reduce intake by compaction and interrupting soil pore space.

Soil Cracking

Cracks form as water is removed from some clay soils. During flood irrigation, cracks fill rapidly before the soil swells; which provides a high initial intake rate. The cracks swell and eventually close as the soil wets. Intake on these fine-textured soils, thereafter, is often negligible or extremely slow. Thus, the amount of water that is applied should be based on crack size and number. Under sprinkler irrigation, if the water application rate is less than the infiltration rate, the application amount is related to the duration of irrigation, not to the crack size and number.

Organic Material

Porosity remains high for comparatively long periods when organic material is made available by the production of high residue crops. Infiltration rate can be maintained and even increased by using a cropping system that provides for high rates of crop residues in the upper few inches of soil. Grasses and legumes are examples of crops which increase the organic matter content of soil. The proportion of stable soil aggregates is increased to create larger pores and, consequently, greater infiltration rates. Perennial crops, such as alfalfa, also improve infiltration by protecting the soil surface from sealing, by maintaining organic matter in the soil, and by increasing the water-conducting pores formed by decayed roots.

Salts in Soil

Salts contained in irrigation water accumulate in irrigated soils and may change soil properties. This accumulation is serious in arid regions where the majority of water is supplied by irrigation. It is often necessary to overirrigate (leach) periodically to manage, reduce, or remove soluble salts from the soil in the root zone area. Rainwater, percolating through the soil in humid areas, leaches out most soluble salts.

Some soluble salts in irrigation water, such as potassium nitrate, may benefit crops directly. Under some conditions, calcium and magnesium have a positive effect on the physical properties of soil. High concentration of sodium chloride or sodium sulfate, however, have a detrimental effect. Soil structure breaks down and eventually soil colloids are dispersed, which reduces tilth and the infiltration rate. This type of sealing may be noticeable even on some sandy soils.

The physical properties, such as infiltration, of some sodic soils can be improved by adding chemicals or soil amendments through which exchangeable sodium is replaced by calcium. Calcium sulfate, gypsum, is a comparatively economical and often used amendment to improve infiltration and aeration in order to enhance root development and plant growth. Other chemicals, such as sulfur and aluminum sulfate, are also used if adequate calcium is available in the soil.

Sediments in Irrigation Water

Fine silt and clay particles carried in suspension affect the quality of irrigation water. Whether this is detrimental or beneficial depends on the amount of silt transported, the length of time the silty flow continues, and the texture of the soil to which water is applied. Occasionally, deliveries of silty water may be beneficial on coarse-textured soils inasmuch as the sediments improve the physical condition of the root zone and reduce the rate of water movement. Silty water applied to fine-textured soil generally adds to the surface sealing problems, because it slows intake and makes the soil difficult to cultivate. Sediments add some plant nutrients, such as potassium, calcium, and phosphate, to the soil.

Soil Erosion

As erosion progresses, the infiltration rate of many soils is reduced because of the loss of surface soil and organic material. This is because less permeable material, such as dense clay subsoil, is uncovered or finer textured subsoil is mixed into the plow layer. In some soils erosion may expose coarse-textured layers, such as sand and gravel, which increases infiltration.

Land Leveling

Moving and mixing of soil during land leveling may change infiltration characteristics. The effects are similar to those of erosion when more or less permeable soil is uncovered. Earth-moving equipment that is used in land leveling may compact the soil, which reduces infiltration. Subsoiling and additions of organic material are often necessary to remedy the problem. In cases where a less permeable layer overlays a permeable layer, the upper layer may be removed to expose the permeable layer in order to improve infiltration.

Temperature

Water intake is greater when it rains in the summer than when it rains in the winter. Apparently, the coefficient of viscosity of water decreases rapidly as temperature increases and this causes more rapid infiltration. Most authorities, however, consider its effect on infiltration negligible.

Surface Storage

Soil surface roughness and slope influence the amount of water which can be collected on the surface and thus be reserved for infiltration. Runoff begins when the application rate exceeds the infiltration rate and surface storage becomes filled. Storage generally is greater on flat, rough, vegetated slopes than on smooth, steep, bare slopes. Thus, surface storage affects the amount of water which infiltrates.

Infiltration Stages

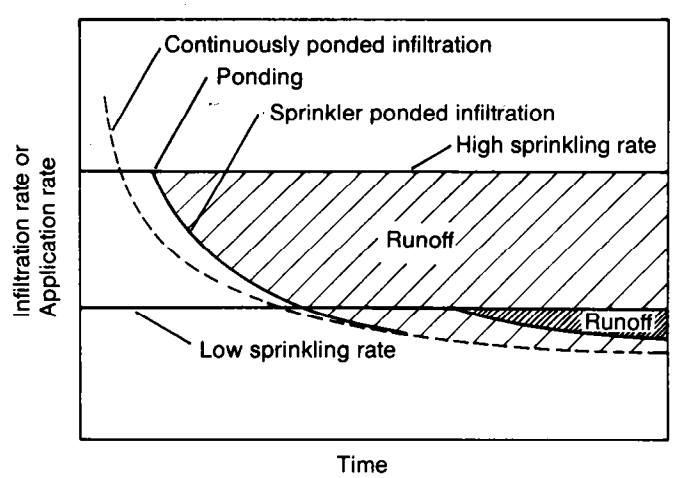
Water does not collect on the soil surface if the precipitation or water application rate from a sprinkler is less than the ability of the soil to absorb water. Figure 1-15 shows the rate at which water enters the soil with time for high and low steady application rates. Early in the process, application rate controls, and is equal to, the infiltration rate; both curves are on the same horizontal line. In time, the ability of the soil to absorb water declines and may be exceeded by the water application rate; in which case, ponding commences and water accumulates on the soil surface. The shaded area between the horizontal steady water application line and the falling infiltration rate curve represents surface storage which may be lost to runoff. Ponding takes place sooner and potential runoff is greater with the high application rate.

The decline in infiltration rate with time under continuously ponded or flooded conditions is the broken line in figure 1-15. At the start of irrigation, the infiltration rate is high but declines rapidly. The infiltration rate is called transient because it changes with time. At the point that the rate changes very little, it becomes the steady infiltration rate. Water will not pond as long as the precipitation rate is less than the steady infiltration rate.

Ponding does not take place when the horizontal, steady precipitation rate line meets the broken continuously ponded line (fig. 1-15). It is later for both high and low application rates; therefore, ponding time and potential runoff are not accurately predicted by superimposing a line that represents

Figure 1-15.

Potential Runoff for High and Low Steady Water Application Rates Similar to Stationary Sprinklers



application rate on a flooded infiltration test curve. In doing so, runoff would be overestimated because ponding takes place later than predicted by the above graphical method. Furthermore, the shape of the three solid curves is slightly different. Thus, ponding time is not accurately predicted by superimposing a line that represents precipitation rate on a flooded infiltration test curve. Runoff may be overestimated because ponding takes place later than predicted by the above graphical method (fig. 1-15).

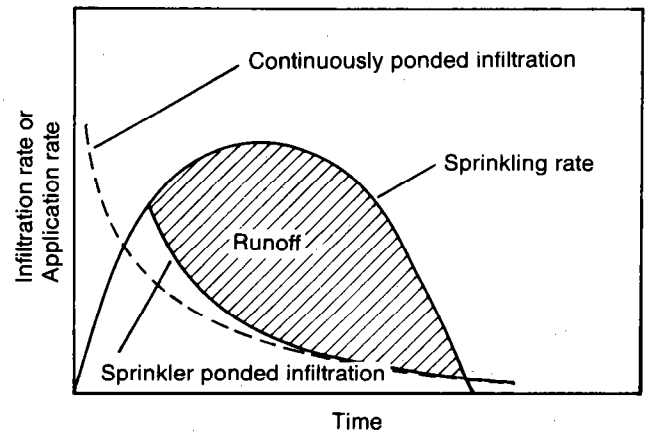
Similarly, ponding time and potential runoff cannot be predicted by superimposing flooded infiltration test curves over water application rate curves for nonstationary sprinklers. As shown in figure 1-16 for moving sprinklers, water application rate at a point increases and then falls rather than being steady as in the case of stationary sprinklers. The infiltration curve follows the water application curve until the application rate exceeds the infiltration rate at which time ponding takes place. Potential runoff is the shaded area between the application rate curve and the solid line representing ponded infiltration under sprinkling. Again, if the dashed line representing continuously ponded infiltration is used, ponding time is too early and potential runoff is overestimated.

Cumulative Infiltration and Infiltration Rate Relations

The time required for a soil to absorb a specified amount of water under ponded conditions can be found by plotting cumulative infiltration with time. This relation is given in figure 1-17 for a high, moderate, and low intake rate soil. The moderate intake rate soil absorbed 3 inches (7.6 cm) of water in about 1.75 hours. Only about one-third of an hour is required to infiltrate 1 inch (2.5 cm), whereas, about 4.5 hours are needed to absorb 6 inches (15.1 cm). Thus, infiltration amount can be controlled by varying application time.

Figure 1-16.

Potential Runoff for Nonstationary Sprinkler



Corresponding plots of instantaneous infiltration rate with time, similar to the one given by the dashed line in figure 1-16, are shown in figure 1-18 for the high, moderate, and low infiltration rate soils. Infiltration rate is high at the start of irrigation, but the rate declines rapidly until it approaches a steady rate.

A comparison of figures 17 and 18 shows that the high intake soil absorbs 3 inches (7.6 cm) of water in about one-third of an hour; at which time intake rate declines to about 4.6 inches (11.7 cm) per hour. In contrast, infiltration rate is 0.3 inches (0.8 cm) per hour for the low intake soil over a total time of 6.5 hours. The relative position on the intake-rate curve, at the time that 3 inches have been infiltrated, differs markedly for the three soils. The infiltration rate declines rapidly for the high intake soil but has approached a nearly stable rate for the low intake soil.

Basic or Steady Infiltration Rate

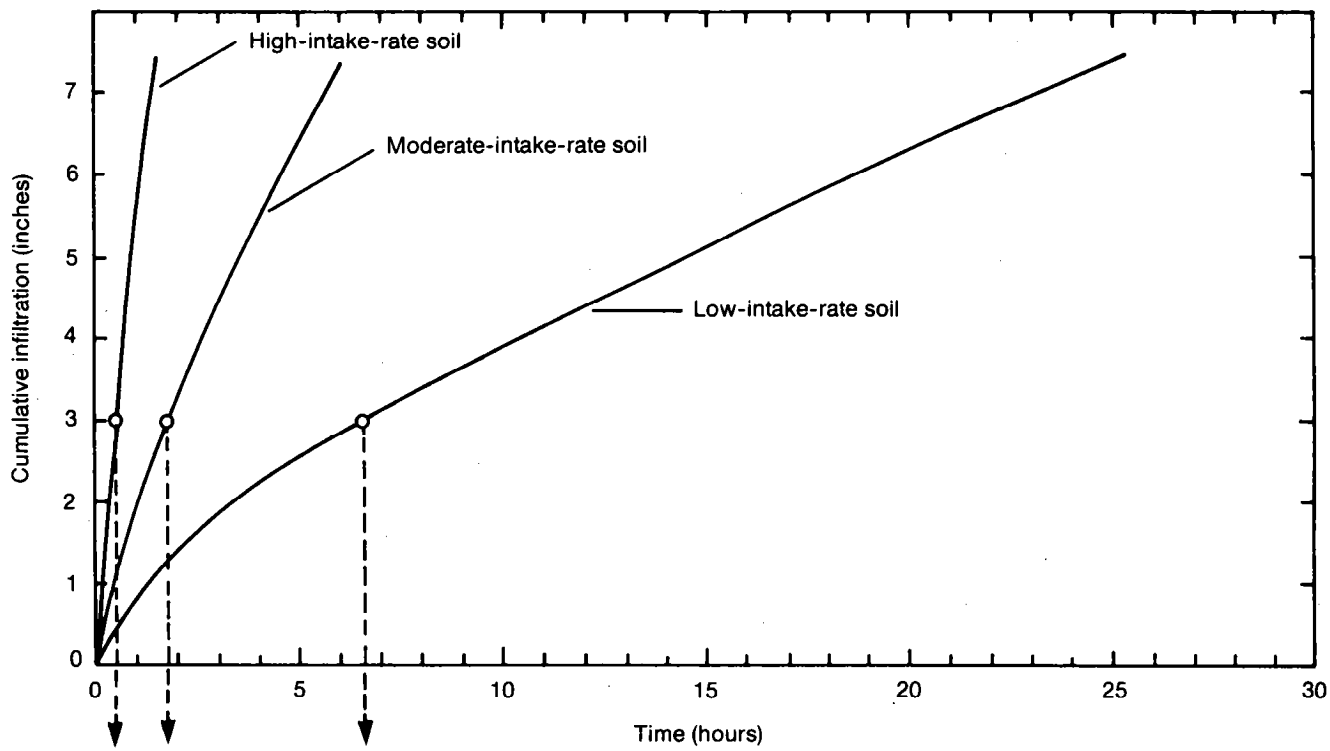
Generally, steady or basic infiltration rate is defined as the nearly constant rate that develops after some time has elapsed from the start of irrigation. The low intake soil shown in figure 1-18 probably would be assigned a basic rate of 0.3 inch (0.8 cm) per hour. Assigning the basic rate to the high-intake soil is more difficult because usually irrigation ceases before the basic infiltration rate is reached. The basic infiltration rate is considered by the Soil Conservation Service to be the point on the curve at which the change in rate is 10 percent. Infiltration rate changes thereafter are considered unimportant.

Seasonal and Spatial Variation

The changes in factors which affect infiltration, discussed above, cause changes in infiltration during the season and from season to season. Infiltration generally decreases during the season from one irrigation event to the next. Reduction in infiltration during the season is usually more significant for an annual crop than for a perennial crop. Season-to-season variation is generally associated with perennial crops because the soil is often cultivated less than annual crops. To meet this changing condition, irrigation management should be flexible so the irrigator can apply

Figure 1-17.

Relation of Cumulative Infiltration to Time for Three Soils



water efficiently. In any case, if the soil is manipulated through tillage or other practices that create larger soil pores, the trend can be slowed or reversed.

Seldom, if ever, do all parts of a field or a soil type have the same ponded infiltration rate because minor variations in soil and plant properties affect infiltration. The variations may be the result of wheel-traffic compaction or natural changes in soil texture and structure.

Spatial variation in infiltration properties is more critical for irrigation systems in which the surface is flooded than for sprinkling systems in which application rate controls infiltration rate. Because infiltration rate varies from place to place in surface irrigation, total infiltration will vary even if the time water is ponded is the same across the field. Variations between fields are easier to manage than variations within a field because irrigation systems can be designed for a specific field.

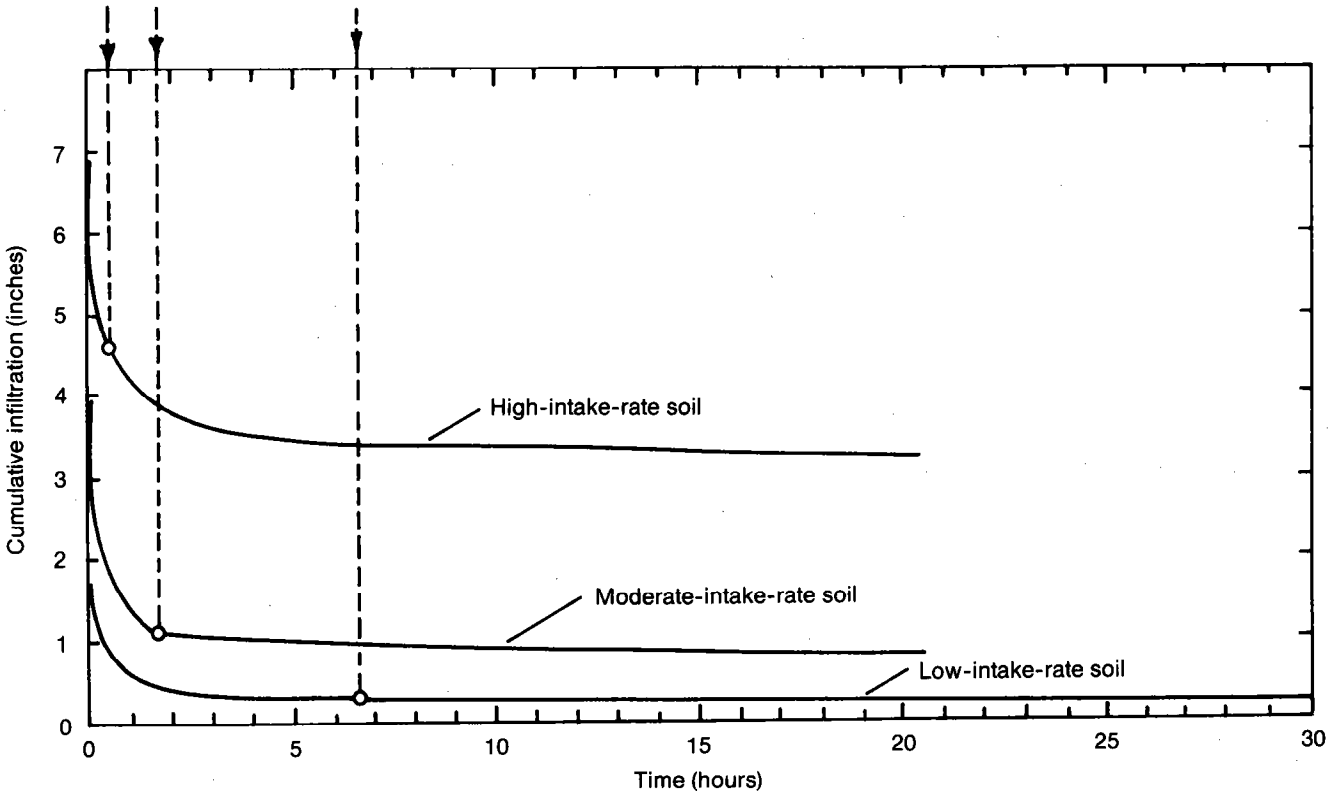
Field Infiltration Measurements

Infiltrometers can be classified as flooding and sprinkling types. Flooding infiltrometers are appropriate for surface irrigation; sprinkling infiltrometers measure infiltration for sprinkler systems. Flooding devices, however, are far more frequently used because they require less equipment and are easier to install and operate than the sprinkling type.

The most common type of flooding infiltrometer consists of a metal cylinder 8 to 18 inches (20 to 45 centimeters) in diameter and 12 to 14 inches (30 to 36 centimeters) in length, which is pressed or driven into the soil. Infiltration is measured by ponding water inside the cylinder and measuring the rate that the free surface falls or by measuring the rate that water must be added to maintain a constant depth of ponding. Once the wetted front exceeds the buried cylinder depth, lateral flow may cause the measured infiltration rate to be higher than would otherwise take place during irrigation. Lateral flow is especially troublesome if restrictive

Figure 1-18.

Relation of Infiltration Rate to Time for Three Soils



layers, such as plow pans, exist or if the hydraulic conductivity decreases with depth. When restrictive layers are at a shallow depth, the infiltration cylinder should be driven into or through the layer if possible. Another means of preventing erroneous measurements because of lateral flow is to use a guarded ring or buffer area around the outside of the infiltration cylinder. Water is ponded between the two cylinders at all times to prevent edge effects and to maintain vertical flow below the central infiltration cylinder.

Infiltration under furrow irrigation involves soil water movement in both vertical and horizontal directions. Because the rate of infiltration depends on the size and shape of the furrow, the rate water moves into the soil is often called the intake rate rather than the infiltration rate. Regardless of the term used, the determination of intake rate is important to the design of an efficient furrow irrigation system. Infiltration rates that are determined by sprinkler or cylinder infiltrometers represent primarily vertical flow, so it is difficult to apply these results directly. One method frequently used to determine intake rates is to make inflow and outflow measurements in an irrigation furrow. Measuring flumes or orifices are used to make flow measurements at two points in an irrigation furrow that are located 30 to 90 feet apart. Intake rates are computed from the difference of inflow and outflow for various times after water application begins. Although this method provides a good means of evaluating existing furrow irrigation systems, it is often not convenient to use this method to determine intake rates for the design of new systems. To avoid this problem, a furrow infiltrometer to measure intake rates in a short section of an irrigation furrow was developed. The furrow is blocked off by metal plates, and water is applied at a rate sufficient to maintain a constant depth. Intake rate is then determined in a manner similar to that described for cylindrical infiltrometers.

Ring and blocked furrow infiltrometers may not simulate actual conditions accurately because water is stagnant, not flowing. To circumvent this problem, a recirculating or flowing furrow infiltrometer may be more appropriate. Water is introduced at one end of a blocked furrow test section and is collected at the other end by a small sump pump and recirculated. Additional water from a supply

reservoir is supplied to the furrow to replace the water that has infiltrated. Infiltration is measured by a change in the water-supply reservoir volume versus time.

Sprinkling or spray infiltrometers usually consist of a plot surrounded by partially buried sheet metal barriers with facilities for measuring the rate of surface runoff. Water is sprinkled onto the surface of the plot at a constant rate or intermittently, as with a rotating sprinkler. If a constant application rate is applied, infiltration rate with time is determined from the recorded runoff measurements by subtracting runoff rate from application intensity. Storage rate should also be considered to avoid significant errors. In the case of a rotating sprinkler, design infiltration rate (not the intake rate with time relation) is taken as the rate where the applied water just disappears from the surface as the sprinkler jet returns to apply more water to the same location. An advantage of the last method is that the infiltration measurements are made for conditions very similar to those that will exist during an actual irrigation.

Models

Attempts to characterize infiltration for field applications have usually involved simplified concepts which permit the infiltration rate or cumulative infiltration volume to be expressed algebraically in terms of time and certain soil properties. The most obvious characteristic of the infiltration process is that the rate decreases rapidly with time during the early stages of the event. One of the most common and simple algebraic expressions is the Kostiakov equation:

$$f = kt^{-a}$$

where f is infiltration rate, t is time after irrigation starts, and k and a are constants which depend on soil and initial conditions.

Although simple, it cannot be adjusted for different field conditions, such as initial water content; moreover, it predicts an infiltration rate approaching zero at long times, which is known to be incorrect. A constant term can be added to correct the latter problem to give the extended Kostiakov equation:

$$f = kt^{-a} + f_c$$

where f_c is the final, constant infiltration rate. Horton presented another three-constants infiltration equation:

$$f = f_c + (f_o - f_c)e^{-bt}$$

where f_o is the infiltration rate at time = 0, and b is the soil constant which controls the rate of decrease of the infiltation rate. Again, the equation parameters are usually evaluated from experimental infiltration data.

Philip proposed that the first two terms of a series solution for infiltration from a ponded surface into a deep homogenous soil be used as a concise infiltration equation as:

$$f = 0.5St^{-.5} + C$$

where S and C are constants which can be related to soil characteristics. S can be adjusted for initial water content; and, similar to the extended Kostiakov equation, a regression fit to experimental data will tend to give:

$$C = f_c$$

A similar, more physically based equation evolved from Green and Ampt:

$$f = K_s\,(1 + M_d S_f/F)$$

where K_s is saturated hydraulic conductivity, M_d is the difference between initial and final volumetric water content, S_f is the suction at the wetting front, and F is the cumulative infiltration.

This model assumes that water enters the soil as slug flow, resulting in a sharply defined wetting front which separates a zone that has been wetted from a totally uninfiltrated zone.

Although more physically based models can estimate infiltration from measured soil properties, generally in practice it is easier to measure and fit infiltration data than to measure soil properties. Actual infiltration measurements also tend to lump effects such as heterogeneities, worm holes, and crusting in the equation parameters. This results in more reliable infiltration predictions than if the parameters are determined from basic soil property measurements.

Plant Root Systems

Plant root systems provide the linkage between the soil water and nutrients and the aboveground parts of plants. Two general types of root systems are recognized: fibrous roots and taproots. Cereal grains and other grasses (monocotyledons) have fibrous root systems. Other crops, such as sugar beets and alfalfa (dicotyledons), have taproot systems. The two types are illustrated in figure 1-19.

Fibrous roots are comprised of many slender roots that are similar in length and diameter. The first root appearing from a germinating seed is a seminal or primary root. The seminal root gradually elongates and increases in diameter. Secondary roots develop from the primary root as lateral branches and subbranches. With continued growth, nodal roots arise from the underground stem nodes. Roots may also develop from aboveground nodes such as the brace roots of maize.

In contrast to the fibrous root system, other crop plants have an entire root system subtended by a single taproot (taproot system). Crops, such as alfalfa and sugar beets, have this type of root system. Although a taproot may extend to a considerable soil depth, the major part of the total root system is made up of first order laterals.

Regardless of the basic rooting characteristics of monocotyledons and dicotyledons, the length and complex branching of an intact root system is considerable after a few weeks of growth. Laterals are initiated in the parent root member with primary laterals giving rise to secondary laterals, and so on, until an extensive network is formed under favorable conditions. Typical growth rates for various root class members are:

root axes, 0.8 inch per day;
primary laterals, 0.2 inch per day; and
secondary laterals, 0.04 inch per day.

Root elongation as high as 2.4 inches per day has been reported for maize. In contrast, unfavorable conditions due to climate, soil composition, soil aeration, or soil chemistry may severely restrict root growth and proliferation.

Crop Species Rooting Characteristics

Proper irrigation management requires good information on crop rooting characteristics with both depth development and rooting density being important considerations. An extensive literature search resulted in the compilation of a list of the maximum rooting depth achieved by some 55 plant species reported from 135 field observations (table 1-5). The range in depth achieved within a crop species probably arises from genetic varietal characteristics and less than desirable growth conditions. An effort was made to exclude data that was based on less than desirable growth conditions.

Figure 1-19.

Fibrous Root System of Corn (Left) and Taproot System of Sugar Beet (Right): Both Are Approximately Two Months Old

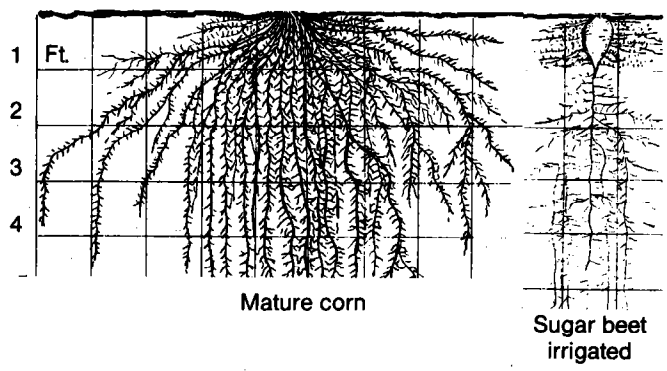


Table 1-5.—*Data source summary of several crop species on the depth development of roots with time and expected maximum rooting depth (RD_m) under favorable environmental conditions (H. Borg and D. W. Grimes, 1986. Depth development of roots with time on empirical description. Transactions of the ASAE. Vol. 29, No. 1, pp. 194-197).*

Crop	No. of Observations	RD_m (cm)
alfalfa (*Medicago sativa*)	7 several (sev.)yrs.	1st yr. 180-240 300-600
asparagus (*Asparagus officinalis*)	1	1st yr. 100-200 sev. yrs. 300+
barley (*Hordeum vulgare*)	7	150-290
sugar beet (*Beta vulgaris*)	1	180-330
broad bean (*Vicia faba*)	1	150-190
bromegrass (*Bromus inermis*)	2	1st yr. 100-140 sev. yrs. 200+
cabbage (*Brassica oleracea*)	1	150-240
carrot (*Daucus carota* var. *sativus*)	1	150-300
cauliflower (*Brassica oleracea*, Botrytis Group)	1	90-150

field corn (*Zea mays* L.)	11	180-300
cotton (*Gossypium hirsutum* L.)	8	150-300
cowpea (*Vigna sinensis*)	1	100-150
cucumber (*Cucumis sativus*)	1	120-180
eggplant (*Solanum melongena*)	1	150-240
flax (*Linum usitatissimum* L.)	1	100-150
garlic (*Allium sativum*)	1	60-100
horseradish (*Amoracia rusticana*)	1	sev. yrs. 300-450
kidneybean (*Phaseolus vulgaris*)	1	100-300
Kohlrabi (*Brassica oleracea*, Gongylodes Group)	1	150-270
leek (*Allium ampeloprasum*, Porrum Group)	1	40-80
lentils (*Lens culinaris Medic*)	1	60-70
lettuce (*Lactuca sativa*)	1	150-250
lima bean (*Phaseolus limensis*)	1	100-200
muskmelon (*Cucumis melo*, Reticulatus Group)	11	100-150
oats (*Avena sativa*)	10	160-260
okra (*Abelmoschus esculentus*)	1	120-160
onion (*Allium cepa*)	1	40-100
parsley (*Petroselinum hortense*)	1	90-150
parsnip (*Pastinaca sativa*)	1	200-300
pea (*Pisum sativum*)	2	100-240
pepper (*Capscium annum* var. *annum*)	1	90-150
potato (*Solanum tuberosum*)	4	50-240
pumpkin (*Cucurbita pepo* var. *pepo*)	1	150-210
radish (*Raphanus sativus*)	2	140-240
rape (*Brussica napus*)	1	200-300
red clover (*Trifolium pratense*)	2	1st yr. 140-180 sev. yrs. 200-300
rhubarb (*Rheum rhaponticum*)	1	sev. yrs. 200-300
rutabaga (*Brassica napus*, Napobrassica Group)	1	150-200
rye (*Secale cereale*)	2	150-240
sorghum (*Sorghum vulgare*)	4	150-300
soybean (*Glycine max*)	22	150-250
spinach (*Spinacia oleracea*)	1	150-200
squash (*Cucurbita pepo* var. *melopepo*)	1	150-240
strawberry (*Fragaria chiloensis*)	1	60-120
sugar beet (*Beta vulgaris* L.)	2	140-200
sugar cane (*Saccharum officinarum*)	3	200-600
sunflower (*Helianthus annuus*)	2	150-300
sweetclover (*Melilotus alba*)	3	1st yr. 150-240 sev. yrs. 300+
sweet corn (*Zea mays* var. *rugosa*)	1	150-180
sweet potato (*Ipomoea batatas*)	1	100-150

Swiss chard (*Beta vulgaris*, Cicla Group)	1	180-240
tomato (*Lycopersicon esculentum*)	1	140-260
turnip (*Brassica rapa*, Rapitera Group)	1	150-200
watermelon (*Citrullus lanatus*)	1	100-150
wheat (*Triticum sativum*)	13	150-300

Factors Affecting Root Growth

Although root growth generally proceeds rapidly under ideal conditions, both the rate of development and the maximum depth to which roots grow can be severely restricted by several factors. Even though crop root systems may be severely restricted, these systems have the capacity to support considerable shoot growth if the effective root system is well aerated and supplied with adequate water and nutrients. The stresses experienced by roots generally fall into categories that include: chemical stress caused by nutrient deficiencies, an unbalanced nutrient supply, or by toxic subtances; physical stress from mechanical impedance, from anaerobic conditions, from lack of water, and from unfavorable temperatures; and biological stresses caused by plant pests and diseases.

Mechanical impedance considerations are responsible for a majority of root limiting situations. These may be genetic in origin for shallow soils that overlie consolidated parent material or pans caused by soil compaction that is associated with certain management systems. Root limitations may be very abrupt with consolidated soil materials or pans or gradual in the case of soil compaction. Soil compaction usually results in reduced root growth rates with total root exclusion only observed in very extreme cases. Compaction of soil reduces the volume occupied by pores, especially those of a large size. This causes mechanical impedance to root extension, lowers the rate of gas exchange between the soil and atmosphere, and changes the water retention and transmission properties of the soil. All of these factors modify root growth and they are affected simultaneously by soil compaction.

Layered soils may offer severe impedance to an expanding root system. The reduced root proliferation of a sand or gravelly layer can be substantial because such layers are usually characterized by high bulk density and strength. These layers are normally well drained, but they are highly rigid as a growing root enters the matrix and expands. A clay layer underlying a medium-textured or sandy soil zone may cause a perched water condition and poor aeration on a transient basis that is restrictive to root expansion through such a layer.

Water Flow Into Roots

Water moves in the soil-plant-atmosphere continuum in response to differences in the potential energy of water in the system. Transpiration causes a lower water potential in the plant shoot and root system than in the bulk soil; consequently, soil water moves into the root system along this potential gradient. Water first enters the root system through epidermal cells in contact with the moist soil, then in turn through cortical cells, the endodermis, pericycle cells, and finally to the xylem that transports the water to the aerial plant parts. The intensity of root development and physical contact between the root and soil are important physical considerations. When the upper part of the root zone becomes comparatively dry and water is available in the lower zone, the uptake of water per unit volume of soil has been observed to be proportional to the rooting density. Thus, the distribution of roots that varies with crop species and soil physical properties becomes an important management concern.

The presence of salts in the soil water solution must be considered when evaluating available water. The plant root contains a semipermeable membrane that allows water to pass but not most of the salt. Therefore, the main effect of soluble salts on plants is osmotic with high salt levels making it difficult for the plant to obtain enough water from the soil solution to meet transpirational demand. Cell enlargement is affected initially, and plants exhibit the typical color changes associated with water stress.

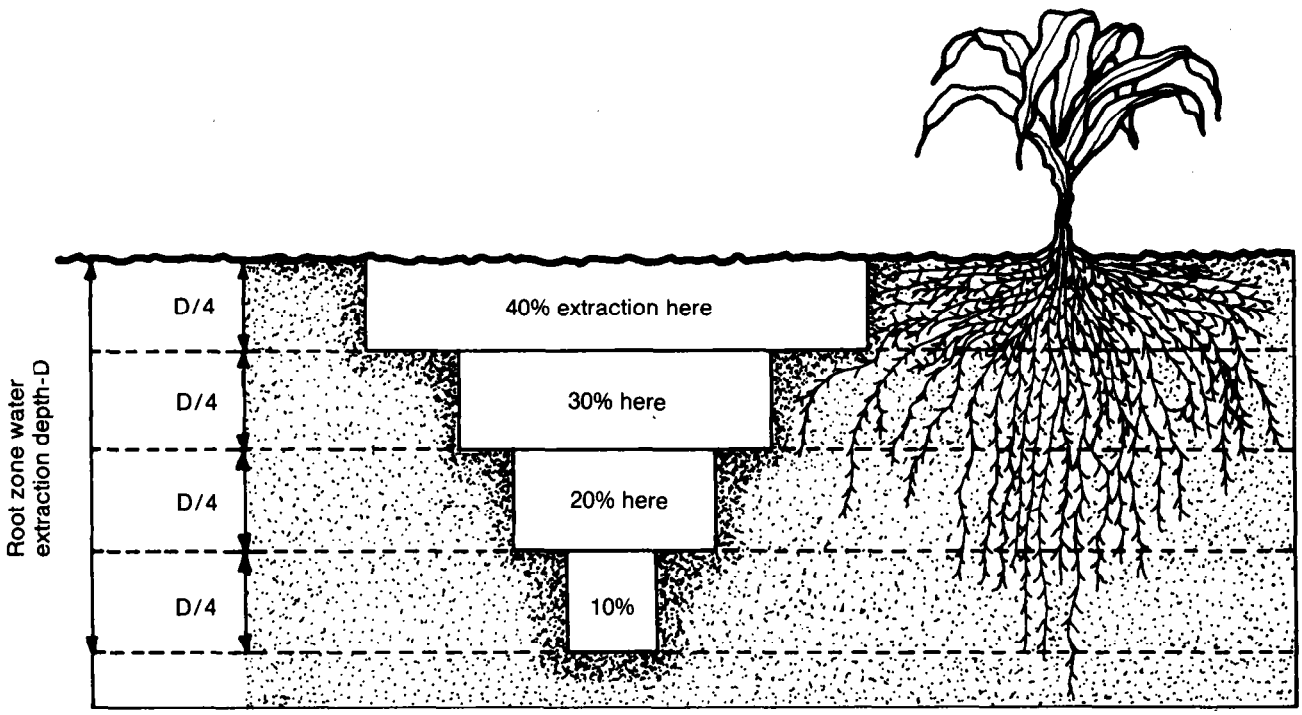
Water Uptake-Root Profile Relations

The root length density (length of roots per unit volume of soil) is generally greatest near the soil surface and declines with increasing depth to the maximum depth to which roots are observed for a given crop species. This general trend is illustrated graphically in figure 1-20.

Extraction of water is most rapid in the zone of greatest root concentration and under the most favorable conditions of temperature and aeration. Because water also evaporates from the upper few inches of soil, water is withdrawn rapidly from the top part of the soil profile. Soils normally show a more rapid loss of water at shallower depths until the potential becomes low enough to be rate limiting. Basic water-extraction curves, based on quarters of the root zone depth, indicate that almost all plants growing in soil that is

Figure 1-20.

Average Water Extraction Pattern of Plants Growing in a Soil Without Restrictive Layers and With an Adequate Supply of Available Water Throughout the Root Zone



uniform and adequately supplied with water have similar moisture-extraction patterns. Figure 1-20 shows that about 40 percent of the extracted water comes from the upper quarter of the root zone, 30 percent from the second quarter, 20 percent from the third quarter, and 10 percent from the bottom quarter. Values for comparative crops are normally within 10 percent of this range. In nonuniform soils, the amount of soil water for crop growth may be determined by the soil layer that has the lowest soil water retention capability. For example, a top soil layer with a low water retention capacity may be rapidly depleted following an irrigation or rain. Even though soil water may be adequate at the lower depths, water stress could be experienced in the early stages of plant development if the root system is not yet fully established. Some examples of limiting soil layers are illustrated in figure 1-21. The normal extraction pattern for a given crop will change when restrictive barriers are encountered. Also, if the water level in the upper soil layers is allowed to remain excessively dry, larger than normal amounts of water will be supplied by the lower soil layers.

Plant Water Use from Shallow Water Tables

Many agricultural production regions are characterized by having a water table close to the soil surface. Upon soil profile drying by evaporation from the soil surface or transpiration from plants, a water potential gradient develops that allows water to move upward in the soil profile and be taken up by plant roots. The magnitude of upward movement will depend on the strength of the water potential gradient that develops, the unsaturated water flow properties of the soil, and depth of the water table. Upward movement for eight North Carolina soils illustrates this phenomenon from values reported in the literature (fig. 1-22).

The practice of subirrigation utilizes this concept; water is introduced to the lower soil profile zones and moves upward into the active root zone by capillarity. Perched shallow water tables in the Central Valley of California contribute up to 50 percent of the total season ET requirement for cotton and seed alfalfa production.

Design Water-Extraction Depth

By definition, the design water-extraction depth is the soil depth used to determine irrigation water requirements for system design purposes. It is the depth to which a reasonably high soil water content should be maintained for optimum production of agricultural crops. It should not be the maximum depth of rooting, especially for long taproot systems, but it is important that it corresponds to the depth at which most of the active plant roots are able to meet transpirational demand. The design depth should be based on local water-extraction data for adopted crops. If two or more plant species with different rooting characteristics are to be grown together, the design depth should be that of the plant having the shallower root system.

The rooting depth of well-established perennials is reasonably stable from one growing season to the next and can generally be considered as constant; however, for annuals, root development depends on time. The researchers who developed table 1-5 formed a functional relationship between relative time and relative rooting depth for annual crops (fig. 1-23). Relative time represents the fractional time lapse to crop maturity from the planting date. Actual rooting depth at a given site and time can be determined by multiplying maximum rooting depth at maturity that is either known or estimated for a specific location by the relative rooting depth determined in figure 1-23.

Evapotranspiration

Evapotranspiration is the process by which water is moved from the surface of the earth to the atmosphere. It consists of the evaporation of liquid or solid water from soil and plant surfaces, plus water that transpires through plant tissues.

Potential ET

The relationship between crop, climate, water, and soil is complex and involves many processes. The processes can be explained somewhat simplistically through a series of concepts and relationships established through research.

Crop water requirement is defined as the depth of water per unit soil area needed to meet the water loss from evapotranspiration (ET_{crop} or ET_c) of a disease-free crop growing in a large field under nonrestricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment

Figure 1-21.

Water Extraction Patterns as Determined by Available Water Content in Various Parts of Soil Profile. Width of Each Profile Represents Total Available Water. Gross Area (Height and Width) of Each Profile Represents Total Available Water in Profile; Hatched Area Shows Water Extraction Pattern for Each Profile.

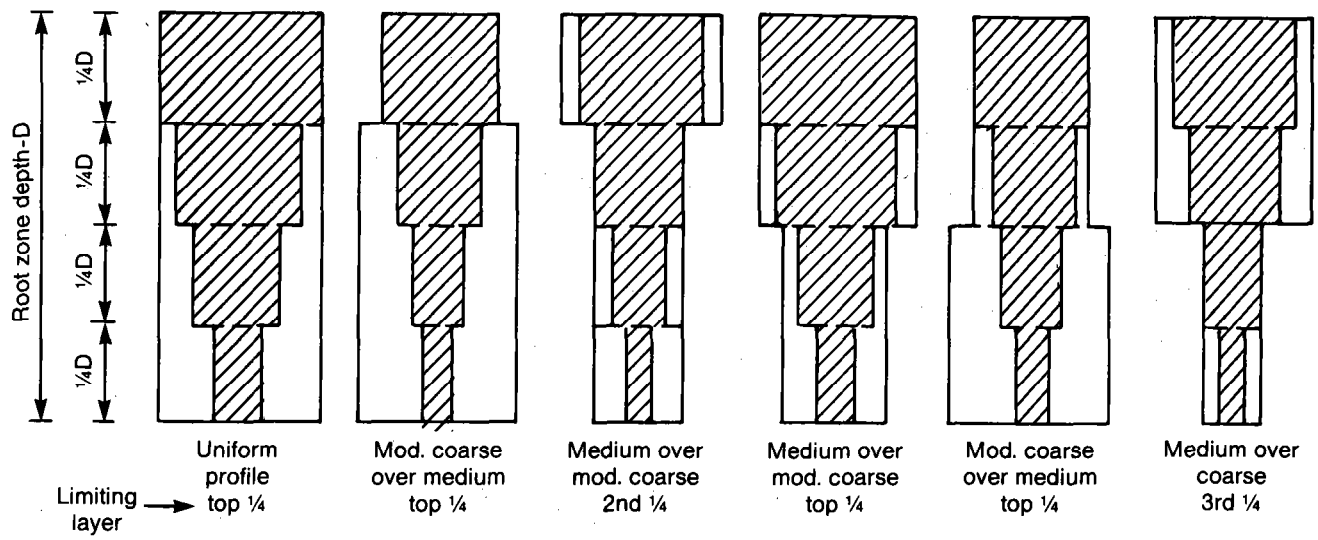


Figure 1-22.

Upward Flux-Water Table Depth Relationships for Eight North Carolina Soils

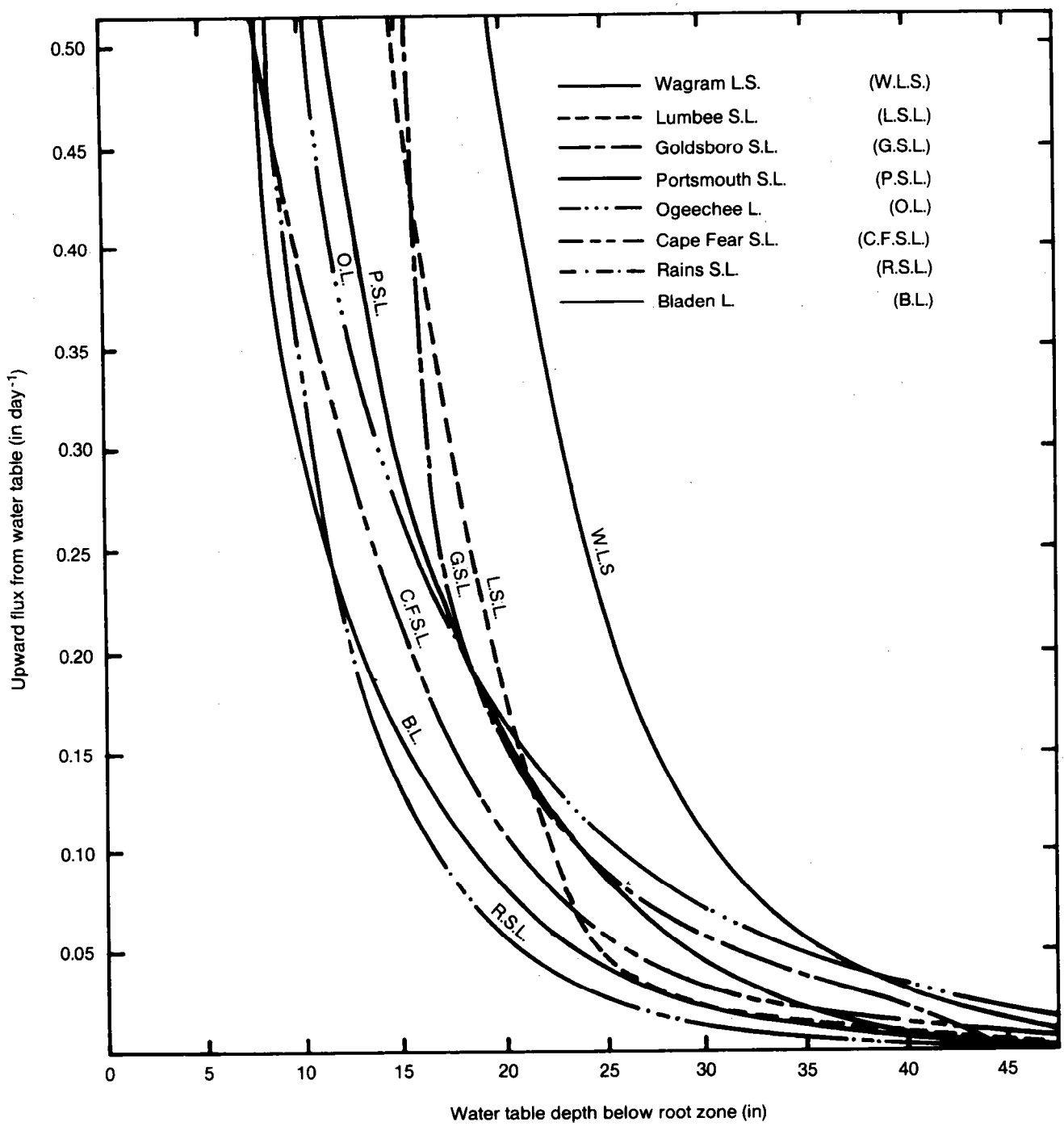
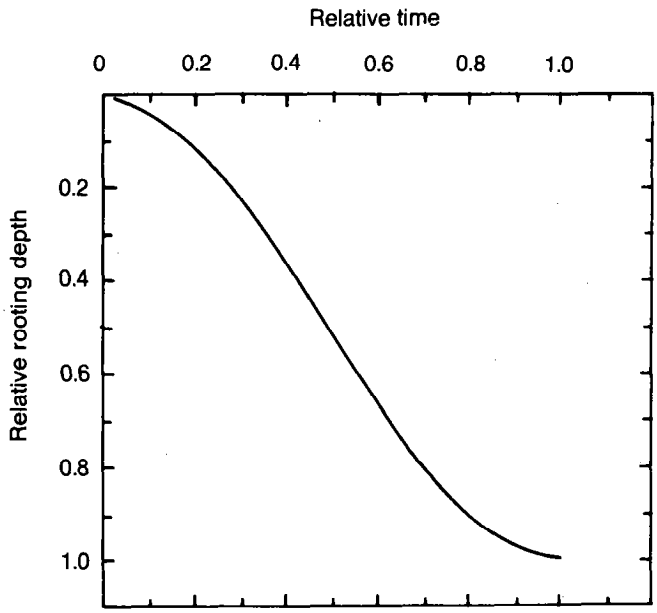


Figure 1-23.

Change in Relative Rooting Depth With Relative Time for Annual Crops



(Doorenbos & Pruitt, 1977). When these conditions are met the crop will produce at the potential or maximum yield (Y_m) and transpire at the maximum rate (ET_m).

Potential ET refers to the maximum ET rate determined by climatic conditions for a specific crop at a specific location at a specific time. Climatic conditions largely determine the potential ET. Various methods, based on meteorological factors, have been developed by researchers to predict the potential ET rates. Solar radiation is the main factor that determines the ET rate; but air temperature, humidity, and wind speed also have an effect.

Direct measurement of ET rates is laborious, time consuming, and requires considerable instrumentation. Therefore, the measurement of climatic factors is most often used to estimate ET based on an equation or model that relates the climatic factors to the ET rate. ET models usually estimate the potential ET of a reference crop such as grass or alfalfa. Conversion factors called "crop coefficients" are used to relate the reference crop ET to the actual crop ET.

Some ET models, such as the pan evaporation and Modified Blaney-Criddle models, relate climatic factors directly to the crop rather than to a reference crop. Crop coefficients are still required to adjust for the plant development stages because the crop transpiration rate is directly related to the canopy leaf area. As the canopy area increases, the crop coefficients must be increased.

When soil water is deficient, the plant is not able to take up enough water to meet the evapotranspiration demand set by the climatic conditions and is said to be under stress. When plants are stressed from soil water deficiency, the actual crop evapotranspiration rate (ET_a) will be less than the potential evapotranspiration rate (ET_m) and the actual crop yield (Y_a) will be less than the maximum yield (Y_m) (Doorenbos & Kassam, 1979). The ET-yield relationship is discussed in detail in a later section.

Predicting Crop ET

Actual crop ET (ET_a), in addition to climate, depends on soil factors and plant factors such as the degree of ground cover, plant leaf characteristics, and surface roughness of the crop canopy. Plant factors are characterized by the crop coefficient that varies during the growing season and according to the model used to estimate ET.

Estimating the actual ET of a growing crop from climatic observations requires the reference crop ET and the specific crop coefficient. The ET of a specific crop is calculated by:

ET_c = (reference crop ET) (specific crop coefficient)

Standard terminology has been established for referring to the various ET models and crop coefficients.

$$ET_c = (ET_o) \quad (K_c)$$
$$ET_c = (E_{pan}) \quad (K_p)$$
$$ET_c = ET_p) \quad (C_{et})$$

Where:

ET_o = Reference ET (approximates 4- to 7-inch tall grass)
ET_p = Potential ET (approximates uncut alfalfa)
E_{pan} = Evaporation from National Weather Service "class A" evaporation pan
ET_c = Evapotranspiration of a specified crop
K_{pan} = Coefficient to convert E_{pan} to ET_o
K_p = Coefficient to convert E_{pan} to ET_c
K_c = Coefficient to convert ET_o to ET_c
C_{et} = Coefficient to convert ET_p to ET_c

Several equations or models are available for estimating reference crop ET. The two reference crops used for estimating crop ET are grass and alfalfa. Grass is the

reference crop most often used and is becoming the standard reference. Care must be used to avoid mixing methodologies and coefficients. The selection of the method to be used may be determined by the available information; however, conversion from one reference base to another can be made by a general factor. If local conversion factors have been determined, they should be used. General conversion factors listed in table 1-6 may be used until specific local factors can be determined.

Generally, the selection of a method to estimate ET will be based on the kind of climatic data available and the degree of accuracy required in determining crop water-use rates. Prediction accuracy will usually be best for those procedures requiring the greatest input detail of climatic parameters. The following are sample methods used for calculating ET: Penman-Monteith (variable canopy height), FAO Blaney-Criddle, FAO Radiation, Jensen-Haise, Pan Evaporation, and SCS Blaney-Criddle. The monthly reference estimates of these procedures, plotted against lysimeter measured ET (ASCE Water Requirements Committee, 1987), are shown in figures 1-24a through 1-24f. All of these methods can be used to determine monthly ET_o, but the SCS Blaney-Criddle method cannot be used to determine daily ET_o for scheduling purposes.

Methods of estimating crop water requirements are discussed in detail in SCS National Engineering Handbook, section 15 : Irrigation, chapter 2 : Irrigation Water Requirements.

Table 1-6.—*General factors for conversion from one method of estimating crop ET to another (Snyder & Dickey, 1982)*

Evapotranspiration		Coefficients	
To ET_o		*To K_c*	
ET_o	$= (E_{pan})(K_{pan})$	K_c	$= K_p/K_{pan}$
	$= (E_{pan})(0.75)$		$= (K_p)(1.33)$
	$= (ET_p)(0.87)$		$= (C_{et})(1.15)$
To Et_p		*To C_{et}*	
ET_p	$= (ET_o)(1.15)$	C_{et}	$= (ET_o)(0.87)$
	$= (E_{pan})(1.08)$		$= (K_p)(0.93)$
To E_{pan}		*To K_p*	
E_{pan}	$= ET_o/K_{pan}$	K_p	$= (K_c)(K_{pan})$
	$= (ET_o)(1.33)$		$= (K_c)(0.75)$
	$= (ET_p)(0.93)$		$= (C_{et})(1.08)$

Crop Coefficient

A crop coefficient is the ratio of the actual crop ET to reference crop ET at a specific time. A plot of the crop coefficient as a function of time is known as a crop curve. An illustration of a crop curve is given in figure 1-25.

Figure 1-25 delineates the time during the growing season as initial, crop development, midseason, and late. Selection of these categories is arbitrary; using calendar days does not account for the possible year-to-year differences in climatic conditions that affect growth rate. The use of accumulated growing degree days, when available for the crop, avoids this disadvantage.

Monthly Reference Estimates From Several Different Procedures Versus Lysimeter-Measured ET

Figure 1-24(a).

Penman-Monteith, Var. Canopy Height

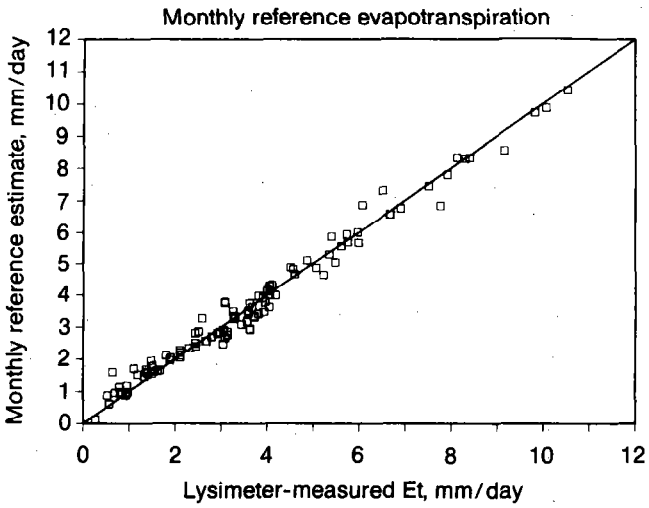


Figure 1-24(b).

FAO Blaney-Criddle

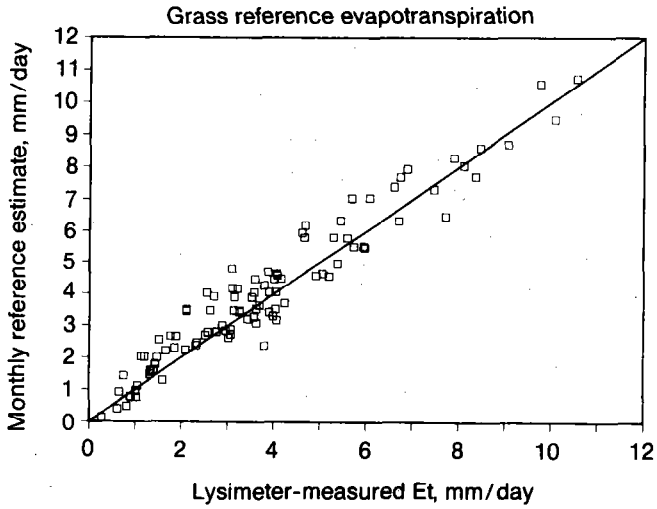


Figure 1-24(c).

FAO Radiation

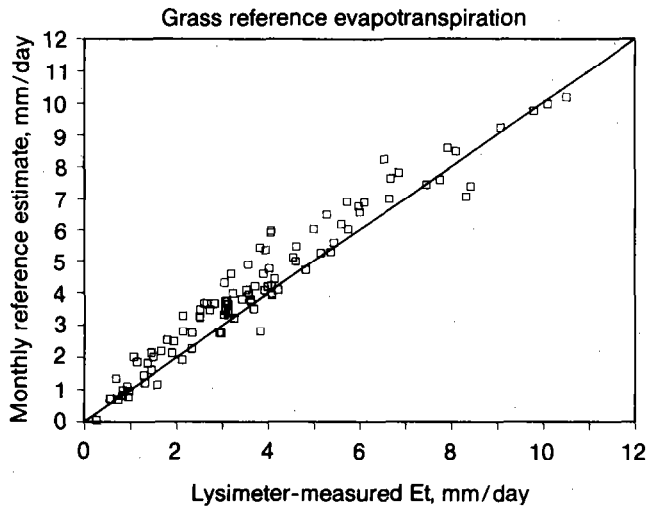


Figure 1-24(d).

Jensen-Haise

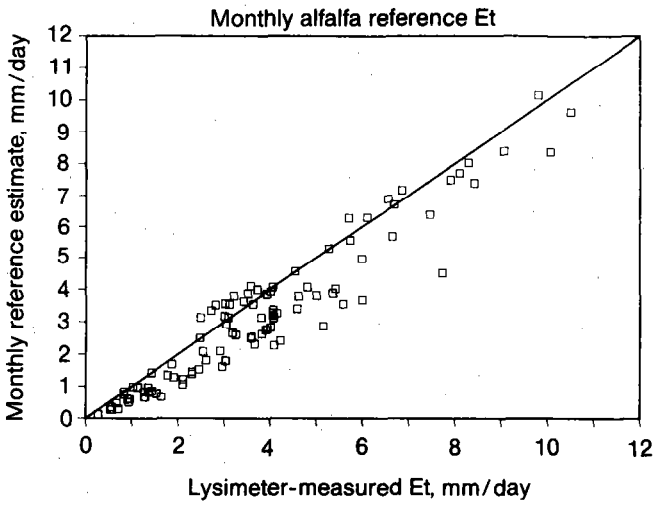


Figure 1-24(e).

Pan Evaporation

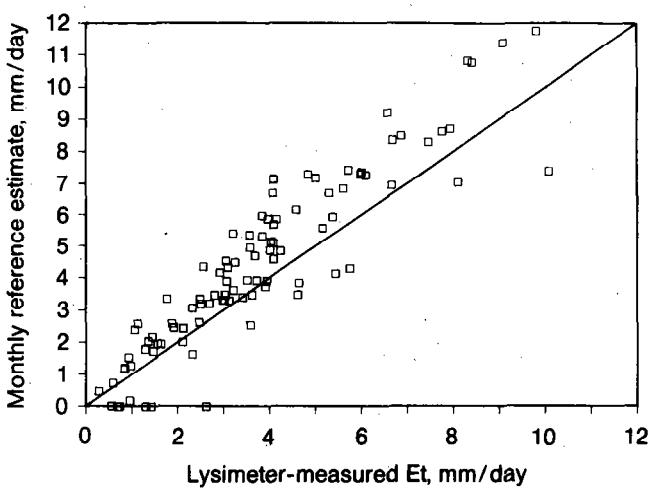
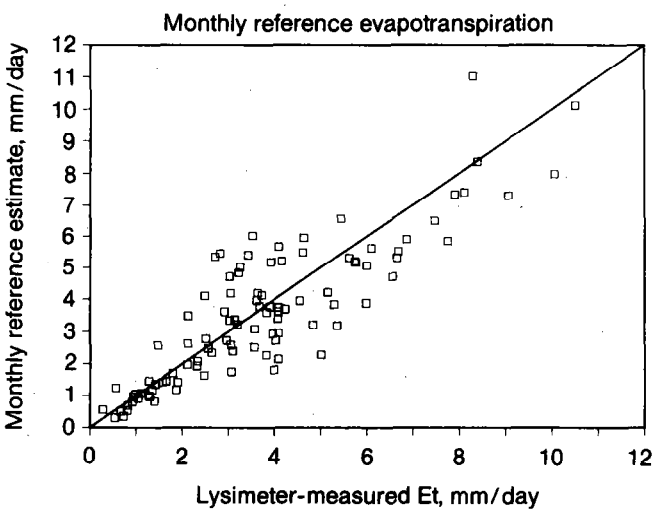


Figure 1-24(f).

SCS Blaney-Criddle (TR-21)



Crop Critical Stress Periods

For many crops there are critical periods during the growing season when a water deficit or stress is detrimental to crop yield. For most crops that have a critical period, the period generally is associated with some stage of reproductive growth; exceptions, however, do take place. The critical period for a number of commonly grown crops under an irrigated culture is given in table 1-7.

Table 1-7.—*Critical periods for water stress, symptoms, and some other considerations for several important crops.*

Crop	Water Stress	Critical Period	Other Considerations
Alfalfa	Darkening color, then wilting	Early spring & immediately after cuttings	Normally 3-4 inches of water needed between cuttings. Fall irrigation is desirable.
Corn	Curling of leaves by mid-morning	Tasseling, silk stage until grain is fully formed	Needs adequate water from germination to dent stage for maximum production.
Sorghum	Curling of leaves by mid-morning	Boot, bloom & dough stages	Yields are reduced if water is short during seed development.
Sugar Beets	Leaves wilting during heat of the day	Post thinning	Excessive fall irrigation lowers sugar content.
Beans	Wilting	Bloom and fruit set	Yields are reduced if water is short at bloom or fruit set.
Small Grain	Dull green color, then firing of lower leaves	Boot and bloom	Last irrigation is at milk stage.
Potatoes	Wilting during heat of the day	Tuber formation to harvest	Water stress during critical period may cause deformation of tubers.
Onions	Wilting	Bulb formation	Keep soil moist during bulb formation, let soil dry near harvest.
Tomatoes	Wilting	After fruit set	Wilt and leaf rolling can be caused by disease.
Cool Season Grass	Dull green color, then wilting	Early spring, early fall	For seed production critical period is boot to head formation.
Fruit Trees	Dulling of leaf color, and drooping	Any point during growing season	Stone fruits are sensitive to water stress during last irrigation.

Yield-Evapotranspiration Relationships

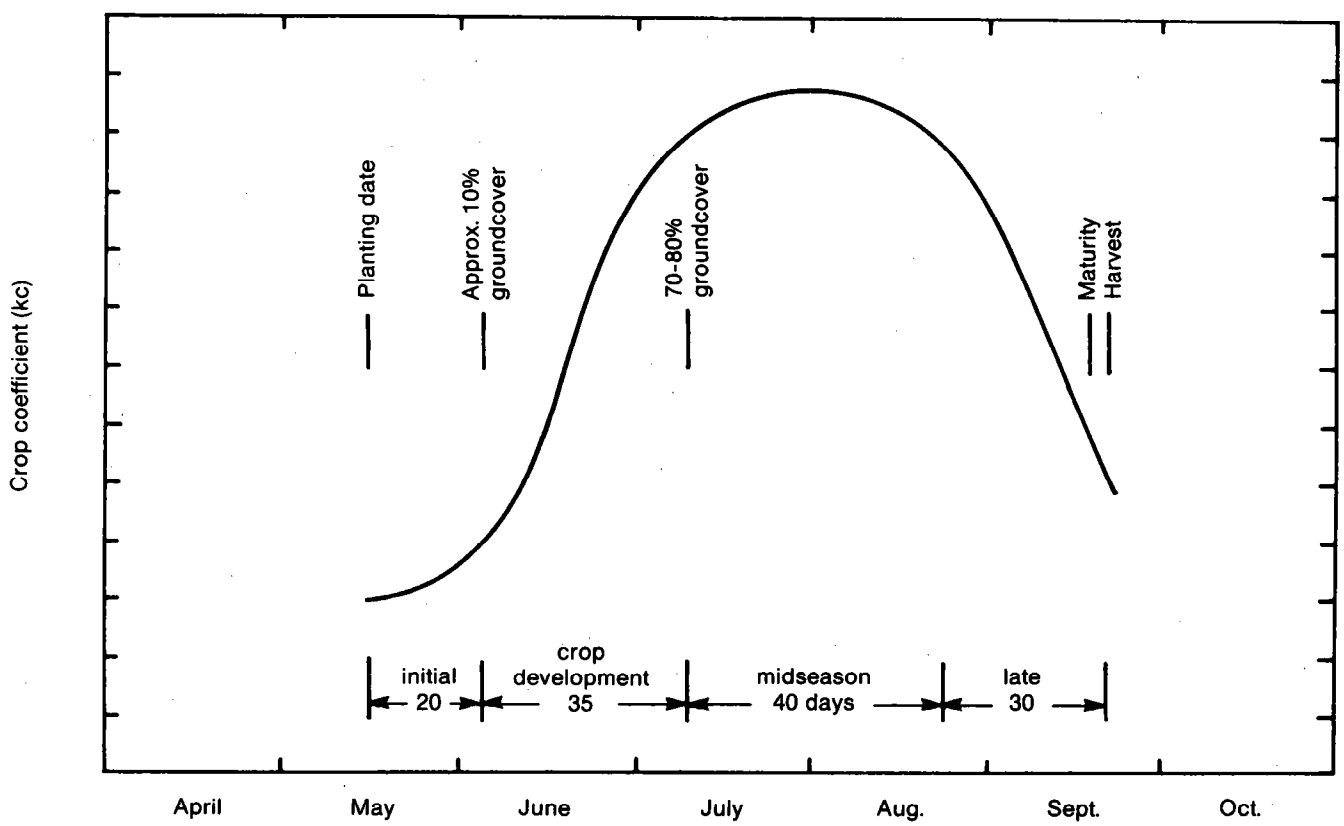
The amount of water evapotranspired to produce the highest crop yield at a given location will depend on the climate, soil, and characteristics of the specific crop. A supply of irrigation water is essential for sustained high levels of crop productivity. In arid and semiarid regions salinity is a potential problem that must be considered at the same time. If a water deficit develops in the soil beyond a threshold level for the specific stage of growth, the resulting water stress will reduce ET, and crop yield will be reduced proportionately. In recent years, recognition of this characteristic has led researchers to establish mathematical functions that characterize this direct relationship. Generally, studies to develop yield-ET functions have been conducted under nonlimiting salinity conditions. This is somewhat unfortunate because it is now usually accepted that the detrimental effects of excess salinity result from a reduction in ET that forms a direct linkage to reduced crop yields. It has been effectively demonstrated that yield-ET and yield-salinity effects can be reduced to a single yield-ET function in the absence of specific toxic ions that manifest yield loss on their own.

Concepts of Production Functions

The production function provides a useful means of analyzing water-productivity relations if the function is based on data that utilize proper irrigation scheduling to give the least yield reduction possible from a defined water deficit. Water response functions for a variety of crops have been developed. Although many variables are used to quantify the amount of water used in the production process, three of the greatest importance are ET, applied water, and soil water. Evapotranspiration has the greatest rigor and potential for transferability between contrasting soils and geographic regions. The amount of applied water, however, is the controlled variable and, in an economic sense, represents the cost consideration. Soil water status provides a link between ET and applied water and is an indication of management and the application uniformity of the irrigation system.

Figure 1-25.

Illustration of a Crop Coefficient Curve

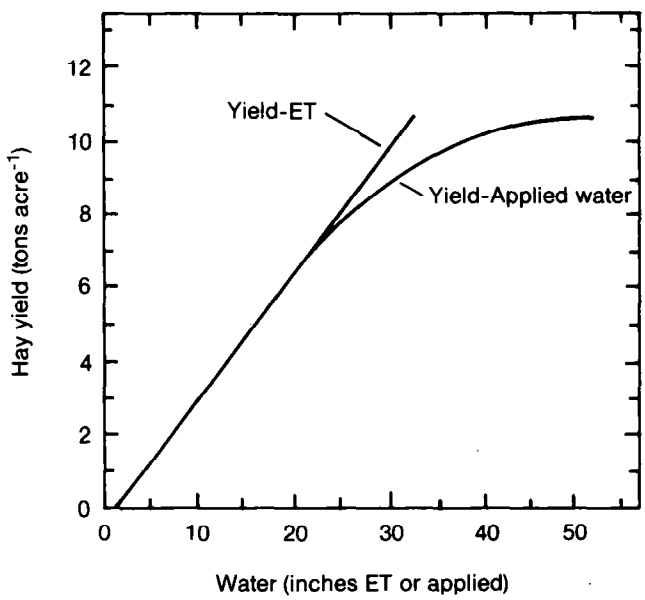


Yield-Evapotranspiration Production Functions

For many crops and growing conditions, the relationship between ET and yield is linear up to ET values that result in maximum productivity; this is especially true for crops where the aboveground biomass represents yield. This type of response is illustrated in figure 1-26 for total growing season alfalfa hay yield and ET in the San Joaquin Valley. Approximately 33.5 inches (85 centimeters) were required to achieve a maximum yield of 10.7 tons per acre (24 metric tons per hectare). Figure 1-27 shows a relationship between cotton lint yield and ET that is nonlinear. The relatively complex nature of vegetative-reproductive growth partitioning of cotton accounts for the slight curvature for this function; however, other crops, such as corn and sorghum, have been shown to have linear functions between seed or reproductive growth and ET.

Figure 1-26.

Alfalfa Hay Yield-ET and Yield Applied Water (AW) Functions for the San Joaquin Valley, California



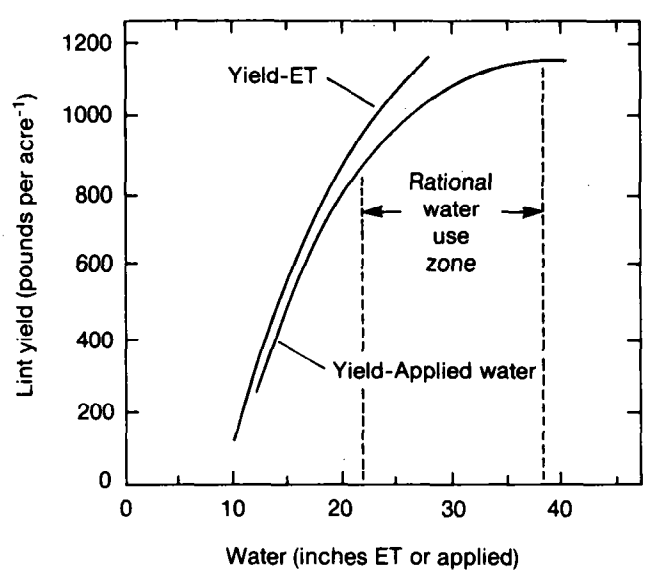
Yield-Applied Water Relationships

Figures 1-26 and 1-27 show that an applied water (AW) function progressively departs from the ET function as ET and applied water increase. This results primarily from increased drainage below the root zone and larger amounts of AW remaining in the soil profile at the end of the growing season which is directly related to the level of management.

The limits of a "rational water use zone" are depicted in figure 1-27. Applied water to achieve maximum yield is the upper limit, and AW required to reach a maximum average product (yield/applied water) is the basis for the lower limit. Applied water to maximize profit always will fall within the limits of the rational input zone. Adding additional water beyond that associated with achieving maximum yield may frequently be associated with yield reduction. Mechanisms that may be responsible for the yield loss include leaching of nutrients, reduced aeration, and excessive vegetative growth at the expense of reproducing seed yield.

Figure 1-27.

Cotton Lint Yield-ET and Lint Yield-Applied Water (AW) Functions for the San Joaquin Valley, California

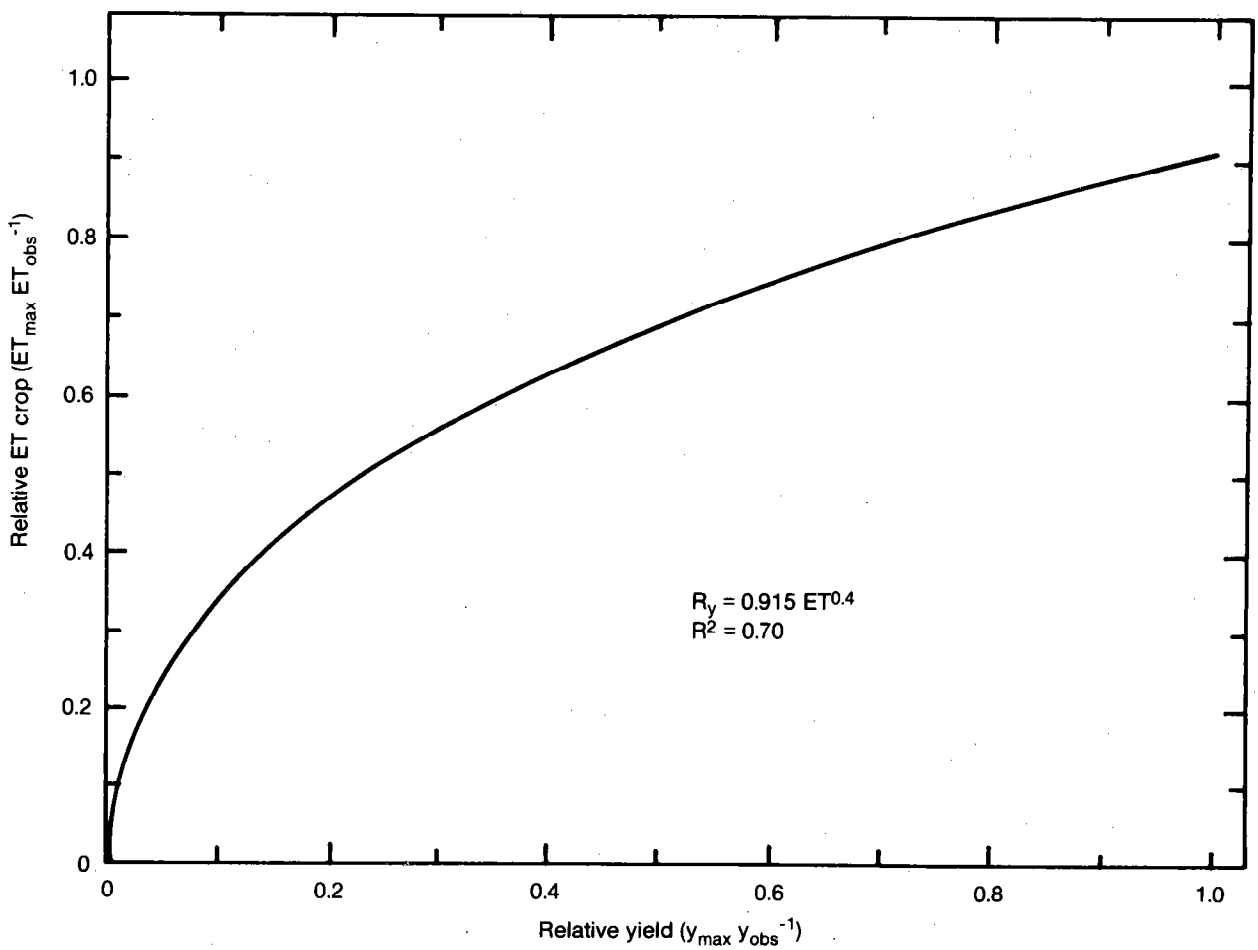


Transferability of Yield-Evapotranspiration Functions

Empirically derived water production functions are usually correct only for the site specific conditions under which they are developed; however, functions which use relative ET (actual ET/potential ET) and relative yield (actual yield/maximum yield) offer some advantage toward a more generalized function. A crop yield-water function for a specific region can be obtained from the dimensionless form by scaling the observed maximum yield and water use required to achieve this yield of a site to the relative values. Research shows that a fair amount of transferability, among geographic regions of contrasting soil and climatic conditions, is possible under this procedure. Figure 1-28 illustrates a dimensionless yield-ET function for Thompson grapevines.

Figure 1-28.

Relative Yield of Thompson Grapes Versus Relative Evapotranspiration



Salinity Effects

Dissolved salts in irrigation water contribute to soil salinity that causes a yield loss to the crop for salinity levels beyond the threshold of tolerance for a given crop. Yield loss is generally associated with reduced plant size and lower ET. For a given amount and salt load of irrigation water, over a lengthy time period, an equilibrium will be established between ET, leaching, soil salinity, and crop yield. Under these conditions, the detrimental effects of salinity are related to crop yield reduction that is associated with the reduced ET.

Generally, crops will tolerate salinity without yield reduction up to a definable threshold level. As salinity increases beyond the threshold level, yields are linearly diminished until crop production is no longer feasible. Table 1-8 uses this concept for four categories of crop sensitivity to soil salinity (EC_e, conductivity of the soil saturation extract); namely, sensitive (S), moderately sensitive (MS), moderately tolerant (MT), and tolerant (T). The table gives the threshold values and slope of the linear yield loss function with increased salinity. Although generalized categories of crop salt tolerance can be made, it must be recognized that salt tolerance depends on many plant, soil, and climatic variables. The time-averaged salinity of a root zone is determined by the amount of drying that occurs between rains or irrigations. Both matric and osmotic potentials decline on drying, and it is generally thought that the sum of the two is the total soil water potential that the plant responds to. As soil water is depleted from a soil profile having a nonuniform distribution of salts, the total potential of water being absorbed tends to approach a uniform potential at all depths. Following irrigation or rain, plants absorb water first from root zone regions of low osmotic stress, usually the upper, less saline part of the profile. As matric stress increases in the upper profile, total water stress is equalized on the entire soil profile since more salts are present toward the lower part of the root zone. Frequent irrigation to maintain a high level of soil moisture in the upper profile will maintain a low level of water stress even though considerable salinity may be present in the lower root zone.

Table 1-8.—*Salt tolerance of herbaceous crops (E. V. Maas, 1986. Applied Agricultural Research 1:12-26).*

Crop		Electrical conductivity of saturated soil extract		
Common name	Botanical name	Threshold dS/m	Percent[1] yield reduction	Rating[2]
Fiber, grain, and special crops				
Barley	*Hordeum vulgar*	8.0	5.0	T
Bean	*Phaseolus vulgaris*	1.0	19.0	S
Broadbean	*Vicia Faba*	1.6	9.6	MS
Corn	*Zea Mays*	1.7	12.0	MS
Cotton	*Gossypium hirsutum*	7.7	5.2	T
Cowpea	*Vigna unguiculata*	4.9	12.0	MT
Flax	*Linum usitatissimum*	1.7	12.0	MS
Guar	*Cyamopsis tetragonoloba*	-	-	MT
Millet, foxtail	*Setaria italica*	-	-	MS
Oats	*Avena sativa*	-	-	MT
Peanut	*Arachis hypogaea*	3.2	29.0	MS
Rice, paddy	*Oryza sativa*	3.0	12.0	S
Rye	*Secale cereale*	-	-	MT
Safflower	*Carthamus tinctorius*	-	-	MT
Sesame	*Sesamum indicum*	-	-	S
Sorghum	*Sorghum bicolor*	6.8	16.0	MT
Soybean	*Glycine Max*	5.0	20.0	MT
Sugarbeet	*Beta vulgaris*	7.0	5.9	T
Sugarcane	*Saccharum officinarum*	1.7	5.9	MS
Sunflower	*Helianthus annuus*	-	-	MS
Triticale	*X. Triticosecale*	-	-	T
Wheat	*Triticum aestivum*	6.0	7.1	MT
Wheat (semidwarf)	*T. aestivum*	8.6	3.0	T
Wheat, Durum	*T. turgidum*	5.9	3.8	T
Grasses and forage crops				
Alfalfa	*Medicago sativa*	2.0	7.3	MS
Alkaligrass, Nuttall	*Puccinellia airoides*	-	-	T
Alkali sacaton	*Sporobolus airoides*	-	-	T
Barley (forage)	*Hordeum vulgare*	6.0	7.1	MT
Bentgrass	*Agrostis stolonifera palustris*	-	-	MS
Bermudagrass	*Cynodon Dactylon*	6.9	6.4	T
Bluestem, Angleton	*Dichanthium aristatum*	-	-	MS
Brome, mountain	*Bromus marginatus*	-	-	MT
Brome, smooth	*B. inermis*	-	-	MS
Buffelgrass	*Cenchrus ciliaris*	-	-	MS
Burnet	*Poterium Sanguisorba*	-	-	MS
Canarygrass, reed	*Phalaris arundinacea*	-	-	MT
Clover, alsike	*Trifolium hybridum*	1.5	12.0	MS
Clover, Berseem	*T. alexandrinum*	1.5	5.7	MS
Clover, Hubam	*Melilotus alba*	-	-	MT
Clover, ladino	*Trifolium repens*	1.5	12.0	MS
Clover, red	*T. pratense*	1.5	12.0	MS
Clover, strawberry	*T. fragiferum*	1.5	12.0	MS
Clover, sweet	*Melilotus*	-	-	MT
Clover, white Dutch	*Trifolium repens*	-	-	MS
Corn (forage)	*Zea Mays*	1.8	7.4	MS
Cowpea (forage)	*Vigna unguiculata*	2.5	11.0	MS
Dallisgrass	*Paspalum dilatatum*	-	-	MS
Fescue, tall	*Festuca elatior*	3.9	5.3	MT
Fescue, meadow	*F. pratensis*	-	-	MT
Foxtail, meadow	*Alopecurus pratensis*	1.5	9.6	MS
Grama, blue	*Bouteloua gracilis*	-	-	MS
Hardinggrass	*Phalaris tuberosa*	4.6	7.6	MT
Kallargrass	*Diplachne fusca*	-	-	T
Lovegrass	*Eragrostis*	2.0	8.4	MS
Milkvetch, Cicer	*Astragalus cicer*	-	-	MS
Oatgrass, tall	*Arrhenatherum, Danthonia*	-	-	MS
Oats (forage)	*Avena sativa*	-	-	MS
Orchardgrass	*Dactylis glomerata*	1.5	6.2	MS
Panicgrass, blue	*Panicum antidotale*	-	-	MT
Rape	*Brassica napus*	-	-	MT
Rescuegrass	*Bromus unioloides*	-	-	MT
Rhodesgrass	*Chloris Gayana*	-	-	MT
Rye (forage)	*Secale cereale*	-	-	MS
Ryegrass, Italian	*Lolium italicum multiflorum*	-	-	MT
Ryegrass, perennial	*L. perenne*	5.6	7.6	MT
Saltgrass, desert	*Distichlis stricta*	-	-	T

Crop		Electrical conductivity of saturated soil extract		
Common name	Botanical name	Threshold dS/m	Percent[1] yield reduction	Rating[2]
Sesbania	*Sesbania exaltata*	2.3	7.0	MS
Siratro	*Macroptilium atropurpureum*	-	-	MS
Sphaerophysa	*Sphaerophysa salsula*	2.2	7.0	MS
Sudangrass	*Sorghum sudanense*	2.8	4.3	MT
Timothy	*Phleum pratense*	-	-	MS
Trefoil, big	*Lotus uliginosus*	2.3	19.0	MS
Trefoil, narrowleaf birdsfoot	*L. corniculatus tenuifolium*	5.0	10.0	MT
Trefoil, broadleaf birdsfoot	*L. corniculatus arvenis*	-	-	MT
Vetch, common	Vicia angustifolia	3.0	11.0	MS
Wheat (forage)	*Triticum aestivum*	4.5	2.6	MT
Wheat, Durum (forage)	*T. turgidum*	2.1	2.5	MT
Wheatgrass, standard crested	*Agropyron sibiricum*	3.5	4.0	MT
Wheatgrass, fairway crested	*A. cristatum*	7.5	6.9	T
Wheatgrass, intermediate	*A. intermedium*	-	-	MT
Wheatgrass, slender	*A. trachycaulum*	-	-	MT
Wheatgrass, tall	*A. elongatum*	7.5	4.2	T
Wheatgrass, western	*A. Smithii*	-	-	MT
Wildrye, Altai	*Elymus angustus*	-	-	T
Wildrye, beardless	*E. triticoides*	2.7	6.0	MT
Wildrye, Canadian	*E. canadensis*	-	-	MT
Wildrye, Russian	*E. junceus*	-	-	T
Vegetable and fruit crops				
Artichoke	*Helianthus tuberosus*	-	-	MT
Asparagus	*Asparagus officinalis*	4.1	2.0	T
Bean	*Phaseolus vulgaris*	1.0	19.0	S
Beet, red	*Beta vulgaris*	4.0	9.0	MT
Broccoli	*Brassica oleracea botrytis*	2.8	9.2	MS
Brussels sprouts	*B. oleracea gemmifera*	-	-	MS
Cabbage	*B. oleracea capitata*	1.8	9.7	MS
Carrot	*Daucus carota*	1.0	14.0	S
Cauliflower	*Brassica oleracea botrytis*	-	-	MS
Celery	*Apium graveolens*	1.8	6.2	MS
Corn, sweet	*Zea Mays*	1.7	12.0	MS
Cucumber	*Cucumis sativus*	2.5	13.0	MS
Eggplant	*Solanum Melongena esculentum*	-	-	MS
Kale	*Brassica oleracea acephala*	-	-	MS
Kohlrabi	*B. oleracea gongylode*	-	-	MS
Lettuce	*Lactuca sativa*	1.3	13.0	MS
Muskmelon	*Cucumis Melo*	-	-	MS
Okra	*Abelmoschus esculentus*	-	-	S
Onion	*Allium Cepa*	1.2	16.0	S
Parsnip	*Pastinaca sativa*	-	-	S
Pea	*Pisum sativum*	-	-	S
Pepper	*Capsicum annuum*	1.5	14.0	MS
Potato	*Solanum tuberosum*	1.7	12.0	MS
Pumpkin	*Cucurbita Pepo Pepo*	-	-	MS
Radish	*Raphanus sativus*	1.2	13.0	MS
Spinach	*Spinacia oleracea*	2.0	7.6	MS
Squash, scallop	*Cucurbita Pepo Melopepo*	3.2	16.0	MS
Squash, zucchini	*C. Pepo Melopepo*	4.7	9.4	MT
Strawberry	*Fragaria*	1.0	33.0	S
Sweet potato	*Ipomoea Batatas*	1.5	11.0	MS
Tomato	*Lycopersicon Lycopersicum*	2.5	9.9	MS
Turnip	*Brassica Rapa*	0.9	9.0	MS
Watermelon	*Citrullus lanatus*	-	-	MS

[1]Percent reduction in yield per increase in solinity unit (ds/m).
[2]S, T, MS, and MT indicate a classification of sensitive, tolerant, moderately sensitive, and moderately tolerant, respectively.

Plant Factors

While plant species are classed as to their general sensitivity to salinity, considerable flexibility may be achieved by varietal selection, especially within the grass family (Gramineae). Rootstock differences in the tolerance of salinity and toxic ions are an important consideration for vine and fruit-tree crops. Several woody species show tolerance levels that are related to the accumulation properties of the rootstocks.

For some crops, salinity sensitivity varies with growth stage; cereal crops appear particularly variable. Rice, barley, wheat, and corn appear to be more sensitive during emergence and early seedling growth than at germination and later growth stages and grain development. Sugar beets and safflower are more sensitive during germination than at other stages.

Soil Factors

Immediately after an irrigation event the salt concentration of the soil solution will be at the lowest possible level. With ET, the solution becomes more concentrated as the time for the next irrigation approaches. As indicated previously, with very saline soil water, frequent irrigations are needed to minimize salinity stress; however, maintaining frequent irrigations may lead to aeration problems, especially for fine-textured soils.

Crops grown on infertile soils may exhibit quite high levels of apparent salt tolerance because salinity is not the factor limiting growth. Proper fertilization results in higher yield, but it seems to increase salt sensitivity.

Climatic Factors

Temperature, humidity, and air pollution have been observed to markedly influence salt tolerance. As evaporation demand increases (high temperature and lower relative humidity), many crops appear less salt tolerant. The detrimental effects of ozone have been observed to be moderated by maintaining moderate levels of salinity. This interaction may be of practical significance for some leafy vegetables and forage crops.

Specific Ion Effects

A few specific ions have a direct toxic effect on certain sensitive crops at relatively low concentrations. Tree crops and woody ornamentals are sensitive to low concentrations of sodium and chloride; annual crops do not show this degree of sensitivity. Boron affects a broad range of crop species. Studies of crop sensitivity to specific ions generally report absorption to be through the crop root system; an equally important mode of entry, in the case of sodium and chloride ions, is through leaves wet by a sprinkler.

Boron may be present in either soils or irrigation waters. In the soil, boron can be leached, but it is difficult to do so. Boron that is present in irrigation water requires corrective action by switching water supplies, if this is possible, or by selecting a crop less sensitive to boron. Table 1-9 provides a list of crops that have varying degrees of boron sensitivity.

Table 1-9.—*Tolerance classification of plants to boron (Robert S. Ayers, 1977. Quality of water for irrigation. J. Irrig. Drain. Div. ASCE, IR2, 103:135-154).*

Sensitive*	Semitolerant*	Tolerant*
Lemon	Lima beans	Carrot
Grapefruit	Sweet potato	Lettuce
Avocado	Bell pepper	Turnip
Orange	Tomato	Cabbage
Thornless blackberry	Pumpkin	Onion
Apricot	Zinnia	Broad bean
Peach	Oat	Gladiolus
Cherry	Milo	Alfalfa
Persimmon	Corn	Garden beet
Kadota fig	Wheat	Mangel
Grape (sultonina and malaga	Barley	Sugar beet
Apple	Olive	Palm (phoenix conariensis)
Pear	Ragged robin rose	Date palm (phoenix dactylifera)
American elm	Radish	Asparagas
Navy bean	Sweet pea	Athel (tamarix aphylla)
Jerusalem artichokes	Pima cotton	
Persian (English) walnut	Acola cotton	
Black walnut	Potato	
Peron	Sunflower (native)	

* Within each group, the plant first given is most sensitive and the last most tolerant.

Acid Soils

Soil leaching (weathering) takes place over much of the Earth's land surface where rainfall exceeds evapotranspiration for the greater part of the year. The leached soil becomes acidic as soluble salts, soluble soil minerals, and bases are removed. Under slight to moderate intensity weathering, only the surface soil becomes acidic while the subsoil may remain neutral or alkaline. As leaching becomes more intense, the entire soil profile becomes acidic. In humid tropical zones, strongly weathered soils return again to neutral to slightly acid conditions if soils are high in aluminum (Al) and iron (Fe) hydroxide.

Many factors other than the normal weathering processes of soils cause them to be acid. The parent materials of the soils may have been acidic, or the soils may have been contaminated by mine spoils containing iron pyrite (FeS_2) or other sulfides which are oxidized to H_2SO_4 and $Fe(OH)_3$ in the presence of air and water and can result in soils having a pH as low as 2. Marine flood plains that are high in sulfides become extremely acid in one to two years following drainage. Organic acids are formed as plant residues are decomposed by organisms and cause forest soils and organic soils to be acidic. Acid precipitation, having a pH as low as 3 to 4 because of the emissions from the combustion of fossil fuels (coal and petroleum), may lower the pH of sensitive soils, noncalcareous soils that have low organic matter contents and low clay contents and, consequently, very low cation-exchange capacities. Finally, most nitrogen and phosphorous fertilizers increase the acidity of soils. Nitrogen increases the acidity of soils when the ammonium form is converted to nitrate by soil micro-organisms; and diammonium phosphate does so when the ammonium ions, which are part of the chemical formula of the fertilizer, are also converted to nitrate.

Chemistry of Acid Soils

The chemical nature of acid soils is linked closely to the solution chemistry of Al and, to some extent, Fe. When the soil cation-exchange capacity is saturated with hydrogen ions from strong acids, the hydrogen ions are rapidly replaced with Al and Fe ions from within the crystal structure of the clay mineral.

Hydrolysis reactions lead to hydroxy complexes such as $Al(OH)^{2+}$, $Al(OH)_2^+$, and $Fe(OH)(H_2O)_5^{2+}$. Such reactions are important because these compounds form a thin layer around layered silicate minerals; and, because they are positively charged, they influence the cation-exchange capacity of soils. At low soil pH values (4.5 to 5.0), the net cation-exchange capacity of the soil will be lowest because the 2+ ion species above predominate and neutralize some of the negative charge. At neutral to slightly basic conditions, $Al(OH)_3^0$ is the dominant species and the net negative charge of the mineral complex is that of the silicate mineral. In highly weathered soils, oxides of Fe and Al are abundant. Such soils may have a large part of the cation-exchange capacity that is pH dependent.

Effects of Soil Acidity on Plant Growth

Many soil parameters are changed as soil acidity is altered; therefore, it is difficult to determine the exact reason for poor plant growth under acid conditions. Many experiments have emphasized, however, the different nutritional abnormalities that take place under field conditions. Provided the soil pH does not go below 4.0 - 4.5, there is little direct detriment because of hydrogen ions; rather, Al_3^+ and Mn_2^+ are present in soil solution in sufficient quantities to be toxic to plants in varying degrees, depending on the species and cultivar of the specific crop.

Deficiencies of calcium (Ca) frequently hinder crop growth under acid soil conditions, as do deficiencies of magnesium (Mg) and molybdenium (Mo). Generally, phosphorous (P) availability is suppressed in acid soils, but the resulting deficiencies frequently have been acccounted for by P immobilization in roots by the conduction elements of plants. In addition to the direct effects of acidity on the chemical status of inorganic elements, the impedance of the populations and the activities of micro-organisms that are responsible for transformations involving nitrogen (N), sulfur (S), and phosphorus (P) reduce the availability of these elements to crops.

Correcting acid soil conditions by liming has, in some instances, been associated with reduced availability of some inorganic ions. Therefore, care should be taken that adequate amounts of affected ions are made available by fertilization. Liming acid soil reduces the availability of exchangeable potassium (K). Boron (B) deficiency has been associated with liming in the southern region of the United States and zinc (Zn) deficiencies have been attributed to liming. Figure 1-29 illustrates nutrient availability in acid soils.

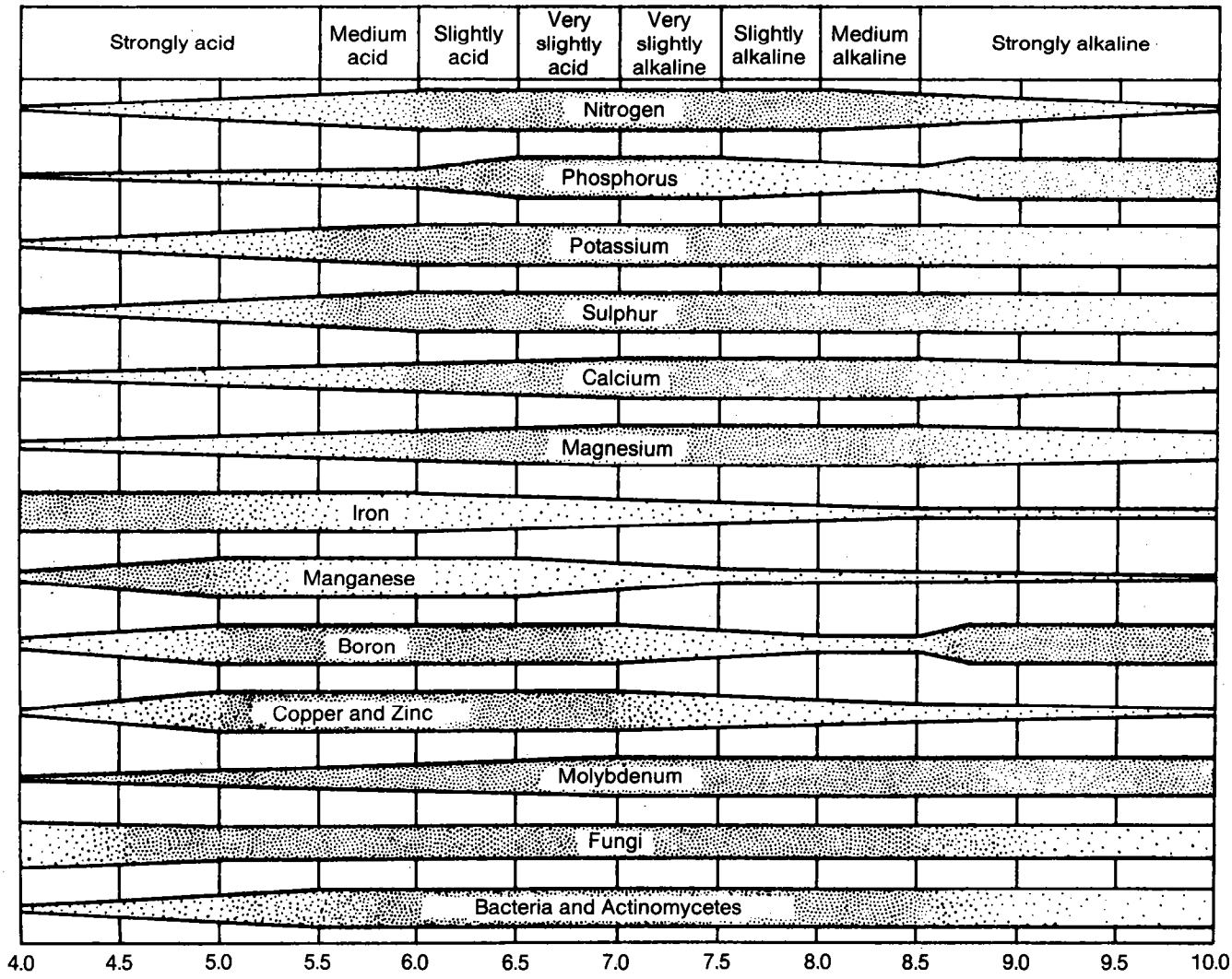
Crop Response to Liming in the United States

Soil acidity in the United States that is sufficient to limit crop production is generally restricted to subhumid and humid regions (fig. 1-1). Localized conditions that are favorable for acid soil development, however, may take place even in low rainfall areas.

Liming is considered to be an essential component of sustained crop productivity in the Southern United States. High usage of acid forming fertilizers increases the need for liming in the region; however, actual lime usage has not historically kept pace with that required for optimum crop production.

Figure 1-29.

Nutrient Availability in Acid Soils: The Wider the Bar, the More Available is the Nutrient.



Lime usage in the Midwest was higher before the 1950's when leguminous meadow crops were used extensively as a source of nitrogen to maintain acceptable crop yields. Following this period, the use of large quantities of commercial N-fertilizer materials was introduced, and the basic cation reserves were markedly lowered. Soils now require regular applications of lime to maintain productivity.

Most soils in the Northeastern States require regular applications of lime for normal plant growth and yield. Some very young limestone-derived soils are still calcareous in their upper horizons and require no lime at this stage of development. As in all regions, some growing crops actually perform best on acid soils.

In the Western States, precipitation that is sufficient to develop acid soil conditions in the normal course of soil development is restricted to areas relatively close to the Pacific Ocean. These areas are most frequently of mountainous terrain on the western slope that is not substantially cultivated.

Determining Lime Requirement

Contrasting crop species vary considerably in their tolerance of acid soils; therefore, the crops that are to be

grown affect liming recommendations. Table 1-10 gives the optimum soil pH range for several crops commonly grown on mineral soils in regions requiring lime additions. Some potato growers in Maine maintain low pH to control scab disease. Legumes are generally the crops most sensitive to soil acidity. Organic soils should be allowed to decline to much lower pH values than mineral soils; satisfactory crop yields are achieved at pH values ranging as low as 5.0 to 5.7. At these pH values organic soils usually contain an abundance of Ca and Mn. Generally, Al and Fe contents are well below toxic levels.

Table 1-10.—*Permissible soil pH ranges for various crops growing on mineral soils in Michigan (C. M. Woodruff, 1967.* In *Soil Acidity and Liming. Robert W. Pearson and Fred Adams, eds. Agronomy Monograph No. 12. Amer. Soc. Agron. Madison, WI, p. 222).*

Crop	Soil pH range	Crop	Soil pH range
Least acid-tolerant		More acid-tolerant	
Alfalfa	6.3 to 7.8	Buckwheat	5.0 to 7.0
Asparagas	6.0 to 8.0	Oats	5.0 to 7.0
Barley	6.5 to 7.8	Potatoes	5.2 to 6.5
Beans	6.0 to 7.5	Raspberry	5.0 to 7.0
Peas	6.0 to 7.5	Rye	5.0 to 7.0
Red clover	.0 to 7.5	Strawberries	5.0 to 6.5
Soybeans	6.0 to 7.0	Vetch	5.0 to 7.0
Sugar beets	6.0 to 7.5		
Sweet clover	6.5 to 7.9		
Medium acid-tolerant		Strongly acid soils required	
Corn	5.5 to 7.5		
Cotton	5.5 to 7.5	Cranberries	4.2 to 5.0
Grasses	5.5 to 7.5		
Trefoil	5.5 to 7.5		
Wheat	5.5 to 7.0		

A problem in managing acid soils is to determine the amount of lime needed to elevate soil pH to a desired level. Theoretically, the best procedure is to titrate a soil sample with a standard base to measure the amount of base needed to bring the pH to a specified level. To be accurate, however, a relatively long reaction time must accompany each titration step, which renders this approach somewhat impractical. A more commonly accepted technique is to add a pH buffer solution to the soil. The amount of buffer consumed or the pH of the soil-buffer suspension after equilibration is compared with the calibrated results of field lime experiments for similar soils of a specific geographic region.

The Ca and Mg compounds in agricultural lime will neutralize soil acidity. A listing of liming materials includes quicklime, hydrated lime, limestone, marl, shells, by-products such as slag, and irrigation water. The calcium and magnesium contents of ground water that is used for irrigation can be equal to 1,000 pounds or more of calcium carbonate per acre foot of water and can neutralize all the acidity generated by added fertilizers, yet still raise the pH of the soil over a period of time.

If the soils to be irrigated have a sodium adsorption ratio greater than 13 and the irrigation water contains calcium or magnesium and carbonate or bicarbonate ions, a slightly or moderately acid soil is preferable. In the acid soil calcium ions remain in the soil solution, rather than precipitating as the carbonate, and compete with sodium ions for adsorption on the exchange complex. The dispersion of clays due to sodium can also be reduced by maintaining some salinity in the irrigation water.

Limestone is the most common liming material used; it may be calcite ($CaCO_3$), dolomite ($CaCO_3 \cdot MgCO_3$), or a mixture of these materials. Agricultural lime usually contains impurities that have no effect on soil acidity. The chemical effectiveness of lime is measured by its $CaCO_3$ equivalency.

The rate of the reaction of lime with soil depends not only on its chemical purity, but also on particle size. Fineness is usually measured by expressing the percentages of material passing a series of specific, sized sieves. The approximate amounts of finely ground limestone that are needed to raise the pH of soils are shown in table 1-11. Adjustment of these amounts may be required to fit local conditions.

Table 1-11.—*Approximate amounts of finely ground limestone needed to raise the pH of a 7-inch layer of soil.*[1]

Soil regions and textural classes	Limestone requirements		
	From pH 3.5 to pH 4.5	From pH 4.5 to pH 5.5	From pH 5.5 to pH 6.5
Soils of warm-temperate and tropical regions:[2]	-------Tons per acre-------		
Sand and loamy sand	0.3	0.3	0.4
Sand loam	—	0.5	0.7
Loam	—	0.8	1.0
Silt loam	—	1.2	1.4
Clay loam	—	1.5	2.0
Muck	2.5[3]	3.3	3.8
Soils of cool-temperate and temperate regions:[4]			
Sand and loamy sand	0.4	0.5	0.6
Sandy loam	—	0.8	1.3
Loam	—	1.2	1.7
Silt loam	—	1.5	2.0
Clay loam	—	1.9	2.3
Muck	2.9[3]	3.8	4.3

[1]All limestone goes through a 2 mm mesh screen and at least 1/2 through a 0.15 mm mesh screen. With coarser materials, applications need to be greater. For burned lime, about 1/2 the amounts given are used; for hydrated lime, about 3/4.

[2]Red-yellow podzolic, red latosol, etc.

[3]The suggestions for muck soils are for those essentially free of sand and clay. For those containing much sand or clay the amounts should be reduced to values midway between those given for muck and the corresponding class of mineral soil. If the mineral soils are unusually low in organic matter, the recommendations should be reduced about 25 percent; if unusually high, increased by about 25 percent, or even more.

[4]Podsol, gray-podzolic, brown forest, brown podzolic, etc.

Water Balance

A water balance procedure states the appropriate time to irrigate and the amount of water to apply. The water balance procedure requires specific information in order to make the proper calculations.

Figure 1-30 illustrates the components of a field water balance. Both rainfall and irrigation water are stored in the soil; therefore, the effective plant root zone provides a reservoir for water storage. In order to determine effectively the capacity of the reservoir, information is required for the water retaining properties of the soils and the root development characteristics of the individual crops. A reliable estimate of the potential ET or ET_o is required along with the appropriate crop curve so that k_c values are known. With ET_o and K_c, estimates of ET_{crop} are determined from the relation: $ET_c = (ET_o)(K_c)$.

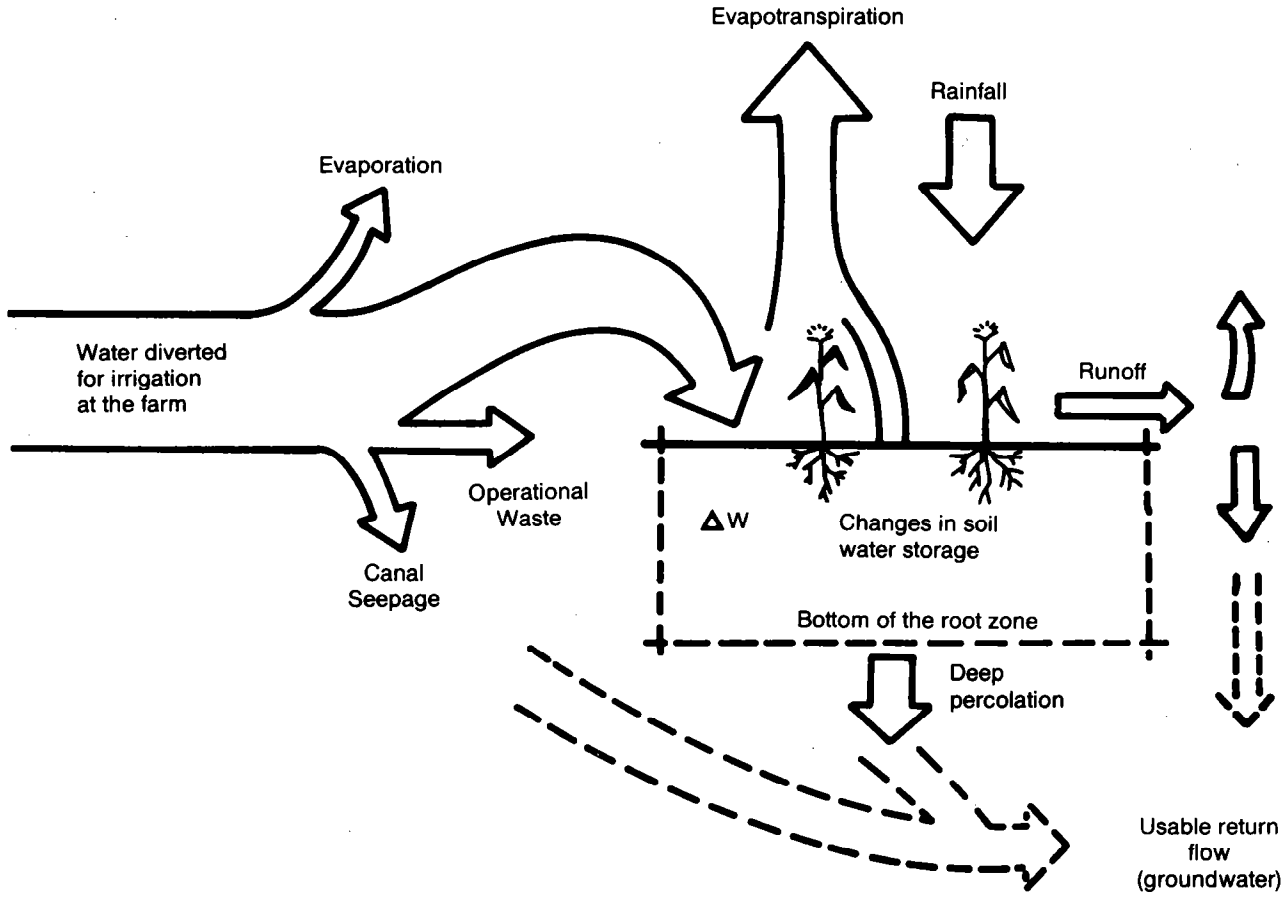
Allowable Water Depletion

Growth of most agricultural crops is favored by a soil water content that is high enough to encourage crop growth and development, but not so high that aeration becomes restrictive. These concepts are illustrated in figure 1-31. If soil water is plant-extracted to levels approaching the PWP, water is held so tenaciously by the soil that plants can no longer obtain sufficient water to meet the potential for transpiration. Transpiration is restricted and yield losses take place. Excessive filling of the soil pore space with water excludes sufficient air to meet plant oxygen requirements, and yields are again reduced. Plant species vary in their tolerance to either deficits or excesses. Water management programs must reflect individual crop characteristics.

A critical water level varies with the soil as well as with the crop. Figure 1-10 shows that at a 15 percent available water level the soil water tensions are at 5.8, 8.7, and 10.7

Figure 1-30.

Components of a Field Water Balance.



bars, respectively, for sand, loam, and clay. The water content of the sand, however, is almost down to the wilting point. More energy is required for a plant to extract water from the clay at the 15 percent level than from the sand at that level, but more water is available in the clay soil which provides a greater safety factor. To provide a reasonable safety factor, the lower limit of water depletion in the sandy soil must be higher than 15 percent for most crops. To illustrate this point, suppose the sand, loam, and clay soils hold 0.7, 1.4, and 2.4 inches of plant available water, respectively, per foot of soil depth at field capacity or 100 percent available water. At 15 percent available water remaining, there are 0.10, 0.21, and 0.36 inch per foot of soil depth for the sand, loam, and clay soils. For a root profile depth of five feet, the sandy soil only has a total of 0.5 inch of available water remaining.

Table 1-12 lists some commonly grown crops and suggested available water content that should remain in the soil profile at the time irrigations are made.

Table 1-12.—*Suggested percentage of available soil water content remaining in the crop root zone when an irrigation should be scheduled for several common crops.*

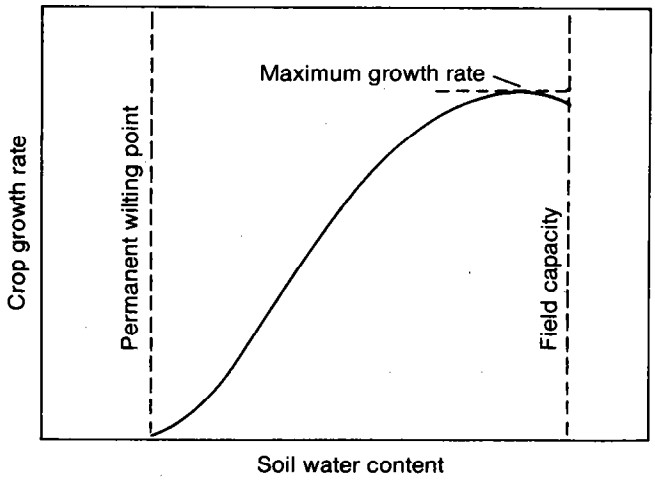
Crop	Season	First Irrigation	Later Irrigation
	percent of the available water remaining		
Potatoes	65	65	50 (vine killed)
Sugar beets	50	50	50
Sweet corn	60	40	60
Field corn	50	40	50
Mint	60	60	60
Beans	60	60	60
Small grains	40	40	60 (boot through flowering)
Onions	70	60	70
Alfalfa hay	50	50	50
Pasture	50	50	50

Soil-Water Extraction Depth

This is the soil depth used to determine the effective region of water uptake by plants. It is not necessarily the maximum rooting depth, especially for plants that have a long taproot. It is the depth to which an average mature plant can actively extract an appreciable amount of soil water. Because of the many factors that influence root development and proliferation, the effective depth must be determined for a specific location.

Figure 1-31.

Generalized Relationship Between Soil-Water Retention and Crop Growth



Net Water Calculations

The available water in a soil can be calculated if water contents representing FC and PWP are known for the appropriate soil depths. Some characteristics of a Hinckley loamy sand are given in table 1-13 to illustrate the procedure. The PWP is usually taken as the water content at the 15-bar tension level; FC is approximated by the 1/10 bar tension for sandy soils, and 1/3 bar represents the FC for medium- to fine-textured soils. For irrigation purposes, water content is expressed in units of water depth (inches, centimeters, etc.) per unit depth of soil; water and soil depths must be in the same units. Water content expressed in this manner represents a volumetric base instead of a gravimetric or weight base and is most appropriate for water depth calculations. Gravimetric water content is converted to a volumetric content by multiplying gravimetric water content by the soil bulk density. To calculate the available water between FC and PWP, the following formula can be used:

$$D = (B.\ D.)\ (d)\ (AWC)\ /\ (dw)\ (100)$$

where D is inches or centimeters of water in soil depth (d), B.D. is soil bulk density (grams oven dry soil/cm^3 volume sampled), d is soil depth in inches or centimeters, AWC is gravimetric water content between FC and PWP in percentage by weight, and dw is density of water taken as 1 g/cm^3.

Table 1-13.—*Water retention characteristics of a Hinckley loamy sand.*

Horizon	Textural class	Depth (in)	Bulk density (g/cm³)	1/10 bar[1] (gravimetric percent)	15 bar[2] (gravimetric percent)	In soil (in/in)	In horizon (in)
Ap	Loamy sand	0-8	1.15	21.1	8.3	0.147	1.18
B21	Loamy sand	8-14	1.25	22.5	8.7	0.172	1.03
B22	Loamy sand	14-20	1.23	17.0	5.1	0.146	0.88
C	Sand	20-26	1.39	9.8	3.0	0.095	0.57
D	Sand	26-32	1.47	6.0	1.4	0.068	0.41
						Total =	4.07

[1]Field capacity.
[2]Permanent wilting point.

The last two columns of table 1-13 were calculated using this formula. For example, the available water in the Ap horizon for a 1-inch soil depth is:

$$D = (1.15)\,(1)\,(12.8) / (1)\,(100) = 0.147 \text{ inch}$$

or (0.147 inch/inch) (8 inches) = 1.18 inches water for the Ap horizon.

For an irrigation system design, the total available water is calculated for a soil depth based on the root system of a mature plant of the crop to be grown. Root systems of plants were discussed earlier. The total amount of available water held by the soil of table 1-13 for all horizons is 4.07 inches. Suppose a mature, effective crop root system extends to a depth of 26 inches in this soil; then the total available water at FC in the root zone is 1.18 + 1.03 + 0.88 + 0.57 = 3.66 inches. If research or experience shows that crop yield is lowered when more than 50 percent of the available water is depleted from the effective or design root zone, then the crop should be irrigated when (0.50) (3.66) inches = 1.83 inches of water have been depleted from the soil profile.

Water Balance Accounting Procedures

The water-accounting procedure is based on two fundamental concepts, namely:

1. If there is an adequate supply of soil water, evapotranspiration rate for a given crop depends on the climatological evaporative demand.

2. If the soil water content of a soil is known at a given time, the water content at any later time can be computed by adding irrigation or rainfall and subtracting ET during the elapsed period.

Within recent years, reasonably reliable daily ET data have become available from climatic stations at strategic locations. This information is frequently available through one or more news media sources or computer linkage. By knowing the daily values at a site for rainfall events, ET, and net irrigation amount, the daily balance can be computed and compared to the amount of available water that can be depleted safely before an irrigation is required.

Computation is started when the soil is at field capacity or a known water content. Following a heavy rain or an irrigation, the soil may be at field capacity, but this should be verified in the field. The soil water content should always be verified at the starting time. At a given time of the day, each morning if convenient, the available water in the soil is computed by subtracting the previous day's ET from the previous morning's balance. The previous day's irrigation or rainfall is added to the previous morning's balance. When the daily balance reaches the point at which soil water is depleted to the predetermined allowable limit, it is time to irrigate. Ignoring application efficiency, the net amount of water to be replaced in the soil by irrigation is the amount that brings the soil water content up to FC. To arrive at the balance on the morning following irrigation, this amount is added. The balance is then computed daily until another irrigation is indicated. Should an irrigation amount not be adequate to return the profile to field capacity, the profile available water content is set to the actual amount present. This tactic is used in humid areas to more efficiently utilize rainfall should it occur shortly after an irrigation application and to reduce the leaching of nutrients into the ground water.

The water retention properties of table 1-13 can be used to illustrate the procedure. Suppose a crop rooting depth is 26 inches, the total plant available water is 3.66 inches for this depth in the Hinckley loamy sand. If a crop is allowed to deplete 60 percent of the amount, 2.2 inches of allowable depletion can occur before soil water must be replenished. A water balance accounting procedure for these conditions is shown in table 1-14.

When rainfall or irrigation takes place in excess of the amount needed to bring the soil back to FC, the extra amount is assumed to percolate below the root zone; the daily balance is recorded as the FC level. Should high intensity rains cause runoff before the soil is filled to FC, it will be necessary to either estimate or measure the effective rainfall percolating into the soil that is available for plant use. This amount is added to achieve the daily balance.

Table 1-14.—*Example of water balance accounting procedure.*

Day after initialing	Profile available water remaining (in)	ET of crop (in)	Cumulative ET (in)
0	3.66		
1	3.51	0.15	0.15
2	3.33	0.18	0.33
3	3.19	0.14	0.47
4	3.02	0.17	0.64
5	2.83	0.19	0.83
6	2.63	0.20	1.03
7	2.42	0.21	1.24
8	2.20	0.22	1.46
9	2.00	0.20	1.66
10	1.82	0.18	1.84
11	1.63	0.19	2.03
12	1.46	0.17	2.20

At the end of 12 days, 2.2 inches of water are needed to bring the profile back to field capacity.

Plant-Based Concepts

The primary advantage of plant-based measurements for irrigation scheduling is due to the fact that plant growth is directly related to plant water status and only indirectly related to soil water and atmospheric conditions. The plant essentially integrates its soil water and atmospheric environments and reflects the prevailing conditions in growth processes. Because the rate of many of these expansive growth processes are related to plant-water status, measurement of the plant-water status can yield valuable data indicative of plant growth and development.

The visual appearance of crops has been used for many years as a guide to scheduling irrigations. In the early 1960's, the pressure chamber became commercially available as a practical method for measuring leaf water potential. More recently, infrared thermometry techniques have been developed to measure leaf or canopy temperatures. Growing indicator plants that will exhibit water stress symptoms earlier than the crop itself is an old idea that is not used frequently. All plant-based techniques have in common the property of indicating when to irrigate, but they provide no information on how much water to add at an irrigation. Leaf water potential measurements and leaf or canopy temperature measurements provide excellent scheduling techniques; a good water management scheme can be achieved by combining these techniques with measurements of the soil water status in order to determine the required amount of irrigation water.

Pressure Chamber

The primary features of the pressure chamber are the chamber, pressure gauge, control valve, and a small nitrogen gas tank to serve as a pressure source. Leaving sufficient petiole length to extend through a sealed stopper to make a measurement, the petiole and attached leaf are cut from the plant. Once the petiole or spur is severed, water withdraws within the xylem vessels, because the external pressure is several times that inside the conducting tissue. Leaves are sealed inside the chamber with the petiole cut surface extending upward through a pressure-sealed rubber stopper or "O" ring. The chamber is pressurized to force the water in the xylem back exactly to the cut petiole surface; pressurization is stopped and a reading is taken from the gauge. The positive chamber pressure now matches the negative potential of the xylem fluid. Care must be taken during this measurement process to suppress water evaporation from the leaf so as to ensure accurate readings.

Pressure chamber readings change drastically during the day. Figure 1-32 shows two curves for different stress levels in cotton. Leaves have the highest leaf water potential just before sunrise. After sunrise the increased light causes stomata to open and transpiration begins; leaf water potential declines until approximately solar noon. Readings remain relatively stable after solar noon for about 2.5 to 3 hours; then leaf water potential progressively increases, reflecting plant water recovery until a slightly lower leaf water potential than the level of the previous day is reached in late evening or early morning.

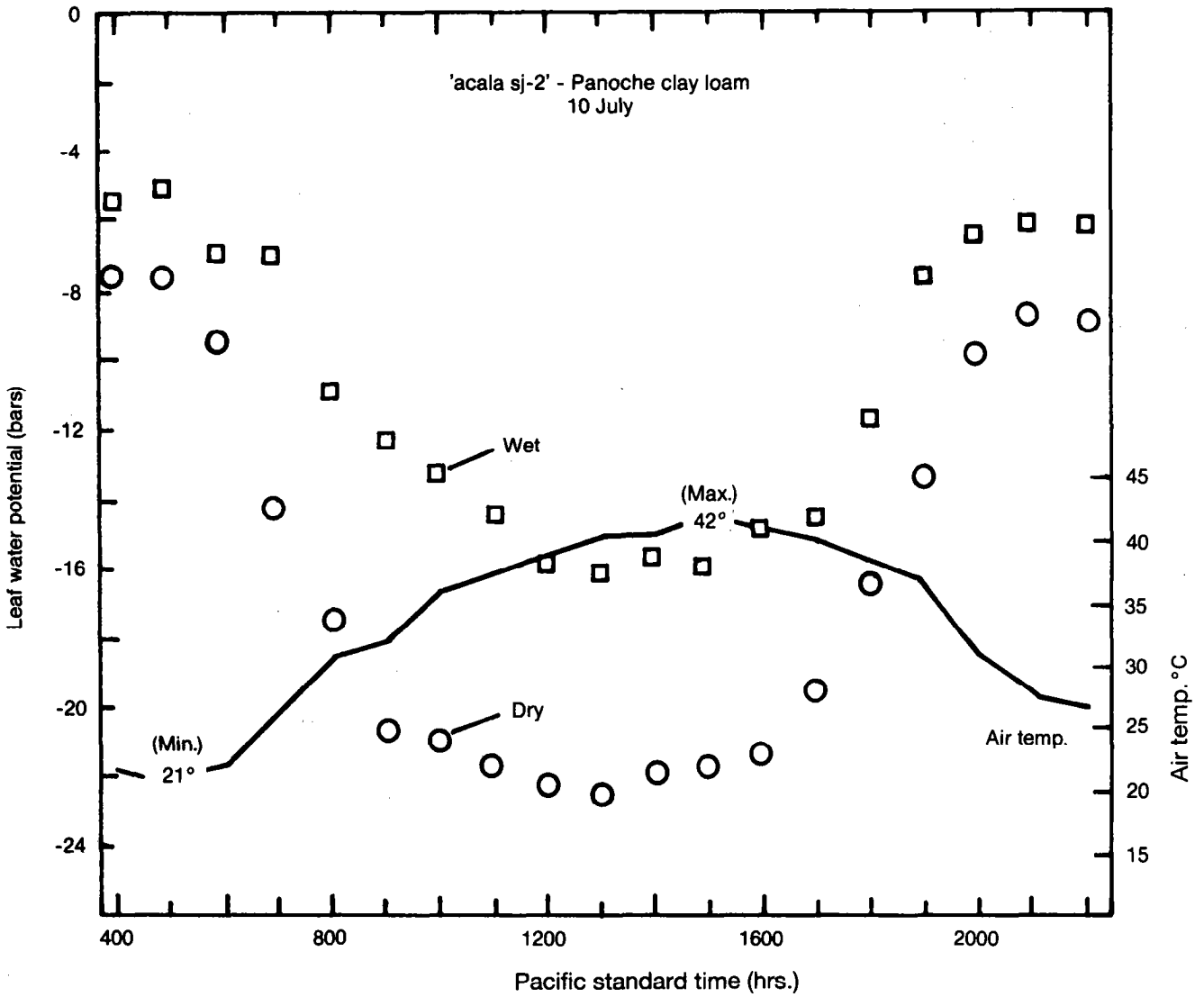
With cotton and some other crops, midday readings can be made conveniently for irrigation scheduling; however, some crops, like tomatoes, may have rather erratic midday readings due to stomatal closure when water stress develops. When this takes place, predawn readings of crop water status must be used to schedule irrigations. Predawn readings can be made on essentially all crop species.

Predawn leaf water potential uses the plant much like a tensiometer except the range of readings is not restricted to one atmosphere or less as with tensiometers. Readings reflect the integration of the soil matrix potential throughout the root zone. Research has shown that the relationship between soil water depletion and leaf water potential is linear. When correlated, the leaf water potential can be used to determine when to irrigate and how much water to apply.

There are some advantages, however, to making midday readings for those crops that allow this approach. At midday, greater differences in leaf water potential exist between water-stressed and adequately irrigated plants; this is illustrated for cotton in figure 1-32. An additional advantage is the convenience of making measurements at midday rather than predawn. Regardless of whether measurements are

Figure 1-32.

Diurnal Leaf Water Potential Curves for Cotton of Contrasting Water Stress Levels



made at predawn or at midday, success depends on having water status-growth relationships identified for individual crops. This information is available only for a few crop species, but research to develop more information is ongoing.

After an irrigation, pressure chamber readings decline linearly with time. The decline is fairly rapid for sandy soils that hold comparatively little available water for plants, but quite slow for clay soils that have a high water retention capability. Once the rate of decline has been established, the time to the next needed irrigation can be estimated by extrapolating the decline function. For uniform climatic conditions this estimate will be fairly accurate, but accuracy will decline with increased variability in evaporative demand.

Leaf or Canopy Temperature Methods

Crop leaf or canopy temperature measurements as a means of assessing crop water stress have been extensively researched in recent years, and the technique is proving to be

of considerable utility. The technique relies on the concept that, if a crop is well supplied with water, transpiration will be at the maximum possible rate and the crop canopy will be relatively cool compared to the surrounding air. When the available soil moisture is depleted to some threshold level, which depends on the environmental evaporation demand, transpiration will be reduced from the maximum potential and the crop canopy will increase in temperature. At this stage or later, photosynthesis is reduced; this results in yield reduction.

In using plant temperature measurements to quantify crop water stress, the foliage-air temperature difference is obtained. Because this parameter is influenced by environmental factors such as air vapor pressure deficit, net radiation, and windspeed in addition to soil water content, the leaf or canopy air temperature difference (T_f - T_a) is "normalized" for environmental variability. In this use, the term normalize means that the readings for crop stress will be constant regardless of whether the evaporative demand of a measurement time of day is high or low. The approach that is illustrated in figure 1-33 uses the air vapor pressure deficit alone to normalize the air (T_f - T_a) parameter. Since evaporative demand is normalized, readings can theoretically be made during a relatively broad time span; in practice, readings are usually done shortly after solar noon.

The two essential components of this method are a no water-stress base line for a particular crop and an upper limit representing T_f - T_a when transpiration is completely suppressed. A detailed discussion of the various parameters of the method is given by Idso et al.

A crop water stress index (CWSI) is calculated by measuring the relative amount of departure of T_f - T_a from the nonstressed base at a particular, observed value of vapor pressure deficit. A CWSI value of 0 represents no stress, and a value of 1 represents a total cessation of transpiration. As the rates of actual to potential evapotranspiration go from 1 to 0, the CWSI index goes from 0 to 1.

A considerable amount of reliable equipment is available commercially for making CWSI measurements. Advantages of this technique include the ability to make rapid measurements of a large number of plants, especially if canopy temperature is the measurement objective.

CWSI can be correlated with soil water depletion at a specific site. Information to date indicates that this relationship is linear until soil water is depleted to a relatively low level. When this is done, the CWSI can be used to determine when to irrigate and how much water to apply. Correlation of CWSI and soil water depletion can be made by periodically measuring the soil water content in the crop root zone and plotting CWSI vs. soil water depletion or by observing the change in CWSI when a specific amount of water is applied. The amount applied should be just enough to produce the return of the CWSI to the nonstressed condition.

Visual Appearance

The appearance of a crop gives some indication of when an irrigation is needed. Plant wilting is perhaps the most obvious sign of water stress; however, the growth of most crops may be retarded before visible wilting takes place.

Some crops undergo a distinct color change in the foliage with the onset of plant water stress. Beans, cotton, and peanuts, for example, become bluish green to dark green as available soil water becomes limiting. Color changes may be visible in such crops sufficiently early to allow irrigation without much yield loss.

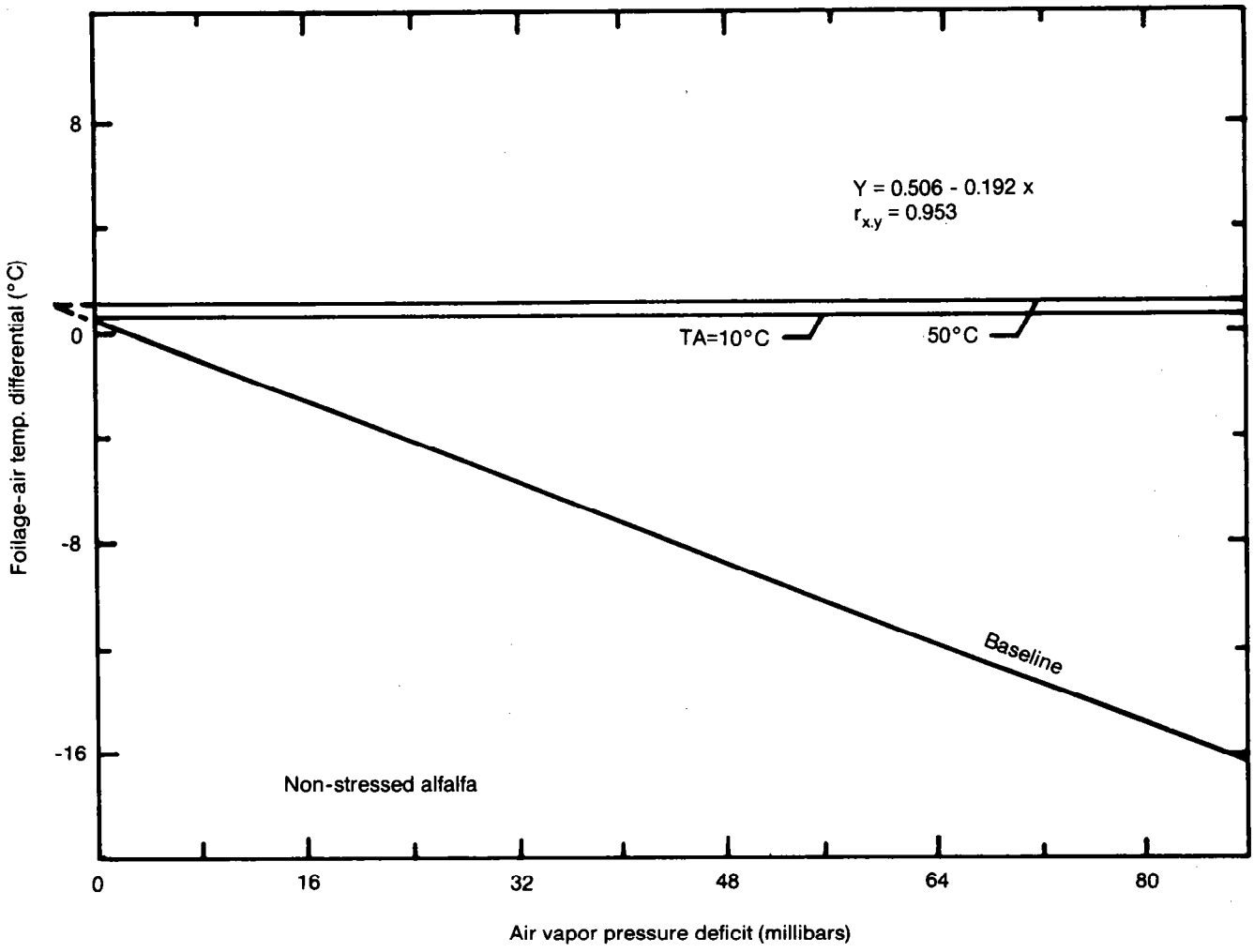
Pronounced diurnal movement of leaves takes place in some crops because of the reduced turgor pressure of plant cells. Sorghum undergoes changes in leaf angle that reportedly can be used successfully to schedule irrigation.

Indicator Plants

Indicator plants that are naturally more susceptible to soil water deficits can be used to provide a visual signal for a needed irrigation. A general requirement is that the indicator plant must have a top to root ratio exceeding the main crop; therefore, water stress will occur earlier for the indicator plants. The crop itself can be used this way by preparing test plants that have restricted root systems. Restricted root systems can be achieved by mechanical barriers or by placement of the plants in a soil that is mixed with sand to reduce its available water supply.

Figure 1-33.

Foliage-Air Temperature Differential Versus Air Vapor Pressure Deficit for Well-Watered Alfalfa Grown at a Variety of Specific Sites and Dates



Automation in Irrigation Scheduling

Plant water uptake to satisfy growth and evapotranspiration processes follows a diurnal cycle. The water moves from a periodically replenished root zone (source), through the plant, then to the atmosphere (sink). At the end of a typical irrigation cycle, soil-water storage becomes depleted, the hydraulic conductivity decreases drastically, and the root system cannot resupply water fast enough to meet the atmospheric evapotranspiration demand of the plant, thereby creating a plant-water deficit or stress condition.

Irrigation methods capable of operating frequently, such as mini-sprinkler, trickle, and subsurface, offer the means to maintain soil water at nearly constant levels. They place the soil-water-root environment under the control of the irrigator, whether the irrigator is a human or computer. Because any disruption to the irrigation schedule creates detrimental water or oxygen stress for the crop automatically, control of high-frequency irrigation must be automatic, redundant, and capable of responding to small and rapid changes in soil water, plant water, or evapotranspiration.

Scheduling frequent irrigations can be accomplished with automatic feedback control that is based on soil water potential. Because the storage capacity of soil is deemphasized and water is applied to supply the water potential continuum and match the evapotranspiration rate, there is less margin for error. Timeliness is important.

To monitor soil moisture and control an irrigation system automatically, equipment is required that will sample several sensors sequentially, will compare each sensor output to the set threshold level, and will compute outputs capable of controlling the irrigation system. Desktop computers and microprocessors have been used successfully.

In addition, commercial equipment is available to measure soil matric potential and to control the irrigation system automatically. The computer calculates the average readings of soil matric potential sensors, compares the average soil matric potential that is measured to the threshold value at which each irrigation is to be applied, and turns on the irrigation system for a preselected time period if needed.

* U.S. G.P.O.:1992-311-411:60016/SCS