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EVAPOTRANSPIRATION AND IRRIGATION WATER REQUIREMENTS

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Basic factors controlling the evapotranspiration process for irrigated crops are similar to those for other plant communities, except that the water requirement is largely satisfied by irrigation rather than by precipitation. A natural consequence of crop growth is the withdrawal of soil water from the crop root zone, accompanying the evaporative loss of water from exposed plant and soil surfaces, with the water vapor subsequently being carried away in the atmospheric air flow. We have traditionally come to speak of this evaporative water loss as evapotranspiration, or ET for short, though the process is strictly evaporation, whether from plant or soil surfaces (McIlroy, 1984). The aim of efficient and effective irrigation management is to provide sufficient water to a growing crop to replenish depleted soil water in time to avoid physiological water stress in the growing plants. Meeting this objective requires knowing when to irrigate and for how long or how much water to apply. The determination of irrigation requirements is thus of major importance in providing desirable irrigation management in arid and semiarid climates, or humid or subhumid climates where irrigation supplements precipitation.

The intent of this paper is to briefly review the development of our present ability to determine irrigation water requirements using ET methods. ET methodology is only briefly mentioned as these matters are specifically covered in other papers. Particular emphasis is given to the application of the "reference ET-crop coefficient" approach using meteorological data.

EVAPOTRANSPIRATION AND IRRIGATION SCHEDULING

Systematic irrigation scheduling procedures, utilizing the relationship of crop ET to irrigation needs, provides a means whereby scientific knowledge on irrigation can be transferred to the commercial irrigated farm. While in some instances a degree of plant water stress may be tolerable, or even desirable, the effects of underirrigation on crop production are so major that usually the goal is to make sure that soil water is adequate for desirable crop growth. Irrigating in excess of the storage capacity of the soil root zone can be an inefficient use of water, and/or energy, and may lead to other serious problems. With the critical need to improve farm profitability while conserving soil and other resources, we need to be able to tailor irrigation to evaporative water loss within the constraints of the plant-soil-system.

The exact measurement of crop ET is largely a scientific endeavor. However, progress in ET research has permitted development of procedures which are well suited for practical use in irrigation scheduling and other water resource management programs. These methods permit us to estimate daily

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crop-water use with available information on the climate, crop, and soil conditions. Crop ET information is also well suited for use in forecasting future evaporative demand and irrigation needs on a field or a project basis.

Ideally, ET methodology should provide the rate of ET in relation to all causative factors such as plant morphology, the development of plant cover, stage of growth, soil conditions, particularly as they affect soil evaporation directly or the availability of water for uptake by the roots, and climatic factors as they affect the energy and mass exchange processes. Completely ideal methods are not yet available, but estimates of crop irrigation requirements can be within the accuracy of most systems to deliver water to the crop. Conditions in irrigated agriculture may generally be more amenable to ET methods than conditions in rain-fed agriculture or natural plant communities because irrigated lands are often level, ET rates are relatively high, crops are grown in well-defined boundaries, and the crop surfaces are relatively uniform.

A procedure for using a meteorologically related reference evapotranspiration and a set of ET crop coefficients to estimate crop-water use has evolved during the past 20 years. This approach uses formulae accounting for the basic physical processes of crop evaporation to obtain reference ET and empirically derived crop coefficients to account for specific crop conditions. This "reference ET-crop coefficient" method requires careful matching of computational procedures and empirical coefficients. The method is a conservative practical technique based on relatively easily obtainable data which has potential for extended development and use.

DEVELOPMENT OF PRESENT PROCEDURES

Since early in the nineteenth century, many formulae have been suggested to describe the ET process. Brutsaert (1982) provides an interesting chronological sketch of the history of the theories of evaporation. Texts such as those of Monteith (1975) and Rosenberg et al. (1983) are available describing the relationship of crop development and the microclimate to the ET process. This subject has also been reviewed in other papers of this 1985 ASAE ET conference. The depth of understanding of early investigators concerning the basic processes of ET is impressive. Progress during the last 25 years has certainly been facilitated by the early contributions to basic knowledge. Our recent advancements in using ET methods to estimate crop-water use have been primarily in the area of improved meteorological instrumentation and data acquisition, along with the adaptation of basic physical relationships to specific conditions.

Blaney and Criddle (1950) introduced their empirical formula based on a simple correlation between crop ET and temperature and daylight factors. The method has been revised with time (USDA 1970; Doorenbos and Pruitt 1977) and has been widely used because of its relative simplicity. Estimates of crop ET by the Blaney-Criddle (B-C) method are, however, generally only applicable for longer time periods, about a month, and the estimating accuracy is limited by the dependence on only a few variables.

The contributions of Penman (1948, 1963) have had a major impact on our present methodology. The combination method he introduced provided a means of combining the effects of energy inputs and the aerodynamic transfer of water vapor away from the evaporating surface in a fairly rigorous manner with a minimum of empiricism. The method provided a convenient means of calculating ET on a daily basis from meteorological data and fostered the concept of potential ET. However, further refinement was needed to account for individual crop differences and climatic situations.

Monteith (1963) modified the Penman equation to include resistance terms accounting for specific plant effects such as those due to leaf stomata and crop morphology. Brown and Rosenberg (1973) modified the Monteith resistance approach to provide estimates of resistance parameters. The resistance modifications have not yet been incorporated into practical procedures for determining irrigation requirements.

Another modification of the Penman method that led to present practical procedures involved relating specific crop ET to a potential ET with an empirically derived, dimensionless crop coefficient. This approach overcame the problem of using a single evaporation formula to account for the plant and soil effects on crop ET. The use of the approach in the development of computerized irrigation scheduling procedures provided a major application of ET concepts to the determination of irrigation water requirements (Jensen et al. 1971; Jensen 1974; Doorenbos and Pruitt 1977). Improved crop coefficients have now been developed for some of the more common crops (Burman et al. 1980; Wright, 1981, 1982). Since certain aspects of the original potential ET concept do not hold for arid climates, the use of a reference crop ET is now recommended (Perrier 1979).

At the ASAE conference on evapotranspiration in 1966, authorities involved in research on ET and its relationship to the management of water resources reviewed ET theory and methods and assessed practical methods for estimating or predicting crop-water use. The ASA monograph (Hagan et al. 1967) provided a uniform reference book for the encouragement and improvement of academic courses on irrigation. It then seemed likely that concurrent estimates or measurements of ET during the crop season could provide improvements in scheduling irrigations. ET formulae were considered useful for calculating or predicting potential ET, but not useful for calculating ET during periods when crop cover was being established. Tanner (1967) emphasized that procedures, especially those employing empirical equations for estimating ET, needed to be calibrated for regions in which the estimates were made, particularly in arid and semiarid regions because of the increased crop ET due to the advection of energy from dry surroundings.

The ASCE Technical Committee handbook, "Consumptive Use of Water and Irrigation Water Requirements," (Jensen 1974) furthered the use of evapotranspiration formulae to predict potential ET from meteorological data. Crop coefficients were included for use with modified Penman potential ET in estimating crop ET. The results of methods for estimating ET were compared with lysimeter measurements obtained at several locations around the world. The Penman combination method was shown to generally provide estimates in closest agreement with measured ET.

The FAO Irrigation and Drainage Paper 24, FAO-ID-24 (Doorenbos and Pruitt 1977), further advanced the reference ET-crop coefficient concept. This guideline provided procedures for determining reference ET, crop coefficients, and adjustment factors to calculate crop ET for a wide variety of conditions. Correction coefficients were developed for four methods of estimating reference ET so that a single set of crop coefficients would suffice. The methods covered a range of data availability from a minimum of temperature to a maximum of temperature, humidity, wind, and sunshine or solar radiation.

The recent ASAE monograph (Jensen 1980) provided guidance for practicing engineers and engineering students in designing irrigation systems. A chapter on water requirements (Burman et al. 1980) focused on the selection of suitable methods for estimating crop ET and provided information on the use of the reference ET-crop coefficient approach. It included tables of then available improved crop coefficients derived from lysimeter-ET studies. Now serial publications such as *Advances in Irrigation* (Hillel 1982) and *Irrigation Science* (Stanhill 1978) aim to keep readers informed of recent advances in the science and practice of irrigation.

The nature and origin of various sets of crop coefficients used to estimate crop evapotranspiration were discussed by Wright (1981, 1982). A brief discussion of the basic nature of crop coefficients is repeated here for clarity.

The derivation and use of the general ET crop coefficient are given by:

$$K_c = E_{tc}/E_{tr} \tag{1}$$

$$E_{tc} = K_c \, E_{tr} \tag{2}$$

where K_c is the dimensionless crop coefficient for a particular crop at a given growth stage and for given soil moisture conditions, E_{tc} is daily crop ET (mm/day), and E_{tr} is daily reference ET (mm/day). Crop ET is dependent on the extent to which the crop canopy shades the soil, on the degree to which available soil moisture supports transpiration, and on the rate of evaporation from the soil which is largely dependent upon surface wetness. Consequently, the crop coefficient can be factored as given by:

$$K_c = K_{cb} \, K_a + K_s \tag{3}$$

where K_{cb} is a basal crop coefficient (Wright, 1982), K_a and K_s are relative coefficients related to available soil water and surface soil wetness, respectively. In some cases (Jensen et al. 1971; Jensen 1974), K_a may be assumed to be proportional to the logarithm of the percentage of remaining available soil water (AM) by: $K_a = \ln (AM + 1)/\ln 101$. The effects of surface wetness may be estimated by (Wright 1981):

$$K_s = f_w \, (K_1 - K_{cb}) \, [1 - (t/t_d)^{1/2}] \tag{4}$$

where K_1 is the maximum K_c usually occurring after rain or irrigation, t is number of days after rain or irrigation, t_d is the usual number of days for the soil surface to dry, and f_w is the relative portion of surface soil originally wetted. It may be assumed that $K_1 = 1$ unless data are available for a given location to indicate otherwise. For cases where the surface soil is completely wetted and stays wet for at least one day, $F_w = 1$; otherwise progressively less. Local experience will dictate the value of t_d. For silt loam soils $t_d = 5$. If irrigation is completed before noon, then $t = o$ for that day. A form of Eq. (3) which may be used is:

$$K_c = K_a \, K_{cm} \tag{5}$$

where K_m is a mean crop coefficient including effects of a wet soil surface. Values of K_{cm} are derived when $K_a = 1$ so that $K_c = K_{cm}$.

Crop coefficients are typically derived using Eq. (1) while Eq. (2) is used to estimate crop ET when applicable crop coefficients are available. The distribution of K_c with time throughout the season forms an "ET crop coefficient curve." Relations between K_c, K_{cm}, K_{cb}, K_s, and K_a are indicated in Fig. 1. The basal crop coefficient curve, K_{cb}, represents conditions when the soil surface is visually dry, so that soil evaporation is minimal, but soil water is sufficiently available to support maximum plant growth and transpiration. Some basal coefficients have been developed utilizing ET data obtained with weighing lysimeters in southern Idaho and central California (Burman et al. 1980; Wright, 1982). Daily values of K_{cb} may be adjusted for the effects of surface soil wetness, differences in soil drying properties, and available soil water using Eqs. (3) and (4). The exact nature of the relative adjustment coefficients depends on soil properties and crop rooting patterns. Only limited data are yet available on these relationships.

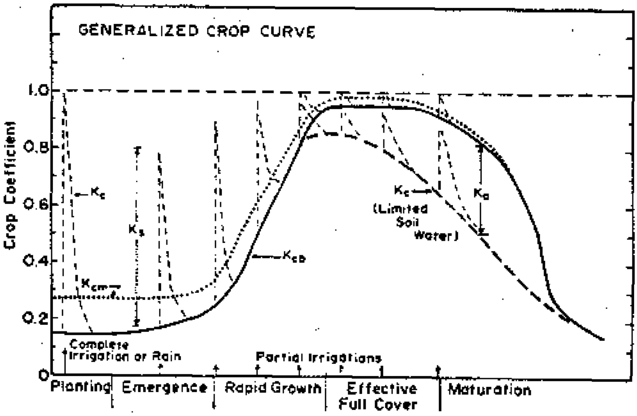

Fig. 1 Generalized ET Crop Coefficient Curves

A mean ET crop curve, K_{cm}, including the effects of rain or irrigation may be more useful than a K_{cb} curve for estimating daily crop ET when it is impractical to assess wet soil effects, or it is necessary to estimate total seasonal water requirements for a general area from historical climatic data and dates of rain or irrigation are not known. The K_{cm} curve lies above the basal curve (see Fig. 1) to various extents depending on the irrigation and rainfall pattern and soil drying properties. When K_{cm} is used to estimate E_{tc}, adjustment is not made for the effects of surface soil wetness, but adjustments can be made for the effects of limiting soil moisture, Eq. (5), if appropriate K_a relationships are available. Mean daily crop coefficients, developed from the same lysimeter ET data used for basal coefficients, were reported by Wright (1981). If soil water budget data are to be used in developing K_{cm} curves when daily lysimeter data are unavailable, care must be taken to include all ET throughout the season and to account for deep root extraction as well as deep drainage.

Daily lysimeter measurements of E_{tc} are preferable over values based on soil sampling procedures in the development of K_{cb} or K_{cm} curves. Methods available for estimating E_{tr} for use with Eqs. (1) and (2) depend on data availability and local circumstances (Jensen 1974; Burman et al. 1980, 1983; Doorenbos and Pruitt 1977). The Penman combination approach is recommended where sufficient data are available. Methods based solely on temperature are generally inadequate for arid or semiarid regions. Pruitt and Doorenbos (1977) adapted the method of Blaney and Criddle (1950), as modified by the USDA Soil Conservation Service (1970), to estimate reference ET for situations where only a minimum of climatic data are available.

Alfalfa reference ET, E_{tr}, has been used for arid climates (Jensen et al. 1971; Wright and Jensen 1972, 1978; Wright 1981, 1982) and is defined as the daily ET of an actively growing alfalfa crop covering an extensive area, at least 30 cm tall and standing erect, and well watered so that soil water availability does not limit ET. Wright and Jensen (1972) used lysimeter data and a modified Penman combination equation to develop procedures for estimating alfalfa E_{tr} from meteorological data. Wright (1982) later modified these procedures to further account for seasonal variability.

Grass reference ET, frequently denoted as E_{to}, has also been used and is defined as the ET of well-watered, actively growing, green grass which is clipped to a uniform height of 8-15 cm, completely shading the soil, not short of water, and covering an extensive area (Doorenbos and Pruitt 1977). Short grass ET is less than alfalfa ET. Thus when E_{to} is used in place of E_{tr} in Eq. (1), the resulting crop coefficients for a given crop are larger than when E_{tr} is used. Because of its interactions with the energy exchange and mass transfer processes operating within the atmosphere over a field, E_{tr} is affected by the nature of the crop canopy and general topographical and climatic conditions. Consequently, specific wind functions representing local conditions should be used with the combination equation for the most satisfactory results (Slatyer and McIlroy 1961). The same procedures should be used in computing the vapor pressure deficit for use with the various wind functions as were used in their derivation (Cuenca and Nicholson 1982).

COMPARISON OF RESULTS

Daily K_{cm} curves developed for several crops grown in southern Idaho (Wright 1981) are shown in Fig. 2 as an example of the general nature of such crop curves. These were derived from daily E_{tc} data obtained with weighing lysimeters and alfalfa E_{tr} calculated from meteorological data using the modified Penman method described by Wright (1982). A percentage time scale is used from planting until full cover in Fig. 2, while time after full cover is expressed as elapsed days. Dates of planting and the occurrence of key growth stages typical for Kimberly were given by Wright (1981, 1982). The differences between curves are due to the early growth characteristics of the crops, the maximum crop cover achieved, and the nature of crop maturity.

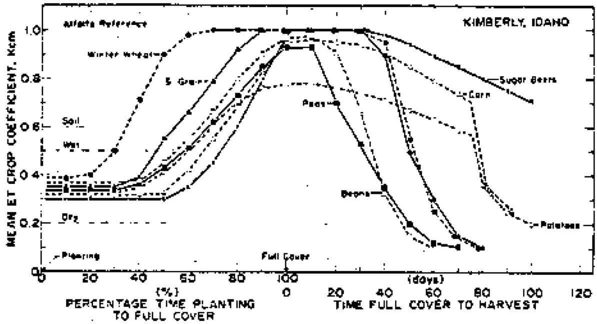

Fig. 2 Daily Mean ET Crop Coefficient Curves, K_{cm}, for Several Crops

Accumulative, mean monthly evaporation curves, measured or calculated in various ways, are compared in Fig. 3 for a 7-year period. The Epan data were obtained with a Class A evaporation pan at the National Weather Service (USWS) station near the ET site. The alfalfa E_{tr} curve was obtained from daily calculations using the before mentioned procedures of Wright (1982). The E_{to} data, representing computed grass reference ET, were based on the results of Allen and Brockway (1983) who used the methods of Pruitt and Doorenbos (1977). The E_{ta} curve was obtained from seven seasons of daily alfalfa ET, measured with weighing lysimeters, where the alfalfa was harvested for hay three times per season. The E_{tg} data are lysimeter ET for clipped grass recently measured during two seasons where the grass was clipped to the suggested FAO-ID-24 heights. The grass ET data were adjusted to the same 7-year period using the crop coefficient approach. The B-C data were calculated with the SCS modified Blaney-Criddle method (USDA 1970) for alfalfa hay.

The differences between the several curves of Fig. 3 are appreciable. The Epan curve for free water evaporation was highest, as expected. The measured alfalfa hay curve, E_{ta}, was less than the computed reference alfalfa curve,

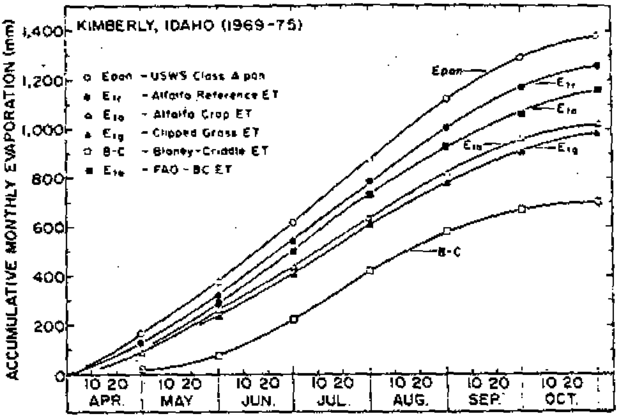

Fig. 3 Comparison of Several Types of Accumulative Mean Monthly Evaporation for a 7-Year Period

E_{tr}, because of reduced ET following harvest and at other times during the season when the alfalfa was not in reference crop condition. The calculated E_{to} curve was only about 12% less than the E_{tr} curve, while the measured E_{tg} curve was about 28% less. The grass should have been in reference condition throughout the season. Reasons for the discrepancy are not certain at this time. Possibilities are that the FAO-ID-24 procedures overcorrected for arid conditions, or that there are major differences between grass references. The similarity between the E_{ta} and E_{tg} curves shows that the net effects of alfalfa harvest are about equal to those of keeping the grass clipped. The major difference between the E_{ta} and B-C curves is indicative of the possible underestimation of actual crop ET with the B-C method.

NEEDED IMPROVEMENTS

Rather than percentage time or elapsed days as a basis for normalizing the crop coefficients, as in Fig. 2, it would be better to have a means of relating crop coefficients more directly to crop development. Attempts to correlate crop coefficients to variables such as accumulated growing degree days or reference ET have not always provided improvement. Models relating crop growth directly to climatic and growing conditions may be needed to provide the desired refinement. Current research along these lines by various agencies and universities is aimed at providing such models (Hill et al. 1985). When the lysimeter based ET crop coefficients are used with the appropriate reference ET, the accuracy of crop ET estimates are sufficient for many irrigation requirements (Jensen and Wright 1978). However, additional research is needed to test the transferability of reference ET procedures, to provide additional crop curves, and to provide improved relationships concerning the effects of limiting soil water on crop ET.

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