Future research requirements into micrometeorological aspects of irrigation

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Abstract

Crop surface conductance ϕ_s, aerodynamic conductance ϕ_a, and crop surface temperature T_c are shown to be the most important micrometeorological concepts deserving of further research. Suggested possible methods of determining ϕ_s are: establishing its relationship to soil water potential in the root zone, or the utilization of estimates of evaporation rate from a large open water surface and lysimeters, or estimates of crop hydraulic conductance, or the use of modified estimates of equilibrium evaporation. With respect to ϕ_a the errors introduced by failure to adjust ϕ_a for atmospheric stability must be evaluated. The most promising advances in determining T_c for purposes of scheduling irrigation appear to be remote sensing of the infrared rays emanating from the crop surface. The need for developing a model whereby T_c may be calculated using routine meteorological observations is emphasized.

List of symbols

β	Bowen ratio
E	crop evaporation rate
s	slope of the saturated water vapour density-temperature curve
γ	the psychrometric constant
H	$R_n - G$
R_n	net radiation
G	soil heat flux density
a and b	constants
u	windspeed
ϱ_v'	saturated water vapour density of the air
ϱ_v	water vapour density of the air
ϕ_a	aerodynamic conductance of the atmosphere
ϕ_s	whole crop surface conductance for water vapour exchange
λ	coefficient of latent heat of evaporation
E_e	equilibrium evaporation rate
E_o	evaporation rate from an open water surface
T_c	crop foliage temperature
T_a	ambient air temperature
k	von Karmon constant (0,4)
z	height above ground surface
d	displacement level
z_0	*roughness parameter*
F	atmospheric stability factor

Introduction

Meteorology is defined as the study of the physical processes in the atmosphere (Huschke, 1959) and micrometeorology as the study of the physical processes in that portion of the atmosphere up to a height where the earth's surface characteristics no longer influence such processes (Huschke, 1959). Hence micrometeorological aspects of irrigation are constrained to the latter regime. Irrigation research workers, however, concentrate upon studying the interaction between the physical processes in this layer and whatever crop is under consideration. This paper then will consider not only radiation, temperature, humidity and wind in the earth's boundary layer, but also the resultants of their influence manifested as crop surface temperature and whole crop *surface conductance to diffusive gaseous interchange.*

The objective of this paper will be to indicate which of these aspects require further investigation and which avenues of research could most fruitfully be pursued.

Crop evaporation rate

The major significance of micrometeorology in irrigation, is found particularly in the control of crop evaporation rate by the thermal energy budget at the crop surface (Thom, 1975). Study of this interaction could lead to the explanation of irrigation perplexities and/or improved irrigation scheduling.

A universal crop evaporation formula has evolved (Monteith, 1973) after initial research which had led to the well-known Penman formula (Penman, *1948*) for calculating evaporation from an open water surface

$$E_o = \underset{\substack{\text{Energy}\\ \text{term}}}{\frac{s}{s+\gamma}H} + \underset{\substack{\text{Aerodynamic}\\ \text{term}}}{\frac{\gamma}{s+\gamma}(a+bu)(\varrho_v' - \varrho_v)} \qquad (1)$$

When units of mm d^{-1} are selected for evaporation and energy flux density and m s^{-1} for windspeed, and vapour pressure (in units of mbar) is utilized instead of water vapour density, then the values of a and b in Eqn. 1 are 0,26 and 0,14 respectively (Campbell, 1977).

To account for the mechanisms of momentum, gas and mass exchange in the atmosphere, Penman (1948) had initially utilized *empirical relationships in formulating the aerodynamic term in* Eqn. 1. Monteith (1973), however, generalized this formula for crop surfaces. He accomplished this by introducing a whole, or bulk, crop surface resistance. It is suggested that this Monteith form of the Penman formula, often called the Penman-Monteith formula (e.g. De Bruin and Holtslag, 1982) be accepted as the universal fundamental crop evaporation formula. The Penman-Monteith formula is completely general and valid at all times. The major problem impeding its widespread application in practice is the difficulty encountered with the evaluation of the appropriate whole crop surface resistance. A derived form of the Penman-Monteith formula is given by:

$$E = \frac{s}{s+\gamma^*}H + \frac{\gamma}{s+\gamma^*}\lambda\,\phi_a(\varrho_v' - \varrho_v) \qquad (2)$$

where

$$\gamma^* = \gamma(1 + \phi_a/\phi_s) \qquad (3)$$

Here Eqn. 2 is essentially the Penman-Monteith formula. It has, however, been written utilizing conductances rather than resistances as it is probably easier to conceptualize the physical significance of conductance than resistance. Conductance is simply the inverse of resistance.

Conductance is the facility with which a substance is transported through a medium. Conductance will here be defined as the distance through a given medium which unit mass per unit volume (concentration) of a diffusing substance can move in unit time. Distance per unit time represents velocity and hence the units of conductance are $m\ s^{-1}$. A simple dimensional analysis will substantiate this definition. Whole crop surface conductance is discussed and defined by Thom (1975).

Whole crop surface conductance

As stated, the major problems encountered in the application of this universal formula (Eqn. 2) to irrigation research, reduce specifically to the evaluation of aerodynamic and surface conductances for water vapour exchange. Future micrometeorological research into irrigation will, of necessity, include the evaluation of these entities utilizing existing well established methodology.

Consider Eqn. 2. Uncertainties in the ratio ϕ_a/ϕ_s can introduce major errors. Under natural conditions ϕ_a, the aerodynamic conductance above the crop, varies within the range 0,03 to 0,3 $m\ s^{-1}$, while the conductance of a complete vegetative surface wherein no water stress exists is usually of the order of 0,03 $m\ s^{-1}$. Hence, the value of ϕ_a/ϕ_s can vary between 1 and 10 under unstressed growing conditions and between unity and infinity when water stress in the crop becomes appreciable ($0 < \phi_s < 0{,}03\ m\ s^{-1}$). Consequently when no stress exists, the value of γ^* can vary between 0,5 and 5,0 $g\ m^{-3}K^{-1}$ ($\gamma \div 0{,}5\ g\ m^{-3}K^{-1}$). Since the value of s varies between 0,7 and 1,4 $g\ m^{-3}K^{-1}$ through the range $10°C < T_a < 30°C$, aerodynamic conductance could cause $s + \gamma^*$ to vary between approximately 1,5 and 5,0 $g\ m^{-3}K^{-1}$ or a range of 400%. In the limit when $\phi_a/\phi_s >> 1$, and hence $\gamma^* >> s$, a given error in ϕ_s will produce an equal error in γ^*, $s + \gamma^*$ and the estimate of E. This case can occur either when crop water stress is prevalent ($\phi_s < 0{,}03\ m\ s^{-1}$), or as a result of high wind speed ($\phi_a > 0{,}1\ m\ s^{-1}$). The lowest error sensitivity in ϕ_s occurs when $\phi_a/\phi_s \sim 1$ and $\gamma^* \sim 2$ s. Then a given error in ϕ_s or ϕ_a could cause approximately one-half as large an error in γ^* or one-quarter as large an error in $s + \gamma^*$ and the estimate of E. This case occurs when $T_a \sim 10°C$ with low wind speeds above an unstressed crop. It is therefore obvious that the value of this ratio seriously influences the calculation of evaporation rate. Accuracy in the determination of both ϕ_a and ϕ_s is therefore extremely vital.

Russel (1980) showed that ϕ_s maintains a maximum value while soil water does not limit crop evaporation rate. Immediately the crop surface conductance decreases, a decrease in crop evaporation rate results (see Eqn. 2). It is however conceivable that stomatal closure could commence before ϕ_s decreases from its maximum, implying a yield loss even though atmospheric evaporative demand is met (De Jager *et al.* 1982).

From the above it follows that research into the evaluation of whole crop surface conductance, and its relation to photosynthetic rate, particularly when soil water supply becomes critically low, could prove to be both illuminating and rewarding.

Direct measurement

Leaf stomatal conductance may be measured utilizing the diffusion porometer. Much difficulty has been experienced with the calibration of the diffusion porometer (Bristow, 1982). This instrument creates an artificial environment around the leaf which induces a transient state of stomatal aperture which could induce erroneous measurements. The instrument has fallen into disrepute. Steady state porometers largely overcome this problem, but use of this instrument and instruments for measuring leaf water potential are still beset with tremendous sampling problems because observations are made on single leaves (Bristow *et al.* 1981). Micrometeorological techniques on the other hand look at the crop surface as a whole and are therefore preferred.

The use of large cuvettes (Reicosky, 1981, De Jager *et al.*, 1982) containing a number of whole plants instead of single leaves also offers an attractive approach to solving this problem.

Estimation using micrometeorological methods

Eqn. 2 has been modified to three versions which are used in irrigation research. These are the following:

Equilibrium evaporation

$$E_e = \frac{s}{s+\gamma} H \qquad (4)$$

Open water evaporation

$$E_o = \frac{s}{s+\gamma} H + \frac{\gamma}{s+\gamma} \lambda \phi_a (\varrho_v' - \varrho_v) \qquad (5)$$

(the assumption here is $\phi_s >> \phi_a$),

Potential crop evaporation

$$E_p = \frac{s}{s+\gamma^*} H + \frac{\gamma}{s+\gamma^*} \lambda \phi_a (\varrho_v' - \varrho_v) \qquad (6)$$

where

$$\gamma^* = \gamma(1 + \phi_a / \phi_s') \qquad (7)$$

and

ϕ_s' = the maximum value of ϕ_s for the given crop.

Equilibrium evaporation removes the aerodynamic term from the evaporation formula and provides an estimate of the lower limit of crop evaporation (Davies and Allen, 1973). This occurs when the atmospheric surface layer is saturated and $\phi_s >> \phi_a$, implying no soil water deficit. De Bruin, *et al* (1982) propose interesting yet simple modifications to Eqn. 4 which improve its accuracy.

Of major importance to irrigation research, is Eqn. 6. Here crop conductance is given a finite constant value which is the maximum possible for the given growth stage. Irrigation research will benefit greatly where this value is accurately determined for each crop and management practice. An intriguing technique of determining ϕ_s is suggested by Russel (1980) in Eqn. 8:

$$\phi_s = \frac{\phi_a}{(\frac{E_o}{E} - 1)\frac{s+\gamma}{\gamma}} \qquad (8)$$

Eqn. 8 is derived from Eqns. 2 and 5, via the intermediate equation

$$\frac{E_o}{E} = \frac{\frac{s}{s+\gamma} H + \frac{\gamma}{s+\gamma} \lambda \phi_a (\varrho_v' - \varrho_v)}{\frac{s}{s+\gamma^*} H + \frac{\gamma}{s+\gamma^*} \lambda \phi_a (\varrho_v' - \varrho_v)}$$

Strictly speaking Eqn. 8 can only be derived from the intermediate equation if ϕ_a in the numerator equals ϕ_a in the denominator. This implies that the surface roughness influencing E must equal that influencing E_0. Aerodynamic conductance, apart from depending upon wind speed and atmospheric temperature gradients, is also influenced by the nature of the underlying surface. This is so because the magnitude of z_0 in *Eqn. 9, from which* ϕ_a *is calculated*, is determined by crop surface characteristics. Hence, for a given set of atmospheric conditions, the numerical value of ϕ_a obtained in Eqn. 5 will differ from that in Eqn. 6, because an open water surface has a very different surfance roughness to that of a crop. Hence measured open pan, or even open water, evaporation rate cannot strictly be used to provide values for E_0 in Eqn. 8. It might however be interesting to investigate the magnitude of the error involved if open pan evaporation is used for E_0. Alternatively, it might be interesting to try to design an experimental system in which free water evaporation can be *measured from a surface with roughness* characteristics similar to those of the crop.

Relationships to soil water conditions

Once having established whole crop surface conductance, it must be determined whether a relationship between this value and soil water potential exists. Russel (1980) found the relationship shown in Fig. 1 for barley. He also related maximum crop surface conductance to soil moisture extraction. The nature of these relationships as *well* as the *magnitude and constancy of critical soil* water potential (Fig. 1) are of prime importance to irrigation research. Knowing whether the critical soil water potential is applicable to all soil types and depths and crop management practices would be invaluable. It is expected that the relationship of ϕ_s to soil water potential could be unique. This deserves to be verified.

Estimation of crop surface conductance utilizing whole crop hydraulic conductance

De Jager and Kaiser (1977) discussed crop hydraulic conductance as a function of soil water potential and atmospheric demand. This concept can possibly play an important coupling role (Van Zyl, *et al.*, 1981) between soil water status and atmospheric demand. Because the hydraulic conductance approach also utilizes plant water status, it should be pursued, perhaps with the inclusion of ideas outlined by Campbell and Campbell (1982).

Aerodynamic conductance

A reliable estimate (Thom, 1975) of aerodynamic conductance under conditions of neutral atmospheric stability is given by Eqn. 9

$$\phi_a = \frac{k^2 u}{[\ln(\frac{z-d}{z_0})]^2} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

As indicated this entity has extreme significance in the calculation of evaporation rates using the above equations. The validity of Eqn. 9 for determining ϕ_a is restricted to neutral atmospheric conditions. It can be corrected for atmospheric stability effects by *multiplication by the atmospheric stability factor*, F, *described by* Thom (1975).

Measurements required for the calculation of F include at least air temperature and wind speed at two heights. Such observations are not normally available in practice – hence the need to determine the frequency and magnitude of the errors resulting from utilization of Eqn. 9 without adjustment according to F.

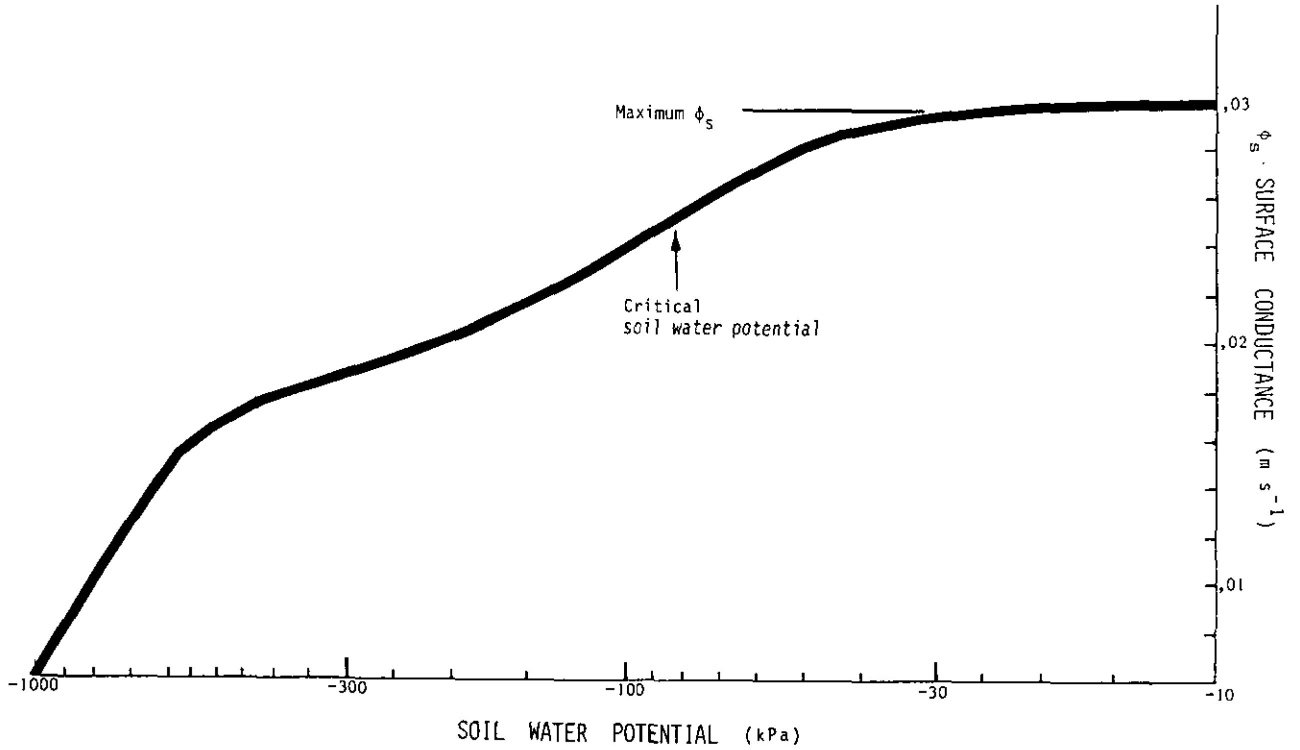

Figure 1
The relationship between surface conductance and soil water potential (at 0,2 m depth) for barley (adapted from Russel, 1980).

Crop foliage temperature

Air-foliage temperature differentials

Crop foliage temperature, T_c, has been shown to be a reliable indicator of moisture stress conditions. For example, the work of Idso, Jackson *et al.* (1981) indicates that crop water status may be assessed from a nomogram of the type shown in Fig. 2. In such nomograms the base line depicts ($T_c - T_a$) over a range of saturation deficits for a well watered crop. Should water stress exist; ($T_c - T_a$) will approach the stress-lines shown in Fig. 2. The stress lines reflect ($T_c - T_a$) differentials at atmospheric temperatures of $T_a = 10°C$ or $T_a = 50°C$ when the crop is experiencing complete water stress. The degree of water stress experienced is in direct proportion to the ratio of measured differential to base line differential at the existing vapour deficit. Such nomograms can prove to be of great value for irrigation scheduling. Hence the base lines and stress lines should be established for all irrigation crops under local conditions. It is interesting to note that the moisture stress index obtained utilizing infrared thermometry (Idso, Reginato *et al.* 1981), indicates a critical leaf water potential approximating that proposed for maize and potatoes by De Jager and Kaiser (1977).

In this type of investigation T_c is measured using the infrared thermometer and screen temperature has been utilized for T_a. It might be useful to examine whether a temperature nearer the crop surface would improve assessments.

Macro-micrometeorological estimation

Because of the significance of ($T_c - T_a$) it is important that a model for estimating T_c, given meteorological inputs, be obtained. The iterative technique for estimation of E developed by Bristow and De Jager (1981) offers a solution. A by-product of this technique is the estimation of T_c. They defined T_c as the temperature measured at the momentum exchange level. Expected accuracy of the technique is illustrated in Fig. 3. The major advantage of the method is the utilization of routine meteorological observations with an estimate of in-crop relative humidity. Furthermore it obviates the necessity of estimating crop surface conductance. While open to criticism because of some of the assumptions regarding the location and status of the effective exchange surface, further verification of this technique might prove rewarding. Alternatively, and for the same reasons, the methods used by Pedro and Gillespie (1982a, b) deserve attention.

The method would find wide application in estimating foliage temperatures and in irrigation scheduling, provided routine macrometeorological measurements undertaken by the national network of observation stations of the National Weather Bureau could be suitably transformed to serve as inputs. The research required on this aspect therefore, is the determination of the formulae required to estimate foliage temperatures from macrometeorological readings.

The variability in foliage temperatures

Clawson and Blad (1982) have indicated that the variability in crop foliage temperatures measured by infrared thermometer may be used as an indicator of the degree of crop water stress. In their experiments this variability was used to indicate when irrigation was required on the treatment plot. The results showed that treatment plot yield equalled control yield, but 150 mm less irrigation water was supplied to the treatment. This gave a marked increase in irrigation efficiency.

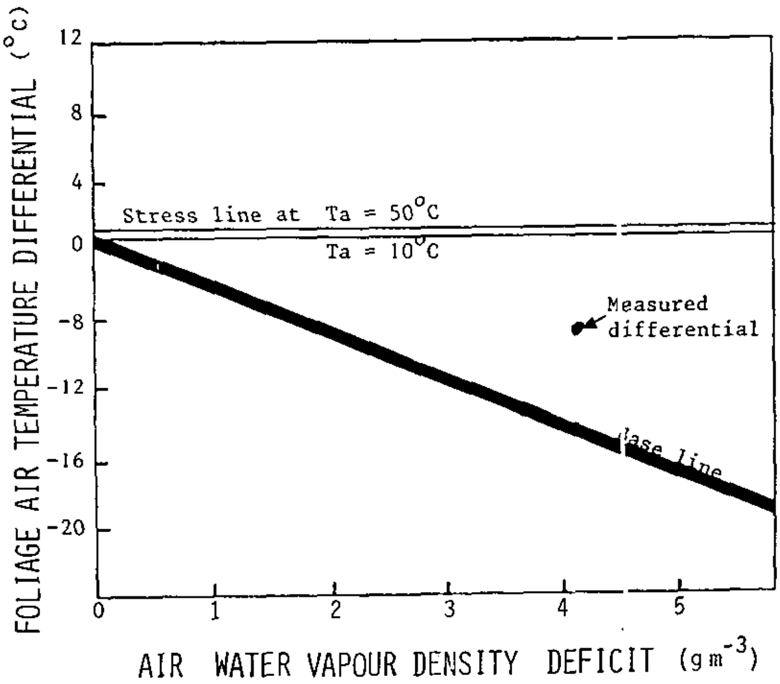

Figure 2
The nomogram proposed by Idso, Jackson et al *(1981) for using foliage-air temperature differentials and ambient saturation vapour density deficit for assessing the degree of water stress existing in a crop.*

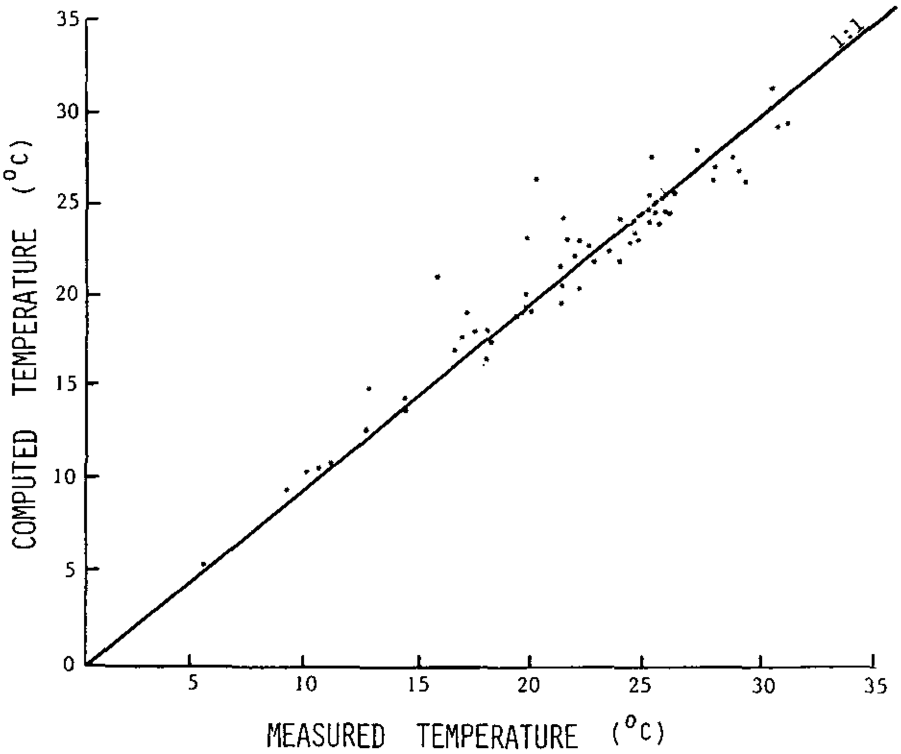

Figure 3
Hourly mean surface temperatures computed using the iterative technique vs. the hourly mean temperature measured at the momentum exchange level over six days. (After Bristow et al., *1981.)*

The variability criterion proposed by Clawson and Blad (1982) for decision making, was the range in six consecutively measured crop foliage temperatures. Unstressed plots yielded a range of 0,6°C. When this range rose to 1,4°C it was inferred that partial stress had been induced and irrigation was applied. This technique for scheduling irrigation deserves attention.

Remote sensing

The application of infrared sensing techniques to irrigation scheduling has already been outlined. The major advantages of this approach are its convenience and ability to provide rapid extended area spatial averages in contrast to individual leaf observations. Pinter (1982) infers the use of aircraft for obtaining data on plant water stress. Furthermore, although cloud frequency does limit the utilization of satellite data, this information source could provide measurements on a scale of resolution appropriate to irrigation schemes and hence this alternative deserves investigation.

Recommendations

Aspects of the micrometeorological control of evaporation have been discussed. In order to exploit this interactive process in irrigation research and irrigation scheduling, certain studies could prove rewarding. These include the following:

- Methods of estimating aerodynamic conductance for all three atmospheric stability conditions above a whole crop surface using routine weather observations.
- Micrometeorological methods of measuring whole crop maximum surface conductance.
- Determination of the relationship between the onset of stomatal closure and the onset of decreased whole crop surface conductance.
- The nature of the relationship of crop surface conductance to soil water potential; whether this is a unique relationship applicable to all crops and soils and how atmospheric evaporative demand influences this relationship.
- Whether a similar relationship as the aforesaid exists between crop surface conductance and soil water extraction and how this differs with crop management practice and soil type must also be investigated.
- The establishment of nomograms for determining crop water stress using foliage-air temperature differentials for all irrigated crops.
- The determination of a reliable technique for estimating foliage temperature using routine weather data.
- The use of crop hydraulic conductance, atmospheric evaporative demand and soil water potential to predict crop surface conductance.
- The application of the range of foliage temperatures as measured with the infrared thermometer for scheduling irrigation.

- The accuracy and feasibility of the use of satellite observations to measure crop temperatures for use in large area irrigation scheduling.

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