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Evapotranspiration and Irrigation Water Requirements

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A manual prepared by the
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When no historical E_t data are available, the engineer uses "[illegible]tional expectation" to predict E_t. This is described by the equation:

$$E[X_1|X_2 = x_2] = m_1 + r\frac{\sigma_1}{\sigma_2}(x_2 - m_2) \quad [6.8]$$

Eq. 6.8 states that the best estimate of the first random variable, X_1, given the value of the second random variable, X_2, as x_2 (in this case x_2 represents the meteorological parameter), is equal to the mean of the first random variable plus the correlation coefficient between X_1 and X_2, r, times the ratio of the standard deviations and the difference between the actual second variable and the mean of the meteorological variable. In simple terms, this equation states that the best estimate of E_t in some areas will be equal to mean E_t in a known area, m_1, plus an adjustment for the meteorological parameter, x_2, that is different from that of the first site, m_2.

The standard deviation of daily E_t estimates may be significantly less than the standard deviation of actual E_t (population), especially when only one or two variables are used in the estimating equation. For example, Allen and Wright (1983) found the standard deviations of E_t estimates using the SCS Blaney-Criddle and the FAO Blaney-Criddle equations to be less than half of the standard deviation of E_t measured in a lysimeter at Kimberly, Idaho. The standard deviation of E_t estimates using the 1982 Kimberly Penman equation (Wright, 1982) was 15-20 percent less than the population standard deviation. When using a resistance form of the Penman-Monteith equation to estimate E_t, Allen and Pruitt (1988) obtained standard deviations that were equivalent to the population standard deviations at Kimberly, Idaho, Davis, California, and Coshocton, Ohio.

When comparing standard deviations of measured, estimated, or predicted E_t, the same time periods must be used because the standard deviation of the mean for a given time period decreases with the number of daily values represented by the mean. In the case of E_t, the standard deviation of the mean for a given time period will vary with the number of days represented in the period as indicated later.

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}} = \frac{\sigma_x}{\sqrt{\Delta t}} \quad [6.9]$$

where $\sigma_{\bar{x}}$ is the standard deviation of the mean of variable x; n is the number of values used (in this case, daily values); and Δt equals the number of days in the time period. Eq. 6.9 indicates that the standard deviation of the mean for a given time period will become less as the number of days in the time period increases. Therefore, as the length of the time period being considered increases, the correlation coefficient relating E_t to a meteorological parameter also increases. For example, seasonal E_t may correlate closely with the sum of daily air t[illegible]atures since both increase with time, but weekly or daily values may be poorly correlated.

Calculation Methods

Most current methods of estimating E_t involve two steps. First, an estimate of E_t for a well-watered reference crop with standard canopy characteristics is made. The two most common reference crops are grass and alfalfa. Where these crops cannot be grown and evaluated, the reference E_t is for a "hypothetical" reference crop. Then, an estimate of E_t for the crop being considered is obtained by multiplying the E_t for the reference crop, E_{tr} or E_{to}, by a "crop coefficient," or K_c, which varies by growth stage for each crop. The distribution of the crop coefficient during its growing cycle of the crop is called a "crop curve." Crop curves are currently obtained experimentally. They represent the integrated effects of changes in leaf area, plant height, degree of cover and canopy resistances, and albedo on E_t relative to the reference crop.

Crop coefficients relate E_t for each crop to a specific reference crop. Therefore, when selecting and using published crop coefficients, the correct reference crop E_t must be used to obtain reliable estimates of E_t. Crop coefficients derived using a grass reference crop should not be used with alfalfa reference E_t or vice versa. Developers of crop curves emphasize the importance of consistency in estimating E_t (Doorenbos and Pruitt, 1977; Wright, 1981, 1982).

The concept of reference crop E_t relative to potential E_t is discussed in detail in Chapter 4. The differences between the reference E_t values for grass and alfalfa are discussed in more detail in Section 6.3 and in Table 6.10. A flow chart showing the alternative paths for estimating E_t using either a reference crop or the Blaney-Criddle method and estimating irrigation water requirements is presented in Fig. 6.1.

6.3. Estimating and Predicting Reference Crop Evapotranspiration

Combination Methods

Penman (1948) first derived the combination equation. He combined components to account for energy required to sustain evaporation and a mechanism required to remove the vapor (sink strength). He also eliminated surface temperature and surface vapor pressure in the process. Most studies prior to 1940 dealt with the difference in vapor pressure at the surface, e_o^0, and some height z, or $(e_o^0 - e_z)f(u)$. The energy source involved an estimate of net radiation from extraterrestrial radiation, percentage of sunshine, and humidity. Beginning with Eq. 3.27, Penman developed the combination equation as follows:

$$\lambda E = \frac{R_n - G}{1 + \beta} = \frac{R_n - G}{1 + \dfrac{\gamma(T_s - T_z)}{(e_s^o - e_z)}} \quad [6.10]$$

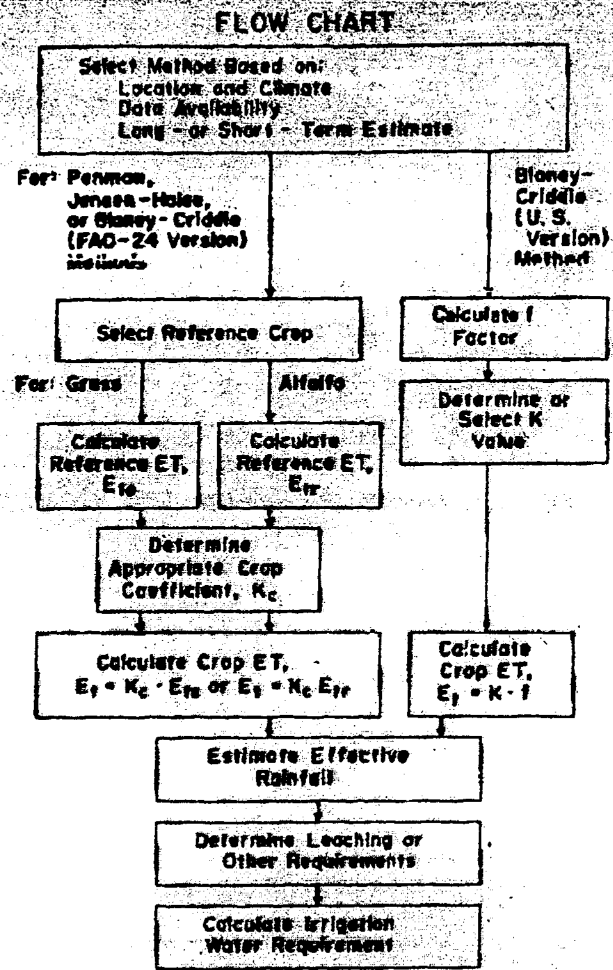

FIG. 6.1. Flow Chart for Estimating Irrigation Water Requirements from Climatic Data (Burman et al., 1980, 1983).

Penman defined E_a as the value of E if e_z^o were used instead of e_o^o in the Dalton-type equation for evaporation from a free water surface:

$$E_a = (e_z^o - e_z)f(u) \qquad [6.11]$$

from which:

$$\frac{E_a}{E_o} = \frac{(e_z^o - e_z)}{(e_o^o - e_z)} = \frac{(e_o^o - e_z) - (e_o^o - e_z^o)}{(e_o^o - e_z)} = 1 - \frac{(e_o^o - e_z^o)}{(e_o^o - e_z)} \qquad [6.12]$$

By substituting $(e_o^o - e_z^o)/\Delta$ for $(T_o - T_z)$ in Eq. 6.10, whe evaluated at T_z, substituting $(1 - E_a/E_o)$ from Eq. 6.12, and by algebraic manipulation, then:

$$\lambda E_o = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma}\lambda E_a \qquad [6.13]$$

where E_o represents evaporation from a free water surface for which the albedo, r, is 0.05. Penman derived an estimate of E_a by plotting daily $E_a/(e_o^o - e_z)$ versus u_2 values where E_o was measured with a 63-cm (2.5-ft) diameter ground evaporation pan surrounded by turf. The resulting linear regression equation was similar to that obtained by Rohwer (1931) in an intensive evaporation study conducted at Fort Collins, Colorado, and the results of other investigators. Penman's linear equation for evaporation from the free water surface expressed in mm d^{-1} with vapor pressure in mm Hg and wind speed in miles per day was $E_o = 0.35(1 + 0.0098\, u_2)(e_o^o - e_d)$. When converting vapor pressure to mb, and assuming $\lambda = 585$ cal g^{-1}, and using the notation e_z for e_d, the expression becomes:

$$\lambda E_o = 15.36(1 + 0.01\ u_2)(e_o^o - e_z) \qquad [6.14a]$$

where λE_o is latent heat flux from a water surface in cal cm^{-2} d^{-1}, u_2 is wind speed at 2 m above ground surface in miles d^{-1}, and e_o^o and e_z are the vapor pressures of the water surface and the air, respectively, in mb. For wind speed in m s^{-1}, vapor pressure in kPa, and λE_o in MJ m^{-2} d^{-1},

$$\lambda E_o = 6.43(1 + 0.53\ u_2)(e_o^o - e_z) \qquad [6.14b]$$

The general form of Eq. 6.14b for wind speed in m s^{-1}, vapor pressure in kPa, and λE_o in MJ m^{-2} d^{-1} where $W_f = a_w + b_w u_2$ is:

$$\lambda E_o = 6.43\ W_f(e_o^o - e_z) \qquad [6.14c]$$

Penman substituted Eq. 6.14a, derived from pan evaporation, for E_a in Eq 6.13 with e_o replaced by e_z^o. Substituting the empirical E_o relationship for E_a approximated the aerodynamic equation for evaporation from turf if the surface was wet and at the same temperature as the air at height z, and the aerodynamic roughness was the same as that existing for the surrounding turf. Following the evaporation studies at Lake Hefner, Oklahoma, Penman (1956) suggested that the wind function in Eq. 6.14a be replaced by $(0.5 + 0.01\ u_2)$ for estimates of evaporation from large water surfaces. Wright and Jensen (1972) determined constants for the wind term for Eq. 6.14a to be $(0.75 + 0.0185\, u_2)$ for a well-watered alfalfa field under the arid, advective conditions of southern Idaho. The larger coefficient, 0.0185 versus 0.01, illustrates the effects of increased surface roughness of alfalfa compared to short grass and the combined effects of lower leaf diffusion