AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523
BIBLIOGRAPHIC INPUT SHEET

FOR AID USE ONLY

1. SUBJECT CLASSIFICATION	A. PRIMARY Agriculture	AP12-0000-0000
	B. SECONDARY Drainage and irrigation	

2. TITLE AND SUBTITLE
Irrigation requirements from evaporation and climatic data

3. AUTHOR(S)
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4. DOCUMENT DATE 1970	5. NUMBER OF PAGES 37p.	6. ARC NUMBER ARC

7. REFERENCE ORGANIZATION NAME AND ADDRESS
Utah State

8. SUPPLEMENTARY NOTES *(Sponsoring Organization, Publishers, Availability)*

9. ABSTRACT

10. CONTROL NUMBER PN-RAA-402	11. PRICE OF DOCUMENT
12. DESCRIPTORS Climatology Evaporation Evapotranspiration Formulas Water supply	13. PROJECT NUMBER
	14. CONTRACT NUMBER CSD-2167 Res.
	15. TYPE OF DOCUMENT

AID 590-1 (4-74)

IRRIGATION REQUIREMENTS FROM EVAPORATION AND CLIMATIC DATA

by

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Introduction

Evapotranspiration data are available from lysimeters, field plot sampling and other methods for a variety of crops at various locations. At a given location there is frequently considerable spread or scatter in the data. This paper presents formulas and methodology for estimating evaporation equivalent to Class A pan evaporation from a standardized exposure, for estimating potential evapotranspiration from climatic data, for estimating actual or normal evapotranspiration from evaporation or from potential evapotranspiration, and for estimating irrigation requirements.

The relationships between evaporation, potential evapotranspiration, and climatic data have been determined from computer analyses. Data from experimental work at Davis, California, using

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a 20-foot (6.1 meters) diameter weighing lysimeter planted to rye grass as described by Pruitt and Angus (22, 23)[c] were used to develop formulas for potential evapotranspiration. In this paper potential evapotranspiration is considered the evapotranspiration equivalent to that from rye grass on a 20-foot diameter weighing lysimeter under a standardized exposure.

Potential evapotranspiration estimated from the formulas presented are believed to be reasonably reliable for use in nearly all parts of the world and for various levels of data availability. Crop coefficients are presented for the principal irrigated crops grown under conditions of good growth and for a fairly high level of productivity. These will vary with the various factors that influence rates of growth, roughness coefficients, and crop cover. Therefore, it seems desirable that additional work be undertaken in the more important irrigated areas so as to more accurately define the crop coefficients for local cultural practices and conditions.

Irrigation requirements may be estimated from crop evapotranspiration taking into consideration leaching requirements, irrigation efficiencies, and the utilizable rainfall. This paper is written for use by those engaged in research, for irrigation planning and design, for water use management, and for uses which relate to plant-soil-water relationships and the hydrologic balance. It is planned that it will be used in connection with a cooperative effort sponsored

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[c] Numbers in parentheses refer to corresponding numbers in the appendix references.

by CIDIAT[d] for the preparation of irrigation manuals on a country by country basis. Some work has been initiated for Venezuela, and it is anticipated that the first national irrigation manual will be for that country.

Relationship of Evapotranspiration to Evaporation

Evaporation from an evaporation pan, or from a free water surface, is a physical process that depends on the availability of energy to evaporate the water. This energy may reach the water surface by radiation from the sun and sky, or by conduction from the air or through the walls of the evaporation pan. The rate of evaporation is, therefore, largely dependent on the solar radiation and climatic parameters such as air temperature, wind velocity, and relative humidity. The solar radiation reaching the earth's surface depends on the extraterrestrial radiation, or theoretical radiation reaching the outer surface of the atmosphere, and the factors affecting the transmission of that energy through the atmosphere such as the percentage of possible sunshine and the elevation of the station.

Evapotranspiration, which includes the direct evaporation from moist surfaces such as leaves and soil, in addition to the transpiration through the leaves of the crop, is similar to evaporation in many respects, but it also involves the physiological responses of the

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vegetation, the availability of soil moisture to the crop, the crop cover, or percentage of area covered and shaded by the crop, and possibly the total leaf surface available to transpire water into the atmosphere. Potential evapotranspiration is considered that which takes place from a succulent crop when available soil moisture, crop cover, and leaf surface are not limiting factors.

Evaporation from a bare soil varies from approximately that for a free water surface when the surface is moist and dark in color, to a negligible amount when the surface soil has been dried to a depth of 15 cm (6 inches) or so. Thus, the evapotranspiration from bare soils before the emergence of annual crops may vary from approximately the potential rate to a much smaller amount depending on the frequency of precipitation or the irrigation practice. In arid regions, where precipitation occurs infrequently, the mean evapotranspiration during the period between planting and emergence may be in the order of 20 to 30 percent of the potential rate as shown by Grassi (6) and Hansen (7).

Evaporation from a standard pan, such as the Class A pan, is perhaps the best single index of climate as it pertains to evapotranspiration. Most measurements of evapotranspiration, or consumptive use, have been compared with the evaporation from some kind of evaporation pan by means of simple ratios or coefficients. These ratios of evapotranspiration, Et, to evaporation, Ev, do, of course, vary with the kind of crop, and seasonally with the crop cover, especially for annual crops, and with the maturity and ripening of the crop, as well as with the kind of pan used. Standards (28) have been published for the installation and operation of Class A pans, but many installations do not meet these standards, and thus the reported evaporation may exceed that from a standard installation by as much as twenty percent as reported by Pruitt (19).

Some factors that influence the evaporation from pans, and result in errors in the reported values, are variations in size and shape of the pans, the depth of water in the pans, the color of the pans, whether unpainted, aluminum color, or white, and the exposure as related to the surrounding area, whether on grass, bare soil or gravel. Cleanliness, the presence or absence of algae, the specific methods of measuring the loss of water from the pans, and protection against use of the water by birds and animals are factors that influence the accuracy and reliability of the data. Some pans are located near the edge of a lake or reservoir and the prevailing wind direction makes an important difference in the recorded evaporation. For climates where there are alternately wet and dry seasons, the pan may be surrounded by green rapidly growing vegetation part of the time and by a dry arid environment at other times.

In spite of these limitations, evaporation pans do provide fairly satisfactory indices of evapotranspiration, especially where installation and operating standards are complied with. A very good statement of the relationship between evapotranspiration and evaporation is provided by Pruitt (21). He showed a very good agreement between the evapotranspiration for alfalfa and Class A pan evaporation at several locations, with a 1 to 1 ratio. Jensen and Middleton (14) reported a near constant relationship between evaporation and evapotranspiration. Brutsaert (2) reported a better correlation between evapotranspiration and pan evaporation than between the evapotranspiration and that computed from several well known formulas. Pruitt (20) demonstrated a high degree of correlation between evapotranspiration and pan evaporation for Ladino clover during stages of rapid growth. He reported a ratio of 0.92 for the evapotranspiration to Class A pan evaporation.

For the purpose of estimating water requirements for irrigation, one is interested in two main aspects of evapotranspiration:

(1) The seasonal variation and especially the mean maximum value for a period of from 2 weeks to a month.

(2) The total seasonal requirement.

The application of large excesses of irrigation water over the actual requirements is of no value, and often very detrimental in that it may create a high water table and cause serious drainage and salinity problems. Deficiencies in water applications usually results in decreased yields. Thus, it is important for the irrigation engineer charged with the planning or design of irrigation systems to have a knowledge of actual requirements instead of relying on the old rule of thumb, "one liter per second per hectare," which has been the basis for planning in many places in the world.

Formulas for Estimating Evaporation and Evapotranspiration

Unfortunately, Class A pan evaporation is not available in many places where estimates of evapotranspiration are needed. Also, because of exposure conditions, or for other reasons mentioned above, available pan evaporation data may need to be standardized before it should be used in order to obtain reliable estimates of evapotranspiration. Pan evaporation estimated by means of a reliable formula may give more reliable results than reported pan evaporation.

Both of the authors have been interested in estimating evaporation and/or evapotranspiration and irrigation water requirements, and they have both developed formulas for this purpose. Many others have also developed and proposed such formulas but space does not permit a discussion or comparison of these formulas.

Hargreaves Formulas

Hargreaves (8, 9, 10, 11, 12) proposed the use of Class A pan evaporation as a climatic index and basis for estimating actual evapotranspiration as early as 1948. Because pan evaporation data are not always available, and due to the variation in measured evaporation with pan exposure, he developed an equation for computing a climatic factor equal to Class A pan evaporation from a pan located in a standardized exposure, or in a large irrigated area. The formula developed can be written

$$Ev = 0.38\,D\,(1.0 - Hn)\,(T-32) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

in which Ev is Class A pan evaporation in inches per month; D is a monthly daytime coefficient, which is the ratio of the mean day length for the month to 12 hours times the ratio of the number of days in the month to a mean value (365/12), values are given in Table 1; Hn is mean monthly relative humidity at noon expressed in decimal form, e.g., Hn = 60% = 0.60, (humidity at 13:00 hours, or the average of humidity at 11:00 and 17:00 hours can be used satisfactory); T is mean monthly temperature in °F. Expressed in metric units the above formula becomes

$$Ev = 17.4\, D\, Tc\, (1.0 - Hn) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

in which Ev is Class A pan evaporation in mm.; and Tc is mean monthly temperature in °C. These formulas are used to compute evapotranspiration, Et, from the relationship

$$Et = k\, Ev \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

in which k is a crop factor or crop coefficient.

For metric units, Eq. 3 can be improved by modifying the humidity factor (1.0 - Hn), and incorporating factors for wind, sunshine, and elevation as follows (12). The modified equation can then be written

$$Ev = 17.4\, D\, Tc\, F_H\, F_W\, F_S\, F_E \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

and

$$F_H = 0.59 - 0.55\, Hn^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4a)$$

$$F_W = 0.75 + 0.0255 \sqrt{W_{kd}} \quad . . . . \quad (4b)$$

or

$$F_W = 0.75 + 0.125 \sqrt{W_{kh}} \quad . . . . \quad (4c)$$

$$F_S = 0.478 + 0.58\ S \quad . . . . \quad (4d)$$

$$F_E = 0.950 + 0.0001\ E \quad . . . . \quad (4e)$$

where Hn is the mean noon humidity expressed decimally; W_{kd} is the mean wind velocity in km/day at a height of 2 meters; or, W_{kh} is the mean wind velocity in km/hour at a height of 2 meters; S is the sunshine percentage, expressed decimally; and E is the elevation in meters.

Sometimes published data for noon humidity are not available, but either mean humidity, or mean maximum, and mean minimum humidity are available. Noon relative humidity can be estimated with reasonable accuracy from the expressions

$$Hn = 0.40\ Hm + 0.60\ Hm^2 \quad . . . . \quad (5)$$

$$Hn = 0.40\ Hi + 0.10\ Hx + 0.18\ Hm + 0.32\ Hm^2 \quad . . \quad (6)$$

where Hm is the mean daily relative humidity, and Hi and Hx are minimum and maximum values, all expressed decimally.

The values of each of the correction factors can be tabulated for convenience as given in Table 2. When data for wind velocity or sunshine are not available, an estimate may be made or a value of 1.00 used for the factor. However, it should be noted from an inspection of Table 2 that evaporation is reduced appreciably with decreasing percentages of possible sunshine.

Christiansen Formulas

Christiansen (4, 5) and co-workers first developed a formula for estimating Class A pan evaporation using as a basis extraterrestrial radiation, Rt, and climatic data. He later developed formulas for relating potential evapotranspiration to pan evaporation, and also formulas relating both pan evaporation and evapotranspiration to measured incoming radiation and climatic data.

In the development of the formulas and procedures discussed here, certain considerations and limitations were kept in mind. These may be enumerated as follows:

(1) Only data of the kind that are readily available to the user should be required for application of the procedure, and only such data should be used in the development of formulas.

(2) The procedures or formulas should utilize all of the available climatic parameters that are found to significantly affect evaporation or evapotranspiration, but they should permit use of more limited data.

(3) The procedures should require a minimum of personal judgment on the part of the user.

(4) The formulas developed should be dimensionally sound, and should be applicable in either English or metric units.

(5) The formulas should, insofar as possible, provide the practicing engineer with a working tool that will give reliable results when applied to climatic data from any part of the world.

Formula for pan evaporation using extraterrestrial radiation, Rt, as a base. The basic formula for pan evaporation, based on data from many countries of the world and a wide range of climatic conditions, is

$$Ev = 0.459 \, Rt \, C_T \, C_W \, C_H \, C_S \, C_E \, C_M \quad \ldots\ldots\ldots \quad (7)$$

where

Rt = extraterrestrial radiation reaching the earth's atmosphere, computed from a solar constant of 2 calories per cm^2 per minute, Tables 3 and 4.

The coefficients given in the dimensionless form are:

For mean temperature in degrees Fahrenheit, for $T_0 = 68^o$,

$$C_T = -0.0673 + 0.8976 \, (T/T_0) + 0.1722 \, (T/T_0)^2 \quad \ldots\ldots \quad (7a)$$

For mean temperature in degrees centigrade, for $T_0 = 20^o$

$$C_T = 0.393 + 0.5592 \, (Tc/T_0) + 0.04756 \, (Tc/T_0)^2 \quad \ldots\ldots \quad (7b)$$

For mean wind velocities above the evaporation pan, height above ground 2 feet, for W_0 = 60 miles per day, or 96.56 kilometers per day,

$$C_W = 0.708 + 0.3276 \, (W/W_0) - 0.036 \, (W/W_0)^2 \quad \ldots\ldots \quad (7c)$$

For mean relative humidity at noon, or average humidity for 11 and 17 hours, for H_0 = 40%, or 0.40

$$C_H = 1.250 - 0.348 \, (H/H_0) + 0.120 \, (H/H_0)^2 - 0.0218 \, (H/H_0)^4 \quad \ldots\ldots \quad (7d)$$

Or, where mean humidity is available,

$$C_{Hm} = 1.265 - 0.249 \, (Hm/Hm_0) - 0.016 \, (Hm/Hm_0)^6 \quad \ldots\ldots \quad (7e)$$

where Hm_0 = 60%, or 0.60

For mean sunshine percentage, for S_0 = 80%, or 0.80

$$C_S = 0.542 + 0.64 (S/S_0) - 0.4992 (S/S_0)^2 + 0.3174 (S/S_0)^3 \quad \ldots\ldots \quad (7f)$$

For elevation, for E_0 = 1000 ft., or 305 meters,

$$C_E = 0.970 + 0.030 (E/E_0) \quad \ldots\ldots \quad (7g)$$

The monthly coefficient, C_M, is the ratio of the reported pan evaporation to the computed value, which appears to vary somewhat from place to place and possibly depend on factors not taken into consideration in the formula such as the pan exposure, days of precipitation, and shading of area from mountains. The mean value of C_M is 1.00, and the standard deviation for 3928 months of data from more than 80 stations in 8 countries was 0.116. Tabulated values for these locations were summarized by Christiansen (4).

Tabulated values of C_T, C_W, C_H, C_S and C_E are given in Tables 5, 6, 7, 8, and 9. These tables give the logarithms of the coefficients so that a computation of Ev can readily be made by adding the logarithms of the coefficients and of the constant and Rt values, and taking the antilogarithm. The equations for the coefficients in simplified form are given at the bottom of the tables.

Formulas for potential evapotranspiration, Etp. Three formulas have been developed for potential evapotranspiration using data from Pruitt for rye grass from a 20-foot (6.1 meters) diameter weighing lysimeter. These evapotranspiration data were recorded to 1/1000 inch per day

(1/40 mm) and all climatic factors generally considered were carefully measured.

<u>Using measured pan evaporation, Ev, as a base.</u> A formula relating potential evapotranspiration, Etp, to pan evaporation, Ev, can be expressed by the equation

$$\mathrm{Etp} = 0.755\ \mathrm{Ev}\ C_{T2}\ C_{W2}\ C_{H2}\ C_{S2} \quad \ldots\ldots\ldots \quad (8)$$

where Ev is measured Class A pan evaporation

$$C_{T2} = 0.670 + 0.476\ (T/T_0) - 0.146\ (T/T_0)^2 \quad \ldots\ldots \quad (8a)$$

where T is the mean temperature, °F, and $T_0 = 68°$ F. In metric units,

$$C_{T2} = 0.862 + 0.179\ (Tc/Tc_0) - 0.041\ (Tc/Tc_0)^2 \quad \ldots\ldots \quad (8b)$$

where Tc is the mean temperature, °C, and $Tc_0 = 20°$ C

$$C_{W2} = 1.189 - 0.240\ (W/W_0) + 0.051\ (W/W_0)^2 \quad \ldots\ldots \quad (8c)$$

where W is the mean wind velocity 2 meters above ground level in miles per day or km per hour, and W_0 = 100 miles per day or 6.7 km per hour

$$C_{H2} = 0.499 + 0.620\ (Hm/Hm_0) - 0.119\ (Hm/Hm_0)^2 \quad \ldots \quad (8d)$$

where Hm is the mean relative humidity, expressed decimally, 60% = 0.60, and $H_0 = 0.60$

$$C_{S2} = 0.904 + 0.0080\ (S/S_0) + 0.088\ (S/S_0)^2 \quad \ldots\ldots\ldots \quad (8e)$$

where S is the percentage of possible sunshine, expressed decimally and $S_0 = 0.80$.

Using extraterrestrial radiation, Rt, as a base. The formula relating potential evapotranspiration to extraterrestrial radiation and climatic factors can be expressed by the equation

$$Et = 0.324\, Rt\, C_{TT}\, C_{WT}\, C_{HT}\, C_{ST}\, C_{E} \quad \ldots \ldots \quad (9)$$

where

$$C_{TT} = 0.174 + 0.428\,(T/T_0) + 0.398\,(T/T_0)^2 \quad \ldots \ldots \quad (9a)$$

where T is the mean temperature, °F, and $T_0 = 68°$ F. In metric units this becomes

$$C_{TT} = 0.463 + 0.425\,(Tc/Tc_0) + 0.112\,(Tc/Tc_0)^2 \quad \ldots \quad (9b)$$

where Tc is the mean temperature in °C

$$C_{WT} = 0.672 + 0.406\,(W/W_0) - 0.0780\,(W/W_0)^2 \quad \ldots \quad (9c)$$

where W is the mean wind velocity 2 meters above ground level, and W_0 = 100 miles per day or 6.7 km/hour

$$C_{HT} = 1.035 + 0.240\,(Hm/Hm_0)^2 - 0.275\,(Hm/Hm_0)^3 \quad \ldots \quad (9d)$$

where Hm is the mean relative humidity expressed decimally and $Hm_0 = 0.60$

$$C_{ST} = 0.340 + 0.856\,(S/S_0) - 0.196\,(S/S_0)^2 \quad \ldots \ldots \quad (9e)$$

where S is the mean sunshine percentage expressed decimally, and $S_0 = 0.80$.

$$C_{E} = 0.970 + 0.030\,(E/E_0) \quad \ldots \ldots \ldots \quad (7g)$$

Using measured incoming radiation, Rs, as a base. The formula relating potential evapotranspiration, Etp, to measured incoming radiation as a base can be written

$$Etp = 0.492\, Rs\, C_{TT}\, C_{WT}\, C_{HT} \quad \ldots \quad (10)$$

where Rs is the measured incoming solar radiation expressed as equivalent depth of evaporation. The equations for the coefficients, C_{TT}, C_{WT}, and C_{HT} are the same as given in Eqs. 9a, 9b, 9c, and 9d.

The measured incoming solar radiation is generally reported as langleys per day (calories per cm^2 per day). The equivalent depth of evaporation per day is obtained by dividing langleys per day, Rly, by the latent heat of vaporization, L.

$$Rs = Rly/L \quad \ldots \quad (10a)$$

At a temperature of 20° C (68° F), L has a value of 584.9 calories per gram. For other temperatures in °C, the relation is

$$L = 595.9 - 0.55\, Tc \quad \ldots \quad (10b)$$

and for temperatures in °F,

$$L = 595.9 - 0.305\, (T - 32) \quad \ldots \quad (10c)$$

To obtain Rs for the month, one must multiply the mean daily value of Rs by the number of days in the month, or use the total langleys per month in Eq. 10a. Because of the small variation of L with temperature, the value for 20° C is generally used.

From a comparison of Eqs. 9 and 10, it will be seen that

$$Rs = 0.660\, Rt\, C_{ST}\, C_E \quad \ldots\ldots \quad (11)$$

This equation, developed solely from Davis, California, data may be compared with an equation developed by Pizarro (18) from a study of incoming radiation from 38 U. S. Weather Bureau stations well distributed geographically over all of the continental United States. Pizarro's equation can be written

$$R_{SP} = 0.640\, Rt\, C_{SP}\, C_E \quad \ldots\ldots \quad (12)$$

where

$$C_{SP} = 0.328 + 0.832\,(S/S_0) - 0.160\,(S/S_0)^2 \quad \ldots\ldots \quad (13)$$

and C_E is the same as given in Eq. 7g.

The difference between Eqs, 11 and 12 is well under 5% for most values of S.

Christiansen - Hargreaves Formula

A formula of the Hargreaves type, for Etp in mm per month using mean temperature, Tc, in °C, was developed from the Davis, California, data.

$$Etp = 8.38\, D\, Tc\, F_E\, CH_H\, CH_W\, CH_S \quad \ldots\ldots \quad (14)$$

where D is the monthly daytime coefficient as given in Table 1, and F_E is the elevation factor as given in Eq. 4e and Table 2.

$$CH_H = 0.464 + 1.661\,(Hm/Hm_0) - 1.125\,(Hm/Hm_0)^2 \quad \ldots\ldots \quad (14a)$$

where Hm_0 is 0.60 (60%)

$$CH_W = 0.439 + 0.850\,(W/W_0) - 0.289\,(W/W_0)^2 \quad . . . . \quad (14b)$$

where W is the wind velocity 2 meters above ground level and W_0 is 10 km per hour, or 14.91 miles per day

$$CH_S = 0.475 + 0.964\,(S/S_0) - 0.439\,(S/S_0)^2 \quad . . . . \quad (14c)$$

where S_0 is 0.80 (80%).

For Etp in inches per month, and the mean temperature, T, in °F, Eq. 14 becomes

$$Etp = 0.183\,D\,(T-32)\,F_E\,CH_H\,CH_W\,CH_S \quad . . . . \quad (15)$$

It may be of interest to compare the fit obtained with Eqs. 8, 9, 10, and 14 for the 10-day mean values of evaporation, evapotranspiration, and climatic data at Davis, California, on the basis of mean absolute differences expressed as a percentage of the mean value of Et.

Eq.	Base	Mean Absolute Error, %
8	Ev	7.64
9	Rt	5.46
10	Rs	6.04
14	D Tc	9.22

This shows that the best fit of the data was obtained using as a base the extraterrestrial radiation, Rt, Eq. 9, the next best fit being the measured incoming radiation, Rs, and the third best fit being the measured pan evaporation, Ev. This may be due to the fact that Et values were reported on a daily basis to the nearest 0.001-inch (0.0254m and Ev values to the nearest 0.01-inch. (0.254 mm) The relative differences between the measured and computed values of Et for all four equations was greatest during the winter period when both Et and Ev values were very low.

Pruitt (21) has reported that, except for periods of strong advective winds from the north, the ratio of Et to Ev was approximately 0.80, but that during these periods, the ratios, Et/Ev were lower; sometimes as low as 0.50. From Eq. 8, it will be found that for a mean humidity of 0.40, other factors remaining normal, the ratio of Et/Ev would be 0.550. For a wind velocity of 250 miles per day, (16.75 km/hour) or about twice the mean average value, other factors remaining normal, the ratio would be 0.68. A combination of a wind of 250 miles per day (16.75 km/hour) and mean humidity of 0.40 (40%) would reduce the ratio, Et/Ev, to 0.50.

Use of Evapotranspiration in Computing Irrigation Requirements

Evapotranspiration data are generally used indirectly for the computation of irrigation requirements. Evapotranspiration for each stage of the crop growing season constitutes only one of the factors. Shockley (25) has presented the irrigation water requirements equation as follows

$$IR = \frac{100\,(Et + LR - Pe - Mc - Mg)}{E} + Lc \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

when IR = irrigation water requirement, Et = evapotranspiration, LR = leaching requirement, Pe = effective precipitation, Mc = carry over soil moisture, Mg = groundwater contribution, E = field irrigation efficiency, and Lc = conveyance and operation losses. The various factors vary greatly. In arid areas LR may be high and Pe almost negligible and in areas where water is relative pure and rainfall sufficient for leaching, LR may be zero. If depths to groundwater are in excess of the depth of the root zone Mg can be disregarded.

Various methods are available for estimating the effective precipitation. One of the most satisfactory methods of computing utilizable precipitation is that published by the U. S. Soil Conservation Service (27).

Possibly of more importance than the effective precipitation as used by Shockley, would be the dependable precipitation, or the amount of precipitation for each month that can be depended upon to occur a given percentage of the time. A study of precipitation in Uruguay (3) using data from 13 stations indicated that the average precipitation that occurred 15 out of 18 years of record (83%) varied from 33 to 51 percent of the mean precipitation for different months, with an overall average of 43.5% of the mean for the 6 months, October to March. Likewise, the average minimum precipitation (lowest of record) varied from 13 to 29 percent of the mean, with an average of 21.5%. In most arid and semi-arid places, the dependable precipitation is much less than the mean precipitation, and this is an important consideration in connection with the determination of water requirements for irrigation.

Crop Evapotranspiration Coefficients

The relationship of evapotranspiration to Class A pan evaporation has been used by many engineers and technicians for the computation of crop consumptive use coefficients. Hargreaves (8, 10, 11, 12) used data from Davis, California, to calculate monthly and seasonal consumptive use coefficients for 15 crops, and data from Puerto Rico (9) to calculate coefficients for sugar cane. He computed coefficients by percent intervals of the crop growing season for 7 crop groups and for rice. He prepared crop consumptive use coefficients by percent of the crop growing season for 21 crops based upon available data from many sources. Jensen and Middleton (14) give coefficients, Kc, for standardized modified Class A pan data for crops after reaching full crop cover. Anderson (1) gives ratios of evapotranspiration to Class A pan evaporation (Et/Ev) by percent of the crop growing season for 8 crops. Thompson, Pearson, and Gleasby (26) give ratios of evapotranspiration to Class A pan evaporation for full canopy of sugar cane. Brutsaert (2) gives monthly Et/Ev ratios for Bahiagrass. Lopez and Matheson (16) give Et/Ev ratios for Bermuda grass. Grassi (6) gives data on evapotranspiration and Class A pan evaporation by crop cover percentage from experiment stations located in 8 states.

Various authors have used potential evapotranspiration computed by an empirical formula as a standard and have computed crop curves and crop coefficients from the computed values and experimental evapotranspiration data. Robb (24) gives crop curves of evapotranspiration to potential evapotranspiration (Et/Etp) for 7 crops. These values multiplied by 0.88 are approximately equal to Et/Ev values. The USDA, Soil Conservation Service (27) uses crop growth coefficients, Kc. Values of Kc x 0.78 approximate values of Et/Ev. However, values given of Kc for grain and sugar beets are higher than those available from most other sources and were, therefore, not used in obtaining the factor of 0.78. Monthly values are given of Kc for 8 crops. Values are given for 13 crops based upon the percent of the crop growing season. Jensen (15) has developed crop curves for 15 or more crops showing soil-plant-air transfer coefficients, Ket. Values of Ket x 0.90 are roughly equal to Et/Ev. McDaniels (17) uses use coefficients KU which are ratios of evapotranspiration to computed lake evaporation. KU x 0.70 gives a good approximation of Et/Ev.

Based upon the above data and other sources, monthly crop consumptive use (evapotranspiration) coefficients, or Et/Ev ratios, for U.S.A. locations were determined as shown in Table 10. Care should be exercised in using monthly coefficients for other climatic conditions. Crop coefficients by percent of crop growing season are given in Table 11. These data should be more reliable for other latitudes and climatic conditions. Evapotranspiration from the 20-foot (6.1 meters weighing lysimeters planted to rye grass at Davis, California, indicate that this standardized evapotranspiration potential is usually above 80 percent of standardized Class A pan evaporation. Et/Ev ratios multiplied by 1.25, therefore, may be used to obtain coefficients for potential evapotranspiration as developed from the data from Davis, California.

Since considerable scatter exists in most evapotranspiration data, the selection of consumptive use coefficients is subject to considerable judgment. Values shown are those associated with high yields largely under experiment station conditions. Because of the scatter of the data, coefficients are rounded to the nearest five in the last significant figure. Ratios given in Tables 10 and 11 are to be used with standardized measured or computed Class A pan evaporation data, and when multiplied by 1.25 they may be used with computed potential evapotranspiration to obtain monthly crop evapotranspiration, or crop evapotranspiration by percent of crop growing season.

Conclusion

Pan evaporation, as measured with a Class A pan under standardized conditions, is a reliable index of climate as it pertains to evapotranspiration. Pan evaporation is now being measured in many places in the world, but when it is not available it may be estimated from many formulas, some of which are included here. Potential evapotranspiration can be estimated from pan evaporation or computed directly from radiation and climatic data. Actual evapotranspiration varies with crops, and many factors besides climate, but can be best estimated from potential evapotranspiration or directly from pan evaporation.

Irrigation water requirements depend basically upon the evapotranspiration, but also upon many other factors including precipitiation and water application efficiency. As water resources become more limiting, the need for better estimates of evapotranspiration will increase.

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TABLE 1. MEAN MONTHLY VALUES OF THE DAYTIME COEFFICIENT, D.

LATITUDE (FOR USE WITH ALL HARGREAVES FORMULAS)

DEGREES	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
NORTH												
60	.55	.67	.97	1.17	1.42	1.51	1.50	1.30	1.03	.83	.59	.48
55	.64	.71	.98	1.13	1.34	1.40	1.40	1.25	1.02	.86	.67	.60
50	.71	.75	.98	1.11	1.29	1.32	1.33	1.21	1.02	.89	.72	.67
45	.76	.78	.99	1.09	1.24	1.26	1.28	1.18	1.01	.91	.77	.73
40	.81	.80	.99	1.07	1.21	1.22	1.23	1.15	1.01	.93	.80	.78
35	.84	.82	1.00	1.06	1.17	1.18	1.20	1.13	1.00	.94	.83	.82
30	.87	.84	1.00	1.05	1.15	1.14	1.17	1.11	1.00	.96	.86	.86
25	.90	.85	1.01	1.03	1.12	1.11	1.14	1.09	1.00	.97	.89	.89
20	.93	.87	1.01	1.02	1.10	1.08	1.11	1.08	1.00	.98	.91	.92
15	.95	.88	1.01	1.01	1.08	1.06	1.09	1.06	.99	.99	.93	.95
10	.98	.90	1.01	1.00	1.06	1.03	1.06	1.05	.99	1.00	.95	.97
5	1.00	.91	1.02	1.00	1.04	1.01	1.04	1.03	.99	1.01	.97	1.00
0	1.02	.92	1.02	.99	1.02	.99	1.02	1.02	.99	1.02	.99	1.02
SOUTH												
-5	1.04	.93	1.02	.98	1.00	.96	1.00	1.01	.98	1.03	1.01	1.04
-10	1.06	.95	1.02	.97	.98	.94	.97	.99	.98	1.04	1.02	1.07
-15	1.09	.96	1.03	.96	.96	.91	.95	.98	.98	1.05	1.04	1.09
-20	1.11	.97	1.03	.95	.94	.89	.93	.96	.98	1.06	1.06	1.12
-25	1.14	.99	1.03	.94	.92	.86	.90	.95	.97	1.07	1.09	1.15
-30	1.16	1.00	1.04	.93	.89	.83	.87	.93	.97	1.08	1.11	1.18
-35	1.20	1.02	1.04	.91	.86	.80	.84	.91	.97	1.10	1.14	1.22
-40	1.23	1.04	1.04	.90	.83	.76	.80	.89	.97	1.11	1.17	1.26
-45	1.27	1.06	1.05	.88	.80	.71	.76	.86	.96	1.13	1.21	1.30
-50	1.33	1.09	1.06	.86	.75	.65	.71	.83	.96	1.15	1.25	1.36
-55	1.39	1.13	1.06	.84	.69	.58	.64	.79	.95	1.18	1.31	1.44
-60	1.49	1.17	1.07	.81	.62	.47	.54	.74	.94	1.21	1.38	1.56

TABLE 2. VALUES OF CORRECTION FACTORS FOR EQ. 4[a]

Relative Humidity			Wind Velocity at 2 Meters				Sunshine		Elevation	
Hn at noon percent	Hm mean daily percent	F_H	W_{kd} kilo-meters per day	F_W	W_{kh} kilo-meters per hour	F_W	S percent possible.	F_S	E in meters	F_E
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
20	34	0.568	20	0.864	1.0	0.875	20	0.666	0	0.950
30	46	0.540	40	0.911	2.0	0.927	30	0.713	500	1.000
40	55	0.500	60	0.948	3.0	0.966	40	0.761	1000	1.050
50	65	0.452	80	0.978	4.0	1.000	50	0.809	1500	1.100
60	73	0.392	100	1.005	5.0	1.030	60	0.857	2000	1.150
70	82	0.320	125	1.035	6.0	1.056	70	0.905	2500	1.200
80	87	0.238	150	1.062	7.0	1.081	80	0.952	3000	1.250
85	91	0.193	175	1.087	8.0	1.104	90	1.000	3500	1.300
90	94	0.145	200	1.111	9.0	1.125	100	1.048	4000	1.350

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[a] From Eqs. 4a to 4e.

TABLE 3. MEAN MONTHLY VALUES OF EXTRATERRESTRIAL RADIATION EXPRESSED AS EQUIVALENT EVAPORATION IN MILLIMETERS PER DAY

LATITUDE DEGREES	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
NORTH												
60	1.41	3.36	6.88	11.31	15.14	17.06	16.25	13.03	8.67	4.58	1.92	.96
55	2.55	4.62	8.08	12.18	15.55	17.18	16.50	13.71	9.77	5.85	3.11	2.02
50	3.77	5.89	9.23	12.98	15.93	17.30	16.73	14.34	10.79	7.09	4.35	3.21
45	5.04	7.14	10.30	13.69	16.23	17.38	16.91	14.87	11.74	8.30	5.63	4.46
40	6.32	8.36	11.30	14.31	16.45	17.38	17.01	15.32	12.59	9.45	6.90	5.75
35	7.59	9.53	12.21	14.82	16.58	17.30	17.01	15.66	13.35	10.54	8.15	7.04
30	8.84	10.64	13.03	15.23	16.60	17.13	16.92	15.90	14.01	11.55	9.36	8.32
25	10.05	11.68	13.75	15.52	16.51	16.85	16.72	16.02	14.56	12.48	10.53	9.56
20	11.20	12.64	14.37	15.70	16.32	16.48	16.42	16.04	15.00	13.33	11.63	10.76
15	12.29	13.51	14.88	15.77	16.02	16.00	16.02	15.93	15.33	14.07	12.66	11.91
10	13.30	14.28	15.27	15.72	15.61	15.42	15.51	15.72	15.54	14.71	13.61	12.98
5	14.23	14.96	15.55	15.55	15.09	14.74	14.90	15.39	15.63	15.24	14.47	13.98
0	15.07	15.53	15.71	15.27	14.47	13.97	14.19	14.95	15.61	15.66	15.23	14.90
SOUTH												
-5	15.81	15.98	15.75	14.88	13.76	13.12	13.39	14.41	15.46	15.96	15.89	15.72
-10	16.45	16.33	15.67	14.37	12.95	12.18	12.51	13.76	15.20	16.15	16.45	16.44
-15	16.98	16.55	15.48	13.76	12.06	11.17	11.54	13.01	14.82	16.21	16.89	17.06
-20	17.40	16.66	15.16	13.05	11.09	10.10	10.51	12.17	14.33	16.16	17.22	17.57
-25	17.71	16.65	14.73	12.24	10.05	8.97	9.42	11.25	13.73	15.99	17.43	17.97
-30	17.91	16.52	14.19	11.34	8.95	7.80	8.28	10.25	13.03	15.70	17.54	18.27
-35	17.99	16.27	13.54	10.36	7.80	6.61	7.10	9.18	12.23	15.29	17.52	18.46
-40	17.98	15.92	12.79	9.31	6.61	5.40	5.89	8.06	11.33	14.78	17.40	18.54
-45	17.86	15.46	11.94	8.19	5.41	4.19	4.69	6.89	10.35	14.16	17.18	18.54
-50	17.66	14.90	11.00	7.02	4.20	3.02	3.49	5.68	9.29	13.45	16.87	18.46
-55	17.40	14.25	9.98	5.81	3.01	1.90	2.34	4.46	8.16	12.64	16.49	18.33
-60	17.12	13.54	8.88	4.57	1.88	.91	1.28	3.24	6.97	11.76	16.07	18.20

TABLE 4. MEAN MONTHLY VALUES OF EXTRATERRESTRIAL RADIATION.

EXPRESSED AS EQUIVALENT EVAPORATION IN INCHES PER MONTH

LATITUDE DEGREES	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
NORTH												
60	1.73	3.70	8.40	13.35	18.47	20.14	19.83	15.90	10.24	5.59	2.26	1.17
55	3.11	5.10	9.87	14.39	18.98	20.29	20.14	16.74	11.54	7.14	3.67	2.47
50	4.60	6.49	11.26	15.33	19.44	20.43	20.42	17.50	12.75	8.66	5.14	3.92
45	6.15	7.87	12.58	16.17	19.81	20.53	20.64	18.15	13.86	10.13	6.65	5.45
40	7.72	9.21	13.79	16.90	20.08	20.53	20.76	18.70	14.87	11.54	8.15	7.02
35	9.27	10.50	14.91	17.50	20.23	20.44	20.76	19.12	15.77	12.86	9.63	8.59
30	10.79	11.73	15.91	17.99	20.26	20.23	20.65	19.40	16.55	14.10	11.06	10.15
25	12.26	12.87	16.79	18.33	20.16	19.91	20.41	19.56	17.20	15.24	12.43	11.67
20	13.67	13.93	17.54	18.55	19.92	19.46	20.04	19.57	17.72	16.26	13.74	13.14
15	15.00	14.89	18.16	18.63	19.55	18.89	19.55	19.45	18.11	17.17	14.95	14.53
10	16.24	15.75	18.64	18.57	19.05	18.21	18.93	19.18	18.35	17.95	16.07	15.85
5	17.37	16.49	18.98	18.37	18.42	17.41	18.18	18.78	18.46	18.60	17.09	17.07
0	18.40	17.12	19.17	18.04	17.67	16.50	17.32	18.25	18.43	19.11	17.99	18.18
SOUTH												
-5	19.30	17.62	19.22	17.57	16.79	15.49	16.34	17.58	18.26	19.48	18.77	19.18
-10	20.06	18.00	19.13	16.97	15.81	14.39	15.26	16.79	17.95	19.71	19.43	20.07
-15	20.73	18.24	18.39	16.25	14.71	13.19	14.09	15.88	17.51	19.79	19.95	20.82
-20	21.24	18.36	18.50	15.41	13.53	11.93	12.83	14.86	16.93	19.72	20.34	21.45
-25	21.62	18.35	17.98	14.45	12.26	10.60	11.49	13.73	16.22	19.51	20.59	21.94
-30	21.85	18.21	17.32	13.39	10.92	9.22	10.10	12.51	15.39	19.16	20.71	22.30
-35	21.96	17.94	16.52	12.24	9.52	7.80	8.66	11.21	14.44	18.67	20.70	22.53
-40	21.94	17.55	15.61	10.99	8.07	6.38	7.19	9.83	13.38	18.04	20.56	22.63
-45	21.80	17.04	14.57	9.67	6.60	4.95	5.72	8.40	12.23	17.28	20.30	22.63
-50	21.55	16.42	13.43	8.29	5.13	3.56	4.26	6.93	10.98	16.41	19.93	22.53
-55	21.24	15.71	12.18	6.86	3.68	2.25	2.86	5.44	9.64	15.43	19.48	22.37
-60	20.89	14.93	10.84	5.40	2.29	1.07	1.56	3.96	8.24	14.35	18.98	22.21

TABLE 5. MEAN TEMPERATURE, T AND T_c, COEFFICIENT OF TEMPERATURE, C_T, AND LOG C_T.

T	T_c	C_T	Log C_T	T	T_c	C_T	Log C_T	T	T_c	C_T	Log C_T
°F	°C	----	----	°F	°C	----	----	°F	°C	----	----
				56	13.33	.787	-.1040	81	27.22	1.243	.0944
32	0.00	.393	-.4060	57	13.89	.804	-.0946	82	27.78	1.262	.1010
33	0.56	.408	-.3891	58	14.44	.822	-.0853	83	28.33	1.281	.1076
34	1.11	.424	-.3727	59	15.00	.839	-.0761	84	28.89	1.300	.1141
35	1.67	.440	-.3569	60	15.56	.857	-.0671	85	29.44	1.320	.1205
36	2.22	.455	-.3415	61	16.11	.874	-.0583	86	30.00	1.339	.1269
37	2.78	.471	-.3267	62	16.67	.892	-.0495	87	30.56	1.359	.1332
38	3.33	.487	-.3122	63	17.22	.910	-.0410	88	31.11	1.379	.1394
39	3.89	.503	-.2982	64	17.78	.928	-.0325	89	31.67	1.398	.1456
40	4.44	.519	-.2845	65	18.33	.946	-.0242	90	32.22	1.418	.1517
41	5.00	.536	-.2712	66	18.89	.964	-.0160	91	32.78	1.438	.1577
42	5.56	.552	-.2582	67	19.44	.982	-.0080	92	33.33	1.458	.1637
43	6.11	.568	-.2455	68	20.00	1.000	.0000	93	33.89	1.478	.1696
44	6.67	.585	-.2332	69	20.56	1.018	.0078	94	34.44	1.498	.1754
45	7.22	.601	-.2211	70	21.11	1.037	.0156	95	35.00	1.518	.1812
46	7.78	.618	-.2093	71	21.67	1.055	.0232	96	35.56	1.538	.1870
47	8.33	.634	-.1978	72	22.22	1.073	.0307	97	36.11	1.558	.1927
48	8.89	.651	-.1865	73	22.78	1.092	.0382	98	36.67	1.579	.1983
49	9.44	.668	-.1755	74	23.33	1.110	.0455	99	37.22	1.599	.2039
50	10.00	.684	-.1647	75	23.89	1.129	.0527	100	37.78	1.620	.2094
51	10.56	.701	-.1541	76	24.44	1.148	.0599	101	38.33	1.640	.2149
52	11.11	.718	-.1437	77	25.00	1.167	.0670	102	38.89	1.661	.2203
53	11.67	.735	-.1335	78	25.56	1.186	.0739	103	39.44	1.682	.2257
54	12.22	.753	-.1235	79	26.11	1.205	.0808	104	40.00	1.702	.2311
55	12.78	.770	-.1137	80	26.67	1.224	.0876	105	40.56	1.723	.2364

$$C_T = -0.0673 + 0.0132\,T + 0.0000367\,T^2 \qquad \text{Equation 7a}$$

$$C_T = 0.393 + 0.02796\,T_c + 0.0001189\,T_c^2 \qquad \text{Equation 7b}$$

TABLE 6. WIND VELOCITY, W, COEFFICIENT OF WIND, C_W, AND LOG C_W.

Anomometer Height							
2 ft	0.6 M	6.6 ft	2 M	20 ft	10 M	C_W	Log C_W
mi/da	km/hr	mi/da	km/hr	mi/da	km/hr		
0	0.0	0	0.0	0	0.0	0.708	-0.1497
5	0.3	17	1.2	20	1.5	0.735	-0.1334
10	0.7	31	2.1	37	2.7	0.762	-0.1180
15	1.0	44	2.9	51	3.7	0.738	-0.1034
20	1.3	54	3.7	64	4.6	0.814	-0.0896
25	1.7	64	4.3	75	5.4	0.839	-0.0764
30	2.0	74	4.9	86	6.2	0.863	-0.0639
35	2.3	82	5.5	96	6.9	0.887	-0.0520
40	2.7	90	6.1	106	7.6	0.911	-0.0406
45	3.0	98	6.6	115	8.3	0.934	-0.0297
50	3.4	105	7.1	123	8.9	0.956	-0.0194
55	3.7	112	7.5	132	9.5	0.978	-0.0095
60	4.0	119	8.0	140	10.0	1.000	-0.0000
65	4.4	125	8.4	147	10.6	1.021	0.0090
70	4.7	132	8.8	155	11.1	1.042	0.0177
75	5.0	138	9.2	162	11.6	1.062	0.0260
80	5.4	144	9.6	169	12.1	1.081	0.0339
85	5.7	149	10.0	175	12.6	1.100	0.0415
90	6.0	155	10.4	182	13.1	1.119	0.0488
95	6.4	160	10.8	188	13.5	1.137	0.0557
100	6.7	166	11.1	194	14.0	1.154	0.0624
110	7.4	176	11.8	206	14.8	1.138	0.0748
120	8.0	186	12.5	218	15.7	1.220	0.0862
130	8.7	196	13.1	230	16.5	1.249	0.0966
140	9.4	206	13.8	241	17.4	1.277	0.1061
150	10.1	216	14.5	253	18.2	1.302	0.1147
160	10.7	226	15.1	265	19.0	1.326	0.1225
170	11.4	236	15.8	276	19.9	1.348	0.1296
180	12.1	246	16.5	288	20.7	1.367	0.1358
190	12.7	255	17.1	300	21.6	1.385	0.1414
200	13.4	265	17.8	311	22.4	1.400	0.1463
210	14.1	275	18.5	323	23.2	1.414	0.1504
220	14.8	285	19.1	335	24.1	1.426	0.1540
230	15.4	295	19.8	346	24.9	1.435	0.1569
240	16.1	305	20.5	358	25.7	1.443	0.1592
250	16.8	315	21.1	370	26.6	1.448	0.1609

$C_W = 0.708 + 0.00546\ W - 0.00001\ W^2$ Equation 7c

TABLE 7. RELATIVE HUMIDITY, Hn AND Hm, COEFFICIENTS, C_{Hn} AND C_{Hm}, AND LOGARITHMS OF C_{Hn} AND C_{Hm}.

Hn	C_{Hn}	Log C_{Hn}	Hm	C_{Hm}	Log C_{Hm}
%/100			%/100		
0.10	1.170	0.0683	0.10	1.223	0.0876
0.15	1.136	0.0554	0.15	1.203	0.0802
0.20	1.105	0.0432	0.20	1.182	0.0726
0.22	1.093	0.0386	0.22	1.174	0.0695
0.24	1.082	0.0341	0.24	1.165	0.0664
0.26	1.071	0.0296	0.26	1.157	0.0633
0.28	1.060	0.0253	0.28	1.149	0.0602
0.30	1.050	0.0210	0.30	1.140	0.0570
0.32	1.039	0.0168	0.32	1.132	0.0538
0.34	1.030	0.0126	0.34	1.123	0.0505
0.36	1.020	0.0085	0.36	1.115	0.0472
0.38	1.010	0.0043	0.38	1.106	0.0439
0.40	1.000	0.0000	0.40	1.098	0.0404
0.42	0.990	-0.0042	0.42	1.089	0.0369
0.44	0.981	-0.0085	0.44	1.080	0.0334
0.46	0.970	-0.0130	0.46	1.071	0.0297
0.48	0.960	-0.0177	0.48	1.062	0.0259
0.50	0.949	-0.0226	0.50	1.052	0.0220
0.52	0.938	-0.0277	0.52	1.042	0.0180
0.54	0.927	-0.0331	0.54	1.032	0.0138
0.56	0.914	-0.0389	0.56	1.022	0.0094
0.58	0.902	-0.0450	0.58	1.011	0.0047
0.60	0.888	-0.0517	0.60	1.000	-0.0000
0.62	0.873	-0.0588	0.62	0.988	-0.0053
0.64	0.858	-0.0666	0.64	0.975	-0.0108
0.66	0.841	-0.0751	0.66	0.962	-0.0167
0.68	0.823	-0.0844	0.68	0.948	-0.0231
0.70	0.804	-0.0945	0.70	0.933	-0.0300
0.72	0.784	-0.1057	0.72	0.917	-0.0374
0.74	0.762	-0.1180	0.74	0.900	-0.0456
0.76	0.738	-0.1317	0.76	0.882	-0.0545
0.78	0.713	-0.1469	0.78	0.862	-0.0643
0.80	0.686	-0.1638	0.80	0.841	-0.0751
0.82	0.657	-0.1827	0.82	0.818	-0.0871
0.84	0.625	-0.2040	0.84	0.793	-0.1005
0.86	0.592	-0.2280	0.86	0.767	-0.1155
0.88	0.555	-0.2553	0.88	0.737	-0.1324
0.90	0.517	-0.2867	0.90	0.705	-0.1515
0.95	0.408	-0.3893	0.95	0.613	-0.2122
1.00	0.280	-0.5528	1.00	0.500	-0.3010

$C_{Hn} = 1.250 - 0.87\ Hn + 0.75\ Hn^2 - 0.85\ Hn^4$ Equation 7d

$C_{Hm} = 1.265 - 0.415\ Hm - 0.343\ Hm^6$ Equation 7e

TABLE 8. SUNSHINE PERCENTAGE, S, COEFFICIENT OF SUNSHINE, C_S, AND LOG C_S.

S	C_S	Log C_S	S	C_S	Log C_S	S	C_S	Log C_S	S	C_S	Log C_S
%	----	----	%	----	----	%	----	----	%	----	----
0	.542	-.2660	26	.708	-.1499	51	.829	-.0813	76	.972	-.0125
2	.558	-.2536	27	.713	-.1467	52	.834	-.0787	77	.979	-.0094
3	.565	-.2477	28	.718	-.1436	53	.839	-.0761	78	.986	-.0063
4	.573	-.2420	29	.724	-.1405	54	.844	-.0736	79	.993	-.0031
5	.580	-.2365	30	.729	-.1375	55	.849	-.0710	80	1.000	.0000
6	.587	-.2311	31	.734	-.1346	56	.854	-.0684	81	1.008	.0033
7	.594	-.2259	32	.738	-.1317	57	.859	-.0658	82	1.015	.0066
8	.601	-.2209	33	.743	-.1288	58	.865	-.0632	83	1.023	.0099
9	.608	-.2160	34	.748	-.1260	59	.870	-.0606	84	1.031	.0133
10	.615	-.2112	35	.753	-.1232	60	.875	-.0579	85	1.039	.0167
11	.621	-.2066	36	.758	-.1204	61	.880	-.0553	86	1.047	.0201
12	.628	-.2021	37	.763	-.1177	62	.886	-.0526	87	1.056	.0236
13	.634	-.1978	38	.767	-.1150	63	.891	-.0499	88	1.064	.0271
14	.640	-.1935	39	.772	-.1123	64	.897	-.0472	89	1.073	.0307
15	.647	-.1894	40	.777	-.1096	65	.903	-.0444	90	1.082	.0343
16	.653	-.1854	41	.782	-.1070	66	.908	-.0417	91	1.091	.0379
17	.659	-.1814	42	.786	-.1044	67	.914	-.0389	92	1.101	.0416
18	.664	-.1776	43	.791	-.1018	68	.920	-.0361	93	1.110	.0454
19	.670	-.1739	44	.796	-.0992	69	.926	-.0332	94	1.120	.0491
20	.676	-.1702	45	.801	-.0966	70	.932	-.0304	95	1.130	.0529
21	.681	-.1666	46	.805	-.0940	71	.939	-.0275	96	1.140	.0568
22	.687	-.1631	47	.810	-.0915	72	.945	-.0245	97	1.150	.0607
23	.692	-.1597	48	.815	-.0889	73	.952	-.0216	98	1.160	.0646
24	.698	-.1564	49	.820	-.0864	74	.958	-.0186	99	1.171	.0686
25	.703	-.1531	50	.825	-.0838	75	.965	-.0156	100	1.181	.0725

$C_S = 0.542 + 0.80 S - 0.78 S^2 + 0.62 S^3$ Equation 7f

TABLE 9. ELEVATION E, COEFFICIENT OF ELEVATION, C_E, AND LOG C_E.

Elev. E	Elev.	C_E	Log C_E	Elev. E	Elev.	C_E	Log C_E
1000 feet	meters			1000 feet	meters		
.0	0	.970	-.0132	5.5	1676	1.135	.0550
.5	152	.985	-.0066	6.0	1829	1.150	.0607
1.0	305	1.000	.0000	6.5	1981	1.165	.0663
1.5	457	1.015	.0065	7.0	2134	1.180	.0719
2.0	610	1.030	.0128	7.5	2286	1.195	.0774
2.5	762	1.045	.0191	8.0	2438	1.210	.0828
3.0	914	1.060	.0253	8.5	2591	1.225	.0881
4.0	1219	1.090	.0374	9.0	2743	1.240	.0934
4.5	1372	1.105	.0434	10.0	3048	1.270	.1038
5.0	1524	1.120	.0492	11.0	3353	1.300	.1139

$C_E = 0.970 + 0.030\,E$ (E = 1 for 1000 feet) Equation 7g

TABLE 10. MONTHLY CROP CONSUMPTIVE USE COEFFICIENTS - Et/Ev RATIOS

(To be multiplied by actual or estimated Class A Pan Evaporation)[a]

CROP	Source of Data[b]	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Alfalfa	(27)	0.55	0.65	0.75	0.85	0.95	1.00	0.95	0.90	0.85	0.80	0.70	0.55
Avocados	(27)	0.20	0.35	0.45	0.55	0.60	0.65	0.60	0.60	0.60	0.40	0.35	0.25
Citrus	(27)	0.50	0.50	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.50	0.50
Dates	(14)	0.85	0.85	0.80	0.80	0.75	0.75	0.75	0.80	0.85	0.90	0.90	0.90
Dates with heavy cover	(15)	1.05	1.00	1.00	0.95	0.95	0.95	0.95	1.00	1.00	1.10	1.10	1.10
Deciduous Orchard	(27)	0.15	0.20	0.30	0.50	0.70	0.75	0.75	0.65	0.45	0.25	0.15	0.10
Grapes	(27)	0.15	0.20	0.25	0.40	0.55	0.60	0.60	0.60	0.50	0.40	0.25	0.20
Orchard with clover	(27)	0.50	0.55	0.65	0.75	0.85	0.90	0.85	0.85	0.75	0.70	0.60	0.50
Oranges & lemons	(15)	0.45	0.40	0.35	0.35	0.35	0.35	0.40	0.45	0.50	0.55	0.55	0.50
Pasture grass	(27)	0.40	0.45	0.55	0.65	0.70	0.70	0.70	0.70	0.70	0.60	0.50	0.45
Bahiagrass	(2)	0.65	0.70	0.75	0.70	0.75	0.70	0.70	0.60	0.60	0.60	0.67	0.65
Bermuda grass	(16)	0.75	0.70	0.75	0.80	0.70	0.70	0.70	0.70	0.75	0.75	0.80	0.75
Pangola grass	(13)	1.15	1.05	0.80	1.00	0.90	1.20	1.10	0.95	0.80	0.60	1.00	1.05
Trenza grass	(13)	0.80	0.80	0.90	1.20	1.30	1.60	1.20	1.45	0.80	0.95	1.30	1.30
Platano[c]	(13)	0.80	0.90	1.10	0.85	0.85	0.70	0.70	0.75	0.85	1.00	1.10	0.95
Sugar Cane[d]	(9)	0.75	0.70	0.50	0.50	0.55	0.55	0.60	0.75	0.85	0.85	0.90	0.85
Walnuts	(21)	0.05	0.10	0.20	0.35	0.55	0.70	0.75	0.70	0.55	0.40	0.25	0.10

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[a] These values multiplied by 1.25 may be used with potential evapotranspiration estimated from Eqs. 8, 9, 10, and 14.

[b] Numbers in parentheses refer to corresponding numbers in the appendix references.

[c] Data for month of planting and following month disregarded.

[d] Planted late in March and harvested in April following year.

TABLE 11. CROP CONSUMPTIVE USE COEFFICIENTS BY PERCENT OF GROWING SEASON Et/Ev RATIOS[a]

(To be multiplied by actual or estimated class A pan evaporation)

CROP	Percent of Crop Growing Season										
	0	10	20	30	40	50	60	70	80	90	100
Beans	0.20	0.30	0.40	0.65	0.85	0.90	0.90	0.80	0.60	0.35	0.20
Corn	0.20	0.30	0.50	0.65	0.80	0.90	0.90	0.85	0.75	0.60	0.50
Cotton	0.10	0.20	0.40	0.55	0.75	0.90	0.90	0.85	0.75	0.55	0.35
Grain sorghum	0.20	0.35	0.55	0.75	0.85	0.90	0.85	0.70	0.60	0.35	0.15
Grain spring	0.15	0.20	0.25	0.30	0.40	0.55	0.75	0.85	0.90	0.90	0.30
Grain winter	0.15	0.25	0.35	0.40	0.50	0.60	0.70	0.80	0.90	0.90	0.30
Melons & Cantaloupes	0.35	0.35	0.45	0.50	0.60	0.65	0.65	0.60	0.60	0.55	0.55
Nuts-pecan	0.35	0.45	0.55	0.75	0.75	0.65	0.50	0.45	0.40	0.35	0.30
Peanuts	0.15	0.25	0.35	0.45	0.55	0.60	0.65	0.65	0.60	0.45	0.30
Potatoes	0.20	0.35	0.45	0.65	0.80	0.90	0.95	0.95	0.95	0.90	0.90
Rice	0.80	0.95	1.05	1.15	1.20	1.30	1.30	1.20	1.10	0.90	0.50
Soybeans	0.15	0.20	0.25	0.30	0.45	0.55	0.70	0.80	0.70	0.60	0.50
Small Vegetables	0.25	0.30	0.45	0.55	0.60	0.65	0.65	0.60	0.55	0.45	0.30
Sugar Beets	0.25	0.45	0.60	0.70	0.80	0.85	0.90	0.90	0.90	0.90	0.90
Tomatoes	0.20	0.25	0.40	0.60	0.70	0.75	0.75	0.65	0.55	0.30	0.20
Vegetables, shallow rooted	0.10	0.20	0.40	0.50	0.60	0.60	0.60	0.55	0.45	0.35	0.30

Source: Melons and cantaloupes, Soybeans and Small Vegetables (27); Tomatoes (1); Other crops (12).

[a] These values multiplied by 1.25 may be used with potential evapotranspiration estimated from Eqs. 8, 9, 10, and 14.