#468

6

WATER REQUIREMENTS

by R. D. Burman, University of Wyoming, Laramie, WY; P. R. Nixon, USDA-SEA/AR, Weslaco, TX; J. L. Wright, USDA-SEA/AR, Kimberly, ID; and W. O. Pruitt, University of California, Davis, CA

6.1 INTRODUCTION

The main objective of irrigation is to provide plants with sufficient water to prevent stress that may cause reduced yield or poor quality of harvest (Haise and Hagan, 1967; Taylor, 1965). The required timing and amount of applied water is governed by the prevailing climatic conditions, crop and stage of growth, soil moisture holding capacity, and the extent of root development as determined by type of crop, stage of growth, and soil.

Need for irrigation can be determined in several ways that do not require knowledge of evapotranspiration (ET) rates. One way is to observe crop indicators such as change of color or leaf angle, but this information may appear too late to avoid reduction in crop yield or quality. This method has been used successfully with some crops like beans (Haise and Hagan, 1967). Other similar methods of scheduling, which involve determining the plant water stress, soil moisture status, or soil water potential are described in Chapter 18.

This chapter describes methods of estimating crop water requirements expressed as equivalent depth of water over the horizontal projection of the crop growing area. This information, when combined with soil water holding characteristics, has the advantage of not only being useful in determining when to irrigate, but also enables specifying how much water to apply. ET information is also needed in determining the volume of water required to satisfy short-term and seasonal water requirements for fields, farms and irrigation projects, and in designing water storage and distribution systems. In addition, this information is essential for most water right transfers from agriculture to other uses because most such transfers are limited to historic crop water use amounts.

Water use measurements have been made in many field experiments and at many locations. The data available from various sources are of varying quality depending upon the conditions and techniques that were used. The material presented in this chapter emphasizes methods of estimating ET rates and provides guidelines for estimating irrigation water requirements.

6.2. IMPORTANT DEFINITIONS

Several important quantities are defined before measurement or estimation methods are described. Most of these definitions are commonly used in

6.2.1 Evapotranspiration and Potential Evapotranspiration

The definition of evapotranspiration, abbreviated ET or symbolically E_t, presented in this chapter is in widespread use. The definition of potential ET (E_{tp}) is controversial and may have different meanings in various parts of the world and to different people in the same country. The following definitions include several variations of potential ET.

Evaptranspiration. The combined process by which water is transferred from the earth's surface to the atmosphere. It includes evaporation of liquid or solid water from soil and plant surfaces plus transpiration of liquid water through plant tissues expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area.

Potential evapotranspiration. The rate at which water, if available, would be removed from the soil and plant surface expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area.

Other definitions of potential evaptranspiration. Mathematically, in the common derivation of the combination equation, potential ET is the ET that occurs when the vapor pressure at the evaporating surface is at the saturation point (van Bavel, 1966). This definition is not limited to any particular degree of vegetation or growth stage of a crop. Since this definition is not restricted to a standard surface, it has had limited direct use by the designer or operator of an irrigation system.

Some investigators in the Western United States have used the ET from a well-watered crop like alfalfa with 30 to 50 cm of top growth and at least 100 m of fetch as representing potential ET (Jensen, 1974). Others have used ET from well-watered clipped grass as a potential ET. The height of the grass has been historically uncertain. Penman (1948) used clipped grass similar to a lawn to develop his version of the combination equation. Recently, this has been defined as "the rate of evapotranspiration from an extensive surface of 8- to 15-cm, green grass cover of uniform height, actively growing, completely shading the ground, and not short of water" (Doorenbos and Pruitt, 1977). In testing the Penman formula, Makkink (1957) found that the height of the grass did have an influence on the ET rate.

Crop versus potential ET. The realtionship between the ET of a specific crop (E_t) at a specific time in its growth stage and potential ET is of practical interest to the designer or operator of an irrigation system because ET estimates are often made from potential ET (E_{tp}). The relationship has lead to crop coefficients:

$$K_c = \frac{E_t}{E_{tp}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad [6.1]$$

where K_c is referred to as a crop coefficient incorporating the effects of crop growth stage, crop density, and other cultural factors affecting ET. Crop coefficients are discussed in more detail in Section 6.5. The crop coefficient defined in equation [6.1] is not the K factor used in the original Blaney-Criddle method.

6.2.2 Reference Crop Evapotranspiration

Because of the ambiguities involved in the interpretation of potential evapotranspiration, the term "Reference Crop Evapotranspiration," or E_{tr}, is frequently being used. Doorenbos and Pruitt (1977) use ET_o, hereafter

tion from an extensive surface of 8 to 15 cm, green grass cover of uniform height, actively growing, completely shading the ground, and not short of water."

An alternate definition of E_{tr} which is widely used in the Western United States was presented by Jensen et al. (1970); E_{tr} "represents the upper limit or maximum evapotranspiration that occurs under given climatic conditions with a field having a well-watered agricultural crop with an aerodynamically rough surface, such as alfalfa with 12 in. to 18 in. of top growth."

The irrigation engineer or scientist should make sure that the definition of E_{tr} being used is completely understood and that written documentation carefully identifies the basic definitions used in calculations, designs, or reports. Actual E_t is estimated using equation [6.2].

$$E_t = K_c\,E_{tr} \text{ or } E_t = K_c\,E_{to} \quad \dots\dots\dots\dots\dots\dots\dots\dots \quad [6.2]$$

E_{tr} refers to reference crop ET based on alfalfa and E_{to} refers to reference crop ET based on grass.

The definition of K_c used in equation [6.2] is essentially the same as that used in equation [6.1] except that the use of E_{tr} or E_{to} requires identifying the reference base. E_{tr} or E_{to} can either be based on direct measurements or estimates. The use of equation [6.2] is greatly expanded in Section 6.5.

6.2.3 Effective Precipitation

Effective rainfall or precipitation (P_e) is more difficult to define than potential ET. At this point it is sufficient to define P_e according to Dastane (1974) as "that which is useful or usable in any phase of crop production." The definition of P_e is expanded and several methods for estimating P_e are presented in Section 6.8.

6.2.4 Other Factors

Irrigation water requirements may be influenced by salt management, seed germination, crop establishment, climate control, frost protection, fertilizer or chemical application, and soil temperature control. Leaching requirements are discussed in Section 5.2, salt management in Section 5.5 and reclamation of salt affected soils in Section 5.6 Other beneficial uses of water connected with irrigation water requirements are discussed in Section 6.6 (also see Sections 2.8, 14.8 and 18.4).

6.2.5 Irrigation Water Requirements

The designer or operator of an irrigation system must determine irrigation water requirements, R, for both short periods and on a seasonal basis. The units of R usually are volume per unit area or depth. The irrigation water requirement was defined by Doorenbos and Pruitt (1977) as "the depth of water needed to meet the water loss through ET of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment." R also can be stated as:

$$R = E_t - P_e + (\text{other beneficial uses}) \quad \dots\dots\dots\dots\dots\dots \quad [6.3]$$

6.3 DETERMINING EVAPOTRANSPIRATION

The designer or operator obtains ET data from direct field measurements or from estimates based on climatological and crop data. Direct field measurements are very expensive and are mainly used to provide data to calibrate methods for estimating ET from climatic data. Real time field measurements are being used for water administration in some areas such as Colorado. The main thrust of research has been to determine the amounts of water used for crop production and to develop methods of predicting ET from climatic data.

6.3.1 Direct Measurements

Water balance field measurement. The water balance approach to measuring ET involves periodic determinations of root zone soil moisture and recording intervening rainfall, irrigation, or drainage. Soil tanks in which crops are grown, known as lysimeters, have been used to facilitate accurate water accounting. Weighing-type lysimeters, operated in a representative field environment, provide the most accurate ET information. In western areas of the United States the water balance method has also involved stream inflow-outflow measurements. Average ET for the land area involved is equal to inflow, including ground water, surface water and rainfall, minus outflow after taking into account changes in soil moisture storage.

Other methods of field measurement. Short-period ET (i.e. hourly or less) can be determined by applying meteorolgical equations that require involved meteorological measurements. These approaches, based on mass transfer and related concepts, usually require very accurate vapor pressure and wind speed measurements at two or more heights above the crop, and other measurements that may be necessary.

Essentially instantaneous ET can be determined with measurements that enable solving the energy balance equation. This approach is based on the fact that most of the transformed radiant energy (measured net radiation) goes into latent heat (evaporation or dew), and the balance goes into soil heat (measured soil heat flux), and sensible heat (heating or cooling of air). The partitioning between latent and sensible heat is obtained by using vapor pressure and temperature gradient measurements to calculate Bowen's ratio (Fritschen, 1965).

ET for periods of a day or longer can be determined by summing the short-period data obtained with the above methods. The calculations are voluminous, and data uncertainties may occur. These methods are useful for research and currently are seldom used in irrigation scheduling or water resource calculations.

6.3.2 Estimation from Climatic Data

Confidence is developing in the practical utility of ET equations that require weather records. This confidence comes from comparisons of calculated daily and longer-period ET values with water balance measurements, especially those from weighing lysimeters.

Numerous equations that require meteorological data have been proposed, and several are commonly used to estimate ET for periods of a day or more. These equations are all empirical to various extents; the simplest requiring only average air temperature, daylength, and a crop factor. The generally better performing equations require daily radiation, temperature, vapor pressure and wind data.

A method of estimating ET should not be automatically rejected because of the lack of available climatic data. It is often possible to estimate unavailable data; for example, several methods of estimating net radiation exist, (see Subsections 6.4.2 and 6.5.3) and dew point data can be estimated from minimum temperature data (Pochop et al., 1973).

A comprehensive evaluation of common evapotranspiration equations was made by the Technical Committee on Irrigation Water Requirements, American Society of Civil Engineers (Jensen, 1974) using data from 10 world wide locations. They concluded "that no single existing method using meteorlogical data is universally adequate under all climatic regimes, especially for tropical areas and for high elevations, without some local or regional calibration." Local calibration is discussed in Subsection 6.4.6.

The calculation of ET estimates from weather records is appealing because the approach is relatively simple compared with on-site ET measurements. The calculated reference crop ET can be used to estimate actual ET by using coefficients to account for the effect of soil moisture status, stage of growth and maturity of a crop. Coefficients for many crops have been developed from field experiments and are discussed in Section 6.5.

Estimates of actual ET for fields with incomplete cover also can be made using models that separate ET into evaporation and transpiration components (Ritchie, 1972; Tanner and Jury, 1976). The models attempt to account for reduction of evaporation with surface drying.

Crop ET can also be estimated using coefficients which relate crop ET to evaporation as measured with pans (Pruitt, 1966; Doorenbos and Pruitt, 1977). The 1.2-m (4-ft) diameter U.S. Weather Service Class A evaporation pan has been used successfully for this purpose. The evaporation pan provides a measurement of evaporation from an open water surface integrating the effects of radiation, wind, temperature, and humidity. While plants respond to the same climatic variables, pans and plants respond differently on a daily basis. Pan coefficients therefore are better suited for longer time periods. Pans are also very sensitive to the wetness of the immediate surroundings.

A flow chart is presented in Fig. 6.1 outlining the sequential steps for estimating irrigation water requirements from climatic data. These steps are intended to apply to the information presented in this chapter. A similar sequence would be valid for any other source of data.

Important considerations. Observed ET rates for a given crop and growth stage depend on climatic conditions. Water use rates observed at one location may not apply elsewhere. For example, the peak monthly ET rate at Brawley, California, an arid inland location is 2.5 times that at a coastal location at Lompoc, California (Jensen, 1974). In a California coastal valley the summertime ET from alfalfa 37 km (23 mi) inland was found to be more than 1.5 times that 29 km (13 mi) nearer the ocean (Nixon et al., 1963). Conversely, measured or calculated ET values might properly be transferred considerable distance where rather uniform conditions of climate and cropping practices exist on relatively flat terrain.

Obviously, weather records that are used to calculate ET should be representative of the area in question. Thus, weather data should not be used indiscriminately without knowledge of the weather station, site exposure and the care with which the station was maintained.

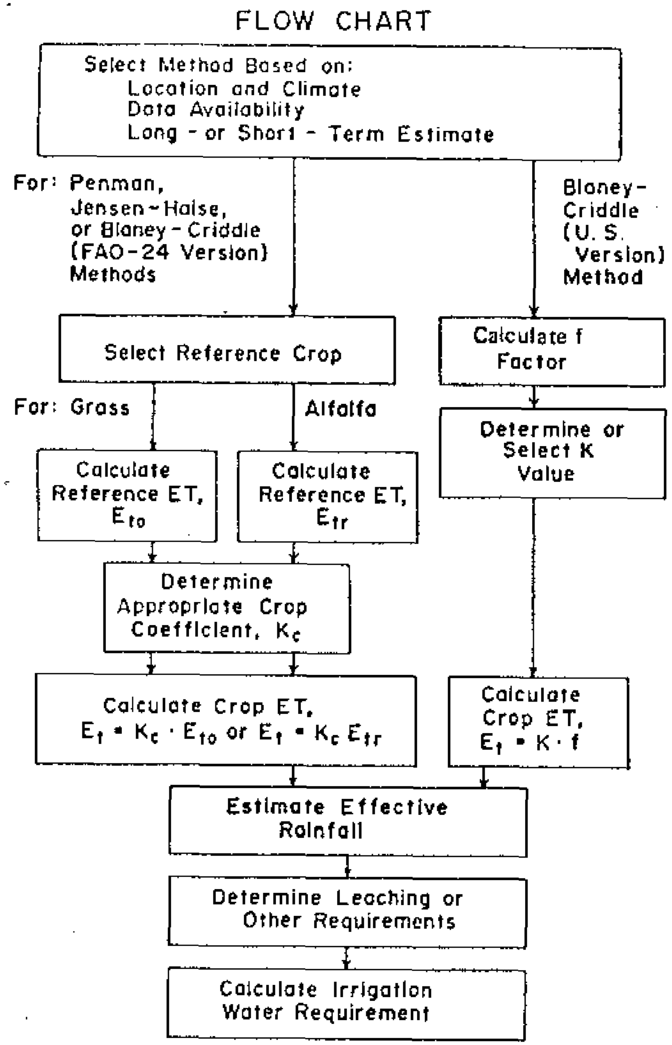


FIG. 6.1 Typical flow chart for estimation of irrigation water requirements from climatic data.

Factors contributing to water requirements. ET is the principal factor in determining irrigation water requirements, but losses in storage, conveyance and applying water, the inability to apply water uniformly, and the need for soil leaching are additional factors. The planning and operation of irrigation systems must take all these factors into consideration in determining water requirements. Other possible requirements and uses for water not directly required for ET are discussed under other beneficial uses in Section 6.6, and in Chapters 2, 14 and 18.

6.4 SELECTED METHODS OF ESTIMATING REFERENCE CROP ET

Many methods of estimating ET have been proposed. The methods may be broadly classified as those based on combination theory, humidity data, radiation data, temperature data, and miscellaneous methods which usually involve multiple correlations of ET and various climatic data. The design engineer or hydrologist unfamiliar with methods is often faced with a bewildering choice. Several publications discuss the choice of methods for various climatic conditions and for various amounts of input climatic data. Among these are a United Nations Food and Agriculture Organization publication, (FAO-ID 24), (Doorenbos and Pruitt, 1977) and a report of the ASCE Irrigation Water Requirements Committee (ASCE-CU Report) (Jensen, 1974).

Recent research by micrometerologists and soil scientists has separated ET calculations into evaporation from the soil and transpiration components (Ritchie, 1974). The transpiration rate has been successfully related to the leaf area index of the plants, the soil moisture status and potential transpiration rate. These have not been used in engineering calculations and have not been refined for a wide range of conditions and therefore, are not presented here. The reader should be aware that these methods may come into wider use in the future.

This chapter presents detailed step-by-step instructions for three of the most commonly used methods of estimating ET for a reference crop plus the use of evaporation from pans as an index of E_{tr}. The reader is referred to other sources for other methods such as Doorenbos and Pruitt (1977) and Jensen (1974).

6.4.1 Basis for Reference ET

Reference crop ET selected must be compatible with the crop coefficients (K_c) that are to be used. For example, K_c used to calculate ET based on alfalfa reference ET must not be used with an E_{tr} intended to simulate grass. The reverse is equally illogical. Engineers also must be certain that the method of estimating E_{tr} is related to the same base as was used for the development of the crop curves that they are using. The Penman and Jensen-Haise methods cited in this chapter both estimate E_{tr} based on alfalfa because these are compatible with recently developed crop coefficients for the Western United States (Wright, 1979). The Blaney-Criddle and pan evaporation methods described in this section are recent FAO modifications which estimate grass based reference ET.

Doorenbos and Pruitt (1977) also present modifications of the Penman method and radiation methods in the FAO publication, which as the first step requires estimates of grass based reference ET. The FAO procedures also require using grass based crop coefficients. The FAO procedures cover a very broad range of wind, sunshine, and humidity conditions because they are based on a world-wide data set. The Penman method presented in this chapter is particularly suited to irrigated areas in the Western United States because of recently developed alfalfa based crop coefficients (Wright, 1979).

6.4.2 Penman Method

The Penman method, first introduced in 1948 (Penman, 1948) and later simplified (Penman, 1963) was the first of several combination equations. Combination equations are derived from a combination of energy balance and a *mass transport or aerodynamic term.* The ASCE-CU Report shows that the combination methods are the most accurate methods for a very wide range of climatic conditions. The accuracy of combination methods results from the theoretical basis of the methods. Estimates obtained with a combination equation are reliable for periods of from 1 day to 1 month. With modifications, reliable hourly estimates are possible.

The Penman equation, modified for estimating alfalfa based reference ET in cal/cm²·d is :

$$E_{tr} = \frac{\Delta}{\Delta + \gamma} (R_n + G) + \frac{\gamma}{\Delta + \gamma} 15.36\, W_f (e_a - e_d) \quad \ldots\ldots\ldots\ldots \quad [6.4]$$

where E_{tr} = reference crop ET in cal/cm²·d; Δ is the slope of the vapor pressure-temperature curve in mb/°C; γ is the psychrometer constant in mb/°C; R_n is net radiation in cal/cm²·d; G is soil heat flux to the surface in cal/cm²·d; W_f is the wind function(dimensionless); $(e_a - e_d)$ is the mean daily vapor pressure deficit in mb; and 15.36 is a constant of proportionality in cal/cm²·d·mb. An expression adapted from Bosen (1960) can be used to approximate Δ:

$$\Delta = 2.00(0.00738\,T + 0.8072)^7 - 0.00116 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [6.5]$$

where T is mean daily temperature (°C). An expression by Brunt (1952) can be used to find γ:

$$\gamma = \frac{0.386\,P}{L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [6.6]$$

where P is average station barometric pressure (mb) and L is the latent heat of vaporization (cal/g). P is usually assumed to be a constant for a given location and may be calculated using a straight line approximation of the U.S. standard atmosphere;

$$P = 1013 - 0.1055\,E \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [6.7]$$

where E is sea level elevation (meters). L may be calculated as follows (Brunt, 1952):

$$L = 595 - 0.51\,T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [6.8]$$

where T is °C. The variations of $\Delta/(\Delta + \gamma)$ with elevation and temperature are given in Table 6.1.

TABLE 6.1. VARIATION OF $\Delta/(\Delta + \gamma)$ WITH ELEVATION AND TEMPERATURE*

	Elev., m					
°C	0	500	1000	1500	2000	2500
0.0	0.401	0.414	0.428	0.443	0.458	0.475
5.0	0.477	0.491	0.505	0.520	0.536	0.552
10.0	0.551	0.564	0.578	0.593	0.608	0.624
15.0	0.620	0.632	0.645	0.659	0.673	0.688
20.0	0.681	0.693	0.705	0.717	0.730	0.743
25.0	0.735	0.745	0.756	0.767	0.778	0.790
30.0	0.781	0.790	0.799	0.809	0.818	0.828
35.0	0.820	0.828	0.835	0.844	0.852	0.860
40.0	0.852	0.858	0.867	0.872	0.879	0.886
45.0	0.878	0.884	0.889	0.895	0.901	0.907
50.0	0.900	0.904	0.909	0.914	0.919	0.924

* $\frac{\gamma}{\Delta + \gamma} = 1 - \frac{\Delta}{\Delta + \gamma}$, based on the U.S. standard atmosphere.

The W_f term is usually determined by regression techniques where W_f has the form:

$$W_f = a_w + b_w U_z \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [6.9]$$

where a_w and b_w are regression coefficients and U_z is the daily wind travel (km/d) at z m above the ground. Many investigators recommend that a_w and b_w be determined for a location if the necessary data are available. Some values of a_w and b_w previously determined are listed in Table 6.2 for z = 2 m. Wright (1981) has developed functional relationships for a_w and b_w which vary with the season and are discussed later in this chapter. Wind travel, U_z, is frequently obtained at an elevation of 2 m above the ground for use in developing the wind functions for the Penman equation. Wind data collect at another elevation can be extrapolated to the 2-m elevation by the followi expression which approximates a logrithmic velocity profile and is based an aerodynamically "rough" crop surface such as alfalfa:

$$U_2 = U_z \left(\frac{2}{z}\right)^{0.2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [6.1$$

where z (m) is the elevation of the wind measurement and U_2 is the estima wind travel at 2 m.

Various procedures have been used to calculate the saturation vap pressure deficit term $(e_a - e_d)$ of equation [6.4] and sometimes the meth used has not been clearly identified. Two possible methods are describ here. Method 1 uses the saturation vapor pressure at mean air temperatu as e_a and the saturation vapor pressure at the mean daily dew poi temperature as e_d. This method is described in more detail by Doorenbos a Pruitt. Method 2 is more applicable in arid areas and high elevations whe large diurnal temperature changes occur:

$$e_a = \frac{1}{2} (e_a\,\max + e_a\,\min) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [6.1$$

TABLE 6.2. SELECTED VALUES OF a_w AND b_w FOR VARIOUS WIND FUNCTIONS FOR THE PENMAN METHOD

No.	Author(s)	Reference crop	a_w	b_w	Method of calculating $(e_a - e_d)$
1	Penman (1963)	Clipped grass	1.0	0.00621	1
2	Wright and Jensen (1972)	Alfalfa	0.75	0.0115	2
3	Doorenbos and Pruitt (1977)	Grass	1.0	0.01	1
4	Wright (1981)	Alfalfa	(varies with time)		2

where e_a max is the saturation vapor pressure at maximum daily air temperature, e_a min is the saturation vapor pressure at minimum daily air temperature, and the saturation vapor pressure at the mean daily dew point temperature is used for e_d. Procedures for calculating the mean daily dew point temperature or mean daily vapor pressure are sometimes not clear or consistent. Future studies and publications are expected to establish a standard procedure for this.

It is extremely important to make certain that the crop coefficients to be used are based on the same W_f that was used to estimate reference crop ET. For example, use the W_f by Wright and Jensen (1972) or Wright (1981) for crop coefficients presented in Subsection 6.5.3. If the grass based E_{to} as defined by Doorenbos and Pruitt (1977) is used, use K_c values from Subsection 6.5.4 or the crop coefficient procedures presented in FAO-ID 24. They emphasize that the wind function used must also be compatible with the method used to calculate the vapor pressure deficit term $(e_a - e_d)$ and the crop coefficients used must have been developed using the same procedure for calculating $(e_a - e_d)$ and the wind function W_f.

The absence of humidity data is often cited as a reason for not using combination equations in engineering calculations of ET. There are alternatives for estimating average daily dew point temperature. For example, Pochop et al. (1973) presented empirical relationships between average daily dew point temperature and daily minimum temperature for Wyoming. Saturation vapor pressure (mb) for any temperature T (°C) may be determined from the following approximation of Bosen (1960):

$$e_s \simeq 33.8639\,[(0.00738\,T + 0.8072)^8 - 0.000019\,|1.8\,T + 48| + 0.001316] \quad \ldots\ldots \quad [6.12]$$

Net radiation (R_n) in langleys per day (ly/d) can be calculated from solar radiation data. A langley is a cal/cm². The signs of R_n and G (equation [6.4]) assume that heat movement toward the soil surface is positive. In practice, G is often assumed to be zero for daily E_{tr} calculations. To estimate R_n:

$$R_n = (1 - \alpha)\,R_s - R_b \quad \ldots\ldots \quad [6.13]$$

where α is reflected short wave radiation, called albedo, expressed as a decimal. Albedo is often taken to be 0.23 for commercial irrigated crops. Merva (1975) presented an extensive table of α values. However, albedo is known to change with sun angle and can be estimated with an equation such as equation [6.36] for alfalfa at Kimberly, Idaho (Wright, 1981), if sufficient data are available. R_s is incoming short wave solar radiation. R_b is net outgoing long wave radiation and may be estimated as follows:

$$R_b = \left[a\,\frac{R_s}{R_{so}} + b\right] R_{bo} \quad \ldots\ldots \quad [6.14]$$

where R_{so} is clear day solar radiation, i.e. the solar radiation expected on a day without clouds. A clear day radiation curve can be plotted from several years of solar radiation data with the upper envelope forming the clear day radiation curves. Some experimentally determined coefficients a and b are shown in Table 6.3. R_{bo} is net outgoing long wave radiation on a clear day and may be estimated as follows:

TABLE 6.3. EXPERIMENTAL COEFFICIENTS FOR NET RADIATION EQUATIONS [6.14] AND [6.16] (from Jensen, 1974)

Region	(a b)	(a_1 b_1)
Davis, California	(1.35, − 0.35)	(0.35, − 0.046)
Southern Idaho	(1.22, − 0.18)	(0.325, − 0.044)
England	(not available)	(0.47, − 0.065)
England	(not available)	(0.44, − 0.080)
Australia	(not available)	(0.35, − 0.042)
General	(1.2, − 0.2)	(0.39, − 0.05)
General	(1.0, 0)	

$$R_{bo} = \epsilon\, 11.71 \times 10^{-8}\, T_k^4 \quad \ldots\ldots \quad [6.15]$$

$$= (a_1 + b_1 \sqrt{e_d})\, 11.71 \times 10^{-8}\, T_k^4 \quad \ldots\ldots \quad [6.16]$$

where e_d has previously been defined in this chapter, T_k is average daily air temperature in °K and some values for a_1 and b_1 can be found in Table 6.3. If humidity data are not available, the following expression developed by Idso and Jackson (1969) may be used to calculate ϵ:

$$\epsilon = -0.02 + 0.261 \exp[-7.77 \times 10^{-4}\,(273 - T_k)^2] \quad \ldots\ldots \quad [6.17]$$

where T_k is in °K.

R_n can also be calculated from the following simplified procedure:

$$R_n = a_3 R_s + b_3 \quad \ldots\ldots \quad [6.18]$$

An extensive table of values of a_3 and b_3 was presented in the ASCE-CU Report (Jensen, 1974).

Penman's original method (Penman, 1948) called for an initial estimate of evaporation from a hypothetical open water surface and then its conversion to potential ET by an empirical coefficient which varied with the season. Doorenbos and Pruitt (1977) developed a somewhat similar approach, but their corrections are related to maximum humidity, the ratio of daytime to night-time winds and wind velocity; their procedures are recommended for E_{to} estimates of periods from 10 days to 1 month.

6.4.3 Jensen-Haise Method

The Jensen-Haise method (Jensen and Haise, 1963) is another procedure for estimating ET from climatic data. Though the method is often classified as a solar radiation method, air temperature is also used and the coefficients are based on other input parameters such as elevation and long term mean temperature. The method produces an estimate of an alfalfa E_{tr} as defined by Jensen et al., (1970). Doorenbos and Pruitt (1977) also presented a solar radiation method for estimating E_{to} for grass. The reader is again cautioned that both the method of estimating E_{tr} and the crop coefficients must be bas-

The Jensen-Haise method is the result of a review of about 3000 measurements of ET that were made in the Western United States over about a 35 year period. The method presented in this chapter is known as the "Modified Jensen-Haise" method. The ASCE Irrigaton Water Requirements Committee recommended that estimates using the Jensen-Haise method be made for periods of 5 days to a month.

The Jensen-Haise method is as follows:

$$E_{tr} = C_T\,(T - T_x)R_s \qquad [6.19]$$

where E_{tr} has the same units as R_s and is compatible with alfalfa based crop coefficients.

$$C_T = \frac{1}{C_1 + 7.3\,C_H} \qquad [6.20]$$

$$C_H = \frac{50\ \text{mb}}{e_2 - e_1} \qquad [6.21]$$

where e_2 is the saturation vapor pressure of water in mb at the mean monthly maximum air temperature of the warmest month in the year (long term climatic data), and e_1 is the saturation vapor pressure of water in mb at the mean monthly minimum air temperature of the warmest month in the year.

$$C_1 = 38 - \frac{2\,E}{305} \qquad [6.22]$$

where E = the site elevation in m.

$$T_x = -\,2.5 - 0.14(e_2 - e_1) - \frac{E}{550} \qquad [6.23]$$

Solar radiation may be measured or estimated.

6.4.4 Blaney-Criddle Method

The Blaney-Criddle method was first proposed in 1945 by H. F. Blaney and W. D. Criddle (Blaney and Criddle, 1945) and was based on Western USA field measurements of ET. The method has been revised many times and there are so many variations that when the method is used the authors must be very careful and complete in their identification of the exact variation used. Perhaps the best known variation in the United States is that found in Technical Release No. 21 of the USDA Soil Conservation Service (USDA SCS, 1970). The method has been used on a world-wide basis but local calibration has been considered highly desirable.

The Blaney-Criddle method is based on the principle that ET is proportional to the product of daylength percentage and mean air temperature. The monthly constant of proportionality has been called the crop growth stage coefficient. This coefficient is not the same as the crop coefficient defined by equation [6.1] and [6.2]. Estimating ET by the early versions of the Blaney-Criddle method is a single stage process which does not involve the intermediate step of estimating reference crop ET. Estimates have been considered to be valid for monthly periods (Jensen, 1974). The one stage Blaney-Criddle method is widely used in the intermountain region of the United States, with local calibration, for water right deliberations (Kruse and Haise, 1974; Burman, 1979).

A recent major revision of the Blaney-Criddle method was published b FAO (Doorenbos and Pruitt, 1977). The FAO Blaney-Criddle method fir produces a reference crop ET estimate for grass (see Subsection 6.2.2). Th FAO modifications were based on data from 20 locations representing a ve wide range of climatic conditions.

The FAO variation uses air temperature measurements for the site i question. The need for local calibration is minimized by the classification climate at a site based on daytime wind, humidity and sunshine. For thes classifications general estimates of wind, humidity or sunshine from source such as a climatic atlas or more exact data may be used.

The FAO variation of the Blaney-Criddle method is as follows:

$$E_{to} = a_4 + b_4\,f \qquad [6.2$$

$$f = p(0.46\,T + 8) \qquad [6.2$$

where E_{to} is in mm/d, p is the percentage of daytime hours of a day compare to the entire year (see Table 6.4), and T is the average monthly ai temperatures, °C.

The numbers a_4 and b_4 represent the intercept and slope of a straigh line relationship between E_{to} and f. E_{to} may be determined directly from using Fig. 6.2 and classifications of daytime wind, minimum humidity an percent sunshine.

Daytime wind may be estimated from daily wind by using the ratio day to night winds.

U day/U night ratio	1.0	1.5	2.0	3.0	3.5	4.0
Correction for U day	1.0	1.5	1.33	1.5	1.56	1.6

TABLE 6.4. MEAN DAILY PERCENTAGE (p) OF ANNUAL DAYTIME HOURS FOR DIFFERENT LATITUDES

Latitude North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Sept	Oc
South*	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Ju
60 deg	0.15	0.20	0.26	0.32	0.38	0.41	0.40	0.34	0.28	0.22	0.17	0.1
58	0.16	0.21	0.26	0.32	0.37	0.40	0.39	0.34	0.28	0.23	0.18	0.1
56	0.17	0.21	0.26	0.32	0.36	0.39	0.38	0.33	0.28	0.23	0.18	0.1
54	0.18	0.22	0.26	0.31	0.36	0.38	0.37	0.33	0.28	0.23	0.19	0.1
52	0.19	0.22	0.27	0.31	0.35	0.37	0.36	0.33	0.28	0.24	0.20	0.1
50	0.19	0.23	0.27	0.31	0.34	0.36	0.35	0.32	0.28	0.24	0.20	0.1
48	0.20	0.23	0.27	0.31	0.34	0.36	0.35	0.32	0.28	0.24	0.21	0.1
46	0.20	0.23	0.27	0.30	0.34	0.35	0.34	0.32	0.28	0.24	0.21	0.2
44	0.21	0.24	0.27	0.30	0.33	0.35	0.34	0.31	0.28	0.25	0.22	0.2
42	0.21	0.24	0.27	0.30	0.33	0.34	0.33	0.31	0.28	0.25	0.22	0.2
40	0.22	0.24	0.27	0.30	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.2
35	0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.30	0.28	0.25	0.23	0.2
30	0.24	0.25	0.27	0.29	0.31	0.32	0.31	0.30	0.28	0.26	0.24	0.2
25	0.24	0.26	0.27	0.29	0.30	0.31	0.31	0.29	0.28	0.26	0.25	0.2
20	0.25	0.26	0.27	0.28	0.29	0.30	0.30	0.29	0.28	0.26	0.25	0.2
15	0.26	0.27	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.2
10	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.28	0.28	0.27	0.26	0.2
5	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27
0	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.2

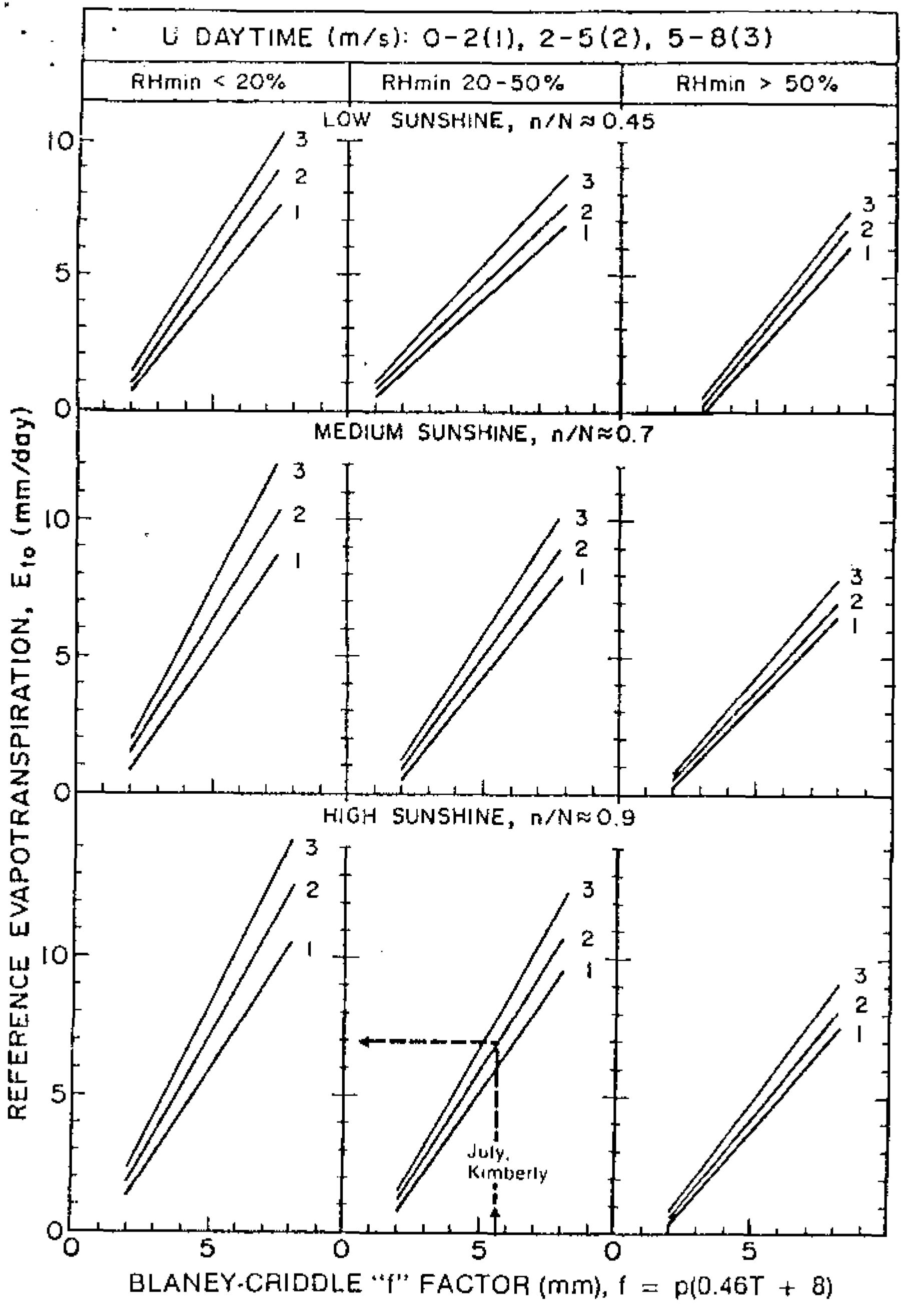


FIG. 6.2 Prediction of reference ET for grass (E_{to}) from Blaney-Criddle f factor for different conditions of minimum relative humidity, sunshine duration and day-time wind (from Doorenbos and Pruitt, 1977).

The minimum relative humidity is the ratio of saturation vapor pressure at average dew point temperature to that at maximum air temperature.

Doorenbos and Pruitt (1977) recommend that individual calculations be made for each month of record and that values of E_{to} may need to be increased for higher elevations or latitudes. They recommend estimation periods of from 10 days to one month. For computerized applications, Doorenbos and Pruitt (1977) recommend interpolation of the slope of the line from an extensive table and the intercept from humidity and sunshine inputs.

6.4.5 Pan Evaporation Method

Evaporation pans are an integral part of most agricultural weather stations. If the stations are visited weekly or more often and the operator is diligent, excellent data may be collected. Reference crop ET may be estimated by the following relationship.

$$E_{to} = K_p E_p \qquad [6.26]$$

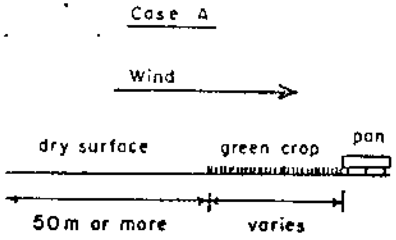
where E_p = pan evaporation in any desired units, for example mm/d, K_p = dimensionless pan coefficient, and E_{to} = reference crop ET (grass) in the same units as E_p.

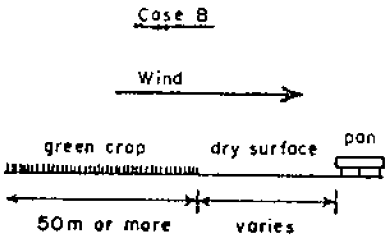
Since E_{to} represents grass ET (see Subsection 6.2.2) it is therefore mandatory that crop coefficients (K_c) used to convert E_{to} to ET for a specific crop and time be taken from Subsection 6.5.4 or from FAO-ID 24. The information in this Subsection, while useful in interpreting data from existing pans, is intended more as guidelines for locating evaporation pans specifically intended for estimating ET.

Data from evaporation pans have been correlated with ET for many years because pan evaporation integrates many of the factors involved in ET; these include wind, radiation, humidity and air temperature. The evaporation pan however is inanimate and does not reflect heat storage and transfer characteristics of a crop. For literature review the reader is referred to Doorenbos and Pruitt (1977) and Jensen (1974).

Types of pans. Discussion in this Subsection is limited to the *U.S. Class A Pan.* This pan is 121 cm in diameter and 25.5 cm deep. The pan is usually constructed of galvanized steel or Monel metal. The pan is placed on a wooden platform and leveled. The bottom of the pan is usually about 15 cm above ground level. The water level is maintained within a range of from 5 to 7.5 cm below the rim by careful water additions, or by a float system and a supply tank. Changes in water level are measured by a vernier hook gage placed in a stilling well. Many other types of evaporation pans have been used; these include different sizes, depths, screens and many are buried below the ground surface (also see Subsection 16.5.3). Doorenbos and Pruitt (1977) present a table of factors plus narrative discussion relating various sizes of pans to the *Colorado Sunken Pan.* Hounam (1973) also discusses various sizes, types of pans, and their relative performance.

Selection of K_p values. The pan coefficient varies with pan exposure, wind velocity, humidity, and distance of homogeneous material to the windward side (fetch). Values of K_p for periods of 10 days to a month may be selected from Table 6.5. Additional factors are discussed later. Table 6.5 is self explanatory except Cases A and B need further elaboration. Case A defines the condition where air moves across at least 50 m of dry surface and then across from 1 to 1000 m of a green crop. The situation is reversed in Case B; see the sketch below for a visual interpretation. Doorenbos and Pruitt (1977) also present a similar table for use with the Colorado sunken pan.





Additional factors. Many additional factors can modify the pan coefficients found in Table 6.5. For example E_p may be increased by 10 percent if the pan is painted black. If pans are placed in a small enclosure surrounded by tall crops, K_p may need to be increased by up to 30 percent for dry windy climates, and only from 5 to 10 percent for calm humid climates. The coefficients presented in Table 6.5 assume no screen is present, that no crops taller than 1 m are within 50 m and that the area within 10 m of the pan is covered by a frequently mowed green grass cover or by bare soils. Doorenbos and Pruitt (1977), Jensen (1974), and Hounam (1973) discuss additional factors that influence pan evaporation.

Location and operation of pans. A weather station which includes an evaporation pan should be located so that its surrounding conditions are easy to classify and maintain in as constant a condition as possible. The temptation to place the station in an unused or otherwise convenient but unrepresentative location should be resisted. The pan's location should be dictated by the intended purposes. With proper location and care in use, reference crop ET estimates to ± 10 percent accuracy should be possible.

TABLE 6.5. PAN COEFFICIENT K_p FOR CLASS A PAN FOR DIFFERENT GROUND COVER AND LEVELS OF MEAN RELATIVE HUMIDITY AND 24 h WIND
(For use in equation [6.26] to estimate E_{to})

Class A Pan	Case A Pan surrounded by short green crop				Case B† Pan surrounded by dry-fallow land			
RH mean %		low < 40	medium 40-70	high > 70		low < 40	medium 40-70	high > 70
Wind‡ km/day	Upwind distance of green crop m				Upwind distance of dry fallow m			
Light < 175	0	0.55	0.65	0.75	0	0.7	0.8	0.85
	10	0.65	0.75	0.85	10	0.6	0.7	0.8
	100	0.7	0.8	0.85	100	0.55	0.65	0.75
	1 000	0.75	0.85	0.85	1 000	0.5	0.6	0.7
Moderate 175-425	0	0.5	0.6	0.65	0	0.65	0.75	0.8
	10	0.6	0.7	0.75	10	0.55	0.65*	0.7
	100	0.65	0.75	0.8	100	0.5	0.6	0.65
	1 000	0.7	0.8	0.8	1 000	0.45	0.55	0.6
Strong 425-700	0	0.45	0.5	0.60	0	0.6	0.65	0.7
	10	0.55	0.6	0.65	10	0.5	0.55	0.65
	100	0.6	0.65	0.7	100	0.45	0.45	0.6
	1 000	0.65	0.7	0.75	1 000	0.4	0.45	0.55
Very strong > 700	0	0.4	0.45	0.5	0	0.5	0.6	0.65
	10	0.45	0.55	0.6	10	0.45	0.5	0.55
	100	0.5	0.6	0.65	100	0.4	0.45	0.5
	1 000	0.55	0.6	0.65	1 000	0.35	0.4	0.45

†For extensive areas of bare-fallow soils and not agricultural development, reduce Kpan values by 20 percent under hot windy conditions, by 5 to 10 percent for moderate wind, temperature and humidity conditions.
‡Total wind movement km/d.

6.4.6 Local Calibration

All methods of estimating ET from climatic data involve empirical relationships to some extent. Even the combination equation, the Penman method for example, utilizes an empirical wind function. The empirical relationships account for many local conditions. The ASCE Irrigation Water Requirements Committee stated that ". . . no single existing method using meteorological data is universally adequate for all climatic regimes, especially for tropical areas and for high elevations, without some local or regional calibration" (Jensen, 1974). If the crop economic importance is high, local calibration is needed to at least give confidence to irrigation water requirement estimates. Doorenbos and Pruitt (1977) present a detailed description of a world wide calibration of the Blaney-Criddle, radiation, and Penman methods. The principles can be applied to a local or regional calibration.

Calibration involves the simultaneous collection of field E_t data and the corresponding climatic data. The time interval for ET estimates has an influence on the methods that are used for field measurements. Preferably, if the method is to be used for short period estimates, comparable data should be used in calibration.

Blaney-Criddle method. The Blaney-Criddle method is suited for monthly estimates of ET, (Jensen, 1974). Therefore, field measurements of ET can be made using careful soil moisture measurements, water table lysimeters, drainage lysimeters, weighing lysimeters or inflow-outflow techniques. Only air temperature and rainfall data are needed to complete the calibration by determining the appropriate monthly crop coefficient.

Jensen-Haise method. The Jensen-Haise method is recommended for 5-day to 1-month periods (Jensen, 1974). Drainage lysimeters are only suitable for 10-day or longer periods (Doorenbos and Pruitt, 1977), and can be eliminated if short period calibration is desired. ET measured by soil moisture change can also be eliminated for short period calibrations. Therefore, if 5-day periods are desired, weighing lysimeters or Bowen ratio techniques should be used to collect the necessary field ET data for local calibration. For monthly calibration, ET may be determined by properly performed measurements of soil moisture depletion, inflow-outflow, lysimeters or other techniques. Climatic data should include solar radiation, air temperature and rainfall data on at least a daily basis.

Local calibration of both C_T and T_x can be obtained by regression of measured E_{tr}/R_s against mean air temperature if data are available from about 5 to 30 °C, or higher. If only a few data points are available over a narrow temperature range, then these data should be used to adjust the T_x value, but not the C_T value.

Penman method. The Penman method can provide accurate estimates of ET for periods of 1 month to 1 hour depending on the method of calibration. For short periods only weighing lysimeters can provide the necessary E_t data. Climatic data must include, solar radiation, net radiation if possible, wind movement, air temperature, vapor pressure and precipitation all collected on intervals suitable for the desired prediction periods. Usually local calibration is accomplished by calibrating the transfer coefficient identification of the variables.

$$h = 15.36\, W_f (e_a - e_d) \quad [6.27]$$

Whenever local calibration is made, consistency between any reference crop used, crop coefficients, and calculation method used to obtain terms as $(e_a - e_d)$ must be followed. If consistency is not followed ET estimates will be illogical and may not represent the crop grown. For daily calibration of the Penman method see Wright (1981) and Subsection 6.5.3.

6.5 ESTIMATING ET FOR CROPS

Estimating ET for a specific crop can be a very complex matter depending on the degree of refinement desired. To obtain the most accurate estimates, all of the major contributing crop and environmental conditions need to be taken into account. These involve climate, soil moisture, the type of crop, stage of growth and the extent to which the plants cover the soil. This section is intended to provide the means for the practicing engineer or irrigation scientist to integrate these inter-related factors into the best possible ET estimates. The procedures primarily involve the use of an estimated reference ET and experimentally developed ET crop coefficients. Such procedures are now extensively used in irrigation scheduling methods and in estimating crop water requirements and have been described in detail in previous publications. For purposes of this section, the most salient principles and information are provided. Those desiring more information should consult the listed references.

The common Blaney-Criddle method does not use ET crop coefficients. Rather, the estimations of crop ET are made in one step. The method was revised by Doorenbos and Pruitt (1977) to provide an estimate of E_{to} for grass so that appropriate crop coefficients could be used to estimate ET for a specific crop. Such procedures produce estimates with accuracies suitable for 10-day to monthly periods.

Detailed and specific procedures and guidelines were summarized by Doorenbos and Pruitt (1977) for predicting crop water requirements for a wide range of crops and conditions and availability of associated information. They outlined a three-stage procedure involving (a) a reference crop ET, (b) a crop coefficient, and (c) the effects of local conditions and agricultural practices. They chose ET for 8- to 15-cm tall, green, well-watered grass as the reference ET and selected or adapted crop coefficients accordingly. Four methods of estimating this reference ET were presented, namely: (a) Blaney-Criddle, (b) radiation, (c) Penman, and (d) pan evaporation. In this section, we present crop coefficients for E_{tr} based on alfalfa, as defined by Jensen et al. (1970) suitable for daily estimates of ET when E_{tr} is determined by the Penman method described in this chapter. These alfalfa based coefficients are also suitable for the Jensen-Haise method as presented in Subsection 6.4.3. We also present a limited set of crop coefficients based on grass E_{to} which are intended for use with the FAO Blaney-Criddle and pan evaporation methods described in Subsections 6.4.4 and 6.4.5.

6.5.1 Crop Coefficients

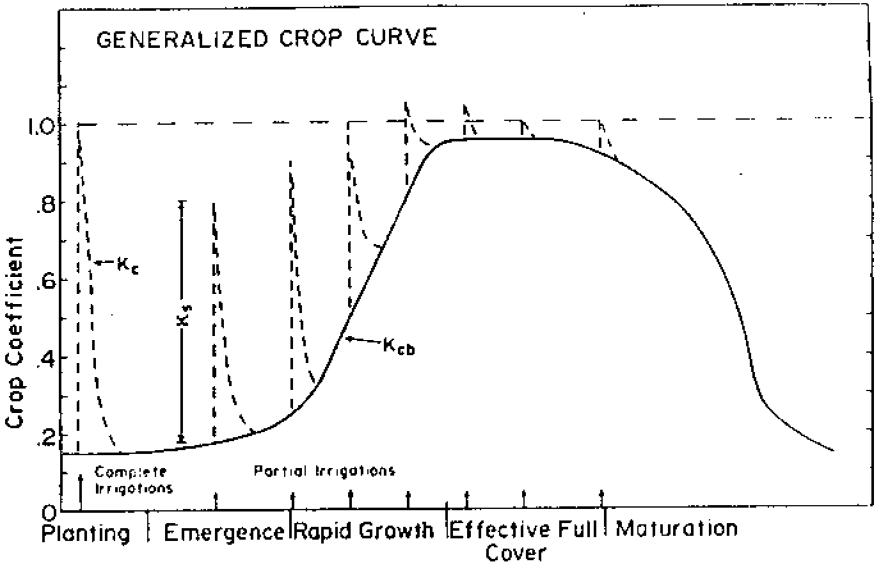


FIG. 6.3 Generalized basal ET crop coefficient curve (K_{cb}) with adjustment for increased evaporation due to surface soil wetness (K_s) to determine the over-all crop coefficient (K_c).

Experimentally developed crop coefficients reflect the physiology of the crop, the degree of crop cover, and the reference ET. In applying the coefficients, it is important to know how they were derived since they are empirical ratios of crop ET to the reference ET, as shown in equation [6.1]. The combined crop coefficient includes evaporation from both the soil and plant surfaces. The contribution of soil evaporation is strongly dependent upon the surface soil wetness and exposure. Transpiration is primarily dependent upon the amount and nature of plant leaf area, and the availability of water within the root-zone. Crop coefficients can be adjusted for soil moisture availability and surface evaporation. The distribution of crop coefficients with time is known as a crop curve. See Fig. 6.3 and 18.1 for examples of crop curves. Other time-related crop parameters may also be used as a base.

In the experimental determination of crop coefficients, ideally both crop ET and reference ET are measured concurrently. The crop coefficient is then calculated as the dimensionless ratio of the two measurements. Well sited, sensitive weighing lysimeters provide ideal daily measurements and problems with soil-water drainage are avoided. Care must be taken to insure that border effects are minimized, that fetch is adequate, and that crop and soil moisture conditions are similar in the lysimeter and the field.

6.5.2 Reference ET

Alfalfa has frequently been selected as a reference crop because it has relatively high ET rates in arid areas where there is considerable advective sensible heat input from the air (Wright and Jensen, 1972; and Wright, 1979, 1981). In such cases, reference ET (E_{tr}) is equal to daily alfalfa ET when the crop occupies an extensive surface, is actively growing, standing erect and at least 20-cm tall, and is well watered so that soil water availability does not limit ET. Reference ET obtained with such an alfalfa surface will usually be greater than that for a clipped grass surface, particularly in windy arid areas.

Daily rates can be accurately measured with sensitive weighing lysimeters. However, it is not possible to maintain the crop surface in a condition to provide near maximum ET because of cutting periods, lodging of plants by wind or rain, and the effects of late and early seasonal frosts. Consequently, daily alfalfa ET, energy balance, and meteorological data can be used to develop and calibrate procedures for computing reference ET. The computed reference then can be used to extend the measured values for periods or locations where measured values are not available.

6.5.3 Alfalfa Related Crop Coefficients

An overall daily crop coefficient can be determined from daily measured reference and crop ET by:

$$K_c = \frac{E_t}{E_{tr}} \quad \ldots\ldots\ldots\ldots\ldots \quad [6.28]$$

in which K_c = the dimensionless crop coefficient for the particular crop at the existing growth stage and surface soil moisture condition. When estimating crop ET from the reference ET, K_c is estimated from crop curves for the day or period involved and information on soil moisture conditions by:

$$K_c = K_{cb}\,K_a + K_s \quad \ldots\ldots\ldots\ldots\ldots \quad [6.29]$$

in which K_c = daily crop coefficient, K_{cb} = daily basal ET crop coefficient, K_a = a coefficient dependent upon available soil moisture, and K_s = a coefficient to allow for increased evaporation from the soil surface occurring after rain or irrigation. These procedures are described in greater detail by Jensen (1974), and Jensen et al. (1971). The generalized basal crop coefficient, K_{cb}, was defined by Wright (1979) to represent conditions when the soil surface was dry so that evaporation from the soil was minimal but soil-water availability did not limit plant growth or transpiration, i.e. $K_c = K_{cb}$ with $K_a = 1$ and $K_s = 0$. He determined daily values of K_{cb} by manually fitting a basal crop curve to overall crop curves obtained with equation [6.28]. This specific designation also distinguished the K_{cb} values obtained with lysimeter ET data from mean crop coefficients previously developed from soil-water-balance data.

When available water within the root zone limits growth and ET, K_a of equation [6.29] will be less than 1.0 and can be approximated by relationships similar to:

$$K_a = [\ln(A_w + 1)]/[\ln(101)] \quad \ldots\ldots\ldots\ldots\ldots \quad [6.30]$$

in which A_w = the percentage of available water (100 when the soil is at field capacity), and K_a = 1 when A_w = 100, and K_a goes to zero as A_w goes to 0. This algorithm was developed from published ET-soil water data (Jensen et al., 1971). Other relationships for K_a were reviewed by Howell (1979).

Increased soil evaporation due to rainfall or irrigation, can be estimated by:

$$K_s = (K_1 - K_{ci})\exp(-\Lambda t),\ K_1 > K_{ci} \quad \ldots\ldots\ldots\ldots\ldots \quad [6.31]$$

in which t = the number of days after the rain or irrigation; Λ = the combined effects of soil characteristics, evaporative demand, etc; and K_{ci} = the value of K_{cb} at the time the rain or irrigation occurred. This algorithm will also vary for various soils and locations. At Kimberly, Idaho K_s was approximated by: $(0.9 - K_c)0.8$; $(0.9 - K_c)0.5$; and $(0.9 - K_c)0.3$; for the first, second, and third days after a rain or irrigation, respectively (Jensen et al., 1971). When K_c exceeds 0.9 no adjustment is needed for rain or irrigation. A diagramatic representation of the expected changes in the crop coefficient as affected by stage of growth and wet surface soil, is presented in Fig. 6.3.

A summary of basal crop coefficients for several crops is presented in Table 6.6 for arid areas. These were derived for use with estimated ET for a reference crop of actively growing, well watered alfalfa at least 20-cm tall. Dates typical of Kimberly, Idaho for planting, emergence, effective cover, and harvest for the various crops are presented in Table 6.7.

Values of K_{cb} are listed on a normalized time scale, instead of actual dates, with time from planting until full cover on a percentage basis, PCT, and time after as elapsed days, DT. Coefficient relationships of this type have been used extensively in irrigation scheduling (Jensen, 1974). The normalized time scale helps account for the effects of seasonal differences on crop development. Alfalfa cuttings are listed individually because of major differences in climate for each of the growth periods.

The alfalfa related crop coefficients described in this section were computed using the Penman method discussed in Subsection 6.4.2 with some modifications. Suitable procedures have been described in many publica-

TABLE 6.6. DAILY BASAL ET CROP COEFFICIENTS (K_{cb}) FOR DRY SURFACE SOIL CONDITIONS

for use with a reference ET representative of alfalfa for irrigated crops grown in an arid region with a temperate inter-mountain climate. Coefficients were determined experimentally using ET data obtained with sensitive weighing lysimeters at Kimberly, Idaho, from 1968 through 1978, (from Wright, 1979)

	Basal ET crop coefficients, K_{cb}									
	PCT, time from planting to effective cover (%)									
Crop	10	20	30	40	50	60	70	80	90	100
Small grains	0.15	0.16	0.20	0.28	0.55	0.75	0.90	0.98	1.00	1.02
Beans	0.15	0.17	0.18	0.22	0.38	0.48	0.65	0.78	0.93	0.95
Peas	0.20	0.17	0.16	0.18	0.20	0.28	0.48	0.67	0.86	0.95
Potatoes	0.15	0.15	0.15	0.21	0.35	0.45	0.60	0.72	0.78	0.80
Sugar beets	0.20	0.17	0.15	0.15	0.16	0.20	0.30	0.50	0.80	1.00
Corn	0.15	0.15	0.16	0.17	0.18	0.25	0.40	0.62	0.80	0.95
Alfalfa (1st)	0.50	0.58	0.67	0.75	0.80	0.85	0.90	0.95	0.98	1.00
(2nd & 3rd)	0.50	0.25	0.25	0.40	0.55	0.79	0.80	0.90	0.98	1.00
Winter wheat	0.65	0.70	0.76	0.80	0.85	0.90	0.95	0.98	1.00	1.02
	DT, days after effective cover									
	10	20	30	40	50	60	70	80	90	100
Small grains	1.02	1.00	0.80	0.50	0.25	0.10	0.10	—	—	—
Beans	0.95	0.94	0.65	0.36	0.18	0.15	0.10	—	—	—
Peas	0.93	0.82	0.50	0.37	0.20	0.10	0.10	—	—	—
Potatoes	0.80	0.80	0.75	0.74	0.73	0.72	0.70	0.50	0.25	0.20
Sugar beets	1.00	1.00	1.00	0.96	0.93	0.89	0.86	0.83	0.80	0.75
Corn	0.95	0.95	0.93	0.91	0.89	0.83	0.76	0.30	0.20	0.15
Alfalfa (1&2)	1.00	1.00	1.00	0.25	—	—	—	—	—	—
(3rd)*	1.00	1.00	0.52	0.30	—	—	—	—	—	—
Winter wheat	1.02	1.00	0.96	0.50	0.20	0.10	0.10	—	—	—

*Final cutting.

TABLE 6.7. DATE OF VARIOUS CROP GROWTH STAGES IDENTIFIABLE IN THE FIELD FOR CROPS STUDIED AT KIMBERLY, IDAHO, 1968-1978
(from Wright, 1979)

Crop	Date of occurrence							Time (days)	
	Planting	Emergence	Rapid growth	Full cover	Heading or bloom	Ripening	Harvest	Planting to full cover	Full cover to harvest
Small grains	4/1	4/15	5/10	6/20	6/15	7/20	8/15	80	55
Beans	5/22	6/5	6/15	7/15	7/5	8/10	8/30	55	45
Peas	4/10	4/25	5/10	6/5	6/15	7/5	7/25	55	50
Potatoes	4/25	5/25	6/10	7/10	7/1	—	10/10	75	90
Sugar beets	4/15	5/15	6/10	7/15	—	—	10/15	91	100
Corn	5/5	5/25	6/10	7/15	7/30	9/10	9/20	79	70
Alfalfa 1st	4/1	—	4/20	5/15	—	—	6/15	45	35
2nd	6/15	—	6/25	7/5	—	—	8/1	20	35
3rd	8/1	—	8/10	8/25	—	—	9/20	25	25
Winter wheat	10/1	10/15	3/20	4/25	6/5	7/15	8/10	205	60

tions, such as those of Jensen (1974), Jensen et al. (1971), Wright and Jensen (1972), Wright and Jensen (1978), and Wright (1981). Other methods can also be adapted, but as mentioned earlier in this chapter, the combination equation seems to give the most consistent results, particularly in arid irrigated regions subject to considerable sensible heat advection. To adequately account for advection, even the combination equation should be calibrated or verified for local conditions.

The changes necessary to permit estimating reference ET for a crop of well watered, actively growing alfalfa, at least 20-cm tall, are presented here for convenience of the reader. This follows procedures developed earlier with recent refinements by Wright (1981). Measurements or estimates of the following daily meteorological parameters are required: (1) solar radiation, (2) maximum and minimum air temperature, (3) average humidity, or at least an 0800-h dew-point temperature, and (4) wind travel.

A combination equation similar to that in Subsection 6.4.2 was used to estimate a reference ET for the development of the basal crop coefficients by:

$$E_{tr} = 10\,\frac{E_t}{L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [6.32]$$

where E_{tr} is on a water depth equivalent basis (mm/d), E_t is the latent heat flux computed with the calibrated equation (cal/cm²·d), L is the latent heat of vaporization (cal/cm³), and 10 is for unit conversion (mm/cm). A wind function with time dependent coefficients was used.

$$W_f = a_w(t) + b_w(t)\,U_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [6.33]$$

where W_f is the wind function and $a_w(t)$ and $b_w(t)$ are variable coefficients to adapt the function to the location or time of year. Varying the wind function permits adapting W_f to changing conditions of the surrounding area which influence sensible heat advection. The following empirical relationships were derived for Kimberly, Idaho.

$$a_w(t) = 23.8 - 0.7865D + (9.7182E\text{-}03)D^2 - (5.4589E\text{-}05)D^3$$
$$+ (1.42529E\text{-}07)D^4 - (1.41018E\text{-}10)D^5 \quad \ldots\ldots\ldots\ldots \quad [6.34]$$

$$b_w(t) = -0.0122 + (5.2956E\text{-}04)D - (5.9923E\text{-}06)D^2$$
$$+ (3.4002E\text{-}08)D^3 - (9.00872E\text{-}11)D^4 + (8.79179E\text{-}14)D^5$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [6.35]$$

where D is the day of the year and the polynomial coefficients are for wind travel measured at 2 m in km/d. Respective values for 4/15, 6/15, 8/15, 10/15, and seasonal mean for a_w are: 0.74, 1.83, 1.01, 0.55, and 1.06; and for b_w: 0.0069, 0.0088, 0.0107, 0.0099, and 0.0091. These mean values compare with the seasonal Penman coefficients of 1.0 and 0.0062 and 0.75 and 0.0115 of Wright and Jensen (1972, 1978) (also see Table 6.2).

The net radiation term, R_n, of equation [6.4] was estimated from daily solar radiation, temperature, and humidity data by equations [6.13] to [6.16] using values and functions as developed by Wright (1981) for Kimberly, Idaho. The albedo (α) was computed by:

$$\alpha = 0.29 + 0.06\ \mathrm{SIN}\ \{30[M+(N/30) + 2.25]\} \quad \ldots\ldots\ldots\ldots \quad [6.36]$$

where M is the number of the month and N is the number of the day. The season long regression coefficients for Kimberly, Idaho are: a_1 is 0.325 and b_1 is -0.044 (Wright and Jensen, 1972). The coefficient a_1 of equation [6.16] was computed with a "normal" distribution equation:

$$a_1 = 0.26 + 0.1 \exp\left\{-[30(M+N/30)-207)/65]^2\right\} \quad \ldots\ldots\ldots \quad [6.37]$$

A constant value of b_1 of -0.044 was used with the variable a_1. Coefficients for equation [6.14] were: for R_s/R_{so} greater than 0.7; a = 1.054 and b = 0; and for R_s/R_{so} less than or equal to 0.7, a = 1.0 and b = 0.

TABLE 6.8. DAILY BASAL ET CROP COEFFICIENTS (K_{cb}) FOR USE WITH GRASS REFERENCE ET (E_{to})
for irrigated crops grown in an arid Mediterranean climate. Coefficients are for dry soil surface conditions and were determined experimentally with ET data obtained with sensitive weighing lysimeters at Davis, CA, 1965-1975. Days from planting to effective full cover and from then to harvest or maturity are listed

Crop	Planting date	Days to peak K_c	Time from planting to peak K_c, %									
			10	20	30	40	50	60	70	80	90	100
Sorghum	5/17	45	0.12	0.13	0.14	0.16	0.22	0.33	0.50	0.75	1.00	1.07
Beans	6/21	43	0.10	0.12	0.16	0.21	0.28	0.39	0.53	0.75	0.98	1.08
Tomatoes	4/29	80	0.14	0.15	0.17	0.19	0.22	0.33	0.48	0.71	1.04	1.18
Barley	10/31	100	0.18	0.20	0.22	0.24	0.28	0.34	0.47	0.66	0.90	1.07
Corn	5/14	52	0.12	0.13	0.15	0.20	0.29	0.45	0.81	0.99	1.08	1.13
Sugar beets (late)	6/16	55	0.12	0.13	0.16	0.20	0.29	0.45	0.65	0.87	1.04	1.10
Sugar beets (early)	3/25	90	0.14	0.16	0.18	0.22	0.27	0.37	0.53	0.77	1.04	1.10
	Harvest date	Days to harvest	Days after peak K_c									
			10	20	30	40	50	60	70	80	90	100
Sorghum	9/13	74	1.08	1.06	1.03	0.99	0.94	0.88	0.79	0.65	—	—
Beans	9/18	46	1.12	1.12	1.10	0.71	0.15	—	—	—	—	—
Tomatoes	9/24	68	1.24	1.21	1.12	1.03	0.90	0.75	0.58	—	—	—
Barley	5/19	100	1.15	1.17	1.19	1.21	1.19	1.12	0.98	0.75	0.50	0.24
Corn	9/20	77	1.17	1.17	1.17	1.14	1.03	0.87	0.67	—	—	—
Sugar beets (late)	11/18	100	1.15	1.16	1.16	1.16	1.15	1.14	1.13	1.12	1.10	1.08
Sugar beets (early)	9/20	90	1.13	1.15	1.15	1.14	1.13	1.11	1.08	1.05	1.01	—

TABLE 6.11. CROP COEFFICIENTS (K_c) FOR ALFALFA, CLOVER, GRASS-LEGUMES AND PASTURE
with mean values for between cuttings, low values for just after cuttings with dry soil conditions, and peak values for just before harvest. For wet soil conditions increase low values by 30% (adapted from Doorenbos and Pruitt, 1977)

		K_c			
Climatic conditions	Period	Alfalfa	Grass hay	Clover, grass-legumes	Pasture
Humid with light to moderate winds	mean	0.85	0.80	1.00	0.95
	peak	1.05	1.05	1.05	1.05
	low	0.50	0.60	0.55	0.55
Dry with light to moderate winds	mean	0.95	0.90	1.05	1.00
	peak	1.15	1.10	1.15	1.10
	low	0.40	0.55	0.55	0.50
Strong winds	mean	1.05	1.0	1.10	1.05
	peak	1.25	1.15	1.20	1.15
	low	0.30	0.50	0.55	0.50

6.5.5 Effect of Irrigation Method on Evapotranspiration

The method of irrigation may affect ET rates while water is being applied and possibly for several days following irrigation. During irrigation, the ET rate may be highest with sprinklers because of the added evaporation opportunity provided by the increased availability of a vapor sink and the sensible energy supplied by the air layer through which the water drops travel. During windy conditions these effects are especially important due to the transport of droplets outside of the area being irrigated.

Wetting of a crop surface by irrigation (or precipitation) does not necessarily result in greater ET than otherwise. A number of studies have shown that surface evaporation replaces vegetative transpiration in equal amounts (Christiansen and Davis, 1967). In such cases ET is already at the potential rate and the site of the evaporative process is merely changed from plant stoma to the wet vegetative surface. Wetting the crop increases ET where ET has been restricted by such factors as low vegetative density and a dry soil surface, limited soil moisture available for plants, high stomatal resistance, or xerophytic plant adaptation.

At low vegetative densities evaporation from wet soil can be an important factor in contributing to ET (Ritchie, 1971). Thus, an irrigation method that does not wet the entire bare soil area can result in less ET than one that does. An advantage of drip irrigation is that it does not wet the entire soil area. However the saving of evaporation is less than the ratio of unwetted area to total bare soil area would suggest because of advective influences (also see Section 16.5).

The effect of irrigation method on ET, while of some consequence during and immediately following irrigation, may be small on a seasonal basis. For example, Bucks et al. (1974) found that the seasonal ET for high production of cabbage in Arizona was about the same with drip, modified furrows and furrow irrigation. Lysimeter studies of grain sorghum in Texas showed no significant differences in yield or water use efficiency (ratio of grain yield to total crop water use) between drip and sprinkler irrigation with three irrigations per week (Ravelo et al., 1977).

6.6 OTHER BENEFICIAL USES

Water applied at appropriate times can sometimes make additional contributions to improved crop production besides the replenishment of soil moisture. While meeting the ET need of crops is the primary purpose of irrigation, conditions may require providing water for additional beneficial uses as discussed in Chapters 2 and 18 and briefly described in this Section.

6.6.1 Germination of Seeds

Germination of seeds may be enhanced by irrigation at planting, and sometimes irrigation is essential for seed germination. Subsequent crop development and harvest are aided by the uniform seed germination and plant emergence. Sprinkler irrigation is especially suited to this application because the amount of water applied can be limited to the amount necessary; this is especially important where water supplies are limited. Soil wetting for germination by furrow irrigation is successfully practiced in many areas, but more water is required than with sprinklers when "subbing" from furrow to ridge planted seed is involved. Furthermore, salinity tends to be concentrated in the ridge by evaporation.

6.6.2 Climate Modification

Climate modification may be possible using water. A large-scale effect is apparent as one drives from the desert into an irrigated area on a hot summer day and feels the effect of evaporative cooling on the atmosphere. This lowering of dry bulb temperature is accompanied by an increase in vapor pressure and may be accompanied by a reduction in wind speeds (Burman et al., 1975). Experiments using sprinkler or mist applications at field sites within irrigated areas have typically decreased crop temperatures 4 to 12 °C. Increases in yield of 10 to 70 percent with such crops as peas, tomatoes, cucumbers, muskmelons and strawberries are reported, and improved quality of apples and grapes have been observed (Westerman et al., 1976). However, crop response to lowered temperature stress may sometimes be less beneficial than judged from the amount of air temperature suppression. Design procedures for climate-control sprinkling and misting systems are not well developed. Misting to improve greenhouse environments is a common practice.

Evaporative cooling experiments to delay bloom of fruit trees, with attendant reduced danger from freeze damage, were reported by Wolfe et al. (1976). They found that with application rates of 3 L/s·ha misting systems did better than low-pressure sprinklers in keeping daytime orchard temperatures down, and thus more successfully delayed bud development until the danger of frost had passed. The mist system required only about 60 percent as much water per day of bloom delay as did the sprinklers.

6.6.3 Freeze Protection

Freeze protection can result from water applied to the soil to increase soil heat conduction and soil heat storage capacity. Significant protection may be achieved by continuous wetting of plant parts by sprinkler water during critical hours.

In general, oil releases much more heat to a crop if it is used to pump water instead of being burned. A more complete discussion of freeze protection methods can be found in Chapters 2 and 18.

Grass Related Crop Coefficients

rop coefficients derived for use with a reference ET for grass enbos and Pruitt, 1977) are discussed in this section. A summary of crop coefficients for several crops is presented in Table 6.8 similarly to in Table 6.6 except that E_{to} was used as a base in their development. coefficients were obtained at Davis, California and are therefore entative of an arid, Mediterranean-type climate. Data for many additi crops are presented in FAO-ID 24 (Doorenbos and Pruitt, 1977).

he adjustments to the Blaney-Criddle and evaporation pan methods of ctions 6.4.4 and 6.4.5 may be used to estimate E_{to} for use with the based crop coefficients. Compatible Penman and radiation methods lso be used. (Doorenbos and Pruitt, 1977). However, the grass-based coefficients should not be used with the Penman and Jensen-Haise ds as presented in Subsections 6.4.2 and 6.4.3.

and vegetable crops. The growing season may be divided into four :

(1)	Initial stage	: germination and early growth when the soil surface is mostly bare, crop ground cover < 10 percent.
(2)	Crop development stage	: from the initial stage to effective full crop ground cover (70 to 80 percent).
(3)	Mid-season stage	: from effective full crop ground cover to the start of maturation as indicated by changes in leaf color or dropping of leaves.
(4)	Late season stage	: from the end of the mid season stage until full maturity or harvest.

urves for other crops may be constructed in the following manner for a location.

Establish planting date from local information or practices in similar ic zones.

Determine total growing season and length of crop development from local information. Guidelines to crop development stages are ted in Table 6.9.

Initial stage: predict irrigation and/or rainfall frequency, then select ue and plot as shown in Fig. 6.3 or 6.8. This is an alternate approach to ting K_c for rain or irrigation (Wright, 1981).

Mid-season stage: based on local climate (humidity and wind), select m Table 6.10 and plot as a straight line.

Late-season stage: for time of full maturity select a K_c value from 6.10. Assume a straight line between the end of the mid-season stage full maturity date.

Development stage: assume a straight line between the end of the in- age and the start of the mid-season stage.

he curve may be refined by sketching a smooth curve, but this may on- e a small difference in results. The construction of such a curve for rn at Kimberly, Idaho is shown in the example calculations, in Sec- 14.

rage crops comprise millions of hectares of irrigated land in the K_c values for these crops reach a high value just prior to cutting and a low value just after cutting. It is essential that local harvest dates be considered in making ET estimates for forage crops. Table 6.11 gives high, average, and low values for alfalfa, grass hay, legumes, and pasture. For seasonal estimates average K_c values may be used. For irrigation timing and depth, the variation due to cutting also must be considered. More detail and a graphical presentation of the seasonal variation in K_c for alfalfa is presented in FAO-IR 24 (Doorenbos and Pruitt, 1977).

TABLE 6.9. LENGTH OF GROWING SEASON AND CROP DEVELOPMENT STAGES OF SELECTED FIELD CROPS: SOME INDICATIONS
(from Doorenbos and Pruitt, 1977)

Beans (dry) Pulses	Continental climates late spring planting 20/30/40/20 and (110); June planting Central California and West Pakistan 15/25/35/20 and (95); longer season varieties 15/25/50/20 and (110).*
Corn (maize) (sweet)	Spring planting East African highlands 30/50/60/40 and (180); late cool season planting, warm desert climates 25/40/45/30 and (140); June planting sub-humid Nigeria, early October India 20/35/40/30 and (125); early April planting Southern Spain 30/40/50/30 and (150).
Grain, small	Spring planting Mediterranean 20/30/60/40 and (150); October-November planting warm winter climates; Pakistan and low deserts 25/35/65/40 and (165).
Potato (Irish)	Full planting warm winter desert climates 25/30/30/20 and (105); late winter planting arid and semi-arid climates and late spring-early summer planting continental climate 25/30/45/30 and (130); early-mid spring planting central Europe 30/35/50/30 and (145); slow emergence may increase length of initial period by 15 days during cold spring.
Sugarbeet	Coastal Lebanon, mid-November planting 45/75/80/30 and (230); early summer planting 25/35/50/50 and (160); early spring planting Uruguay 30/45/60/45 and (180); late winter planting warm winter desert 35/60/70/40 and (205).

*15/25/50/20 and (110) stand respectively for initial, crop development, mid-season and late season crop development stages in days and (110) for total growing period from planting to harvest in days.

TABLE 6.10. SELECTED CROP COEFFICIENTS BASED ON GRASS E_{to} FOR FIELD CROPS FOR DIFFERENT GROWTH STAGES AND CLIMATIC CONDITIONS
(from Doorenbos and Pruitt, 1977)

Crop	Crop stage	Humidity:	RH min > 70%		RH min < 20%	
		Wind m/s:	0-5	5-8	0-5	5-8
Beans (dry)	3		1.05	1.1	1.15	1.2
	4		0.3	0.3	0.25	0.25
Corn (field)	3		1.05	1.1	1.15	1.2
	4		0.55	0.55	0.6	0.6
Grain	3		1.05	1.1	1.15	1.2
	4		0.3	0.3	0.25	0.25
Potato	3		1.05	1.1	1.15	1.2
	4		0.7	0.7	0.75	0.75
Sugarbeet	3		1.05	1.1	1.15	1.2
	4		0.9	0.95	1.0	1.0

Application rates during a freeze period may be dictated by the available irrigation system (2.5 to 6.4 mm/h for sprinklers). Under-tree sprinklers designed specifically for freeze protection may have rates as low as 1.3 mm/h.

Blanc et al. (1963) stated that protection down to -6 °C can be achieved by overhead sprinkler rates of 1.5 to 2.0 mm/h for low growing plants; 2.0 mm/h for fruit trees; and 2.0 to 2.5 mm/h for vines. These rates must be increased when atmospheric dew points are low. The application of water by overhead sprinklers should begin when falling air temperatures reach 1 °C, or when wet bulb temperatures reach freezing. Sprinkling should be continued until ice is melting on its own and air temperature remains above freezing.

6.6.4 Fertilizer Application

Fertilizer application by irrigation water is often the cheapest way, and may be the only way of applying it (except by air) to a crop that runs out of N in mid or late season. Anhydrous and aqua NH_3 and solutions made from dry fertilizers are commonly used as sources of N. Liquid H_3PO_4 and solutions of K are also applied by irrigation water. In some areas the harmful effects of high Na water on infiltration rates are counteracted by the addition of gypsum to the irrigation water.

The amount of water applied during fertilization is usually governed by the ET needs of the crop. Nutrients that do not move rapidly in the soil are applied during the beginning of the irrigation period, whereas nitrate is applied late in the period to prevent penetration to excessive depths.

Fertilizers can be applied by surface or sprinkler systems. All components of the system must be corrosion resistant, and the system should be thoroughly flushed with water at the end of the irrigation period. Further details of fertilizer application techniques and precautions are given by Viets et al. (1967) and in Section 16.9.

6.6.5 Soil Temperatures

Soil temperatures can be markedly affected by irrigation water. Low water temperatures may depress soil temperatures and impede plant development. The literature tends to support the generalization that vegetative growth is largely correlated with root temperature, reproductive events, and with shoot temperature (Raney and Mihara, 1967). Soil cooling may be desirable under certain circumstances, such as establishing seedling stands of head lettuce.

6.6.6 Dust Suppression

Dust suppression, though not related to irrigation, can be achieved by using sprinkler systems. The feedlot dust generated in hot, dry climates when cattle become active in the early evening can be suppressed with sprinkling. Carroll et al. (1974) report applying just enough water in two increments to suppress dust while avoiding problems of odor and pests associated with excessive wetness of pens.

6.7 LEACHING REQUIREMENTS

The amount of water required to maintain a favorable salt balance depends upon local conditions. These include the amount of soluable salts present in the soil, soil type (texture), quality of irrigation water, ET rates, rainfall amounts and distribution, and depth of groundwater (drainage practices). Guidance as to the amount of leaching required for specific situations is available from several sources, especially the U.S. Salinity Laboratory, Riverside, California (U.S. Salinity Lab. Staff, 1954) and the Hebrew University of Jerusalem, Israel (Yaron et al., 1974). Salinity problems and control are discussed in detail in Chapter 5. Procedures for estimating leaching requirements are presented in FAO-ID 29 and the ASCE-CU Report (Ayres and Wescot, 1976; and Jensen, 1974).

6.8 ESTIMATING EFFECTIVE RAINFALL

Effective rainfall is that portion of rainfall that contributes to meeting the ET requirement of a crop (Hershfield, 1964). This differs diametrically from the hydrologic definition which describes effective rainfall as that portion of the total rain that produces runoff. Thus, rain water that neither leaves as surface runoff nor contributes to excess subsurface drainage may be effective precipitation in the context of irrigation water management. An extensive review of models for estimating effective rainfall from measured rainfall has been published by the Food and Agriculture Organization of the United Nations (Dastane, 1974).

Rain water retained by the plant canopy contributes to the satisfaction of the meteorological evaporative demand. This results in a consequent reduction in use of soil moisture. However, some engineers discount each rainfall event by a small amount, say 2 mm (0.08 in.), in situations where vegetative cover is incomplete or where prevailing ET rates are otherwise less than potential.

Estimates of effective precipitation should take local conditions into account. Rainfall of high intensity or large amounts that produce runoff should be considered to be of reduced value. Similarly, rainfall on an already wet soil profile is ineffective to the extent that subsurface drainage exceeds leaching requirements. Soil moisture accretion after the crop reaches physiological maturity is nonbeneficial unless it is stored in the soil for use by a crop during the next growing season.

Heermann and Shull (1976) upon analyzing seasonal, monthly, daily and hourly occurrence and dissipation of different rainfall amounts concluded that daily ET is increased after a rainfall during the early development o the crop (alfalfa). Frequent irrigations and rainfall increased the tota seasonal ET as compared with infrequent rainfall and irrigation. Small rainfall amounts are important, not only in the amount of water received, but because of the associated decrease in potential ET due to cloudy, humid conditions. Techniques are available (Jensen, 1974; Jensen et al., 1971; Ritchie, 1972) to account for increased evaporation immediately after an irrigation or rainfall.

Two of the simple models of estimating effective rainfall from measured rainfall are presented here. The first method is very simple and was apparently developed by the U.S. Bureau of Reclamation for monthly water resource calculations. Stamm (1967) makes the following comments about its use. The method is intended for the arid and semi-arid areas of the Western United States. To be conservative the method should be applied to the driest 5 consecutive years in the growing season only. The latter requirement has

TABLE 6.12. EFFECTIVE PRECIPITATION BASED ON INCREMENTS OF MONTHLY RAINFALL (U.S. BUREAU OF RECLAMATION METHOD)

Precipitation increment range			Effective precipitation accumulated - range	
mm	in.	Percent	mm	in.
0.0- 25.4	0-1	90-100	22.9- 25.4	0.90-1.00
25.4- 50.8	1-2	85- 95	44.4- 49.5	1.75-1.95
50.8- 76.2	2-3	75- 90	63.5- 72.4	2.50-2.85
76.2-101.6	3-4	50- 80	76.2- 92.7	3.00-3.65
101.6-127.0	4-5	30- 60	83.8-107.9	3.30-4.25
127.0-152.4	5-6	10- 40	86.4-118.1	3.40-4.65
Over -152.4	Over 6	0- 10	86.4-120.6	3.40-4.75

often been ignored. Table 6.12 shows factors used to estimate monthly effective rainfall from measured rainfall.

A second commonly used method in the United States of estimating effective rainfall from field measurements was developed by the Soil Conservation Service. The method, which is described in more detail by Dastane (1974), is based on a soil moisture balance performed for 22 stations using 50 years of data. The method recognizes both monthly ET estimates and monthly precipitation measurements. In addition the method indicates that effective rainfall defined for irrigation purposes by the depth of irrigation water applied is directly related to irrigation frequency. The monthly effective rainfall may be estimated for a 75-mm irrigation application using Table 6.13. If the irrigation application differs from 75 mm the effective rainfall may be corrected by an appropriate factor selected from Table 6.14.

6.9 IRRIGATION EFFICIENCY

6.9.1 Estimating Expected Irrigation Efficiency

After determining net irrigation water requirements, an estimate of the expected irrigation efficiency is needed to determine gross irrigation water requirements. No irrigation system is capable of applying an exact amount of water with perfect uniformity. In addition, some water will be lost by evaporation during application, especially with sprinkler systems. Loss of water by evaporation during sprinkling may reduce the rate at which soil water normally would be extracted when not being irrigated so that this may not be a total loss. The effectiveness of evaporation in reducing soil water extraction is expected to vary from near 100 percent when evaporation occurs from water ponded on the surface of an actively growing crop to near zero for evaporation from sprinkler spray discharging several meters above the crop under windy conditions (also see Section 14.5).

Surface runoff, water spillage and leakage from the on-farm water distribution system also affect the expected farm irrigation efficiency. A major part of surface runoff and spillage may be recovered for use on a given farm if an effective reuse system is used.

Seepage from unlined farm ditches and deep percolation through the soil profile due to nonuniform and excessive water applications usually cannot be recovered for use on a given farm so as to affect the design irrigation efficiency. However, from a water supply viewpoint, water returning to the groundwater below a farm reduces net depletion of the water supply. Likewise, recovery of surface runoff and in

TABLE 6.13. AVERAGE MONTHLY EFFECTIVE RAINFALL AS RELATED TO MEAN MONTHLY RAINFALL AND MEAN MONTHLY CONSUMPTIVE USE (USDA, SCS)

Monthly mean rainfall mm	Mean monthly consumptive use mm													
	25	50	75	100	125	150	175	200	225	250	275	300	325	350
	Mean monthly effective rainfall mm													
12.5	7.5	8.0	8.7	9.0	9.2	10.0	10.5	11.2	11.7	12.5	12.5	12.5	12.5	12.5
25.0	15.0	16.2	17.5	18.0	18.5	19.7	20.5	22.0	24.5	25.0	25.0	25.0	25.0	25.0
37.5	22.5	24.0	26.2	27.5	28.2	29.2	30.5	33.0	36.2	37.5	37.5	37.5	37.5	37.5
50.0	25	32.2	34.5	35.7	36.7	39.0	40.5	43.7	47.0	50.0	50.0	50.0	50.0	50.0
62.5	at 41.7	39.7	42.5	44.5	46.0	48.5	50.5	53.7	57.5	62.5	62.5	62.5	62.5	62.5
75.0		46.2	49.7	52.7	55.0	57.5	60.2	63.7	67.5	73.7	75.0	75.0	75.0	75.0
87.5		50.0	56.7	60.2	63.7	66.0	69.7	73.7	77.7	84.5	87.5	87.5	87.5	87.5
100.0		at 60.7	63.7	67.7	72.0	74.2	78.7	83.0	87.7	95.0	100	100	100	100
112.5			70.5	75.0	80.2	82.5	87.2	92.7	98.0	105	111	112	112	112
125.0			75.0	81.5	87.7	90.5	95.7	102	108	115	121	125	125	125
137.5			at 122	88.7	95.2	98.7	104	111	118	126	132	137	137	137
150.0				95.2	102	106	112	120	127	136	143	150	150	150
162.5				100	109	113	120	128	135	145	153	160	162	162
175.0				at 160	115	120	127	135	143	154	164	170	175	175
187.5					121	126	134	142	151	161	170	179	185	187
200.0					125	133	140	145	158	168	178	188	196	200
225					at 197	144	151	160	171	182				
250						150	161	170	183	194				
275						at 240	171	181	194	205				
300							175	190	203	215				
325							at 287	198	213	224				
350								200	220	232				
375								at 331	225	240				
400									at 372	247				
425										250 at 412				
450	25	50	75	100	125	150	175	200	225	250				

within a project, reduces the net depletion of water in a river-groundwater system. Recovery of return flows, both surface and subsurface, for use on downstream projects affects the net depletion of water in river basins. The reuse of return flow is one of the main foundations of Western water right management, and its importance is impossible to overestimate.

The overall farm irrigation efficiency to be used in design should be estimated by considering all components that affect irrigation efficiency.

TABLE 6.14. MULTIPLICATION FACTORS TO RELATE MONTHLY EFFECTIVE RAINFALL VALUE OBTAINED FROM TABLE 6.13 TO NET DEPTH OF IRRIGATION APPLICATION (d)

d mm	factor	d mm	factor	d mm	factor
10.0	0.620	31.25	0.818	70.0	0.990
12.5	0.650	32.5	0.826	75.0	1.000
15.0	0.676	35.0	0.842	80.0	1.004
17.5	0.703	37.5	0.860	85.0	1.008
18.75	0.780	40.0	0.876	90.0	1.012
20.0	0.728	45.0	0.905	95.0	1.016
22.5	0.749	50.0	0.930	100.0	1.020
25.0	0.770	55.0	0.947	125.0	1.040
27.5	0.790	60.0	0.963	150.0	1.060
30.0	0.808	65.0	0.977	175.0	1.070

Identifying the magnitude of the various components will assist in determining the alternative design or types of systems that should be considered.

6.9.2 Irrigation Efficiency Definitions

The following terms proposed by the Irrigation Water Requirements Committee of the American Society of Civil Engineers (Jensen, 1974) are applicable to on-farm systems as well as projects. They are similar to those proposed by the International Commission of Irrigation and Drainage (Bos and Nugteren, 1974).

Reservoir storage efficiency, E_s, is the ratio of the volume of water available from the reservoir for irrigation, to the volume of water delivered to the storage reservoir—surface or underground—for irrigation.

Water conveyance efficiency, E_c, is the ratio of the volume of water delivered to the point of use by an open or closed conveyance system to the volume of water introduced into the conveyance system at the supply source or sources.

Unit irrigation efficiency, E_u, is the ratio of the volume of irrigation water required for beneficial use in the specified irrigated area to the volume of water delivered to this area.

Farm irrigation efficiency, E_i, is the product of the component terms, expressed as ratios.

$$E_i = E_s\,E_c\,E_u \qquad [6.38]$$

The overall irrigation efficiency for a project or a river basin can be expressed in a similar manner. For clarity and comparative purposes, all efficiency estimates or evaluations should be identified as to the size of unit, the period of time or number of irrigations involved, the adequacy of irrigations in meeting net irrigation requirements, and computational procedures used.

Effective irrigation efficiency, E_e, of a farm, project, or river basin is necessary to estimate or evaluate the net depletion of water within a river basin or groundwater system (Jensen, 1977). It is based on the assumption that irrigation efficiency ($E_i = V_c/V_w$) as defined by Israelsen (1950) is the ratio of water consumed (V_c) by the agricultural crops on a farm project to the water diverted (V_w) from a natural source into the farm or project canals and laterals. The net depletion of water, V_{dep}, specifically for irrigation is

$$V_{dep} = V_c + (1 - E_r)\,V_{nc} \qquad [6.39]$$

where V_c is the volume consumed by agricultural crops; V_{nc} is the volume diverted to a farm or project that is not consumed by the crops; and E_r is the fraction of E_{nc} that is recovered (or could be when evaluating the potential efficiency) for agriculture or other uses. The effective efficiency is

$$E_e = \frac{V_c}{V_w} + E_r\,\frac{V_{nc}}{V_w} \qquad [6.40]$$

which also can be expressed as

$$E_e = E_i + E_r\,(1 - E_i) \qquad [6.41]$$

Additional discussions and definitions of similar irrigation efficiency terms can be found in articles by Bos and Nugteren (1974), Jensen et al. (1967), Kruse and Heermann (1977) and Schmueli (1973). A summary of observed and attainable field and farm irrigation efficiencies was presented by Jensen (1978).

Irrigation water use efficiency, E_{iw}, is a measure of the increase in the production of the marketable crop component relative to the increase in water consumed when irrigated, over the consumption under nonirrigated conditions. The Committee on Irrigation Efficiencies of the International Commission on Irrigation and Drainage (Bos, 1980) recently defined this efficiency as the yield/ET ratio, Rye

$$\text{Rye} = \frac{V_i - V_o}{ET_i - ET_o} \qquad [6.42]$$

where V_i is the mass of marketable crop produced with irrigation; V_o is the mass of marketable crop (that could be) produced without irrigation: ET_i is the mass of water used in ET by the irrigation crop; and ET_o is the mass of water (that could be) used in ET by the same crop if not irrigated. Rye as defined is dimensionless, but in practice irrigation water use efficiency would be more conveniently expressed as mass of marketable crop per unit volume of water (kg/m^3) as has been done by many others over the past two decades. Typical maximum values to be expected for grain crops like corn and wheat are 1.5 to 2.0 kg/m^3.

6.10 DESIGN REQUIREMENTS

For many years it has been traditional to base the design capacity of sprinkler or other irrigation systems on what is called the peak ET rate. The peak ET rate is for the irrigation interval (I) and is higher for a one or two day period than for a week or more as the irrigation interval. Several recent studies have shown that the design ET rate (E_{td}) should be based on a probability level of expected ET which changes throughout the growing season. The system designer must make a choice of E_{td} based on soil moisture holding capacity, climatic probability, and the crop grown. The variables involved are: E_{td} is the peak ET rate for the irrigation interval used for design purposes, in depth per time, commonly mm/d (in./d); I is the irrigation interval in days; and D_n is the net depth of water to be applied during the design period in mm (in.). D_n is a function of soil characteristics, plant growth stage, and may include an allowance for leaching. See Chapters 4 and 18 for more information on the determination of D_n.

Two methods of estimating E_{td} are presented. The first involves the use of historic climatic data to estimate the expected ET on a probability basis and the second uses empirical relationships between estimated average monthly ET and E_{td}. The second approach does not involve probability.

6.10.1 Estimating E_{td} Using Climatic Records

An array of daily estimates of ET can be generated by using a long term climatic data set and a method of estimating ET suitable for daily values. One of the combination equations, such as the Penman, should be used and a frequency analysis made. E_{td} can then be selected on a probability basis for any desired interval during the growing season.

A series of recent papers show the statistical variation of E_{td} for selected

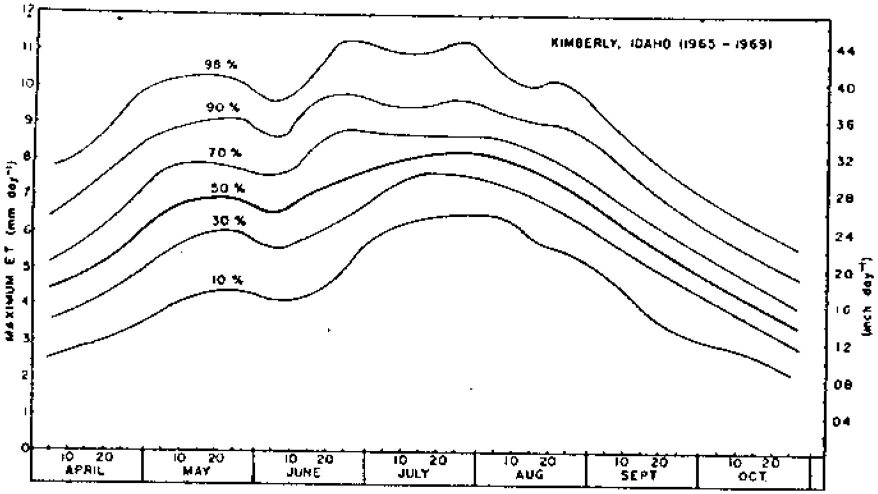


FIG. 6.4 Frequency distributions for reference ET (E_{tr}) for well watered alfalfa with full cover as calculated from 5 years of climatic data for Kimberly, Idaho (from Wright and Jensen, 1972).

locations in California, Idaho, and Nebraska (Pruitt et al., 1972; Wright and Jensen, 1972; Rosenberg, 1972; and Nixon et al, 1972). Typical results for Kimberly, Idaho (Wright and Jensen, 1972) are shown in Fig. 6.4 and 6.5.

6.10.2 E_{td} Based on Monthly Estimates

Engineers often do not have the time and the data needed to perform a statistical analysis to evaluate E_{td} requirements for design purposes. For many years the Soil Conservation Service has used an empirical method of estimating peak ET based on mean monthly values of ET as follows:

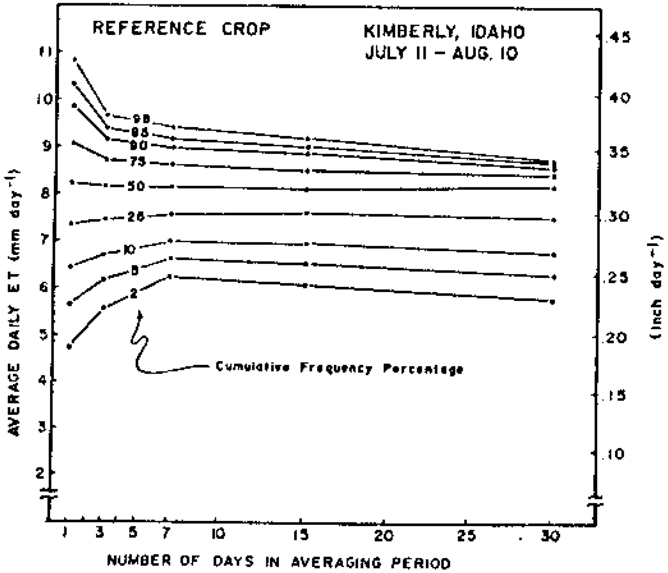
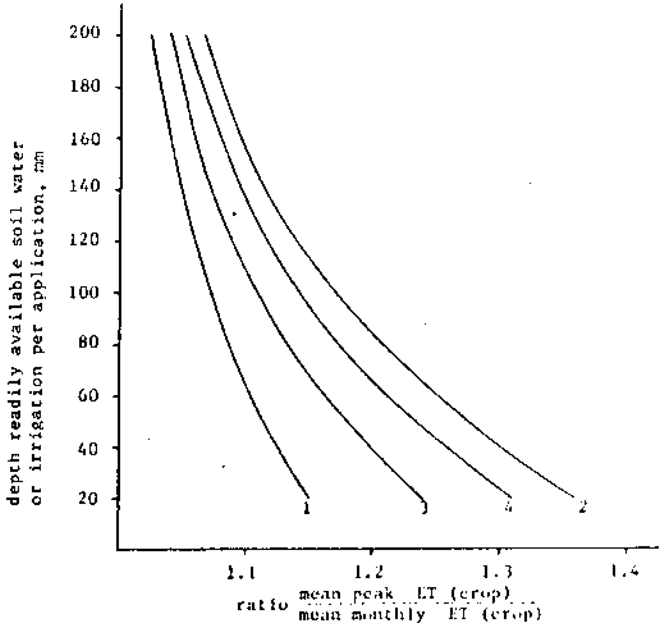


FIG. 6.5 Cumulative frequency percentages of average daily ET, estimated from data in Fig. 6.4 for 1-day, 3-day, 7-day, 15-day, and 30-day averaging periods for the peak 30-day period at Kimberly, Idaho (from Wright and Jensen, 1972).

$$E_{td} = 0.034\, E_{tm}^{1.09}\, I^{-0.09} \qquad [6.43]$$

where E_{tm} = mean ET for the month in mm and I = the net irrigation application in mm. For example, if the mean monthly ET is 200 mm (or about 6.7 mm/d) and the net irrigation is 100 mm, the E_{td} will be 7.2 mm/d. This procedure does not involve climatic probability but does consider the time period between irrigations by accounting for the depth of irrigation water applied. A soil with low water holding capacity would have a short irrigation interval because of the small amount of water retained for plant use. The method does not give the designer the opportunity of selecting a probability level for use in claculating the peak ET rate.

The relationship between monthly ET and peak ET for design purposes is very dependent on climatic conditions. These climatic differences are considered in a method recommended by the FAO (Doorenbos and Pruitt, 1977). The designer can utilize a simple graphical procedure for estimating peak E_t from monthly estimates (Fig. 6.6). The method also does not involve a probability level.



1. Arid and semi-arid climates and those with predominantly clear weather conditions during month of peak ET crop.
2. Mid-continental climates and sub-humid to humid climates with highly variable cloudiness in month of peak ET crop.
3. and 4. Mid-continental climates with variable cloudiness and mean ET crop of 5 and 10 mm/day respectively.

FIG. 6.6 FAO procedure for estimating peak ET from monthly estimates (from Doorenbos and Pruitt, 1977)

TABLE 6.15. APPROXIMATE RANGES OF SEASONAL CROP ET FOR VARIOUS CROPS (from Dorenbos and Pruitt, 1977)

Crop	Seasonal ET, mm	Crop	Seasonal ET, mm
Alfalfa	600-1500	Onions	350- 600
Avocado	650-1000	Orange	650- 950
Bananas	700-1700	Potatoes	350- 625
Beans	250- 500	Rice	500- 950
Cocoa	800-1200	Sisal	550- 800
Coffee	800-1200	Sorghum	300- 650
Cotton	550- 950	Soybeans	450- 825
Dates	900-1300	Sugarbeets	450- 850
Deciduous trees	700-1050	Sugar cane	1000-1500
Flax	450- 900	Sweet potatoes	400- 675
Grains, small	300- 450	Tobacco	300- 500
Grapefruit	650-1000	Tomatoes	300- 600
Maize	400- 750	Vegetables	250- 500
Oil seed	300- 600	Vineyards	450- 900
—		Walnuts	700-1000

6.11 ANNUAL REQUIREMENTS

Seasonal ET estimates are often needed for a variety of water resource deliberations. The Irrigation Water Requirements Technical Committee, American Society of Civil Engineers, published an extensive table of seasonal ET measurements for a wide variety of crops at several locations (Jensen, 1974). Table 6.15 presents a summary of the approximate range in seasonal ET to be expected for various crops (Doorenbos and Pruitt, 1977). Seasonal ET is dependent on climate, time of planting, crop conditions, length of growing season, and other factors, such as the soil water level that is maintained. If ET estimates are greater or less than those shown in Table 6.15, calculations should be reviewed carefully and efforts should be made to verify that conditions are sufficiently different to account for differences in the estimates.

6.12 DESIGN CAPACITY

The design capacity of irrigation systems should meet peak evapotranspiration requirements. The delivery volume is determined by the expected cropping pattern serviced by the system. This involves considering the area devoted to each type of crop and its expected ET rate.

System design also involves the frequency with which each field must be irrigated. This is a function of the soil moisture holding capacity, effective depth of crop rooting, and the rate at which soil water is depleted as governed by the ET rate (Stamm, 1967).

Theoretically, an irrigation system can be designed for less than the peak daily ET rate as long as it can provide the peak average rate during the period between irrigations. The design capacity must allow for conveyance losses in the system and inefficiencies of applying water to the land. Also, the actual delivery rate of a system may be less than the design rate because of such factors as misaligned joints, dented pipe, or changed friction coefficients of channels, etc.

It may be prudent to include a flexibility or safety factor to allow for breakdowns, holidays, requirements for faster coverage for insect or disease control or other agrotechnical reasons, changes from the assumed cropping pattern, and occasional very windy days in the case of sprinkler (Zimmerman, 1966).

The design capacity should provide flow rates that are sufficient for the method of irrigation employed. A parallel consideration is that the design be compatible with the infiltration rate of the soil.

6.13 ESTIMATED RETURN FLOW AND QUALITY

Irrigation water applied in excess of crop requirements will result in surface runoff from the lowest point on the field and/or will percolate beyond the root zone. The surface run-off and deep percolation, moving under the influence of gravity and eventually re-entering streams or lakes, is referred to as "return flow". Return flow quality and quantity is of very great hydrologic importance.

Return flow becomes divertable water for downstream water users and therefore changes in return flow may disrupt the management of water resources. Western water right laws require that changes in water rights must not harm vested water rights. This means that when irrigation water rights are converted to municipal or industrial uses stream flow may have to be augmented by releases from reservoirs to make up lost return flow. Excess soil water which reappears as return flow is water in temporary storage and tends to stabilize Western stream flow.

Irrigation in excess of crop water requirements may create drainage problems. Some excess water is needed to maintain an acceptable salt balance in the soil (see Section 6.7 and Chapter 5 for a detailed discussion of leaching for salt management, and Chapter 7 for details concerning drainage).

Return flows contain more dissolved solids than the irrigation water because ET removes pure water. In addition flow through or over the soil and geologic formations in their path may cause further changes in water quality both chemically and biologically. These changes may be environmentally desirable or undesirable. An example of a desirable change results from the application of wastewater using irrigation methods as a means of renovating the wastewater. This method is now receiving increasing attention.

Irrigation management practices which assure high quality return flow are also receiving widespread attention. Sufficient research has been completed to permit intelligent decision making processes to proceed in solving many water quality problems in irrigated agriculture. Results of irrigation return flow research and development programs were summarized in the proceedings of a national conference on irrigation return flow quality management sponsored by the U.S. Environmental Protection Agency (Law and Skogerboe, 1977).

6.14 EXAMPLE CALCULATIONS

These example calculations are intended for the trained engineer or irrigation scientist with access to a scientific electronic calculator or to a computer. Most of the procedures followed are easy to adapt to a modern computer.

Daily Estimates, Penman method. A calibrated version of a combination equation such as Penman's is probably the most suitable method of accurately estimating daily ET. These calculations refer to the Penman method described in Subsections 6.4.2 and 6.5.3. The data used represent a typical summer day, at Kimberly, Idaho.

Day Number 200, July 19

Elevation	1195 m
Maximum air temperature	32.2 °C
Minimum air temperature	12.2 °C
Average air temperature	22.2 °C
Average dew point temperature	10.0 °C
Average air temperature for the previous 3 days	20.9 °C
Clear day solar radiation	747 ly
Measured solar radiation	686 ly
Measured net radiation	360 ly
Wind velocity at 3.66-m elevation	164 km/day
Estimated daytime wind/nighttime wind	4.0
Measured ET for alfalfa	8.5 mm

Step 1. Estimate E_{tr}, using constant albedo and W_f

$$E_{tr} = \frac{\Delta}{\Delta + \gamma}(Rn + G) + \frac{\gamma}{\Delta + \gamma} 15.36\,(W_f)(e_a - e_d) \quad \ldots\ldots\ldots\ldots \quad [6.4]$$

$$\Delta = 2.00\,(0.00738 \times 22.2 + 0.8072)^7 - 0.00116 \quad \ldots\ldots\ldots\ldots \quad [6.5]$$

$$= 1.627 \text{ mb}/^\circ\text{C}$$

$$P = 1013 - 0.1055 \times 1195 = 887 \text{ mb} \quad \ldots\ldots\ldots\ldots \quad [6.7]$$

$$L = 595 - 0.51 \times 22.2 = 584 \text{ cal/g} \quad \ldots\ldots\ldots\ldots \quad [6.8]$$

$$\gamma = \frac{0.386 \times 887}{584} = 0.586 \text{ mb}/^\circ\text{C} \quad \ldots\ldots\ldots\ldots \quad [6.6]$$

$$\frac{\Delta}{\Delta + \gamma} = \frac{1.627}{1.627 + 0.586} = 0.735$$

$$\frac{\gamma}{\Delta + \gamma} = 1.000 - 0.735 = 0.265$$

$\frac{\Delta}{\Delta + \gamma}$ and $\frac{\gamma}{\Delta + \gamma}$ also can be interpolated from Table 6.1.

$$U_2 = 164 \left(\frac{2}{3.66}\right)^{0.2} = 145 \text{ km/d} \quad \ldots\ldots\ldots\ldots \quad [6.10]$$

$$e_d = 33.8639\,[(0.00738 \times 10.0 + 0.8072)^8 - 0.000019\,|1.8 \times 10.0 + 48|$$
$$+ 0.001316]$$
$$= 12.3 \text{ mb} \quad \ldots\ldots\ldots\ldots \quad [6.12]$$

$$e_a = \frac{1}{2}(48.1 + 14.2) = 31.1 \text{ mb} \quad \ldots\ldots\ldots\ldots \quad [6.11]$$

Meteorological tables also can be used for vapor pressures.

$$R_{bo} = (0.325 - 0.044\sqrt{12.3})\,\frac{11.71(273 + 22.2)^4}{10^8} \quad \ldots\ldots\ldots\ldots \quad [6.15]$$

and Table 6.3

$$R_{bo} = 152 \text{ ly}$$

Alternate R_{bo}

$$\epsilon = -0.02 + 0.261 \exp\left[\frac{-7.77}{10^4}(22.2)^2\right] \quad \ldots\ldots\ldots\ldots \quad [6.17]$$

$$= 0.158$$

$$R_{bo} = \frac{0.158 \times 11.71}{10^8}(273 + 22.2)^4 \quad \ldots\ldots\ldots\ldots \quad [6.15]$$

$$= 140 \text{ ly}$$

$$R_b = [1.22 \times \frac{687}{747} - 0.018]\;152 = 168 \text{ ly} \quad \ldots\ldots\ldots\ldots \quad [6.14]$$

$$R_n = (1 - 0.23)\,687 - 168 = 361 \text{ ly} \quad \ldots\ldots\ldots\ldots \quad [6.13]$$

Assume G = 0

$$E_{tr} = 0.735\,(361 + 0) + 0.265(15.36)(0.75 + 0.0115 \times 145)(31.1$$
$$- 12.3) \quad \ldots\ldots\ldots\ldots \quad [6.4]$$

$$= 450 \text{ ly/d}$$

$$= \frac{450 \dfrac{\text{cal}}{\text{cm}^2 \text{ day}}}{584 \dfrac{\text{cal}}{\text{cm}^3}} \times 10 \frac{\text{mm}}{\text{cm}}$$

$$= 7.71 \text{ mm/day}$$

Monthly ET estimates. Data used for these estimates represent average July conditions for Kimberly, Idaho. Estimates of E_{tr} are based on procedures found in Subsections 6.4.3, 6.4.5, 6.5.3, and 6.5.4:

Mean maximum air temperature	30.0 °C
Mean minimum air temperature	11.7 °C
Mean air temperature	20.8 °C
Mean dew-point air temperature	9.4 °C
Mean vapor pressure	11.8 mb
Mean wind travel at 3.66 m	206 km/day
U-day/U-night (assumed)	3.0
Mean percent sunshine (estimated from radiation data)	84%
Mean day length	14.8 h
Mean pan (Class A) evaporation	8.9 mm/day
Mean measured alfalfa ET	8.1 mm/day
Latitude	42.2 deg N
Mean solar radiation	640 ly/day
Crop (assume)	field corn

ET Estimated by Jensen-Haise Method:

$$E_{tr} = C_T(T - T_x)R_s \quad \ldots\ldots\ldots\ldots \quad [6.19]$$

$e_2^* = 42.4$ mb, for 30 °C .... [6.12]

$e_1 = 13.8$ mb, for 11.7 °C .... [6.12]

$C_H = 50/(42.4 - 13.8) = 1.75$ .... [6.21]

$C_1 = 38 - (2 \times 1195)/305 = 30.2$ .... [6.22]

$C_T = 1/(30.2 + 7.3 \times 1.75) = 0.0233$ .... [6.20]

$T_x = -2.5 - 0.14(42.4 - 13.8) - 1195/550 = -8.7$ °C .... [6.23]

$E_{tr} = 0.0233(20.8 - (-8.7))640 = 440$ ly/day = 7.5 mm/d ..... [6.19]

ET Estimated by Blaney-Criddle (FAO Method):

$E_{to} = a_4 + b_4 f$ (a regression relationship) .... [6.24]

$f = p(0.46T + 8)$ .... [6.25]

$p = 0.33$ (Table 6.4, July at Lat. 42.2 °N)

$(0.46T + 8) = 0.46 \times 20.8 + 8 = 17.57$

$f = P(0.46T + 8) = 5.80$ .... [6.25]

From Fig. 6.2 for $f = 5.80$, $n \simeq 0.9$,

U Daytime $\simeq$ 2 – 5 m/s, and

RH min = 100 × 11.8/42.4 = 28% $\simeq$ 20 – 50 range

$E_{to} = 7.1$ mm/day (ET for grass)

Since $E_{tr} \simeq 1.15\ E_{to}$ (for light to moderate winds in arid climates)

$E_{tr} \simeq 1.15 \times 7.0 = 8.2$ mm/day

ET Estimated by Pan Evaporation, FAO:

$E_{to} = K_p E_p$ .... [6.26]

K_p for case A, with 100 m fetch,

$$RH_{mean} = \frac{100}{2}\ [11.8/13.8 + 11.8/42.4] = 57\%, \text{ and}$$

$U_2 = 183$ km/day (Light to Moderate, extrapolated to 2 meters)

$K_p = (0.8 + 0.75)/2 \simeq 0.78$ (Table 6.5)

$E_p = 8.9$ mm/day for July mean

$E_{to} = K_p E_p = 0.78 \times 8.9 = 6.9$ mm/day .... [6.26]

Since $E_{tr} \simeq 1.15\ E_{to}$ (for light-moderate winds in arid climates)

$E_{tr} = 1.15 \times 6.9 = 7.9$ mm/day

Crop Curve Development, FAO Method. An example of the construction of a grass related crop curve, using the procedure of Doorenbos and Pruitt (1977), is presented for field corn at Kimberly, Idaho. The necessary dates pertaining to crop development from Table 6.7 are planting, 5/5; emergence, 5/25; rapid growth, 6/10; full cover, 7/15; tasselling, 7/30; ripening, 9/10; harvest (silage), 9/20; 70 days. Assuming an E_{to} for May of 6.5 mm/d and irrigation on 7-day intervals; an initial K_c of 0.45, as determined from Fig. 6.7; and the beginning of the mid-season stage of growth on 7/1; the constructed crop curve would be as shown in Fig. 6.8. The maximum K_c for mid-season of 1.05 was determined using a maximum e_s of 42.4 mb (30 °C) and a minimum e_s of 11.8 mb (9.4 °C), giving a minimum Relative Humidity of 28 percent; and a U_2 for daytime wind of 3.2 m/s. A K_c of 0.55 was assumed for stage of maturity for silage harvest.

References

1 Ayers, R. S., and D. W. Westcot. 1976. Water quality for agriculture. FAO Irrig. and Drain. Paper 29, 97 p.

2 Blanc, M. L., H. Geslin, I. A. Holzberg, and B. Mason. 1963. Protection against frost damage. Tech. Note No. 51. World Meteorol. Org., Geneva, 62 p.

3 Blaney, H. F. and W. D. Criddle. 1945. Determining water requirements in irrigated areas from climatological data. (processed) 17 p.

4 Bos, M. G. 1980. Irrigation efficiencies at crop production level. Intern'l Comm. on Irrig. and Drain. Bul. (In print).

5 Bos, M. G. and J. Nugteren. 1974. On irrigation efficiencies. Intern'l Inst. for Land Reclam. and Improve. Publ. 19, Wageningen, Neth., 95 p. (Note: 2nd edition 1978, 142 p.).

6 Bosen, J. F. 1960. A formula for approximation of the saturation vapor pressure over water. Monthly Weather Rev. 88(8):275-276.

7 Brunt, D. 1952. Physical and dynamical meteorology. 2nd ed. University Press, Cambridge, 428 p.

8 Bucks, D. A., L. J. Erie, and O. F. French. 1974. Quantity and frequency of trickle and furrow irrigation for efficient cabbage production. Agron. J. 66:53-57.

9 Burman, R. D. 1979. Estimation of mountain meadow water requirements. Symp.

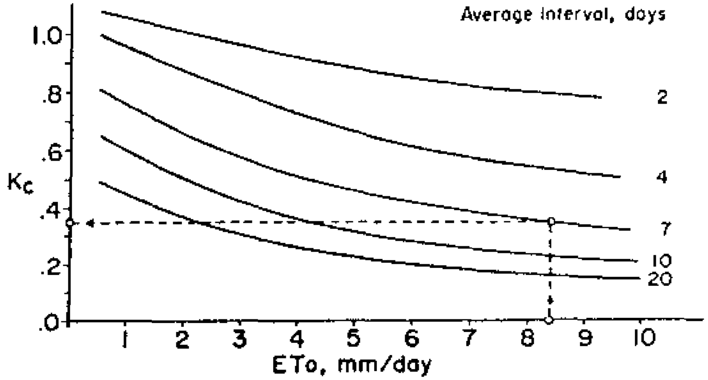


FIG. 6.7 Average crop coefficients (K_c) for grass reference ET (E_{to}) for the initial crop development stage as related to the average recurrence interval of irrigation and/or to the average recurrence interval of irrigation and/or significant rains from an example for Cairo, Egypt. (adapted from Doorenbos and Pruitt, 1977)

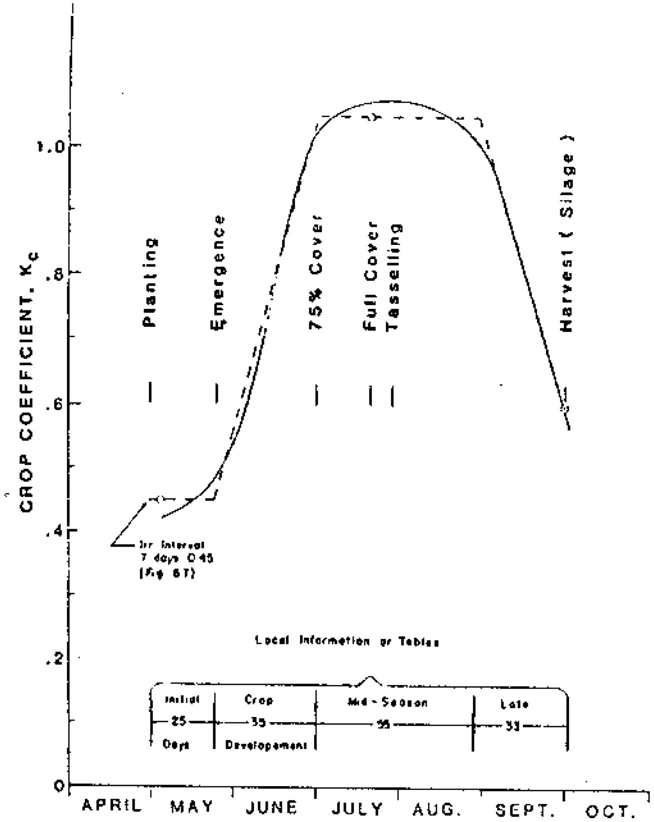


FIG. 6.8 Example of crop coefficient curve constructed for a crop of field corn using grass reference ET (E_{to}).

Proc., Management of Intermountain Meadows, RJ 141, Wyo., 11-23.

10 Burman, R. D., J. L. Wright and M. E. Jensen. 1975. Changes in climate and estimated evaporation across a large irrigated area in Idaho. TRANSACTIONS of the ASAE 18(6):1089-1093.

11 Carroll, J. J., J. R. Dunbar, R. L. Gibens, and W. B. Goddard. 1974. Sprinkling for dust suppression in a cattle feedlot. Calif. Agric. 28(3):12-14.

12 Christiansen, J. E., and J. R. Davis. 1967. Sprinkler irrigation systems. p. 885-904. In: Irrigation of agricultural lands, R. M. Hagan, H. R. Haise, and T. W. Edminster (Ed.). Monog. 11, Am. Soc. Agron., Madison, WI.

13 Dastane, N. G. 1974. Effective rainfall in irrigated agriculture. Food and Agr. Org., United Nations, FAO Irrig. and Drain. Paper, 61 p.

14 Doorenbos, J. and W. O. Pruitt. 1977. Crop water requirements. FAO Irrig. and Drain. Paper 24 (rev.), 156 p.

15 Fritschen, L. J. 1965. Accuracy of evapotranspiration determinations by the Bowen ratio method. Bul. Intern'l. Assoc. Sci. Hydrol. 10:38-48.

16 Haise, H. A. and R. M. Hagan. 1967. Soil, plant, and evaporative measurements as criteria for scheduling irrigation. P 577-604. In: Irrigation of Agricultural Lands, R. M. Hagan, H. R. Haise, and T. W. Edminster (Ed.), Monog. 11, Am. Soc. Agron., Madison, WI.

17 Heermann, D. F. and H. H. Shull. 1976. Effective precipitation of various application depths. TRANSACTIONS of the ASAE 19(4):708-712.

18 Hershfield, D. M. 1964. Effective rainfall and irrigation water requirement. Proc. Am. Soc. Civil Eng., J. Irrig. and Drain. Div. 90:(IR2) 33-37.

19 Hounam, C. E. 1973. Comparison between pan and lake evaporation. World Meteorol. Org. Tech. Note No. 126, WMO-354, 52 p.

20 Howell, T. A. 1979. Evaporative demand as a plant stress. p. 97-113, In: Modification of the Aerial Environment of Crops. B. J. Bardiels and J. F. Gerber (Ed.). ASAE monog. No. 2.

21 Idso, S. B. and R. D. Jackson. 1969. Thermal radiation from the atmosphere. J. Geophys. Res., 74:5397-5403.

22 Israelsen, O. W. 1950. Irrigation Principles and Practices. John Wiley and Sons., Inc (2nd ed.), New York. 405 p.

23 Jensen, M. E. (Ed.). 1974. Consumptive use of water and irrigation water requirements. Rep. Tech. Com. on Irrig. Water Requirements. Am. Soc. Civ. Eng., Irrig. Drain. Div., 227 p.

24 Jensen, M. E. 1977. Water conservation and irrigation systems. Climate-Tech. Sem. Proc., Columbia, MO, p. 208-250.

25 Jensen, M. E. 1978. Irrigation water management for the next decade. Proc. New Zealand Irrig. Conf., Asburton, p. 245-302.

26 Jensen, M. E. and H. R. Haise. 1963. Estimating evapotranspiration from solar radiation. Proc. Am. Soc. Civ. Engr., J. Irrig. and Drain. Div. 89:15-41.

27 Jensen, M. E., D. C. N. Robb and C. E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. Proc. Am. Soc. Civ. Engr., J. Irrig. and Drain. Div. 96(IR1):25-38.

28 Jensen, M. E., L. Swarner, and J. T. Phelan. 1967. Improving irrigation efficiencies. p. 1120-1142. In: Irrigation of agricultural lands. R. M. Hagan, H. R. Haise and T. W. Edminster (Ed.) Monog. 11, Am. Soc. Agron., Madison, WI.

29 Jensen, M. E., J. L. Wright, and B. J. Pratt. 1971. Estimating soil moisture depletion from climate, crop and soil data. TRANSACTIONS of the ASAE 14(5):954-959.

30 Kruse, E. G. and H. R. Haise. 1974. Water use by native grasses in high altitude Colorado meadows. USDA-SEA-AR, ARS-W-6, 60 p.

31 Kruse, E. G. and D. P. Heermann. 1977. Implications of irrigation system efficiencies. J. Soil and Water Conserv. 32(6):265-270.

32 Law, J. P., Jr., and G. V. Skogerboe (Ed.). 1977. Irrigation return flow quality management. Proc. Nat. Conf. sponsored by U.S. Environmental Protection Agency and Colorado State Univ. Colo. State Univ., Fort Collins, Colo. 451 p.

33 Makkink, G. F. 1957. Testing the Penman formula by means of lysimeters. J. Inst. Water Engr. 11(3):277-288.

34 Merva, G. E. 1975. Physioengineering principals. AVI Publishing Co., 353 p.

35 Nixon, P. R., G. P. Lawless, and G. V. Richardson. 1972. Coastal California evapotranspiration frequencies. Proc. Am. Soc. Civ. Engr., J. Irrig. and Drain. Div. (IR2):185-191.

36 Nixon, P. R., N. A. McGillivray, and G. P. Lawless. 1963. Evapotranspiration—climate comparisons in coastal fogbelt, coastal valley, and interior valley locations in California. Publ. No. 62, Internat'l Assoc. Sci. Hydrol. Com. for Evaporation. p. 221-231.

37 Penman, H. L. 1948. Natural evaporation from open water, bare soil, and grass. Proc. Roy. Soc. London. A 193:120-145.

38 Penman, H. L. 1963. Vegetation and hydrology. Tech. Communication No. 53. Commonwealth Bur. of Soils, Harpenden, England, 125 p.

39 Pochop, L. O., et al. 1973. Psychrometric data patterns and prediction models. Wyo. Water Resour. Ser. No. 48, Univ. of Wyo.

40 Pruitt, W. O. 1966. Empirical method of estimating evaportranspiration using primarily evaporation pans. p. 57-61. In: Proc., Evapotranspiration and its role in water resources management. M. E. Jensen (Ed.), ASAE, St. Joseph, MI 49085.

41 Pruitt, W. O., S. von Oettigen, and D. L. Morgan. 1972. Central California evapotranspiration frequencies. Proc. Am. Soc. Civ. Engr., J. Irrig. and Drain. Div. (IR2):203-206.

42 Raney, F. E. and Yoshiaki Mihara. 1967. Water and soil temperature. p. 1024-1036. In: Irrigation of Agricultural Lands. R. M. Hagan, H. R. Haise, and T. W. Edminster (Ed.). Monog. 11. Am. Soc. Agron., Madison, WI.

43 Ravelo, C. J., E. A. Hiler, and T. A. Howell. 1977. Trickle and sprinkler irrigation of grain sorghum. TRANSACTIONS of the ASAE 20(1):96-99, 104.

44 Ritchie, J. T. 1971. Dryland evaporative flux in a subhumid climate: I Micrometeorological influences. Agron. J. 63:51-55.

45 Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8:1204-1213.

46 Ritchie, J. T. 1974. Evaluating irrigation needs for Southeastern U.S.A. Proc., Am. Soc. Civ. Engr., Irrig. and Drain. Div., Spec. Conf., Biloxi, MS.

47 Rosenberg, N. J. 1972. Frequency of potential evapotranspiration rates in central Great Plains. Proc. Am. Soc. Civ. Engr., J. Irrig. and Drain. Div. 98(IR2):203-206.

48 Schmueli, E. 1973. Efficient utilization of water in irrigation. p. 411-423. In: Arid Zone Irrigation, D. Yaron, E. Danfors, and Y. Vaadia (Ed.), Springer-Verlag, New York.

49 Stamm, G. G. 1967. Problems and procedures in determining water supply requirements for irrigation projects. p. 771-784, In: Irrigation of agricultural lands, R. M. Hagan, Monog. No. 11, Am. Soc. Agron., Madison, WI.

50 Tanner, C. B., and W. A. Jury. 1976. Estimating evaporation and transpiration from a row crop during incomplete cover. Agron. J. 68:239-243.

51 Taylor, S. A. 1965. Managing irrigation water on the farm. TRANSACTIONS of the ASAE 8:433-436.

52 U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. L. A. Richard (Ed.)., U.S. Dept. Agr. Handb. 60, 160 pp.

53 USDA, Soil Conservation Service. 1970. Irrigation water requirements. Eng. Div. Tech. Rel. No. 21, U.S. Gov't. Printing Office, 88 p.

54 van Bavel, C. H. M. 1966. Potential evapotranspiration: the combination concept and its experimental verification. Water Resour. Res. 2(3):455-467.

55 Viets, F. G., Jr., R. P. Humbert, and C. E. Nelson. 1967. Fertilizers in relation to irrigation practice. p. 1009-1023, In: Irrigation of Agricultural Lands. R. M. Hagan, H. R. Haise, and T. W. Edminster (Ed.), Monog. 11, Am. Soc. Agronomy, Madison, WI.

56 Westerman, P. W., B. J. Barfield, O. J. Loewer, and J. N. Walker. 1976. Evaporative cooling of a partially-wet and transpiring leaf—I. Computer model and its evaluation using wind-tunnel experiments. TRANSACTIONS of the ASAE 19(5):881-888.

57 Wolfe, J. W., P. B. Lombard, and M. Tabor. 1976. The effectiveness of a mist versus a low pressure sprinkler system for bloom delay. TRANSACTIONS of the ASAE 19(3):510-513.

58 Wright, J. L. 1979. Recent developments in determining crop coefficient values. (Abst) Proc., Am. Soc. Civ. Engr. Irrig. and Drain Div. Spec. Conf. July, p. 161-162.

59 Wright, J. L. 1981. New evapotranspiration crop coefficients. (In process).

60 Wright, J. L. and M. E. Jensen. 1972. Peak water requirements in Southern Idaho. Proc. Am. Soc. Civ. Engr., J. Irrig. and Drain. Div. 98(IR2):193-201.

61 Wright, J. L. and M. E. Jensen. 1978. Development and evaluation of evapotranspiration models for irrigation scheduling. TRANSACTIONS of the ASAE 21(1):88-96.

62 Yaron, D., J. Shalhevet, and E. Bresler. 1974. Economic evaluation of water salinity in irrigation. Res. Rep. to Resources for the Future, Inc. Dep. of Agr. Econ. and Manage. Hebrew Univ. of Jerusalem.

63 Zimmerman, J. D. 1966. Irrigation. John Wiley and Sons, New York, NY.