Chapter V

PLANT AND IRRIGATION WATER REQUIREMENTS*

INTRODUCTION

The primary purpose of irrigation is to provide a soil environment that will permit the germination of seeds, emergence of seedlings, the development of the root system, and supply water for plant use. Soil moisture must be maintained in a range that permits absorption of water by plant roots at a rate comparable to transpiration losses, and the soluble salt content in the root zone must not limit plant growth and water absorption. These are the important factors to be considered in evaluating "plant water requirements." Other factors may be involved, such as: The maintenance of a suitable soil moisture content that will not limit soil aeration, maintenance of a favorable soil temperature range for better quality crops, prevention of injury to young seedlings planted in arid climates.

The planner and operator of sprinkler irrigation systems must know both the seasonal and peak irrigation water requirements for the crops that will be raised on a field, farm, or project in order to design and prescribe operational procedures for a sprinkler system that will provide moisture to the soil and plant for optimum production of quality crops. Seasonal evapotranspiration water requirements are the basis for determining the total water requirements and the irrigation water requirements of a crop, field, farm or project. For efficient irrigation, the variation in water use by a crop from emergence to harvest should be known by the operator.

Definitions

Several terms are used extensively in describing factors affecting water requirements of plants. These are:

"**Transpiration** is the evaporation of water from plant surfaces directly into the atmosphere, or into intercellular spaces and then by diffusion through the stomates to the atmosphere."

"**Evapotranspiration** is the sum of transpiration and water evaporated from the soil, or exterior portions of the plants where water may

*Revisions in this chapter were by: Marvin E. Jensen, Director, USDA-ARS-SWC, Snake River Conservation Research Center, Kimberly, Idaho have accumulated from irrigation, rainfall, dew, or exudation from the interior of the plant." If the unit of time is small, evapotranspiration is expressed in acre-inches per acre or depth in inches. For larger units of time, such as a crop growing season or a 12-month period, the evapotranspiration is expressed as acre-feet per acre or depth in feet or inches.

"**Consumptive Use** is, for all practical purposes, identical with evapotranspiration. It differs by the inclusion of water retained in the plant tissue. However, the maximum amount of water in the plant generally represents less than 1 percent of the total water evaporated during the crop season."

"**Irrigation Water Requirement** is the quantity of water, exclusive of precipitation, required to maintain the desired soil moisture and salinity level during the crop season." It is usually expressed as depth in inches or feet for a given period of time.

Under practical conditions, the total amount of water lost by transpiration and evaporation are combined because the two are not independent (evapotranspiration). Transpiration may be influenced by the evaporation from soil, and evaporation from the soil surface is influenced by the amount of crop canopy existing and the availability of soil moisture near the soil surface.

Evapotranspiration results in the transfer of salt-free water to the atmosphere, thereby concentrating the salts remaining in the soil solution. Maintenance of a favorable root environment requires the replenishment of soil moisture as it is used and the removal of salts that accumulate.

Plant water requirements encompass the total water used in evapotranspiration, ET, whereas irrigation water requirements also include the water necessary for leaching (leaching is the removal of accumulated salts). The amount of water required for leaching is directly proportional to ET and the concentration of salts in the irrigation water, and inversely proportional to salinity tolerance of the crop. Thus ***evapotranspiration is the basic factor determining irrigation water requirements.***

Space will not permit detailed discussions of water requirements of all crops at all stages of growth, soil moisture levels, climatic regimes, and cultural practices. Instead, general relationships will be presented to provide a concise summary of factors affecting and controlling plant-water requirements, and to provide the designer with sufficient material for estimating general water requirements. A summary of general irrigation practices by crops is presented later in this chapter. Those interested are urged to secure additional information on specific crops from local sources such as the Agricultural Extension Service, Agricultural Experiment Stations, the Soil Conservation Service, Bureau of Reclamation, or other organizations involved in detailed irrigation water management studies or providing technical information on irrigation practices.

FACTORS AFFECTING PLANT WATER REQUIREMENTS

The evapotranspiration rate is affected by many factors, the most important of which are the amount of leaf area, stage of crop growth, climate, and soil.

Transpiration rates vary during the season, and vary with the stage of crop growth even though the evaporative demand may be nearly constant. With some annual crops, grain for example, the transpiration rate increases from the sprouting of the seed through the dough stage, then decreases as the grain ripens. Other annual crops, sugar beets for example, do not show a decrease in transpiration rate near harvest if the evaporative demand remains constant.

The most important climatic factor affecting evapotranspiration is solar radiation, because it is the source of energy necessary to transfer water from a liquid to the vapor phase in both plants and soil. Soil and air temperature, humidity, rainfall, and wind also influence evapotranspiration for a given crop.

Soil factors affecting evapotranspiration are: amount of available water in the root zone, temperature of the soil, and salt concentration. When the soil is near field capacity, the plant can obtain water with relative ease, but as the soil approaches the wilting point, it becomes more difficult for the roots to obtain water for transpiration. Evaporation from the soil is greater when the surface is wet and only a partial crop cover exists than when the surface begins to dry. Soil temperature affects the viscosity of the water in the soil, the vapor pressure, and the ability of the roots to absorb water. Lack of adequate soil aeration will slow root and top growth and thus indirectly limit the transpiration rate.

High concentrations of salt in the soil can kill the plant and stop transpiration entirely. In lesser amounts, it makes the plant roots do more work obtaining water and reduces the evapotranspiration and growth rates of the plant. It increases the irrigation requirement of a field because additional irrigation water in excess of that needed for evapotranspiration must be applied to leach the salts from the root zone.

DETERMINING EVAPOTRANSPIRATION

The designer of a sprinkler system seldom can justify the time or funds required to determine the rate of evapotranspiration that occurs in his area for various crops. Instead he must rely on the results of local studies, published results from studies conducted in other areas of similar climatic, and theoretical estimates. However, he should be aware of problems, techniques and reliability of various methods used to determine or measure evapotranspiration in order to evaluate the reliability and applicability of published ET data to his area. The various methods commonly used to determine or measure evapotranspiration are soil-moisture sampling, lysimetry, water balance, and energy balance.

Soil Sampling

The most common method of determining the average evapotranspiration rate is soil sampling. The method has been used for about 75 years in the western United States. Soil samples taken at two different dates and dried in an oven at 105° C are used to determine the decrease in soil moisture. More recently, neutron soil moisture probes have been used extensively and generally result in more reliable data. The rate of evapotranspiration is calculated using the following equation:

$$ET = \frac{W_{et}}{\Delta t} = \frac{-\sum_{0}^{S_r} (\Delta\theta \quad \Delta S) + R_e - W_d}{\Delta t} \qquad 5.1$$

where S = the distance from the soil surface, S_r = the depth of the effective root zone, $\Delta\theta$ = the volumetric change in soil moisture (negative for a decrease), Δt = the time interval between sampling dates (usually days), R_e = effective rainfall, W_{et}= the water used in evapotranspiration, and W_d = the water drained from the 0 to S_r depth. When using gravimetric sampling procedures, the soil moisture is usually expressed as a percentage on a dry-weight basis, P_w, and must be converted to a volumetric basis by multiplying by the bulk density, ρ_s, of the soil.

$$\theta = \rho_s \frac{P_w}{100} \qquad 5.2$$

The first set of samples is usually taken 2 to 4 days after an irrigation, and the second set 5 to 10 days later, or just before the next irrigation.

Evapotranspiration rates determined by soil sampling can be reliable, providing adequate precautions have been taken, such as: (1) at least 6 sampling sites representative of general field conditions are used, a minimum of 4 may be adequate when using a neutron meter; (2) the depth to the water table should be much greater than the root zone depth; (3) only those sampling periods where rainfall was light are used, all others are questionable because drainage (W_d) may be excessive; (4) drainage is minimized by: (a) giving the preplant irrigation at least 10 days before planting, (b) applying less water at each irrigation than the amount that could be retained, (c) the first sample is taken at least 2 days after a normal light irrigation, and longer if excessive irrigations were involved and when evapotranspiration (ET) is small, and (d) only the active root zone depth is used for ET computations. A more comprehensive discussion of the problems encountered in determining evapotranspiration by soil sampling can be found in articles by Jensen (1967)[34] and Davidson and Nielson (1966)[14].

Lysimetry

Lysimeters (evapotranspirimeters) are tanks filled with soil in which crops are grown to measure the amount of water used. Evapotranspiration data obtained from lysimeters are reliable provided the lysimeters are constructed, installed and operated so as to be representative of areas to which the results are to be applied.

Lysimeters can be grouped into the following categories: (1) Nonweighing, constant water-table type. These provide reliable data in areas of high water table conditions. (2) Nonweighing, percolation type, in which changes in water stored in the soil are also determined. These are often used in areas of high precipitation. (3) Weighing types, in which changes in soil water are determined either by weighing the entire soil-filled lysimeter with a mechanical scale system, counterbalanced load cell system, or by supporting the lysimeter hydraulically. These units may be either large fixed-position lysimeters, or with the recent development of electronic load cells they may be made small enough to be moved to new sites. Weighing lysimeters generally provide the most accurate data for short periods. Evapotranspiration can be determined accurately over periods as short as 1 hour. A detailed summary of the use of lysimeters for measuring evapotranspiration can be found in an article by Harrold (1966)[29] and in Technical Note 83, World Meteorological Organization (1966).[84]

Water Balance

Water balance techniques can be used with nonweighing lysimeters to measure evapotranspiration, but this method has generally been used on large areas. A typical example of the results of water balance studies for determining the average evapotranspiration for an area is the study by Lowry and Johnson (1942)[47]. They used annual inflow-outflow data for irrigation projects and obtained an empirical relationship between the annual consumptive use for an "equivalent valley area" of cropped or irrigated land and degree-days above 32 F. The results of studies such as these are generally applicable to similar climatic conditions, similar cropping patterns, and long time periods because long time periods are usually involved in the original developments.

Thornthwaite (1948)[72] correlated mean monthly air temperature with evapotranspiration as determined by water balance studies in the east-central part of the United States. The results of these studies are also generally applicable under similar climatic regions, and reasonably reliable for estimating long-time means, but not short period values.

Energy Balance

The energy balance method of determining evapotranspiration has been successfully used for periods of an hour or more. The general procedure is to determine net radiation, heat absorbed by or released from the soil, and the Bowen[18] ratio. The instrumentation requirements and technical procedures needed limit the general use of this procedure to well-trained individuals with elaborate instrumentation. The results obtained can be very reliable, primarily because they are obtained in fields under natural environment conditions. [A thorough discussion of the energy balance method and general instrumentation requirements is presented by Tanner, 1960[67], and by Fritschen, 1965.[18]]

ESTIMATING EVAPOTRANSPIRATION

Estimates of evapotranspiration are required in areas where no studies have been made, in isolated areas widely separated from those in which studies have been conducted, and when local data are not immediately available. The estimating procedures in use today are generally based on the correlation of measured evapotranspiration with one or more climatic factors. Field determinations of seasonal water requirements were started in the western USA as early as 1887 (Mead, 1887)[51]. Extensive studies of seasonal values of evapotranspiration were conducted since 1900. Attempts to relate seasonal evapotranspiration to common climatic factors were underway in the 1920's. Several of the more common methods that have been developed from early and recent studies are 1. Blaney-Criddle, 2. Thornthwaite, 3. Penman, 4. Jensen-Haise, and 5. Pan evaporation methods.

1. *Blaney-Criddle.* Blaney made numerous measurements of evapotranspiration in the 1920's and 1930's using primarily soil sampling techniques. Blaney and Morin (1942)[5] developed an empirical relationship between evapotranspiration and mean air temperature, average relative humidity, and mean percentage of daytime hours. This relationship was later modified by Blaney and Criddle (1945[2], 1950[3], 1952[6], and 1962[4]) to exclude the humidity term. The relationship was initially developed and intended for seasonal estimates. The principal assumption is that ET varies directly with the sum of the products of mean monthly air temperature and monthly percentage of daytime hours when adequate soil moisture is present. The formula for seasonal estimates is as follows:

$$U = KF = \sum kf \qquad 5.3$$

where U = estimated evapotranspiration (consumptive use) in inches for the growing period or season; K = empirical consumptive use coefficient (irrigation season or growing period); F = the sum of monthly consumptive use factors, f, for the season or growing period ($f = tp/100$ where t = mean monthly air temperature, in degrees F, and p = mean monthly percent of annual daytime hours); and k = monthly consumptive use coefficient.

A summary of monthly percentages of daytime hours is presented in Appendix Table M. A summary of recommended seasonal consumptive use coefficients, K, for irrigated areas is presented in Appendix

Table N. More recent data have shown that crops such as alfalfa and grass begin growth before the average last frost date in the spring and continue to grow after the average first frost date in the fall. Local data should be used for the average growing season wherever possible.

Monthly estimates of evapotranspiration have been made using the Blaney-Criddle formula. However, the monthly coefficients vary considerably more than seasonal values since they must reflect the combined effects of stage of growth and additional climatic factors that are not adequately represented by air temperature. A summary of some monthly coefficients is presented in Appendix Table O to illustrate the variability in mean monthly coefficients during a season. Obviously, if planting dates or dates of maturity change significantly between locations, the monthly coefficients will give long-time values that may be greatly in error. For example, in Texas, planting dates for grain sorghum vary from about March 15 near Brownsville to about June 15 in the high plains area. Monthly consumptive use coefficients must be determined for each major area, or adjusted accordingly. For example, Erie et al. (1965)[15] have summarized semi-monthly coefficients for most crops grown in Arizona. These coefficients are based on average local planting to harvest periods.

When used at a given location and for a given month and year, the percentage of daytime hours is constant and air temperature is the only climatic variable involved. The Blaney-Criddle formula should not be used in climatic zones significantly different from those in western USA unless it can be calibrated in the area. For example, when used at low latitudes, Brutsaert (1965)[9] found that Blaney-Criddle estimates did not correspond adequately to measured evapotranspiration since day length and mean air temperature varied little during the year.

The Soil Conservation Service modified the Blaney-Criddle formula for arid and semi-arid areas in two ways for calculating short period evapotranspiration values (USDA-SCS 1967).[76] One modification was the use of climatic coefficients (k_t) that are directly related to the mean air temperature for the short period. The second modification was the use of a coefficient (k_c) which reflects the influence of the crop growth stages on evapotranspiration rates. The modifications in the original formula are

$$k = k_t\, k_c \qquad 5.4$$

where k_t = a climatic coefficient which is related to the mean air temperature (t) in °F,

$$k_t = 0.0173t - 0.314 \qquad 5.5$$

(see Appendix Table P)

k_c = a coefficient reflecting the growth stage of the crop. Values are obtained from crop growth stage coefficient curves such as those shown in Figures V-1 and V-2.

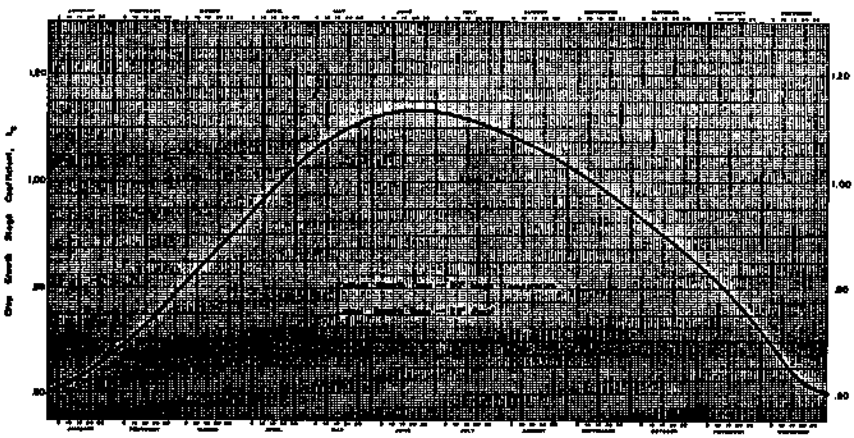

FIGURE V-1
Crop growth stage coefficient curve for alfalfa.

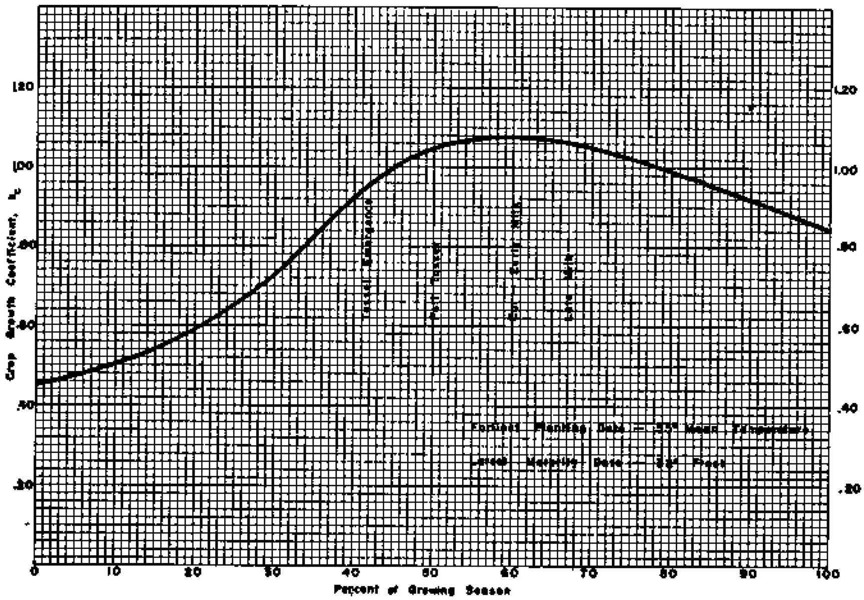

FIGURE V-2
Crop growth state coefficient curve for corn (grain).

2. *Thornthwaite.* Thornthwaite (1948)[72] correlated mean monthly air temperature with evapotranspiration as determined by water balance studies in valleys of east-central USA with adequate soil moisture so as not to limit ET. An empirical equation was obtained

for estimating "potential evapotranspiration" (P.E.T.) which is defined as "the amount of water which will be lost from the surface completely covered with vegetation if there is sufficient water in the soil at all times for use of the vegetation" (Thornthwaite and Mather, 1955) [73]. An additional condition necessary for potential evapotranspiration is that "the size of the area under high moisture conditions has to be large enough so that evapotranspiration from the area is not affected by external forces such as the advection of moist or dry air masses and their modification by local conditions" (Thornthwaite and Mather, 1955). Since these conditions do not exist in arid and semiarid areas, the Thornthwaite equation would not be expected to give accurate estimates in those areas. The Thornthwaite formula is as follows:

$$P.E.T. = 1.6\,L_d \left(\frac{10t}{I}\right)^a \qquad 5.6$$

where P.E.T. = the 30-day value of estimated evapotranspiration, cm; L_d = daytime hours in units of 12 hours; t = mean monthly air temperature, °C; I = heat index obtained by summing 12 monthly indices, $i = (t/5)^{1.514}$; and $a = 0.000000675\,I^3 - 0.0000771\,I^2 + 0.01792\,I + 0.49239$.

Tables are available giving "i" as a function of temperature and mean possible duration of sunlight for various latitudes in northern and southern hemispheres expressed in units of 30 days of 12 hours each. Also, nomograms are available for solutions of the formula (Thornthwaite and Mather, 1955 [73], 1957 [74]). A detailed evaluation of the Thornthwaite method for determining potential evapotranspiration can be found in articles by Pelton, et al. (1960)[54], and van Wijk and de Vries (1954) [78].

3. *Penman.* Penman (1948[55], 1956[56], and 1963[57]) combined the energy balance equation and an experimentally derived aerodynamic equation of the Dalton form. The resulting equation originally gave an estimate of evaporation from open water. These values were multiplied by a constant to arrive at an estimate of the potential transpiration rate from an extensive short grass cover completely shading the ground and adequately supplied with water. Later Penman (1963) indicated that the two-stage process was not necessary, resulting in the equation:

$$E_T = \frac{\Delta}{\Delta + \gamma} R_n + \frac{\gamma}{\Delta + \gamma} (0.35)\,(1.0 + 0.01\,W_2)\,(e_a - e_d) \qquad 5.7$$

where E_T = potential transpiration, mm/day; R_n = net radiation

and is estimated as $0.75\,R_s - R_L$, mm/day, where R_s = solar radiation; R_L = net outgoing long wave radiation Δ = a temperature dependent constant (= slope of the saturation vapor pressure curve at mean air temperature); γ = the constant of the wet- and dry-bulb psychrometric equation; W_2 = mean windspeed at a height of 2 m in miles/day; e_a = saturation vapor pressure at mean air temperature; and e_d = saturation vapor pressure at dew point or the vapor pressure of the atmosphere, mm Hg. The dimensions of the Penman equation as given require net radiation expressed as mm/day evaporation equivalent. A summary of $\Delta/(\Delta+\gamma)$ and $\gamma/(\Delta+\gamma)$ for various air temperatures is presented in Table V-1. The Penman equation is the most reliable for short period estimates.

TABLE V-1
Summary of $\Delta/(\Delta+\gamma)$ and $\gamma/(\Delta+\gamma)$ for Centigrade and Fahrenheit scales

Air temperature °C	°F	$\frac{\Delta}{\Delta+\gamma}$	$\frac{\gamma}{\Delta+\gamma}$
1	33.8	0.417	0.583
5	41	.478	.522
10	50	.552	.448
15	59	.621	.379
20	68	.682	.318
25	77	,735	.265
30	86	.781	.219
35	95	.819	.181
40	104	.851	.149

Computed from Smithsonian Meteorological Tables, 6th Ed., 1958, equation 2, page 365, and Table 103, page 372.

Net radiation may be estimated in several ways. One method is using the regression equation

$$R_n = aR_s + b \qquad 5.8$$

where a and b are coefficients that vary slightly with climatic conditions for the area (Fritschen, 1967)[19]. A more basic equation is:

$$R_n = (1-\alpha)R_s - R_L \qquad 5.9$$

where $(1-\alpha)R_s$ represents the net shortwave radiation received by a green crop with full cover, α is the mean daily shortwave reflectance or albedo, and R_L is the net outgoing longwave radiation. The reflectance coefficient for most green crops is about 0.22 to 0.25. R_L can be estimated as follows:

$$R_L = (1.35\,R_s/R_{so} - 0.35)R_{Lo} \qquad 5.10$$

where R_{Lo} is the net outgoing longwave radiation on a clear day, R_s is observed solar radiation on a given day, and R_{so} is solar radiation on the same day under cloudless conditions. The constants in equation 5.10 were derived from Davis, California, data obtained from Pruitt.

R_{L}, can be estimated using a standard meteorological equation such as:

$$R_{Lo} = \sigma T_k^4 \quad (0.31 - 0.051 \sqrt{e_d}\ ) \qquad 5.11$$

The constants in equation 5.11 are applicable to the arid conditions of southern Idaho and are similar to those obtained in California by Goss and Brooks (1956)[26], and those obtained in Australia by Fitzpatric and Stern (1965).[16] Values of σT_k^4 are summarized in Table V-2, using mean air temperatures at screen or instrument enclosure height. (When vapor pressure is in mb, then 0.044 should be used instead of 0.051 in equation 5.11.) The constants (0.31 and 0.051) in equation 5.11 are not universal and regional coefficients should be used when available.

TABLE V-2

Summary of black body radiation σT_k^4 for Centigrade and Fahrenheit scales (Tanner and Robinson, 1959).

Temp.	σT_k^4	Evaporation equivalent*	Temp.	σT_k^4	Evaporation equivalent*
°C	cal/cm ^{2} day	mm/day	°F	cal/cm ^{2} day	mm/day
1	655	11.2	35	662	11.3
4	695	11.9	40	699	11.9
7	725	12.4	45	727	12.4
10	757	12.9	50	757	12.9
13	789	13.5	55	787	13.5
16	823	14.1	60	818	14.0
19	858	14.7	65	850	14.5
22	893	15.3	70	883	15.1
25	930	15.9	75	918	15.7
28	968	16.6	80	951	16.3
31	1007	17.2	85	987	16.9
34	1047	17.9	90	1024	17.5

*Assuming a constant 585 cal/g heat of vaporization.

Vapor pressure values required for equation 5.7 are obtained from the saturation vapor pressure-temperature curve, and mean air temperature and dew point temperature. Penman used the mean of the maximum and the minimum air temperature for mean air temperature. Dew point temperatures, also required for Penman's equation, are not as readily available. Dew point is reported for many, but not all, USA locations on a 3 or 4-hour interval, as well as average daily dew point temperatures. Saturation vapor pressure at dew point, e_d, can be calculated if dry bulb temperature and relative humidity are determined several times daily since relative humidity = (e_d/e_s) 100, in which e_s = saturation vapor pressure at dry bulb temperature.

Generally dew point temperature or dew point vapor pressure, e_d, does not change greatly during the day. Saturation vapor pressure-temperature values are summarized in Table V-3.

TABLE V-3
Summary of Temperature - Saturation Vapor Pressure Values

Temperature	Saturation vapor pressure	Temperature	Saturation vapor pressure
°C	mm Hg	°F	mm Hg
1	4.93	35	5.17
4	6.10	40	6.29
7	7.51	45	7.63
10	9.21	50	9.21
13	11.23	55	11.07
16	13.63	60	13.25
19	16.48	65	15.80
22	19.83	70	18.78
25	23.76	75	22.23
28	28.35	80	26.22
31	33.70	85	30.83
34	39.90	90	36.12
37	47.07	95	42.18
40	55.32	100	49.11

Windspeed is normally not measured at 2 m above a grassed surface at most weather stations in the USA. The most common value is obtained from an anemometer just above the standard U.S. Weather Bureau Class A evaporation pan. Some of these values are affected by buildings and trees. Other locations report windspeed at an elevation of about 12 feet above ground or as measured by an anemometer above one of the buildings at an airport. Windspeed at the 2 m elevation can be approximated from measurements made at other elevations using the power law $[W_2 = W_z (2/z)^{0.2}]$, where z is the elevation in m at which W_z is measured.

Because of a nonuniform height of windspeed measurements and the additional requirements of dew point temperature, Penman's equation has not been used extensively in the USA by engineers. Penman's equation requires more meteorological data and therefore is more accurate for estimating potential evapotranspiration than Thornthwaite's or Blaney-Criddle's methods under a wide range in climatic conditions. Brutsaert's (1965)[9] and Pruitt's studies support this view point.

4. ***Jensen and Haise.*** Jensen and Haise (1963)[38] reevaluated about 3,000 published and unpublished short period measurements of evapotranspiration using soil sampling procedures during a 35-year period in western USA. Approximately 1,000 measurements for 15 different

crops met the standards established. These data were correlated with solar radiation, the main component of the energy balance equation, resulting in an empirical approximate energy balance equation using solar radiation and mean air temperature. A summary of weekly mean daily and total monthly solar radiation was presented for 20 western USA locations. Procedures were given for estimating solar radiation for other areas where only limited climatic data are available.

Approximately 100 selected measurements were used to evaluate the potential evapotranspiration, E_{tp}, that can occur in irrigated fields located in arid and semiarid areas. These data were selected from crops in which evaporating and transpiring surfaces were not limiting. The results obtained showed a linear increase in ET/R_s, as mean air temperature increased. From this relationship, a simple empirical equation was obtained for estimating evapotranspiration that can occur in well-watered irrigated fields located in semiarid and arid areas in which an effective full crop canopy exists.

$$E_{tp} = (0.014t - 0.37)R_s \qquad 5.12$$

Air temperature, t, in equation 5.12 is in °F. Solar radiation, R_s, should be expressed as evaporation equivalent of inches per day or mm/day.

Mean values of ET/R_s determined for various crops were summarized in tabular form for four regions by Jensen and Haise (1963)[38]. These data can be simplified greatly and composited for these regions by expressing measured evapotranspiration as a function of estimated potential evapotranspiration, E_{tp}, (Jensen and Haise, 1965[39]; Jensen, 1966[35]; Jensen, Robb and Franzoy, 1969)[40]. Because of the convenience of using a single curve for each crop, the modified procedure for estimating evapotranspiration is presented here.

The ratio of measured or actual evapotranspiration to potential evapotranspiration is called a crop coefficient, K_c, (Jensen, 1968)[36]. ET is estimated for various stages of growth by first estimating the potential evapotranspiration or the maximum ET for a reference crop like alfalfa under given climatic conditions, and then applying the crop coefficient.

$$ET = K_c E_{tp} \qquad 5.13$$

Potential evapotranspiration, E_{tp}, as used here, represents the upper limit or maximum evapotranspiration under given climatic conditions that occurs within a field having a well-watered agricultural crop, such as alfalfa, with about 12 to 18 inches of top growth. It is estimated by using solar radiation and mean air temperature in equation 5.12 or as follows:

$$E_{tp} = C_T(T - T_x)R_s \qquad 5.14$$

where C_T is an air temperature coefficient which is constant for a given area and is derived from the long-term mean maximum and minimum temperatures for the month of highest mean air temperature, T is mean daily air temperature, T_x is a constant for a given area and represents the linear equation intercept on the temperature axis, and R_s is daily solar radiation expressed as the equivalent depth of evaporation.

When accurate evapotranspiration data are available for an area, C_T and T_x can be determined by calibration (plotting ET/R_s vs mean air temperature). When calibration data are not available, then for common farm crops the temperature coefficient can be estimated using the general equation

$$C_T = \frac{1}{C_1 + C_2 C_H} \qquad 5.15$$

where C_H, a humidity index, is

$$C_H = \frac{37.5 \text{ mm Hg}}{e_2 - e_1} = \frac{50 \text{ mb}}{e_2 - e_1} \qquad 5.16$$

and e_2 is saturation vapor pressure in mm Hg or in mb at mean maximum air temperature during the warmest month, and e_1 is the saturation vapor pressure at mean minimum air temperature during the same month. At normal summer mean air temperatures and near sea level, C_T in degrees $^{-1}$ may be calibrated using the following constants for equation 5.15:

$$C_T = \frac{1}{68 + 13C_H} \quad (T \text{ in } ^\circ F) \qquad 5.17a$$

or

$$C_T = \frac{1}{38 + 7.3C_H} \quad (T \text{ in } ^\circ C) \qquad 5.17b$$

For clipped grass, the grass coefficient should be used, or multiply the above values by 0.87.

$$C_T = \frac{1}{81 + 13\,C_H} \quad (T \text{ in } ^\circ F) \qquad 5.18a$$

or

$$C_T = \frac{1}{45 + 7.3\,C_H} \quad (T \text{ in } ^\circ C) \qquad 5.18b$$

T_x values, are presented in Table V-4.

Because of the large changes in the air temperature/net radiation relationships at high elevations, the constants 68 and 38 in equation 5.17, and the constants 81 and 45 in equation 5.18 should be changed for high elevations as shown in Table V-5. These adjustments were

TABLE V-4
Summary of T_x vs Humidity Coefficients

Humidity index, CH	T_x* at sea level	
	°F	°C
1.0	15.0	—9.4
1.25	17.5	—8.1
1.5	19.2	—7.1
2.0	21.3	—6.0
2.5	22.5	—5.3
3.0	23.6	—4.7
4.0	24.4	—4.2
6.0	25.5	—3.6

$$^{*}T_x = 27.5°F - 0.33\,(e_2 - e_1)\frac{°F}{mmHg} - \frac{Elev.}{1000}\,°F$$

TABLE V-5
Summary of C_1 Values for High Altitudes

Elevation	C_1*			
	Rough crops		Clipped grass	
ft.	°F	°C	°F	°C
1,000	64	36	77	43
2,000	61	34	73	41
4,000	53	29	65	36
6,000	46	26	57	32
8,000	39	22	49	27
10,000	32	18	41	23

*Rough crop: C_1 = 68—3.6 Elev./1000
*Clipped grass: C_1 = 81— 4 Elev./1000

based on data collected at 9,200 feet elevation in Colorado.* The dimensions of equation 5.14 are the same as the dimensions of daily solar radiation, R_s. Daily solar radiation, as reported by most meteorological services, is usually in cal cm^{-2} or langleys. These can be converted to equivalent depths of evaporation assuming a heat of vaporization of 585 cal/g as follows:

$$\text{langleys} \times 0.000673 = \text{inches}$$
$$\text{langleys} \times 0.0171 = \text{mm}$$

*Haise, H. R. and E. G. Kruse, personal communication.

The curves presented in Figures V-3 to V-6 summarize the data presented by Jensen and Haise (1963). The values for early season, when only a small amount of crop cover exists, may be higher in semihumid areas where more frequent precipitation results in higher surface soil moisture content and more evaporation. A summary of growing season/stage of growth relationships and crop coefficients for other crops is presented in Table V-6. The differences between the curves during the leaf area development period are not great, and a single curve might be adequate if some adjustment in effective full stage of growth were made.

The curves presented in Figures V-3 to V-6 represent average values based on numerous measurements of ET by soil sampling and measurements or estimates of solar radiation. The major factors influencing the crop coefficients are: (1) varying degree of weed growth or cover crops in orchards, (2) light, frequent rains when partial cover exists resulting in high evaporation rates, and (3) adequate soil moisture is not maintained.

Solar radiation can be estimated if meteorological stations are not located in the general area. These estimates can be made by interpolating between meteorological stations, using clear-day values and percentage of sunshine, using clear-day values and degree of cloud cover, or theoretical radiation reaching the outer edge of the atmosphere (extraterrestrial radiation) and either percentage of sunshine

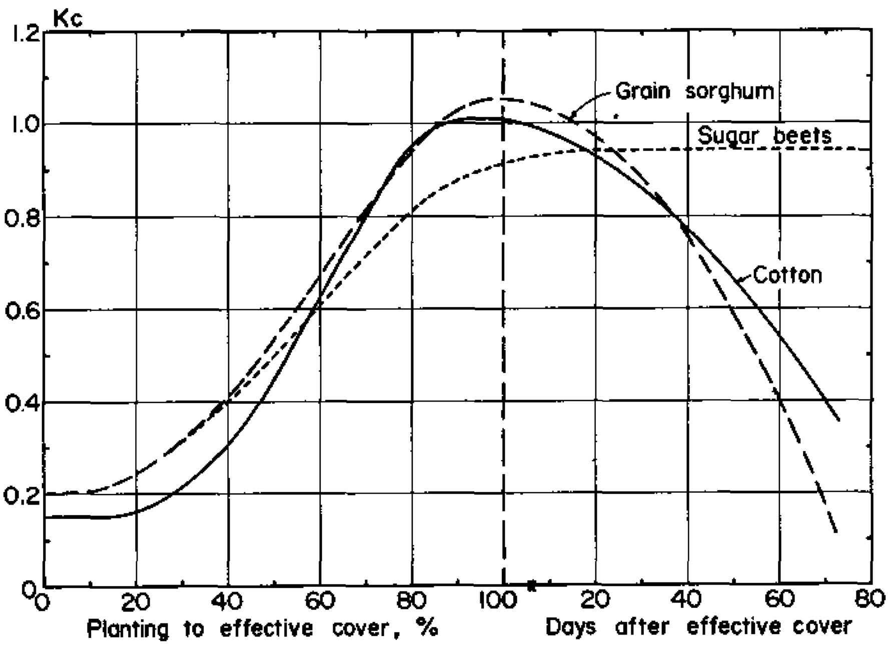

FIGURE V-3

Crop coefficients for cotton, grain sorghum and sugar beets.

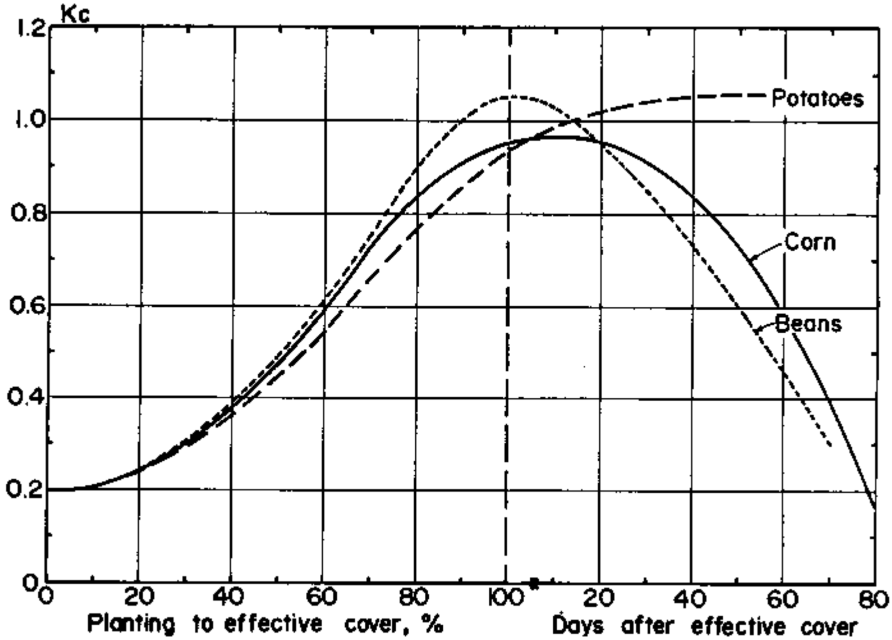

Figure V-4

Crop coefficients for beans, corn, and potatoes.

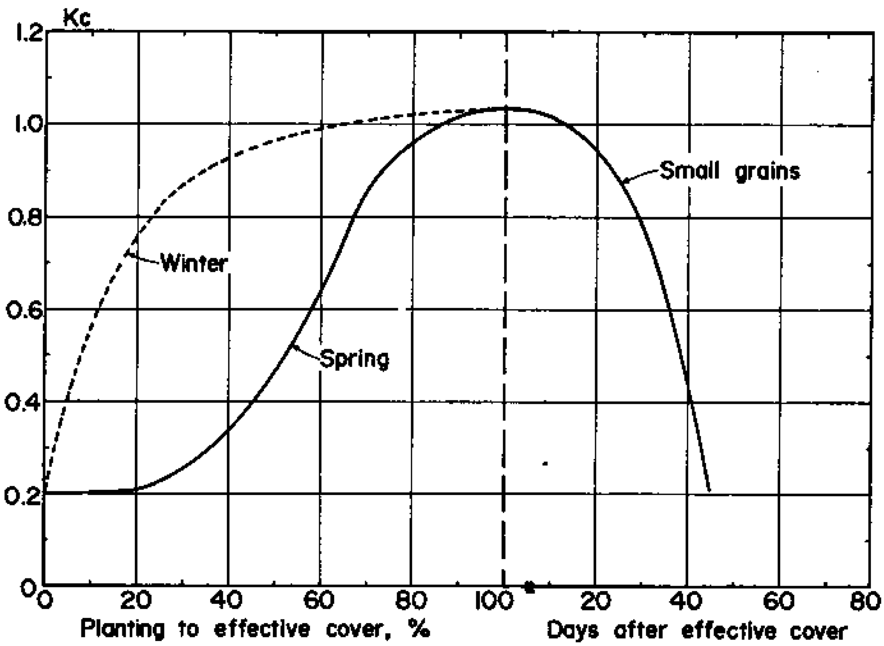

Figure V-5

Crop coefficients for winter and spring small grains.

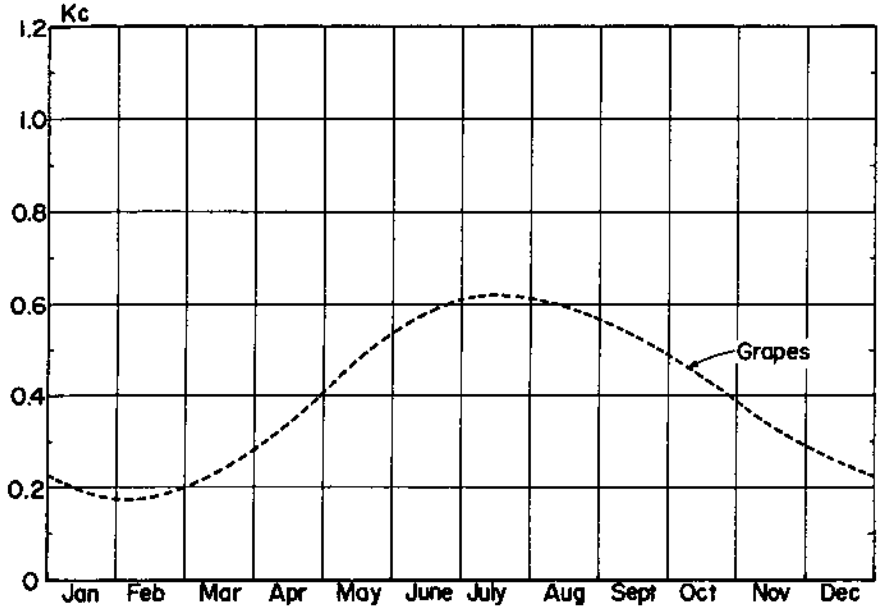

FIGURE V-6

Crop coefficients for grapes.

or cloud cover. Fritz and MacDonald (1949)[21] developed constants for an equation of the form proposed by Angstrom in 1925.

$$R_s = R_{so}(0.35 + 0.61S) \qquad 5.19$$

in which R_s represents solar radiation under existing conditions; R_{so} represents solar radiation on cloudless days; and S is the fraction of possible sunshine for the time period. Similar constants have been obtained for Canada and Australia. Solar radiation during cloudless days for USA locations can be obtained from graphs presented by Fritz (1949)[20].

The tremendous current emphasis on detailed studies of the evapotranspiration process should result in improved and more reliable estimating procedures by 1975. Net radiation or solar radiation will probably be the major meteorological parameter in the improved methods. The empirical procedures reviewed and presented in this section should be considered as a stopgap measure until more scientific procedures can be adapted for practical use.

5. *Pan Evaporation.* Evaporation from pans can be used to estimate mean peak ET and total ET for a season. A variable coefficient generally must be used for estimates of ET during the season to adjust for varying crop cover and stage of growth. Several precautions must be considered in the application of evaporation data for estimating

TABLE V-6
Summary of Growth Characteristics and Mean Crop Coefficients

Crop	Growing season or stage of growth when effective cover = 100%	Mean crop coefficient K_c
Field Crops:		
Alfalfa	When mean air temperature reaches and remains above 43°F	1.0*
Beans, field	When runners begin to form, or about 35 days after planting	**
Corn	10 days after tasseling, or about 85 days after planting	**
Cotton	About 140 days after planting	**
Pastures	When mean air temperature reaches and remains above 43°F	**
Potatoes (early)	About 80 days after planting	**
Potatoes (late)	About 65 days after planting	**
Sorghum (grain)	At heading	**
Small grains	At heading	**
Sugar beets	About 110 days after planting	**
Other Crops:		
Apples w/alfalfa cover crop	When mean air temperature reaches and remains above 43°F	1.1
Lawns	When mean air temperature reaches and remains above 43°F and no dormant or partial dormancy occurs in this interval	1.0†
Date groves		0.9‡
Cultivated orchards (Citrus)		0.6‡

* Decrease to 0.5 after cutting, then increase linearly to 1.0 in 20 days. Assume 0.25 when alfalfa begins to grow in the spring, then increase linearly to 1.0 in 30 days.

** Variable, see Figures V-3 to V-6.

† Use grass coefficients in equation 5.14.

‡ Weed growth or cover crops increase K_c significantly, add 0.1 to 0.3 to K_c for light to heavy weed growth.

ET. These are: (1) the evaporation rate is not the same for all evaporation pans in a given climatic region with similar site conditions; (2) site conditions, such as the presence or absence of actively growing grass around the pan influences the evaporation rate for a given pan; (3) the coefficients recommended are generally more reliable for longer time periods, such as a month, or season, and less reliable for weekly or 10-day estimates; and (4) evaporation from pans will not reflect the influence of decreasing soil moisture on ET (this limitation also applies to the other estimating procedures presented). Estimates of ET are made using the general equation,

$$ET = C_{et}E \qquad 5.20$$

where C_{et} is a coefficient relating pan evaporation to ET which is similar to the crop coefficient K_c, and E is pan evaporation.

The reliability of using evaporation pans depends on the calibration of the pan coefficient with the pan used and its immediate environment. Data obtained by Pruitt (1960)[59] in the Columbia basin project in Washington illustrates the importance of calibration by pan type and its environment. The following ratios of total evaporation from May 1 to November 1 to total evaporation from the BPI pan were obtained: 4-ft. ground pan, 1.05; 2-ft. ground pan, 1.13; USWB pan, 1.36; 2-ft. surface pan, 1.30; 2-ft. elevated pan, 1.51; 3-ft. ground pan located in a 6-acre dryland noncropped area, 1.45; and a 2-ft. surface pan in the dryland area, 1.68. All pans except the two indicated were located in a regular grass-sodded weather station enclosure.

Wolfe and Evans (1964)[86] developed an open pan to provide a 1:1 estimate of ET from pasture (C_{et} = 1.0). The pan was also designed to catch an equivalent depth of water applied by sprinkling, and to hold an amount equivalent to the available water holding capacity. A summary of coefficients relating evaporation from USWB Class A pans to ET, C_{et}, determined in California, is presented in Tables V-7 and V-8. Jensen, et al. (1961)[33] recommended the coefficients shown in Table V-9 for the central Washington area. The most reliable coefficients to use are those determined in the area of interest, or derived under similar climatic conditions for the crop in question. Also, site conditions for the pans should be similar to those under which the coefficients were determined. For example, the data obtained by Pruitt (1960) indicate that a difference in coefficients from 30 to 35% was found for like pans located in different environments.

TABLE V-7
Pan Coefficients (USWB) for Pasture and Grass*

Month	Sacramento River Basin Valley Floor C_{et}	Mountain Valleys C_{et}
January	0.64	----
February	.75	----
March	.72	----
April	.74	0.81
May	.74	.90
June	.75	1.00
July	.72	1.04
August	.77	1.00
September	.68	.90
October	.64	87
November	.51	.45
December	.52	1.21
Growing season	0.72**	0.98***

*Vegetative Water Use Studies, Bul. 113, California Department of Water Resources, 1963.

**April - October.

***May - September.

TABLE V-8
Pan Coefficients (USWB) for Alfalfa and Cotton*

Month	Tulare Lake Basin Valley Floor Alfalfa C_{a}	Tulare Lake Basin Valley Floor Cotton C_{a}	Sacramento River Basin Mountain Valleys Alfalfa C_{a}
January	----	----	----
February	----	----	----
March	0.53	0.75	0.63
April	.64	.14	.61
May	.52	.11	.96
June	.71	.67	.64
July	.64	1.08	.81
August	.76	.99	.97
September	.78	.84	.87
October	.68	.46	.96
November	.88	.26	.89
December	1.11	.15	----
Growing season	0.68**	0.68**	0.84***

*Vegetative Water Use Studies, Bul. 113, California Department of Water Resources, 1963.

**April - October.

***May - September.

TABLE V-9
Recommended Pan Coefficients, C_{a}, for Central Washington (Jensen et al. 1961)

Crops	C_{a}*
Corn, grape, and clean-cultivated peach orchard	0.85
Alfalfa, grains, Ladino-grass pasture and sugar beets	.95
Beans, peach orchard with cover crop, and potatoes	1.00
Apple orchard with grass cover	1.05

*For USWB evaporation pan

6. *Example Calculations.* Data obtained from Pruitt (1960) will be used to illustrate the various methods of estimating evapotranspiration.

Location: Near Prosser, Washington
Latitude = 46° 15' N

Crop: Ladino clover (no cutting periods)

Sampling Period: Dates - July 13 to July 21, 8 days

Climate During Period:
Mean maximum air temperature = 87.9°F
Mean minimum air temperature = 56.5°F
Mean air temperature = 72.2° F
Mean saturation deficit, $(e_a - e_d)$ = 9.3 mm Hg
Mean windspeed at 2-ft. height = 58 miles/day (approximately 79 miles/day at 2-m height)
Mean solar radiation = 756 cal/cm^2 day
Mean amount of cloud cover (at Yakima) = 1.5 tenths
Mean dew point vapor pressure = 9.8 mm Hg
Detailed data given in Table V-10

Other Data:
Mean minimum July air temperature = 52.7 F
Mean maximum July air temperature = 88.7 F
Measured evapotranspiration = 0.307 in./day or 2.46 in. total estimates of ET:

Blaney-Criddle

p = 10.68 for July (from Appendix Table M)

$p = \frac{8}{31} \times 10.68 = 2.76$ for July 13-21

f = tp/100 = (72.2 × 2.76)/100 = 1.99

k = 1.08 (as used by Pruitt, also see Appendix Table O)

U = kf = 1.08 × 1.99 = 2.15 in.

Error = (2.15 — 2.46) 100/2.46 = — 12.6%.

Thornthwaite

Mean day length = 1.32 twelve-hour units (from Thornthwaite and Mather, 1955)

Mean air temperature in °C = 22.3 C

Monthly values of i (from Thornthwaite and Mather, 1955)

Month	Mean temperature		i
	F	C	
Jan.	28.9	-1.7	---
Feb.	35.7	2.1	0.27
Mar.	44.1	6.7	1.56
Apr.	51.5	10.8	3.21
May	58.9	14.9	5.22
June	64.6	18.1	7.01
July	70.7	21.5	9.10
Aug.	69.2	20.7	8.59
Sept.	62.4	16.9	6.32
Oct.	52.1	11.2	3.39
Nov.	39.4	4.1	0.74
Dec.	33.4	0.8	0.06
			45.47 = I

$$a = 0.000000675\, I^3 - 0.0000771\, I^2 + 0.01792\, I + 049239$$

$$a = 0.0635 - 0.1594 + 0.8148 + 0.4924 = 1.211$$

$$\text{P.E.T.} = (1.6)(1.32)\left[\frac{(10)(22.3)}{45.47}\right]^{1.211}$$

$$\text{P.E.T.} = (1.6)(1.32)(6.85) = 14.47 \text{ cm/30 days}$$

$$\text{P.E.T.} = 14.47 \times \frac{8}{30} = 3.86 \text{ cm} = \mathit{1.52\ in.} \text{ (July 8-21)}$$

$$\text{Error} = (1.52 - 2.46)100/2.46 = -38.2\%$$

Penman

Estimates using Penman's method should be made on a daily basis because of the nonlinear relationships involved. A summary of climatic data from Middleton et al.[53] (1965) is presented in Table V-10. From these data, daily values needed for the Penman method were computed and summarized in Table V-11.

TABLE V-10
Summary data for July 13 to July 21 (from Middleton et al. 1965)

Day	Rs	Mean temp	Mean e_s*	Mean e_d	$(e_s - e_d)$	Cloud cover†	Wind-speed††
	cal/cm²	°F	mm Hg	mm Hg	mm Hg	tenths	miles
14	754	82.5	28.4	11.9	16.5	1	65
15	644	82.5	28.4	12.1	16.3	5	48
16	718	82.0	28.0	14.7	13.3	6	114
17	798	66.0	16.4	9.8	6.6	0	107
18	793	66.5	16.6	8.5	8.1	0	107
19	791	63.0	14.7	6.2	8.5	0	87
20	785	65.5	16.1	7.3	8.8	0	45
21	769	69.5	18.5	7.9	10.6	0	60
Average	756	72.2	20.9	9.8	11.1	1.5	79

*Saturation vapor pressure at mean air temperature.
**Computed differently by Pruitt (1960).
†From Yakima, Washington.
††Adjusted to the 2-meter height assuming a log-profile.

TABLE V-11
Summary of computations for the Penman method

	a	b	c	d	e		f	g		h
Day	$0.75R_s$	σT_k^4			R_b	R_n	E_a	$\frac{\Delta}{\Delta+\gamma}$	$\frac{\gamma}{\Delta+\gamma}$	E_T
	mm	mm	—	—	mm	mm	mm	—	—	mm
14	9.67	16.6	0.134	0.94	2.09	7.58	9.52	.77	.23	8.03
15	8.36	16.6	.133	.75	1.66	6.60	8.44	.77	.23	7.02
16	9.20	16.5	.115	.87	1.65	7.55	9.96	.76	.24	8.15
17	10.23	14.6	.150	1.01	2.21	8.02	4.70	.67	.33	6.95
18	10.17	14.7	.161	1.00	2.37	7.80	5.87	.67	.33	7.16
19	10.14	14.3	.183	1.00	2.62	7.52	5.56	.65	.35	6.83
20	10.06	14.6	.172	.99	2.49	7.57	4.46	.67	.33	6.54
21	9.86	15.0	.167	.96	2.40	7.46	5.94	.69	.31	6.99
Average	9.69	15.4	.152	.94	2.19	7.52	6.82	...	...	7.21

a $R_s/58.5$ = mm evaporation equivalent
b From Table V-2.
c $(0.31 - 0.051\sqrt{e_d})$
d $(1.35\frac{R_s}{R_{so}} - 0.35)$
e Equation 5.10
f $0.35\,(1 + 0.01\,W_2)(e_a - e_d)$
g Table V-1.
h Equation 5.7

$$E_T = \frac{8(7.21)}{25.4} = 2.27 \text{ inches}$$

Error = (2.27 — 2.46) 100/2.46 = —7.8%

Jensen-Haise

R_s = 756 × 0.000673 = 0.509 in/day evaporation equivalent

E_{tp} = [(0.014)(72.2) — 0.37] 0.509 = 0.326 in/day (Equation 5.12)

K_c = 1.0 (Table V-6)

ET = (1.0)(0.326) = 0.326 in/day (Equation 5.13)

Total ET = (0.326)8 = *2.61 inches*

Error = (2.61 — 2.46) 100/2.46 = 6.1%

Alternate procedure using equations 5.15 to 5.18:

Mean July e_2 = 34.7 mm Hg (Table V-3)

Mean July e_1 = 10.2 mm Hg (Table V-3)

C_H = 1.53 (Equation 5.16)

C_T = 0.0119 (Equation 5.17a)

T_x = 18.5 (Table V-4)

E_{tp} = [(0.0119)(72.2 — 18.5)] 0.509 = 0.325 in./day

ET = (1.0) (0.325) = 0.325 in/day

Total ET = (8) (0.325) = 2.60 *inches*

Error = (2.60 — 2.46) 100/2.46 = 5.7%.

Pan Evaporation

C_{et} = 0.92 (from Pruitt, 1960)

E = 2.78 inches (calculated from Pruitt, 1960)

ET = 0.92 (2.78) = *2.56 inches*

Error = (2.56 − 2.46) 100/2.46 = 4.1%

7. *Comparison of Methods.* Pruitt (1960) presented a comparison of the Blaney-Criddle, Thornthwaite, Penman, and various evaporation methods of estimating E_T. A portion of this comparison, along with the Jensen-Haise method, is summarized in Table V-12 to illustrate the need for "calibrating" empirical methods in a given area, and that more accurate results are obtained when using more than one climatic parameter. Each estimating procedure summarized by Pruitt was multiplied by a coefficient based on the estimated total compared with the measured total for the 1955 season. Pruitt's data indicate that Penman's method adequately accounts for the effects of changes in climatic conditions. However, improved techniques for estimating R_n must be used because the coefficients for atmospheric emissivity $(0.56 - 0.09\sqrt{e_d})$ given by Penman (1963) do not apply to arid conditions.

TABLE V-12

Measured evapotranspiration for ladino clover during 1955, and the percentage difference between ET and estimates of ET based on various procedures

		Percentage difference between estimated and measured ET						
ET period	Measured ET (inches)	Penman's $E_o \times 0.97$	*Blaney-Criddle**	Blaney-Criddle†	Thornthwaite's P.E.T. × 1.78	Jensen-Haise‡	BPI pan × 1.25	USWB pan × 0.92
5/23-6/3	2.54	....	−11.4	−16.9	−30.0	....	+8.7	+2.8
6/3-6/11	3.26	−6.7	−35.7	−17.8	−25.5	−18.9	−1.5	+8.3
6/11-6/23	3.24	+5.6	−8.6	+8.4	−6.5	−2.7	−1.2	+5.2
6/23-7/1	2.02	+3.5	−8.4	−2.0	−15.8	−7.9	+10.9	−4.5
7/1-7/13	2.48	+5.6	+15.7	+26.2	+14.1	+0.1	−10.1	−7.3
7/13-7/21	2.46	−0.4	−12.2	+8.9	+6.1	+5.9	+1.2	+4.1
7/21-8/2	3.23	+2.2	−6.8	+7.1	+4.6	+0.2	+3.4	+1.5
8/2-8/11	2.35	+6.4	−5.5	+6.4	+7.2	+11.6	+4.7	+10.6
8/11-8/20	2.29	+3.1	−8.3	−2.6	+1.3	+5.9	+3.1	+2.6
8/20-8/31	2.68	−4.5	−11.1	−12.7	−7.8	0.0	+1.9	−4.5
8/31-9/13	2.82	−6.0	+4.6	+6.2	+22.0	+0.6	−11.7	−4.3
9/13-10/5	2.95	−12.5	+20.7	−11.9	−3.8	−15.9	−3.7	−14.2
10/5-10/28	1.49	+7.4	+108.7	+24.8	+43.6	+7.8	+7.4	−4.0
Average percent difference (neglecting sign, 6/3-10/28)		5.3	20.4	11.0	13.2	9.7	5.1	5.9

* Using K = 1.08
† Using K = 0.04 + 5.52 (tm/100)
‡ Using equations 5.14 to 5.17