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Meteorological Approaches For Predicting Irrigation Needs

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I. DEFINING IRRIGATION REQUIREMENTS

The goal of irrigation is to supply water to a crop so that its water requirements are met and it can produce an acceptable yield. However, the amount of water that must be applied as irrigation is often less than the crop water requirement, because part of the crop water requirement can be met by precipitation, stored soil water, or sometimes by upward flow from a shallow water table (Abdulmumin, 1989; Ghali and Svehlik, 1988; Steiner et al., 1985; Tripathi et al., 1987). The water requirements for various crops, grown in different times of the year, under different types of management vary considerably. Growing season heat unit accumulation, frost-free periods, and maximum and minimum temperatures, determine which crops are suited to production in various times of the year. Rainfall and soil water storage patterns determine the extent to which crop water needs must be met by irrigation to avoid the risk of water stress at various times of the year.

In initiating an irrigation project or in evaluating the efficiency of existing projects, there are many tools available to analyze the agroclimatic potentials and limitations for crop production. An excellent review of characterization and classification of agricultural environments is given in Bunting (1987). Agroclimatic analyses for Africa (FAO, 1978a), southwest Asia (FAO, 1978b), South and Central America (FAO, 1981) and southwest Asia (FAO, 1980) give a good overview of agroclimatic characteristics of these regions, organized around the concept of agro-ecological zones. While these analyses were not conducted with irrigation requirements in mind, they provide a clear guideline to identifying the need for irrigation for crop production in various regions.

To have a successful, sustainable irrigation system, more water must be applied than the net irrigation need because some of the water will be evaporated from the soil and/or from plant surfaces at rates greater than unstressed plant transpiration rates. Drainage and salinity management must also be considered in any irrigation system. Additionally, irrigation system losses during conveyances and application have to be considered. Meteorological conditions drive the evapotranspiration (ET) process, which is a major factor in the water balance. Thus a clear understanding of the effects of meteorological factors on ET is important in order to correctly assess a regional or field scale water balance and to properly manage irrigation systems or projects. A knowledge of many non-meterological factors is required to understand drainage requirement and irrigation efficiency, so this chapter will emphasize evaporation and crop water use and the reader is referred to other chapters in this book for more detailed discussion of drainage requirements and irrigation efficiency. Other reviews describing ET processes and estimation of ET which cover aspects not considered in this chapter (e.g., historical aspects, equation forms for many prediction methods, microclimatic aspects of ET, radiation interception) are given by Brutsaert (1982), Hatfield (1990), and Monteith (1973).

Both over-and under-irrigation can reduce the effectiveness and sustainability of irrigation. Historically, more attention has been given to the problems of under-irrigating than to over-irrigating. The effects of under-irrigating are generally exhibited on a field level often within the immediate growing season while many of the problems associated with over-irrigating are exhibited on a regional basis over a longer time period. Two major hazards of under-irrigating are yield loss, which reduces gross economic returns to the system, and salinization of the soil. Salinization exhibits itself over a longer time period than does yield loss; therefore, it has often been ignored until serious degradation of a soil has already occurred.

Over-irrigation can likewise have negative economic and ecological impacts. It increases costs through drainage of water below the root zone with associated leaching of nutrients and chemicals. In situations where these inputs are undervalued or costs are subsidized, the likelihood of over-irrigation increases. Yield reduction may be associated with over-irrigation if leached nutrients and chemicals are not replaced or if waterlogging of a field inhibits crop growth. Waterlogging may be a particular problem during crop establishment (Kanwar, 1988; Kanwar et al., 1988), and is obviously more of a hazard on some soils and with some crops than others. Water applied at rates greater than the soil infiltration rate or in quantities beyond the water storage capacity are lost to runoff or subsurface flow and are associated with ecological degradation, usually off-site. The magnitude of the water quality and environmental problems associated with agricultural use of water resources has gained increased visibility in recent years (Chen and Druliner, 1987; Higgins et al., 1988; Mapp, 1987; National Research Council, 1989) and will likely force improved water management in the future.

II. THE WATER BALANCE

Irrigation is the most common and direct form of manipulating a water balance to improve the conditions for crop production. The water balance for a one dimensional system is defined as

$$SW_t = SW_i + Pr + I - R - D - E - T \qquad [3.1]$$

where SW_i and SW_t are soil water content at the beginning and end of a period, respectively, and Pr is precipitation, I is irrigation, R is surface runoff, D is drainage or flux across the lower boundary of the soil profile, E is evaporation from the soil surface, and T is transpiration, all over the same time period. The E and T terms are often jointly referred to as ET because of the difficulty of measuring the components separately. Water balances have historically been applied in two predominant ways in irrigation science : (1) use of soil water measurements to determine ET or (2) use of estimated or measured ET to estimate soil water content over time. When equation [3.1] is rearranged to define ET in terms of the other components of the water balance, ΔSW represents the measured change in soil water content (SW_i - SW_t) over the period. Water balance approaches for determining ET have been used to develop, test, and calibrate numerous meteorological methods of estimating ET.

The accuracy of the water balance method for determining ET depends on the accuracy with which the components can be measured or estimated. Drainage across the root zone cannot be measured easily under field conditions so ET estimates should be made only when the flux across the lower boundary of the soil profile can be determined (such as with the use of lysimeters) or assumed to be negligible. Precipitation, irrigation, and surface runoff can be measured if the defined area is reasonably small and uniform. A water balance for a watershed may be inaccurate because effective precipitation and irrigation will not be uniform across the area and is very difficult to measure. The accuracy in the measurement of the temporal change in soil water content depends on the method of measurement, and the magnitude of the change in soil water content.

Several methods of measuring SW are discussed in detail by Cary (1981), Schmugge et al. (1980), and Stafford (1985). A widely used method of determining soil water content is by gravimetric sampling. There are inherently large errors involved in gravimetric sampling due to the spatial variability of soils and soil water content in the field and the small volume of soil sampled. Therefore, gravimetric sampling should not be used to estimate ET on a short term basis (daily or weekly) when ΔSW would be small, relative to the other components. Neutron attenuation provides a more accurate measurement of SW because repeated measurements are made over time at the same sampling location and a larger volume of soil is sampled. However, neutron probes are expensive and require trained (and, in the U.S.A., licensed) operators. They are most practical when one group or organization is responsible for soil water measurement on many fields in a region.

Only weighing lysimeters can be used to determine changes in soil water content accurately enough under field conditions to determine ET on a daily or shorter time-scale. Therefore, much of the work leading to the development of ET prediction equations and improvement in our understanding of the physical principles involved in the ET processes has been done using lysimeters. Design and management factors which affect the precision, accuracy, and representativeness of lysimeters is discussed by Aboukhaled et al. (1982), Marek et al. (1988), Pruitt and Lourence (1985), and Tanner (1967).

III. ESTIMATING ET

Relationships between weather and evaporation processes have been analyzed throughout the development of civilization, as excellently reviewed by Brutsaert (1982). The application of ET prediction for irrigation design and management has roots in the work of Penman (1948), Thornthwaite (1948), Blaney and Criddle (1950), and others. The most predominant approach to calculating ET for irrigation management involves (1) calculation of a "potential" ET (ET_p) that depends only on climatic factors, and is independent of surface conditions, (2) relating "actual" ET of a specific crop at a given period of growth to ET_p using empirically derived "crop coefficients", and (3) using the estimated actual ET in the water balance to determine specific irrigation needs based on irrigation efficiency, soil water holding characteristics, and management objectives (Kanemasu et al., 1983). Jensen (1974), Jensen et al. (1990), Doorenbos and Pruitt (1977), and Doneen and Westcot (1984) present comprehensive and practical overviews of estimating ET for irrigation water management applications. Characteristics specific to sprinkler (Rolland, 1982), drip or trickle (Vermeiren and Jobling, 1984), or other types of irrigation that affect management options and system efficiency should be considered in quantifying the irrigation requirement.

A. Climatic Factors Related to ET

Climatic factors that affect ET include temperature, solar or net radiation, precipitation, vapour pressure deficit, wind, and barometric pressure. These data should be collected at a site that is maintained in a standard condition which is generally over short grass away from buildings and trees. If data are collected in non-standard conditions, they must be empirically adjusted to a standard condition before application of equations for predicting ET. Jensen et al. (1990) discuss errors in ET prediction that might be associated with climatic data collected from nonstandard sites. The sensitivity of an ET model to the climatic input variables was analyzed by Camillo and Gurney (1984) who found the prediction was sensitive to errors in radiation and relatively insensitive to errors in wind over both bare soil and wheat surfaces, but was much more sensitive to errors in vapour pressure and temperature measurement over a wheat crop than over a bare soil. Heermann (1988), in a discussion of priorities in ET research for irrigation, identified the uncertainty of limits of transferability of meteorological data for ET prediction as a high priority research need. Harcum and Loftis (1987a, 1987b) conducted a statistical analysis of regional weather networks required for ET prediction for irrigation or hydrologic studies. Analysis of model sensitivity to input parameters will require increased attention as more realistic water balance models are implemented and as physically-based models are substituted for empirical models, where local calibration of equations often corrects for systematic biases in input data.

Temperature and precipitation are the most widely measured weather variables in weather networks, because of the relatively low expense and ease of maintenance of instrumentation. Many of the climatic variables can be extrapolated from weather stations on a regional basis, but precipitation is so spatially variable that on-site measurement is required for accurate water balance work and field-level irrigation management. However, long-term precipitation records from standard sites are invaluable for agroclimatic analyses and irrigation system design. Because thermometers are sensitive to radiation errors if exposed to direct sunlight, weather station temperature measurements are often made in white, ventilated shelters with the sensors mounted about

1.5 m above the surface. Temperature is a major controller of crop growth and phenological development in addition to the ET processes.

Solar radiation is less commonly measured, and much of the data available to determine solar radiation are observations of cloud cover or per cent of possible sunshine hours. The actual driver of ET is net radiation but it is seldom measured outside of the research environment. For most applications, net radiation is calculated as a function of solar radiation, temperature, vapour pressure, and albedo. Radiation is a major factor influencing crop growth as well as ET.

Wind is widely measured, but the siting of the measurement stations is highly variable. A high percentage of wind measurement sites were established for aviation purposes. Measurement of wind is highly sensitive to the surrounding conditions and is often affected by buildings or vegetation. Because the windspeed increases logarithmically with height within the planetary boundary layer, it is essential that the height of measurement be known.

Dewpoint or wet bulb temperature data for determination of vapour pressure deficit are very difficult to collect on a routine basis in a weather network. Relative humidity is often collected instead, but unless air temperature at the time of the relative humidity measurement is known, it can be difficult to accurately interpret the numbers. Vapour pressure deficit is inversely related to water-use efficiency (Tanner and Sinclair, 1983).

Barometric pressure is generally estimated from altitude for application to ET equations and this estimate is simple and adequate for ET prediction. The influence of barometric pressure on ET prediction is sometimes overlooked by practitioners. Use of mean sea level barometric pressure can lead to slight overestimation of ET at high altitudes because of the effect of pressure on the psychrometric constant. Altitude also interacts with the thermal environment as well as the radiative environment.

B. Estimating Potential ET from Meteorological Data

1. Empirical ET equations : Many researchers have attempted to describe mathematical relationships between ET and various climatological or meteorological factors. Temperature methods were developed by Thornthwaite (1948) and Blaney and Criddle (1950) to estimate seasonal ET from mean temperature data. Data for these methods are readily available. Thornthwaite's method has been widely used for climatological classification but has not been widely applied for irrigation planning because it is generally not accurate when applied to dry, advective climates. Doorenbos and Pruitt (1977) described the Blaney-Criddle method and gave tabulated coefficients to estimate latitude effects on monthly radiation and to relate regional windspeed, humidity, and cloudiness conditions to ET. This method is appropriate to estimate monthly or seasonal ET and, therefore, is most commonly used for irrigation system design considerations. It is not applicable for in-season irrigation management decisions. Numerous other limitations to this method are discussed in Doorenbos and Pruitt (1977).

Radiation methods have been proposed by Hargreaves and Samani (1982), Makkink (1957), Jensen and Haise (1963), and Turc (1961), where radiation data are required in addition to temperature. These approaches were developed for in-season irrigation management, and thus are applicable to shorter time-scales than monthly or seasonal. A radiation method presented by Doorenbos and Pruitt (1977)requires observed sunshine hours or measured radiation and temperature with empirical coefficients based on general humidity and wind conditions. The Jensen and Haise (1963) model uses daily temperature and solar radiation as well as long- term temperature data and altitude. It has been widely used in the western U.S.A. for irrigation scheduling programmes.

Christiansen (1968) and Christiansen and Hargreaves (1969) developed regression equations relating ET to pan evaporation or to radiation data and temperature, wind, humidity, and sunlight functions. Evaporation pans have been widely used, and, if properly sited, calibrated to a specific crop and region, and carefully maintained, can provide estimates of crop water use requirements However, the data cannot be extrapolated beyond the immediate region and application for crops grown in non-typical seasons is questionable (e.g., equations developed for a rainy season crop should not be applied to a post-rainy season crop).

The success of empirical methods using limited weather data relies upon the correlation among climatic factors. Radiation is highly correlated with ET_p since radiation supplies much of the energy required for the vapourization of water. Temperature methods rely upon the correlation of temperature to radiation and vapour pressure deficit. Errors can arise because seasonal storage and release of heat from the soil produces annual temperature and radiation cycles that are out of phase.

2. **Aerodynamic methods** : The equation developed by Penman (1948) predicts potential ET (ET_P) as the sum of a radiative component and an aerodynamic, water vapour pressure component. This model combines energy balance and aerodynamic principles and is often termed the combination equation. It was developed to predict ET_P (mmd^{-1} defined as evaporation from a short, well-watered green crop

$$ET_P = [\Delta/(\Delta + \gamma)]\ [(Rn + G)/L] + [\gamma/(\Delta + \gamma)\ f(u)\ (VPD)] \qquad [3.2]$$

where Δ is the slope of the saturated vapour pressure- temperature curve (kPa/C), γ is the psychrometric constant (kPa/C), L is the latent heat of vapourization (MJ/kg), Rn is net radiation (MJ $m^{-2}d^{-1}$), G is soil heat flux (positive toward the soil surface, MJ $m^{-2}d^{-1}$), f(u) is a wind function [mm/(d kPa)], and VPD is vapour pressure deficit (kPa). In this equation, decreased atmospheric pressure with increased altitude decreases the psychrometric constant and the contribution of the advective component to ET. Penman described the f(u) as an empirical, linear function of the form

$$f(u) = a + b\,U \qquad [3.3]$$

where U is average daily windspeed at 2 m (ms^{-1}) and a and b are regression coefficients. Penman (1948) reported values of 2.63 and 1.38 for a and b, respectively, for a grass surface. Doorenbos and Pruitt (1977) evaluated data from many lysimeter sites worldwide and derived a linear wind function with a = 2.70 and b = 2.33 for a grass surface, which they recommended if a locally calibrated wind function is not available. Many other functions have been locally fit. Phene et al. (1986) reported that their data were relatively insensitive to different a and b coefficients, but reported that ET was highly sensitive to mowing the grass on and around the lysimeter that indicates a possible problem with the assumption of Penman (1948) that evaporation would be insensitive to the surface vegetative cover as long as there was a short, green, fully-transpiring canopy. Tanner and Fuchs (1968) pointed out that plant surface can affect soil heat flux, albedo, emissivity, and roughness lengths and, therefore, surface properties should affect ET. The Penman (1948) equation has been used successfully in many forms to predict ET. The combination equation was recommended by Doorenbos and Pruitt (1977) as the method of choice for situations where adequate climatic data are available.

Many attempts have been made to develop a less empirical form of the wind function for the combination equation. van Bavel (1966) developed an aerodynamic form of the resistance term, similar to earlier work of Businger (1956) and others, which incorporates the standard wind profile theory assuming neutral atmospheric conditions, and similarity of the transfer coefficients of sensible heat and vapour. Thom (1972) developed a meteorological based model, again with the aerodynamic resistance term based on the standard log profile for wind, which accounts for separate sinks for sensible heat and vapour. Monteith (1965) developed an aerodynamically-based form of the combination equation that incorporates a canopy or surface resistance as follows

$$ET_P = [\Delta/(\Delta + \gamma^*)] [(Rn + G)/ L] + [\gamma/(\Delta + \gamma^*)] \; Ea \qquad [3.4]$$

with Ea (mm d^{-1}) given as

$$Ea = [(\rho \; Cp \; VPD)/ (L \, \gamma \, r_{av})] \, (8.64E{-}2) \qquad [3.5]$$

where ρ is air density (kg m^{-1}), Cp is specific heat of dry air at constant pressure (J/kg/C) and r_{av} is the aerodynamic resistance (s/m).

The γ^* is defined as

$$\gamma^* = \gamma \, (1 + r_c/r_{av}) \qquad [3.6]$$

where r_c is the canopy resistance (s/m). The r_{av} can be calculated from the log wind profile as

$$r_{av} = \ln[(Z-d)/Z_{om}] \ln[(Z-d)/Z_{ov}]/k^2 U_Z \qquad [3.7]$$

where U_Z is windspeed (m s^{-1}) measured at height Z, d is the zero-plane displacement height, and Z_{om} and Z_{ov} are the surface roughness lengths for momentum and vapour, respectively and k is von Karman's constant (0.41).

Under conditions with a flat, uniform, vegetative surface such as grass, alfalfa (*Medicago sativa* L.), or a full canopy cover row crop, the d, Z_{om}, and Z_{ov} terms are often estimated as a function of vegetation height (Monteith, 1973). With complex surfaces, surface properties may need to be accounted for (Abtew et al., 1989; Azevedo and Verma, 1986; Shaw and Pereira, 1982). For non-stressed, uniform, full cover vegetative surfaces, r_c can be estimated as a function of radiation and leaf area index. For other conditions such as partial canopy cover, sloped fields, stressed vegetation, or rapidly changing partly cloudy conditions, lack of understanding of the behaviour of r_{av} and r_c might limit application of the resistance forms of the combination equation. Idso (1983) proposed a method of calculating r_c by measuring the canopy temperature and solving the energy balance, which might provide an estimate of r_c over a wider range of conditions. Allen (1986) and Allen et al. (1989) have derived and tested ET_p equations using the Penman-Monteith form for general application to irrigation scheduling.

The combination method does not account for interactions between the plant and soil surfaces. When small, isolated plants are surrounded by hot, dry soil surfaces, the microclimatic conditions at the leaf surface are vastly different from ambient weather conditions. Shuttleworth (1976) described a multi-layer model with the lowest level at the soil surface and the highest level above the canopy. The data required to apply the model are not routinely available, but his work provides a theoretical framework to consider cases where flux at the soil surface affects fluxes within and from the canopy.

Tanner and Fuchs (1968) discussed the limitations of the Penman- Monteith equation, which assumes no saturation deficit at the surface, and proposed that inclusion of a surface temperature term eliminates the requirement for this assumption and makes the form applicable to actual as well as potential ET prediction. For conditions where a complex surface is involved (such as with a sparse canopy, a drying soil surface, or a residue or mulch layer that partially covers the soil), additional resistance terms must be estimated to estimate the "average" surface resistance. Examples of this are given by Shuttleworth and Wallace (1985) for a sparse canopy, Staple (1974) for a drying soil, and Snane et al. (1984) for a surface with crop, residue, and soil components.

Many attempts have been made to simplify the Penman equation, particularly for conditions where wind and vapour pressure measurements may not be available. Priestley and Taylor (1972) hypothesized that a strong correlation would exist between the radiative and advective components of the Penman equation under conditions of near-saturation (the potential ET condition requires non-water limiting conditions, by definition) and that the radiative component would be dominant. They described potential ET as

$$ET_P = \alpha\ [\Delta/(\Delta + \gamma)]\ [(Rn + G)/L] \qquad [3.8]$$

and proposed a value of 1.26 for α, based on empirical analysis. The Priestley-Taylor model was developed for large-area prediction, but because of its simplicity it has been adopted for many short-term, local applications.

Jury and Tanner (1975) proposed that α would vary as a function of VPD and proposed a modification that would improve the applicability of the Priestley-Taylor model to regions with variable, advective climate. In order that the data requirement to implement the model not be increased, Jury and Tanner (1975) proposed that dewpoint temperature could be estimated as the daily minimum temperature, but this method would lead to underestimation of the VPD and ET in semiarid or arid climates where minimum temperature is generally considerably warmer than the dewpoint. Kanemasu et al. (1976) proposed an advective modification of α based on maximum air temperature.

Steiner et al. (1989a) tested several forms of ET prediction equations against well-watered, full-cover grain sorghum ET measured on weighing lysimeters and found that the most accurate daily ET predictions were given by the Penman-Monteith form of the combination equation. The Priestley-Taylor model worked quite well with either VPD - or temperature-based advective modifications of α, but the original Priestley-Taylor model was not suited for ET prediction in the semiarid, variable environment at Bushland, Texas, in the U.S. southern Great Plains. Forms of the Penman equation with empirical, linear wind functions over-predicted sorghum ET considerably in this windy environment. Application of any wind function, including the Penman-Monteith form, worked best if daily mean 2 m windspeed was capped at about 3 m s^{-1} (Howell et al., 1989b), which is lower than most daily mean windspeeds in the region.

C. Estimating Actual ET

1. Crop cover effects : Estimating actual ET from a ET_P generally involves gross simplifications of very complex processes. When the plant is not stressed, but the surface is not completely covered by vegetation, actual ET is limited by the amount of crop cover and the condition of the surface that is not covered by vegetation. There is some understanding of the dynamics of evaporation from a bare soil, but little quantitative description of evaporation from residue covered or mulched soils. Prediction of ET from stressed crops may have been de-emphasized because the purpose of irrigation was to prevent stress. however, with increased emphasis on optimization of irrigation and yield, rather than maximization of yield, and on off-site effects of irrigation, the possibility of allowing mild plant stress cannot be discounted and prediction of ET as water becomes limiting is more important.

a. *Crop coefficients*. The most common method of estimating actual ET from ET_p, particularly for irrigation applications, involves empirical crop coefficient (K_c) curves as described by Wright (1985). A crop coefficient curve basically gives the time course of the ratio of actual ET to ET_p for a crop at a location. The K_c is a basal coefficient which assumes that the soil is not wet but that the soil profile is moist enough that some evaporation occurs. Doorenbos and Pruitt (1977) describe how to develop a K_c curve from generalized tables based on crop, sowing date, rate of crop development, length of crop growth stages, and prevailing climatic conditions.

Because irrigation frequency differs tremendously with differe irrigation systems and crops, it is necessary to consider the effect of soil surface wetness, particularly with frequent irrigation. Doorenbos and Pruitt (1977) describe the basal K_c for a bare soil as a function of irrigation and rainfall frequency. Following rain or irrigation, the K_c must be adjusted for wet soil surface conditions as described by Wright (1982) who also gives K_c curves for several crops in the northwestern part of the U.S.A. Sammis et al. (1985) and Hattendorf et al. (1988) presented crop coefficients with the time scale represented by cumulative heat units, which they propose would make the coefficients more transferrable across sites and seasons. de Jager and van Zyl (1988) present an analysis of crop coefficients which accounts for many of the possible surface conditions such as partial canopy cover, soil surface wetness, and plant stress.

Howell et al. (1989b) developed crop coefficient curves for grain sorghum [*Sorghum bicolor* (L.) Moench] at Bushland, Texas, and showed that the crop coefficient curves vary depending on the ET_p equation that is chosen. In their analysis, the peak K_c was 0.7? and 0.99 when referenced to alfalfa and grass ET_p, respectively, calculated by the Penman-Monteith form as described by Allen et al. (1989). When referenced to a Priestley-Taylor form with a VPD-based advective modification as described by Steiner et al. (1989a), the K_c peaked at about 0.9 and had a basically different shape than when referenced to the Penman- Monteith equation forms. Feddes (1987) and Hussien and El Daw (1989) also discuss the importance of the reference equation and surface in the application of crop coefficients.

b. *Leaf area index functions*. An alternative method of calculating actual ET partitions ET_p to soil and plant components based on the crop leaf area index (LAI), which is the ratio of green leaf area to soil surface area (Ritchie, 1972). Potential ET for a full-cover, non-stressed condition is usually calculated by one of the equations described above. The partitioning of ET_p is based on Beer's law for transmission of radiation through a medium. For a crop canopy

$$R_t/R_i = EXP(-k'LAI) \quad [3.9]$$

where R_t is transmitted radiation, R_i is incoming radiation, and k is the extinction coefficient. Soil evaporation (E_s) is assumed to equal $ET_p(R_t/R_i)$ for a wet soil surface and to decline as a function of the square root of days since precipitation for a dry soil surface. The potential transpiration (T_p) is assumed to equal ET_p (1-Rt/Ri). Transpiration (T) may be less than the T_p if the soil in the root zone cannot provide adequate water to meet the plant needs.

In order to apply this model, the LAI over time must be measured or predicted. Because leaf area index is a labour intensive measurement, estimation is often preferred over measurement, particularly for operational applications. There are many crop growth models which predict LAI development, generally as a function of heat unit accumulation over time. Since it may not be practical to run a crop growth model for all crops or fields of interest, there is interest in obtaining estimates of LAI or crop cover from remotely sensed data (Ottle et al., 1989; Bausch and Neale, 1987).

Prediction or measurement of LAI for a specific growing season is more flexible than the assumption of a constant crop coefficient curve (K_c) because it allows for different rates of development to be considered dependent on season, soil, climate, and management. Use of crop growth models also allows analysis of the probability distribution, related to climatic variability, to yield and water use under different management scenarios and provides a powerful tool to predict irrigation requirements, to design irrigation systems, and identify improved irrigation practices for a region (Howell et al., 1989a).

2. Water limited conditions : The effects of limited water on transpiration and on plant productivity are often considered to be similar, since transpiration and plant growth are generally considered to be linearly related. The work of Denmead and Shaw (1962) showed that the relative transpiration rate (T/T_p) of com (*Zea mays* L.) was a function of both soil water content and evaporative demand. Their work was conducted with restricted root zones for each plant (each plant had about one-tenth the soil volume compared to a field with a 1.5 m deep soil profile planted at 7 plants m^{-1}) and, therefore, the availability of water was restricted by volume as well as by soil water potential and flow rate to the root. For crops with a more normal root volume, it has been difficult to establish an effect ET_P on the T/T_P ratio until the soil water content is relatively low, which is consistent with the theoretical paper of Gardner (1960). Water balance models reported by Jones and Kiniry (1986), Ritchie (1985), Rosenthal et al. (1989), have assumed that transpiration would proceed at the potential rate until about 50 to 65% of the plant available water was depleted. These models have been applied successfully under a wide range of conditions.

IV. NEW CONCEPTS AND STRATEGIES

A. Potential ET

There have been few theoretical advances in the concept of potential ET since the work of Monteith (1965). However, there have been tremendous advances in our ability to apply the best theoretical approaches to ever more complex problems. Allen (1986) and Allen et al. (1989) discuss some of the simplifying assumptions required to apply the Penman-Monteith resistance form of the combination equation to calculate ET_p on an operational basis for irrigation scheduling applications. Howell et al. (1989b) have shown that these simplified Penman-Monteith forms can be applied to predict ET for well-watered grain sorghum throughout the growing season.

B. Actual ET

As we increase our quantitative description of the processes and factors that control ET, there are many benefits to abandoning the traditional approach of calculating ET_p and then relating ET_p to actual ET_a through use of crop coefficients. Models to directly estimate ET_a generally use an equation similar to the Penman-Monteith form described above and calculate the surface resistance as a function of the surface condition. Jagtap and Jones (1989) calculated a surface resistance for bare soil and for full crop canopy conditions and interpolated between the values as a linear function of LAI to estimate a surface resistance of a developing canopy. Lascano et al. (1987) developed and tested a model that includes numerous surface resistance components, including an aerodynamic resistance based on logarithmic wind profile theory, sensible heat resistances for soil and canopy as a function of leaf area index, stomatal resistance as a function of light, leaf area index, and leaf water potential, and leaf water potential based on soil water potential and root water uptake. Steiner et al. (1989b) reported excellent prediction of daily ET from planting to maturity of grain sorghum using the model described by Lascano et al. (1987) and van Bavel et al. (1984).

The direct calculation of actual ET, rather than calculating ET as an empirical function of ET_p, will require further theoretical development of explanations of soil water flow processes in field situations where flow in macropores may dominate over flow in the soil matrix (White, 1988). Most of theoretical soil physics is based on the assumption of a uniform matrix. A problem very much in need of better theoretical description is the role of roots in water flow in the soil-plant-atmosphere continuum. If roots are currently accounted for at all, they are treated as a sink term empirically related to soil and plant factors (Clothier, 1988). Even more limiting than our lack of understanding of the physical aspects of root distribution and activity is our lack of understanding of the biology of roots under variable field conditions and the role of roots as sensors of the environment and controllers of biological activities through hormone production (Clothier, 1988).

Shuttleworth and Wallace (1985) and Chen (1984) describe multilayer models of vapour and heat flux for application to situations where the single-layer model of Penman is not appropriate. As computing capability becomes more powerful and as our understanding of the surface resistance and transfer terms in the aerodynamically based equations continues to increase, more complex models can be embedded in the management models which currently rely on many simplifications and empiricisms. However, the input requirements for the more complex models are substantial and multi-layer models will be used for research applications, rather than operationally, for some time to come.

Morton (1983) described the theory of complementarity in which actual ET and potential ET are inversely related and, when summed, equal twice the areal wet ET. The original work was intended for hydrological applications over a large area and, therefore, might be most suited to evaluation of irrigation needs during the planning stages. Morton (1985) discussed the possible application of complementarity theory to field level ET estimation, but this application has yet to be thoroughly tested. Application of complementarity theory to ET prediction requires that meteorological data be collected over the crop surface of interest, rather than over a standard surface in a weather station.

In most applications, soil heat flux has been ignored in making daily ET predictions. This introduces a small error and is reasonable during periods of full canopy cover. When analyses are extended to partial cover crops or to bare soil, omission of soil heat flux can introduce considerable error. Fuchs and Hadas (1972) reported that daily soil heat flux represented up to 35% of net radiation for a bare soil, and Idso et al. (1975) reported that the ratio was 30-50% and varied as a function of soil water content. Soil heat flux cannot be ignored for ET estimation on less than a daily time step, which might be required to evaluate aspects of sprinkler irrigation efficiency. Clotheir et al. (1986) reported that mid-day soil heat flux was 10% of net radiation even under a dense, full-cover alfalfa canopy.

C. Dynamic Soil Water Availability

A major limitation of water balance models commonly used for ET prediction and irrigation scheduling applications is the concept of a static soil water availability dependent only on soil characteristics. In reality, water availability is a function of soil, plant, and climatic factors (Hillel, 1990) but, because our understanding of plant water relations and of root growth, function, and dynamics are so limited under field conditions, the role of the plant is often ignored or greatly simplified. Clothier (1989) identified study of root function as one of the major underdeveloped research areas essential to improved irrigation management. Ahuja and Nielsen (1990) review the changing concepts of soil water availability which can greatly contribute to improved irrigation scheduling and management models. Plant water stress estimations must be made based on the soil water potentials and root densities within different layers of the root zone at a given time. This area of research will be very important in developing deficit or limited irrigation strategies.

D. Irrigation Water Requirements

With the cost of new irrigation development in the range of \$5,000 to \$6,000 U.S. dollars ha^{-1} or even as high as \$10,000 ha^{-1} in small projects in areas without a history of irrigation (Rangley, 1987) and with a very high percentage of the existing irrigation projects in need of renovation (Jensen, 1990), it is essential that the best possible management practices be implemented. In the past, the lack of available climatic data often justified the use of empirical approaches to prediction of crop water requirements. While these approaches have had an important role in irrigation planning and management, they are basically inflexible in their application and often inaccurate when transferred to a new area. Inexpensive, automated weather stations are now available that are suited to operation in remote areas and that can provide standardized data with lower maintenance costs than manually operated stations. The output from automated weather stations must be monitored in real-time by knowledgeble staff to ensure high quality weather records, as discussed by Oldeman (1987), but monitoring of several sites can be done from a centralized location with today's technologies (Hubbard, 1989).

Often, some of the most advanced technologies have been rejected as unsuited to developing countries, but it is essential that the best management approaches and scientific methods and models available be used for new irrigation districts and to improve existing irrigation projects (Jensen, 1990). The goal should be to increase the flexibility of on-farm management decision making, leading to a demand driven irrigation system, rather than a centralized supply driven system. Because all of the models currently available for operational prediction of ET and irrigation water requirements involve some empiricism and/or simplifying assumptions that may not be appropriate for all situations, it is highly desirable, and perhaps necessary, that each major irrigation region or project has a research programme that adapts the available technologies to the specific conditions and needs of the region. These researchers should use the best available technologies such as geographical information systems (Brinkman and Stein, 1987; Dyke, 1987), crop growth models (Jones and O'Toole, 1987; Nix, 1987), and standardized data bases (for example, see discussion of

International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project in Brinkman and Stein; 1987 and Jones and O'Toole, 1987) to enable transfer or extrapolation of research results from other regions to their irrigation region and from their experimental plots to farm level recommendations.

In order to seriously consider ecological impacts of irrigation, drainage and subsurface flow must be treated more realistically than they have been in the past. A valid consideration of the hydrologic balance as affected by irrigation will have to consider all components of the balance. This will require use of sound physically-based models instead of the simplified models which have been used when maximizing yield has been treated as the primary or only objective of irrigation. Variability over space and time has a major influence on irrigation efficiency and on ecological impacts of irrigation and will have to be considered in integrated system management models. Irrigation system design and management will increasingly have to balance the often conflicting needs of maintaining high yields without causing environmental degradation, either on-site or off-site.

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