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# IRRIGATION MANAGEMENT -- WATER REQUIREMENTS AND WATER BALANCE

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This paper seeks to discuss irrigation water requirement estimates in the light of current practice, important developments during the 1970's, significant research and future research and applications of that research. Each of these are elaborated in more detail in the text of this paper.

A major addition to the science and art of estimating irrigation water requirements has been to replace the often ambiguous *"potential evapotranspiration"* with *"reference crop evapotranspiration"*. In the past decade a series of experiments relating irrigation water applications to crop yield now permit a much better economic analysis of the use of water for irrigation. The estimation of monthly irrigation water requirements was facilitated, particularly for varying climatic conditions with the United Nations publication "Crop Water Requirements" by Doorenbos and Pruitt (1977).

Estimation of daily water requirements for purposes of irrigation scheduling has been refined by the development of an albedo model and a wind function for the Penman method, that is variable throughout the season, Wright (1981). Several western states are experiencing lawsuits or other legal deliberations involving seasonal irrigation water requirements because of conflicts between groups of water users or water right transfers from agriculture to industry or municipal use. Irrigation scheduling continues to be refined from the standpoints of predicting ET, verifying yield conditions and other factors like production and peak pumping power reduction. Future research probably will include emphasis on breeding crops that require less water, refinements on the relationships between yields and water consumption, refinements in methods of estimating irrigation water requirements, and the development of irrigation schemes that minimize water and energy requirements.

For other methods and more detail the reader is referred to sources such as Doorenbos and Pruitt (1977), Jensen (1974), Burman, et al. (1981).

## DEFINITIONS

The definitions presented here are similar to those in the technical report "Consumptive Use of Water and Irrigation Water Requirements", Jensen (1974). However, some have been modified slightly or are specifically designated as being from other sources.

### Evapotranspiration

Evapotranspiration, ET, is the combined process by which water is transferred from the earth's surface to the atmosphere; evaporation of liquid or solid water plus transpiration of liquid water through plant tissues expressed as the latent heat transfer per unit area or its equivalent depth per unit area.

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## Potential Evapotranspiration

Potential ET, hereafter represented by $E_{tp}$, is the rate at which water, if available, would be removed from the soil and plant surface expressed as the latent heat transfer per unit area or its equivalent depth per unit area. Mathematically in the common derivation of the combination equation, potential ET is the ET that occurs when the vapor pressure at the evaporating surface is at the saturation point (van Bavel, 1966). This definition is independent of the vegetative and growth characteristics of the crop. Because this definition is not restricted to a standard surface it has had limited direct use by the designer or operator of an irrigation system. These definitions allow considerable variation in interpretations. ET from grass at various heights and alfalfa when not restricted by cuttings has been used as approximately potential ET. These differences though seemingly academic in nature have doubtless been confusing to the practicing irrigation hydrologist.

## Crop Coefficients

The relationship between the ET of a specific crop at a specific time in its growth stage and $E_{tp}$ is of practical interest to the designer or operator of an irrigation system because ET is estimated from $E_{tp}$ utilizing crop coefficients.

$$E_t = K_c E_{tp} \qquad (1)$$

$K_c$ is referred to as a crop coefficient which incorporates the effects of crop growth stage, crop density, and other cultural factors related to $E_{tp}$. The crop coefficient so defined is not the K factor used in the original Blaney-Criddle method, Blaney and Criddle (1962).

## Effective Precipitation

Effective rainfall or precipitation (Pe) is more difficult to define than potential evapotranspiration. Pe according to Dastane (1974) is "that which is useful or usable in any phase of crop production".

## Irrigation Water Requirements

The designer, operator, or hydrologist of an irrigation system must determine irrigation water requirements, R, for short or seasonal periods. The units of R usually are volume per unit area or depth. Doorenbos and Pruitt (1977) define R as "the depth of water needed to meet the water loss through ET of a disease-free crop, growing in large fields under nonrestricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment."

$$R = ET - Pe - G_e + \text{(other beneficial uses)} \qquad (2)$$

where $G_e$ = the contribution of a shallow water table if present

Other beneficial uses may include water for leaching requirements, germination, microclimate control, frost protection, herbicide, fungicide and fertilizer application. This "beneficial use" is not to be confused with legal definitions that appear in state water right laws.

## REFERENCE CROP ET

There are many ambiguities involved in the interpretation of $E_{tp}$ which can carry over into the practical task of predicting crop water requirements. A major advance which clears up much of the ambiguity is the use of reference crop ET. Two definitions of this term are widely used, $E_{tr}$ or $E_{to}$.



Definition of $E_{to}$: Doorenbos and Pruitt (1977) use $E_{to}$ to replace $E_{tp}$. Their definition of $E_{to}$ appears as *"the rate of evapotranspiration from an extensive surface of 8 to 15 cm, green grass cover of uniform height, actively growing, completely shading the ground, and not short of water."*

Definition of $E_{tr}$: An alternate definition of reference crop ET which is widely used in the western United States was made by Jensen et al. (1970); $E_{tr}$ *"represents the upper limit or maximum evapotranspiration that occurs under given climatic conditions with a field having a well-watered agricultural crop with an aerodynamically rough surface, such as alfalfa with 12 in. to 18 in. of top growth"*. The irrigation scientist making water requirement calculations should make sure that the definition of reference crop ET is completely understood and that written documentation carefully identifies the basic definitions used in calculations, designs, or reports. Actual $E_t$ is then calculated by:

$$E_t = K_c E_{tr} \quad \text{or} \quad E_t = K_c E_{to} \qquad (3)$$

The definition of $K_c$ used in Eq. (3) is essentially the same as that used in Eq. (1) except that it must be appropriate to the reference base. Reference crop ET can either be based on direct measurements or estimates. The crop coefficient of Eq. (3) used must be based on the definition of reference crop ET. Complete consistency is required in the method of estimating reference crop ET and in the selection of crop coefficients.

## IMPROVEMENT IN CROP COEFFICIENTS

Coefficients used to relate crop ET for a specific time and crop using Equations 1 and 3 must be determined by careful field measurements which simultaneously measure ET and the climatic parameters needed to determine reference crop ET. If daily ET calculations are desired, procedures based on ET data obtained with a weighing lysimeter should be used to determine ET. If monthly or semimonthly ET values are desired, other procedures including soil moisture sampling and drainage lysimeters can be used although weighing lysimeters are preferred. An extensive table of crop coefficients for grass related ET, $E_{to}$, has been published by Doorenbos and Pruitt (1977). Crop coefficients for forage, field and vegetable and citrus crops are given. In addition, specialty crops such as bananas and coffee also have crop coefficient information. In many cases high, low and average coefficients as functions of humidity are shown. In other cases classifications as to the presence of cover crops or other conditions are made. A method of determining pre-emergence water use based on rainfall or irrigation frequency is given. A method of constructing a seasonal crop coefficient curve is illustrated.

Wright (1979, 1981) has developed an extensive list of crop coefficients related to $E_{tr}$ which are also shown in Burman et al. (1981). These coefficients made use of what is defined as *"basal"* crop curves; to be expanded in later sections of this paper. See figure 1 for a schematic diagram of the *"basal"* concept.

## PRODUCTION FUNCTIONS

Crop yield is somewhat proportional to ET. Dylla and Muckel (1964) related ET from native hay meadows in Nevada to a straight line function of its yield. A research project funded by the then U.S. Bureau of Reclamation lead to a series of papers dealing with ET-yield production functions. As an example, Stewart et al. (1975) describes the effects of reduced ET induced by drought on yields for corn and sorghum. This same project also resulted in the book, Water Production Functions for Irrigated Agriculture, Hexem and Heady (1978). The concept of yield being proportional to ET has been researched in a series of experiments using "line-source" techniques originally used by Hanks et al. (1976). In these experiments irrigation water is applied to a crop by a

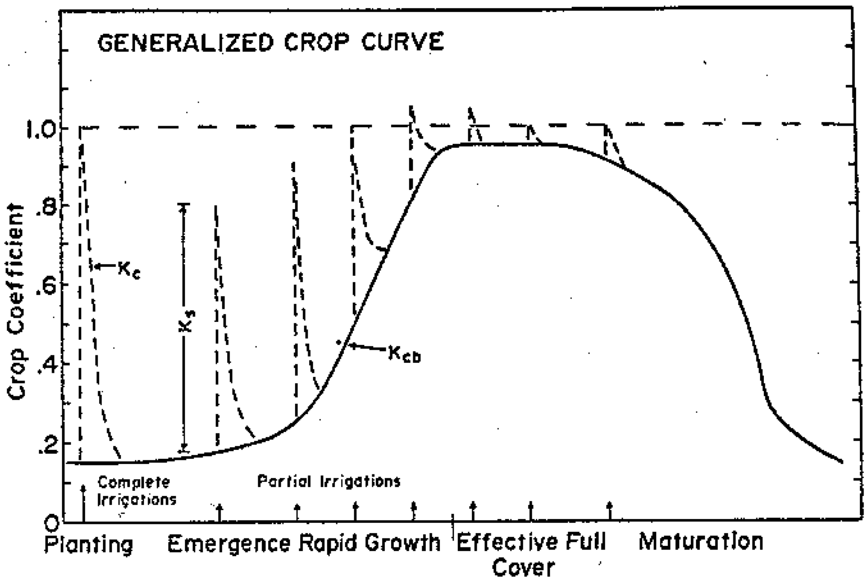


Fig. 1. Generalized basal ET crop coefficient curve with adjustment for increased evaporation due to surface soil wetness used to determine the over-all crop coefficient ($K_c$).

single line of closely spaced sprinklers resulting in uniformity of irrigation water applied along the line and controlled non-uniformity perpendicular to the line. Thus, a gradation of water application is achieved and yield-ET relationships may be determined. As an example of this Retta and Hanks (1980) describe the results of limited irrigation on corn and alfalfa yield. Hill (1980) used a linear relationship between ET and alfalfa yield to determine beneficial use on a large irrigation project in Nevada in connection with court proceedings. Sammis (1980) reported that linear production functions for alfalfa appear to be transferrable among Western states but that cotton functions were not transferrable to other locations.

The relationships between ET-yield and the use of limited irrigation water are expanded by Stegman et al. in the following symposium paper.

## ESTIMATING LONG TERM ET

The technical committee on irrigation water requirements of ASCE, Jensen (1974) noted that most methods of estimating ET from climatic data are suitable for periods of from 5 to 30 days. Only the methods based on the combination theory are suitable for daily or shorter periods. In this section the definition of long term is 10 days to a month and is consistant with Doorenbos and Pruitt (1977).

### Crop Water Requirements, FAO-24, Modifications

A group from the Food and Agriculture Organization of the United Nations assembled an extremely broad based world wide set of ET field data. This data set was used to prepare empirical calibrations for the Blaney-Criddle method,



radiation (essentially the Makkink procedure) and Penman methods. In addition a previously published, Jensen (1974) series of coefficients for predicting grass related $E_{to}$ from pan evaporation measurements was presented. All procedures in FAO-24 first require predicting reference crop ET ($E_{to}$) and then the prediction of actual ET with suitable crop coefficients.

Blaney-Criddle Method: The most radical change in the Blaney-Criddle, Doorenbos and Pruitt (1977) method is presented in this section. This new modification involves the calculation of Eto as the first step and then ET from a grass related crop coefficient as the second step. Prior to this time specific crop ET was calculated in one step (see Eq. 4 below). The single step method is still widely used for water right transfers in Western States with local calibration, Burman (1979). The original Blaney-Criddle "crop growth stage coefficients" are not to be confused with "crop coefficients" as defined in Eq's 1 and 3, Jensen (1974). The earlier version of the Blaney-Criddle method is as follows:

$$u = \frac{ktp}{100} \quad (4)$$

where u = monthly ET in inches

k = monthly crop growth stage coefficient

p = percentage of daylight hours for the month based on the entire year

T = mean monthly air temperature in °F

English units have been used above for historical reasons. The revision by Doorenbos and Pruitt (1977) is as follows:

$$E_{to} = a + b \cdot f = a + b \cdot p(0.46t + 8) \quad (5)$$

where $E_{to}$ = reference crop (grass based) ET in mm $d^{-1}$ (d = day)

a and b are the intercept and slope of a linear regression of $E_{to}$ on f, these are functions of minimum humidity, daytime wind and percent possible sunshine, see figure 2 for functions

p = the percentage of daytime hours of a day compared to an entire year

t = mean monthly air temperature in °C

Figure 2 is a chart showing straight line solutions for $E_{to}$ knowing the "f" factor. It is essential that $K_c$ values used to convert $E_{to}$ to ET using Eq. 3 be grass related. Doorenbos and Pruitt (1977) present extensive tables of such coefficients. A table of coefficients compatable with Eq. 5 based on data from Davis, California, is presented by Burman et al. (1981). Doorenbos and Pruitt provide for two methods of determining the regression coefficients a and b. They developed a chart (figure 2) with 9 straight line relationships for 3 levels each of daytime wind, minimum humidity and sunshine. They also published an extensive table of slope values to be used with a digital computer by interpolation and a methods of estimating the intercept "a" from humidity and sunshine data. The wind, humidity and sunshine data do not have to represent actual measurements from the site in question but can be estimated from sources such as a climatic atlas.

Penman Method: The original Penman (1948) method required a two stage sequence of calculations. First evaporation from an open water surface was estimated and then this was corrected by monthly coefficients ranging from 0.6 in the winter to 0.8 in the summer. The two stage process was later simplified by

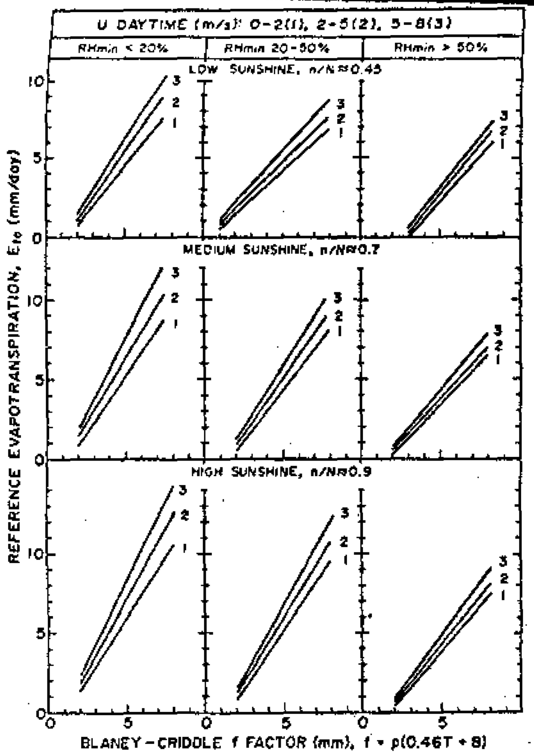


Fig. 2. Prediction of reference ET for grass ($E_{to}$) from Blaney-Criddle f factor for different conditions of minimum relative humidity, sunshine duration and day-time wind (from Doorenbos and Pruitt, 1977).

Penman (1963) and has almost always been used in this fashion since, as it is used later in this paper when daily calculations are discussed.

Doorenbos and Pruitt (1977) have returned to the original two stage process of Penman and have expanded the empirical function so that it is a function of maximum humidity, solar radiation in equivalent depth of water, daytime wind velocity and the ratio of day to night winds. They also utilize a slightly revised version of the Penman equation. Their version of the Penman Method is:

$$E_{to} = \left[ c \quad \frac{\Delta}{\Delta + \gamma}(Rn) + \frac{\gamma}{\Delta + \gamma} \cdot f(u) \cdot (ea - ed) \right] \qquad (6)$$

where $E_{to}$ is as previously defined in Eq's 3 and 5 and is in mm $day^{-1}$

$\Delta$ = the slope of the saturation vapor pressure-temperature relationship in mb °$C^{-1}$

$\gamma$ = the psychrometer constant in mb °$C^{-1}$

Rn = net radiation in equivalent depth, in mm

$f(u)$ = wind function = $0.27\ (1 + \frac{U}{100})$

U = wind travel in km $day^{-1}$



ea-ed = the difference between the mean saturation vapor pressure

and the mean actual vapor pressure.

c = an overall correction coefficient discussed in detail above

The reader is referred to Doorenbos and Pruitt (1977) and Jensen (1974) for details in calculating the above quantities. It is especially important that the wind function f(u) and the vapor pressure deficit term be calculated as Doorenbos and Pruitt recommended. In addition, complete consistency is required in the calculation of ET, from the method of estimating $E_{to}$ through the use of grass related crop coefficients.

A later section of this paper will discuss the estimation of daily ET for irrigation scheduling. The Penman method will be used but the wind function f(u), net radiation and the vapor pressure term (ea-ed) will be calculated in a different way. The result will be the estimation of $E_{tr}$ and alfalfa related crop coefficients must be used.

## ESTIMATING DAILY ET

Estimation of crop water requirements is usually done on a daily basis for purposes of irrigation scheduling. In this manner it is easy to incorporate corrections for a wet soil surface or a dry soil profile, even though other approaches are feasable, see Doorenbos and Pruitt (1977). A version of the combination theory such as the Penman method is presently the only suitable procedure for estimating daily ET.

### Penman Method, Alfalfa Base

The Penman Method, as modified for the prediction of reference crop ET is as follows (Wright, 1981):

$$E_{tr} = \frac{\Delta}{\Delta + \gamma}(R_n + G) + \frac{\gamma}{\Delta + \gamma} 15.36\ W_f(ea-ed) \qquad (7)$$

where $E_{tr}$ = reference crop ET, alfalfa based, in cal $cm^{-2}\ d^{-1}$.

$\Delta$, $\gamma$ are as previously defined in Eq. 6

G = soil heat flux to the surface in cal $cm^{-2}\ d^{-1}$

$R_n$ = net radiation in cal $cm^{-2}\ d^{-1}$

$W_f$ is the wind function, dimensionless

(ea-ed) is the vapor pressure deficit term in mb

15.36 is a constant of proportionality in cal $cm^{-2}\ d^{-1}\ mb^{-1}$

Soil heat flux G is usually assumed to be zero for short term calculations, see references such as Jensen (1974) or Burman et al. (1981) for detail on the method of calculating $\Delta$, $\gamma$ and vapor pressures. The calculation of $R_n$, $W_f$ and the vapor pressure deficit term need specific comment.

Net radiation $R_n$ is not usually measured as part of a climatological station used for irrigation scheduling. However, $R_n$ may be estimated by the following procedure or for an alternative approach, see Doorenbos and Pruitt (1977).

$$R_n = (1 - \alpha)\ R_s - R_b \qquad (8)$$

where $R_n$ = net radiation in cal $cm^2\ d^{-1}$

$\alpha$ = albedo, dimensionless

$R_s$ = incoming shortwave radiation in cal cm$^{-2}$ d$^{-1}$

$R_b$ = net outgoing radiation in cal cm$^{-2}$ d$^{-1}$

$R_b$ in turn may be estimated as follows:

$$R_b = \left[ a \left(\frac{R_s}{R_{so}}\right) + b \right] R_{bo} \qquad (9)$$

where $R_{so}$ is clear day solar radiation in cal cm$^2$ d$^{-1}$

The coefficients "a" and "b" are constants for a regression line, see Jensen (1974) for a table of "a" and "b" values for specific locations. $R_{bo}$ is net outgoing radiation and may be estimated as follows:

$$R_{bo} = (a_1 + b_1 \sqrt{ed})\ 11.71 \times 10^{-8} T_k^4 \qquad (10)$$

where $a_1$ and $b_1$ are the slope and intercept of a regression line. Again, see Jensen (1974) for a list of values for various locations. $T_k$ is the average air temperature in K° and ed is the saturation vapor pressure in mb. at the average dewpoint temperature. See Idso and Jackson (1969) for an alternate approach for estimating $R_{bo}$.

The vapor pressure deficit term (ea–ed) for alfalfa based reference crop ET ($E_{tr}$) is calculated as follows: The term ed is defined above. Equation 11 shown below is used to calculate ea.

$$ea = \frac{1}{2}\ (ea\ max + ea\ min) \qquad (11)$$

where ea max is the saturation vapor pressure at the maximum daily air temperature and ea min is the same quantity at the minimum daily air temperature. Again complete consistency between the method of estimating (ea = ed) and the crop coefficient used is mandatory.

The wind function $W_f$ is again empirically determined and is of the form:

$$W_f = a_w + b_w U_z \qquad (12)$$

where $U_z$ is daily wind travel in km d$^{-1}$ at usually an elevation of 2m above the ground surface. The constants $a_w$ and $b_w$ are again regression coefficients for a particular location. See Burman et al. (1981) for a discussion of values for $a_w$ and $b_w$.

Penman Estimates Using Constant Coefficients: Earlier estimates of $E_{tr}$ used values of $a_w$, $b_w$, $\alpha$, a, b, $a_1$ and $b_1$ which were used as constants for a location and for the season. The following values of these coefficients have been used for the prediction of $E_{tr}$. Wright and Jensen (1978) used $a_w = 0.75$ and $b_w = 0.0115$ for a wind height of 2m. The albedo $\alpha$ has often been used as 0.23 for commercial crops. Wright and Jensen (1972) used $a_1 = 0.32$ and $b_1 = 0.044$; on a seasonal basis they give the values of a = 1.22 and b = −0.18. Wright (1981) shows how these coefficients are not constant within a growing season and how they vary for alfalfa at Kimberly, Idaho.

Penman Estimates With Variable Coefficients: The coefficients a, b, $a_1$, $b_1$, $a_w$ and $b_w$ along with the albedo are not necessarily constant throughout a growing season. Wright (1981) found that estimates of $E_{tr}$ could be materially improved by the following empirical relationships based on alfalfa ET for Kimberly, Idaho.



$$a_w = 38.3 - 1.188D + 0.01397D^2 - (7.615E\text{-}05)D^3 + (1.956E\text{-}07)D^4 - (1.923E - 10)D^5 \qquad (13)$$

$$b_w = 0.0733 - (1.836E\text{-}03)D + (1.915E\text{-}05)D^2 - (9.476E\text{-}08)D^3 + (2.307E\text{-}10)D^4 - (2.267E\text{-}13)D^5 \qquad (14)$$

where D is the day of the year and the polynomial coefficients are for wind travel in km d$^{-1}$ at an elevation of 2m.

Albedo is known to change with the sun angle. For alfalfa at Kimberly:

$$\alpha = 0.29 + 0.06\ \mathrm{SIN}\{30[M + (N/30) + 2.25]\} \qquad (15)$$

where M is the number of the month and N is the number of the day.

$\alpha$ = albedo, dimensionless

The coefficient $a_1$ can be estimated from the following "normal distribution type equation."

$$a_1 = 0.26 + 0.1\ \exp\{ - [30(M + N/30) - 207)/65]^2 \} \qquad (16)$$

The coefficient $b_1$ was used with a constant value of 0.044. The coefficients "a" and "b" were used as follows:

| $\frac{R_s}{R_{so}}$ | a | b |
|---|---|---|
| > 0.7 | 1.054 | 0.0 |
| ≤ 0.7 | 1.000 | 0.0 |

Estimating Daily Crop ET: Daily crop ET at a given stage of growth is determined by:

$$E_t = K_c E_{tr} \qquad (17)$$

where $E_t$ is daily crop ET, $K_c$ is a dimensionless crop coefficient for the particular crop at the existing stage of growth, and $E_{tr}$ is the daily ET of the reference crop as determined by measurement or calculation from meteorological data.

For purposes of calculating crop ET from reference ET, the $K_c$ can be estimated from experimentally developed crop curves and information on soil moisture conditions by

$$K_c = K_{cb}K_a + K_s \qquad (18)$$

where $K_{cb}$ is referred to as the basal crop coefficient, $K_a$ is a coefficient whose value is relative to the available soil moisture, and $K_s$ is a coefficient to adjust for increased evaporation occurring when the soil surface is wetted by irrigation or rains. Details of these procedures are given by Jensen et al. (1971) and Jensen (1974).

The generalized basal crop coefficient, $K_{cb}$, was defined by Wright (1979) to represent conditions when the soil surface was dry so that evaporation was minimal but soil-water availability did not limit plant growth or transpiration i.e. $K_c = K_{cb}$ when $K_a = 1$ and $K_s = 0$. The use of the word "*basal*" represents a major change in the definition of crop coefficients. The mean crop coefficients presented by the Irrigation Water Requirements Committee of ASCE

Jensen (1974) represented average conditions and were mostly based on ET values obtained from soil water balance data. Figure 1 shows a generalized crop curve using the "*basal*" definition. An extensive table of growing season dates and crop coefficients suitable for daily use are presented by Wright (1981) and Burman et al. (1981).

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

$$K_a = [\ln(A_w + 1)]/[\ln(101)] \qquad (19)$$

in which $A_w$ = the percentage of available water (100 when the soil is at field capacity), and $K_a$ = 1 when $A_w$ = 100, and $K_a$ goes to zero as $A_w$ goes to 0. This algorithm was developed for a Southern Idaho soil Jensen et al. (1970). Since it depends on soil properties, appropriate relationships for other soils should be selected. Estimates of the effects of decreasing soil water on ET have been presented by Denmead and Shaw (1962).

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

$$K_s = (K_1 - K_{ci}) \exp(-\lambda t), \qquad K_1 > K_{ci} \qquad (20)$$

in which t = the number of days after the rain or irrigation; $\lambda$ = the combined effects of soil characteristics, evaporative demand, etc; and $K_{ci}$ = the value of $K_c$ at the time the rain or irrigation occurred. This algorithm will also vary for various soils and locations. At Kimberly, Idaho $K_s$ was approximated by: $(0.9 - K_c)\ 0.8$; $(0.9 - K_c)0.5$; and $(0.9 - K_c)\ 0.3$; for the first, second, and third days after a rain or irrigation, respectively Jensen et al. (1970).

## WATER BALANCE CALCULATIONS

Seasonal irrigation water requirement amounts are obviously very important to the irrigation industry. In the western United States laws limit transfers of water from irrigation to industrial or municipal use to the amount historically used for irrigation. For this reason added importance has been given to the measurement and estimation of ET and irrigation water requirements. Most western states are experiencing legal deliberations concerning seasonal irrigation water requirements. Some facets of this are discussed by Burman (1979).

The development of the Blaney-Criddle method led to the publication of statewide atlases that show climatic data, irrigation water requirement estimates, typical growing seasons, and in many cases irrigation efficiency estimates. These atlases have been used for irrigation scheduling, water resource analysis and water right transfers. At least three western states are now revising the atlases. Some of these states are on the third revision and they are being prepared for eastern states where supplemental irrigation is practiced.

Seasonal estimates of irrigation water are useful in the analysis of future regulation of water pumped from aquifers such as the Ogalla Formation. Obviously, water not pumped involves no expenditure of energy and does not further deplete the equifer. Improvements in the art and science of estimating irrigation water requirements are important in management of these resources.

## FUTURE RESEARCH AND DEVELOPMENTS

Future water management will be greatly influenced by three major factors. Firstly, competition for water between agricultural, municipal and industrial water uses will increase. Secondly, energy availability and cost will have a great impact on irrigation. Thirdly, economics will force agriculture to



become more efficient in its use of resources such as [illegible] irrigation equipment, water and manpower in the future. The topics of this paper are germaine to all of these problems. A pointed illustration of some of these is the publicity given to the use of pump irrigation in the Midwest from the Ogallala aquifer formation.

Stone (1977) has reviewed management techniques that can be used to increase or decrease ET.

A case where it is desirable to increase ET is in land application of wastewater for treatment. Techniques that may be applied based on future research are altering plant reflectance, using various kinds of surface mulching, the use of shade, vapor barriers, windbreaks, and favorable canopy geometry.

Many of these management techniques are discussed in detail in the ASAE Monograph "Modification of the Aerial Environment of Crops" Barfield and Gerber (1979). Much future research by plant breeders will be devoted to the task of producing new cultivars of commercial crops that make more efficient use of water Bitoun (1979). In addition to selection for the purpose of water use efficiency, selection will need to be based on crops that can use poorer quality water satisfactorily from irrigation return flows and municipal waste water. These will both have an influence on the science and art of predicting irrigation water requirements.

The optimum timing and application of irrigation water has been researched for many years. It is very likely that this will continue or even accelerate. In many cases maximum yield per unit of water may be more important than maximum yield per acre. These developments will certainly have an influence on the way irrigation water requirements are met.

In spite of the major strides that have been made in predicting irrigation water requirements it is still far from an exact science. The results of agronomic and engineering experiments have to be combined with experience in order for good irrigation water requirement estimates to be made. Academicia and researchers have a tremendous challenge to summarize and simplify results so that field engineers, hydrologists and agronomists can use the vast amounts of information in a correct manner. An often overlooked task is the education of field engineers, agronomists, technicians in irrigation scheduling and others.

## SUMMARY

Many advances in the art and science of predicting irrigation water requirements have been made in the past decade. These include the emergence and acceptance of the reference crop ET concept replacing the often ambigious "potential ET". The additional ET data collected in the past 10 years has resulted in significant improvements in crop coefficients. The concept of a "*basal*" crop curve should benefit irrigation scheduling. The widespread research technique of relating ET or irrigation water applied to crop yield resulting in "production functions" will permit the best possible management of scarce irrigation water. Analysis of a very broad based data set has resulted in calibration of the Blandy-Criddle, radiation, Penman and pan evaporation methods for the estimation of grass related reference crop ET. This modification of the Blaney-Criddle method is the most dramatic in the history of the method. Instead of a one-step process, Blaney-Criddle estimates can be first made for reference crop ET and then crop ET can be calculated by the use of a grass related crop coefficient. This results in much more flexibility for the Blaney-Criddle Method. The Penman method has been improved for the estimation of daily ET estimates using alfalfa related reference crop ET. This is accomplished by using variable albedo, net radiation and wind function coefficients. Some states are now on their third revision of irrigation water requirement atlases and additional eastern states are making these calculations.

Engineers, agronomists, and other scientists engaged in research and teaching involving irrigation water requirements have a tremendous challenge to simplify and adapt the voluminous results of research for field application. One of the biggest challenges is to teach college students, farmers and technicians to use this information in a correct manner.

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