CORRECTION FACTORS FOR EVAPORIMETER COEFFICIENT USED FOR SCHEDULING IRRIGATION OF WHEAT

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VAN ZYL, W.H., DE JAGER, J.M. and MAREE, C.J.

EXECUTIVE SUMMARY

for

WATER RESEARCH COMMISSION

by

DEPARTMENT OF AGROMETEOROLOGY

UNIVERSITY OF THE ORANGE FREE STATE

BLOEMFONTEIN

1989

RATIONALE FOR THE STUDY

The upper limit of evaporation from natural surfaces is termed atmospheric evaporative demand, AED. Estimation thereof is of utmost importance. Amongst other things, irrigation scheduling and mathematical simulation of hydrological and crop growth processes require accurate estimate of AED.

Evaporimeters are used to measure a reference level of evaporation from which this upper limit may be estimated. At present, the United States Weather Bureau Class A pan is often used. This approach however, is fraught with large errors. These could for example cause insufficient or over-irrigation with detrimental financial implications for, not only farmers, but the country as a whole. Piché and carborundum atmometer measurements cannot be used directly. They have been shown to be poorly related to atmospheric evaporative demand, because they do not adequately account for radiation in the energy budget.

Estimation of AED is carried out by multiplying evaporimeter water loss by an evaporation coefficient. The latter has been empirically determined. Such coefficient contains errors both conceptual and of a practical nature. An evaporimeter measures evaporation rate from its surface and nothing else. This water loss is related to evaporation from a natural surface in an extremely complex manner. Because of abovementioned critical significance of these coefficients, an urgent need has arisen to improve their accuracy.

Hence the present study essentially involved determining correction factors for evaporation coefficients.

OBJECTIVES

The overall objective of this study was to develop correction factors for evaporation coefficients used with evaporimeters, such as the American class A pan and Piché and carborundum atmometer, for estimating upper limit evaporation, AED from a wheat surface.

Specific objectives were to:

- Define the atmospheric evaporative demand (AED) concept. AED is essential for developing correction factors for evaporimeters.

- Prove the accuracy of the Penman-Monteith equation for estimating evaporation rate from a short grass surface (E_o) given current weather data. The Penman-Monteith equation was the basis for estimating AED and developing the desired correction factors.

- Develop correction factors for accurately simulating AED from class A pan evaporation measurements during daylight periods.

- Compare these corrected A pan estimated AED values against AED measured in a lysimeter to validate their accuracy.

- Relate evaporation from exposed, but shaded Piché and carborundum atmometers to the aerodynamic component of the Penman-Monteith equation respectively.

- Prove the accuracy of estimating AED from a form of the Penman-Monteith equation, which included atmometer measurements.

- Demonstrate the accuracy of estimating AED, utilizing an empirical expression for the energy component of the Penman-Monteith equation together with atmometer measurements.

- Evaluate wheat crop surface conductance for use in the Penman-Monteith equation. The latter was needed for determining correction factors for evaporimeters.

- Determine for wheat the ratio of upper limit plant evaporation rate to E_o. This ratio formed an integral part of the crop evaporation coefficient.

RESULTS AND DISCUSSION

It was shown that utilization of a single crop evaporation coefficient was incorrect. Two coefficients are required, viz. a coefficient reflecting soil surface drying and a coefficient accounting for the degree of vegetative cover. The sum of these two coefficients multiplied by evaporation from a reference crop, E_o, equals upper limit evaporation rate viz. atmospheric evaporative demand, AED. This concept as here defined is completely general and determined by only atmospheric, plant and soil physical factors. All previously used concepts such as total evaporation, potential total evaporation, reference total evaporation, maximum total evaporation and basal plant evaporation are accounted for in the new definition.

Practical application of the AED concept and development of correction factors for evaporimeters, required reliable values of evaporation from a reference crop (short grass) surface, E_o. Accurate simulations of E_o were shown to be possible using the Penman-Monteith equation, micrometeorological weather data and a canopy surface conductance of 0,08 m s^{-1}. The index of agreement, mean absolute difference and mean difference between simulated and measured E_o was 0,97; 0,05 mm h^{-1} and 0,01 mm h^{-1} respectively.

The accuracy of estimating either AED or E_o from the American Class A pan was tested. Calculating AED or E_o from daily A pan measurements, E_{pan}, was shown to be inaccurate. Pan measurements compared to measured wheat AED for a LAI > 3 yielded unacceptable index of agreement and mean absolute difference of 0,89 and 1,03 mm d^{-1} respectively. Corresponding values for E_{pan} measured and E_o measured yielded 0,74 and 1,49 mm d^{-1}. These results together with theoretical evidence in Van Zyl, De Jager and Maree (1989) proved that uncorrected pan measurements could not be used to estimate AED, especially for experimental purposes.

Poor correspondence between A pan and E_o estimates was largely attributable to heat being stored in the pan during daylight. Correcting for this, significantly improved the above test statistics. An index of agreement of 0,88 and a mean absolute difference of 1,00 mm for the daylight period were found. Application of this correction factor requires two A pan readings daily. The first, in the morning, when leaf stomates open, and the second, in late afternoon when stomatal closure occurs. In addition air and water temperature need to be monitored continuously. These temperatures were needed to calculate the slope of the saturated water vapour density temperature curve and the energy stored in the A pan respectively. It is stressed that this correction is only valid during daylight periods. They could however be conveniently applied.

It was found that Piché and carborundum atmometer, properly shielded from long and short wave radiation, can be used with confidence to measure the aerodynamic component (AC) in the Penman-Monteith equation. The index of agreement, mean absolute difference and mean difference between E_o measured and E_o estimated using the Piché atmometer to measure AC were 0,95, 0,09 and 0,01 mm h^{-1} respectively. Corresponding values when using the carborundum atmometer were 0,95, 0,09 ns 0,03 mm h^{-1}.

Empirical expressions for AC and the incoming solar energy were then substituted in the Penman-Monteith equation. Estimates of AED so obtained were compared against measured values of wheat AED. The index of agreement and mean absolute difference between daily AED measured and AED estimated, were 0,98 and 0,51 mm respectively. This represented highly acceptable accuracy. Of major practical significance was the fact that this atmometer procedure obviated difficult measurement of windspeed and vapour pressure deficit.

The Penman-Monteith equation, weather data from an automatic weather station and a lysimeter were used to determine ϕ_v. Results originating from this work indicated that the value ϕ_v = 0,08 m s^{-1} could be used with confidence in the Penman-Monteith equation together with weather data from an automatic weather station to estimate E_o. The index of agreement, mean absolute difference and mean difference between E_o measured and E_o estimated, using ϕ_v = 0,08 m s^{-1}, were 0,96, 0,00 and 0,07 mm h^{-1} respectively.

The ratio of upper limit plant evaporation to reference crop evaporation (k_{vm}) was determined for incomplete wheat crop cover. The value k_{vm} = 1,11 found, agreed excellently with the value of 1,10 ±0,13 determined by Maree (1989) for complete wheat cover. These results implied that k_{vm} was constant throughout the entire wheat growing season.

CONCLUSIONS

The generality of AED, here defined , makes universal acceptance of this concept desirable. This description of upper limit evaporation eliminated much of the confusion which existed in the past regarding which of maximum, potential, basal or reference evaporation should be used to express upper limit evaporation.

The Penman-Monteith equation, weather data from an automatic weather station and a value for canopy surface conductance of 0,08 m s^{-1} could be used to estimate E_o accurately. This estimate, together with the crop evaporation coefficient defined in this work must now be regarded as a most accurate method of calculating AED. It will be indispensable for scheduling irrigation.

Evaporimeters such as A pan and Piché or carborundum atmometers were proved useful alternatives for estimating E_o. It was however imperative to apply the correction factors developed in this study. Of these, atmometers proved to be more accurate than did the A pan. Application of atmometers required measurement, or estimation, of radiation and air temperature. On the other hand, implementation of pan measurements required measurement of air and water temperature.

The RSA is characterized by severe drought and periodic water shortages. Irrigation water has become increasingly important for the production of vegetables and agronomy crops. To prevent wastage, efficient irrigation strategies and scheduling are required. These can only be developed provided accurate values of AED and crop evaporation coefficients are available. Work here described provided these.

RECOMMENDATION FOR FUTURE RESEARCH

- Accurate evaluation of the crop coefficient requires evaluation of the ratio of upper limit soil evaporation rate to E_o (k_{sm}). This work has already commenced. This should be followed by evaluation of k_c.

- Results Maree (1989) indicated that the value of k_c varies with climatic conditions. A project, titled "Climatic dependence of crop coefficients", has been initiated to investigate this aspect. It is sponsored by the Water Research Commission.

- Now that AED and k_c have been uniquely defined, it is important to evaluate them for as many vegetable and agronomic crops as possible. Such work holds valuable benefits for many fields of agricultural research or operations.

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Practical irrigation scheduling on wheat was carried out in the districts of Aliwal North during 1987 and Prieska during 1988 on request of a fertilizer company. The service is now being repeated on very limited scale at Prieska. It was rendered to the satisfaction of all farmers concerned.

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TABLE OF CONTENTS

LIST OF SYMBOLS

AED	-	Atmospheric evaporative demand (mm)
E_m	-	Maximum total evaporation from an infinitely large crop surface (mm)
E_o	-	Evaporation from a reference crop supplied with adequate water (mm)
E_p	-	Potential evaporation (mm)
E_{pan}	-	Total evaporation from the USWB class A pan (mm)
E_e	-	Total evaporation from an artificial evaporimeter (mm)
k_{pan}	-	Ratio of E_m to E_{pan} (E_m/E_{pan})
k_e	-	Ratio of E_m to E_e (E_m/E_e)
k_o	-	Ratio of E_o to E_e (E_o/E_e)
k_c	-	Ratio of AED to E_o (AED/E_o)
s	-	Slope of the saturated water vapour density-temperature curve (Pa $^oC^{-1}$)
γ	-	Psychrometric constant (Pa $^oC^{-1}$)
ρ	-	Density of air (kg m^{-3})
C_p	-	Specific heat of air (J(kg $^oC)^{-1}$)
Q_n	-	Net radiation over vegetation (W m^{-2})
G	-	Soil heat flux density (W m^{-2})
δ_e	-	Vapour pressure deficit (Pa)
ϕ_a	-	Aerodynamic conductance of the atmosphere (m s^{-1})
ϕ_v	-	Whole crop surface conductance for water vapour exchange (m s^{-1})
r_a	-	Aerodynamic resistance of the atmosphere (s m^{-1})
z_o	-	Surface roughness parameter (m)
d	-	Zero plane displacement level (m)
k	-	Von Karman's constant
u(z)	-	Windspeed at height z (m s^{-1})
Φ_m	-	Atmospheric stability function
Ri	-	Richardson number

EC	-	Energy component in the Penman- Monteith equation ($W\ m^{-2}$)
AC	-	Aerodynamic component in the Penman-Monteith equation ($W\ m^{-2}$)
f(u)	-	A wind function ($mm(d\ Pa)^{-1}$)
C_s	-	Saturated water vapour density at surface temperature ($kg\ m^{-3}$)
C_z	-	Ambient water vapour density at height Z ($kg\ m^{-3}$)
CD	-	Drag coefficient
CR	-	Convection ratio
Q_{nc}	-	Net radiation over the pan ($mm\ d^{-1}$)
S_p	-	Rate of heat storage in the pan ($mm\ d^{-1}$)
$f_{vp}(u)$	-	Penman's windspeed function for vegetation ($mm(d\ Pa)^{-1}$)
$f_{vc}(u_c)$	-	Penman's windspeed function for the A pan ($mm(d\ Pa)^{-1}$)
$(\delta_e)_c$	-	Vapour pressure deficit just above the pan water level (Pa)
T_s	-	Pan surface temperature (^oC)
T_c	-	Air temperature at pan water surface level (^oC)
E_{p1}	-	Estimated evaporation using the model of De Vries and Venema (1953) ($mm(7h)^{-1}$)
E_{p2}	-	Estimated evaporation using the model of Stigter and Uiso (1983) ($mm(7h)^{-1}$)
q_d	-	Energy supply to the disc of the Piché atmometer ($W\ m^{-2}$)
ρ_w	-	Density of water ($kg\ m^{-3}$)
λ	-	Latent heat of evaporation ($J\ kg^{-1}$)
h_w	-	Heat transfer coefficient of water ($W(m^2\ {}^oK)^{-1}$)
D'	-	Diffusivity of still air ($m\ s^{-1}$)
ν_d	-	Kinematic viscosity of air ($m\ s^{-1}$)
d'	-	Length scale of Piché disk evaporimeter (m)
e_a	-	Vapour pressure of air (Pa)
e_s'	-	Vapour pressure of air in contact with Piché surface (Pa)

T_a - Air temperature at 2 m above the grass surface (°C)

E_{ps} - Evaporation from a screen Piché atmometer (divisions)

E_a - Aerodynamic term in Penman's formula (mm d^{-1})

E_{pse} - Estimates of E_m using E_{ps} plus a regional value for the energy component (Stanhill, 1962)

A' - Weighting factor based upon the slope of the saturation vapour-pressure curve at mean air temperature

E_{pen} - Estimated evaporation from the Penman formula (1956) (mm d^{-1})

E_c - Evaporation from the portable capillary evaporimeter (mm d^{-1})??

$I_v(h)$ - Extra-terrestrial radiative flux density for a solar elevation h (W m^{-2})

h' - Solar elevation (degree)

I_o - Solar constant (W m^{-2})

r_v - Earth to sun radius vector

a(h) - Atmospheric transmissivity for direct radiation

p - Atmospheric pressure (Pa)

w - Precipitable water in the atmosphere in zenithal direction (mm)

T_d - Surface dewpoint temperature (°C)

d_p - Dimensionless dust parameter

m' - Optical air mass, generally equal to cosec h, where h exceeds 10^o

q(h')- Diffuse radiation (W m^{-2})

$S_v(h')$ - Direct vertical solar radiation (W m^{-2})

$S_t(h)$ - Total solar radiation (W m^{-2})

E - Total evaporation from a natural surface (mm)

E_v - Plant evaporation (mm)

E_s - Soil surface evaporation (mm)

E_{vm} - Basal plant evaporation (mm)

k_m - Ratio of E_m to E_o (E_m/E_o)

k_{vm} - Ratio of E_{vm} to E_o (E_{vm}/E_o)

k_{sm} - Ratio of E_{sm} to E_o (E_{sm}/E_o)

S_t - Extra-terrestrial daily total solar radiant density (where 1 MJ m^{-2} = 0,41 mm),

F_h - Relative transpiration rate with respect to its potential value

F_l - Ground cover factor

F_g - Relative soil evaporation rate with respect to its potential value

V_m - Volumetric water content in the top 150 mm of the soil at field capacity (mm m^{-1})

V - Current value of the volumetric water content in the top 150 mm of the soil (mm m^{-1})

f(u(z))- Daily windrun at 2m height (km)

n/N - Ratio of actual to maximum possible sunshine duration

c - Adjustment factor for ratio of day to night wind, mean maximum atmospheric vapour pressure (P_a) and incoming daily total solar radiant density (mm)

W - $s/s+\gamma$ = 0,58; 0,71 and 0,77 at temperatures of 10°C, 20°C and 26°C respectively at 1000 m above sea level.

T - Air temperature (°C)

e_s - Atmospheric vapour pressure (P_a). "$_s$" denotes saturated conditions.

C - Sensible heat flux density to the atmosphere (W m^{-2})

$f_p(u)$ - Windspeed function for sensible heat exchange from the A pan, derived from dimensionless numbers (mm(daylight mbar)$^{-1}$)

c* - Ratio of the total area of the A pan (water surface plus the side and a weighted value of the base of the pan) to the surface area of the water in the pan, exposed to ambient air

T_s - Pan water surface temperature (°C)

m - Mass of the water in the A pan (kg)

S_w - Specific heat of water (J (kg °C)$^{-1}$)

A - Cross sectional area of the A pan (= 1,13m^2)

t	-	Length of daylight period (h)
ΔT	-	The total change in water temperature in the A pan during either a heating or a cooling phase (°C) (see Fig. 5.1)
z	-	Height above grass level at which measurements were made (= 2m)
h	-	Height of the reference crop (= 0,1m)
TF	-	Transformation function
E_{psc}	-	Evaporation from the Piché atmometer in the Stevenson screen (Piché water tube divisions)
E_{ps}	-	Evaporation from the exposed but shaded Piché atmometer (Piché water tube divisions)
E_{cs}	-	Evaporation from the exposed but shaded carborundum evaporimeter (mm column height)
T	-	Average Stevenson screen temperature between 08h00 and 17h00 (°C)
E_{ps}	-	Hourly or total daylight evaporation from a Piché atmometer housed in a Stevenson screen(mm)
D	-	Time in days since last wetting event exceeding 5 mm
$S_t(t)$	-	Hourly mean total solar radiant flux density ($W\ m^{-2}$)
AED_o	-	Atmospheric evaporation demand assuming canopy conductance (ϕ_v) equals infinity ($mm\ h^{-1}$)
AED_p	-	Atmospheric evaporative demand on full vegetative cover provided with adequate soil water ($mm\ h^{-1}$)
r_v	-	Canopy resistance to water vapour exchange for a complete vegetative cover ($s\ m^{-1}$)
$u(z)$	-	Wind speed at height 3,15 m above ground level ($m\ s^{-1}$)
F	-	Normalized crop factor
T_c	-	Canopy surface temperature (°C)
Γ	-	Transmission coefficient
α	-	Solar elevation (degree)
ϕ_1	-	Individual leaf stomatal conductance ($m\ s^{-1}$)
$S(t)$	-	Global total short wave radiation ($W\ m^{-2}$)

CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

RATIONALE FOR THE STUDY

Estimation of the upper limit of evaporation from natural surfaces, termed atmospheric evaporative demand, AED, is of utmost important for, amongst other things, irrigation scheduling and mathematical simulation of hydrological and crop growth processes. Evaporimeters are used to measure a reference level of evaporation from which this upper limit may be estimated. At present, the United States Weather Bureau Class A pan is often used. This approach however, is fraught with large errors. Resulting insufficient or over-irrigation has detrimental financial implications, not only for the farmer, but for the country as a whole. Piché anemometer measurements cannot be used directly and have been shown to be poorly related to atmospheric evaporative demand. It does not adequately account for radiative influence in the energy budget.

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OBJECTIVES

The overall objective of this study was to develop correction factors for the evaporation coefficients used with evaporimeters for estimating upper limit evaporation from a wheat crop.

Specifically correction factors for evaporation coefficients used with Piché, carborundum atmometer and American Class A pan measurements were developed, to enable applying them in the accurate estimation of atmospheric evaporative demand.

OUTLINE OF THE STUDY

Shortcomings of evaporimeters and possible means of correcting them are fully discussed in the literature survey following in this chapter.

The concept atmospheric evaporative demand is absolutely critical to this study. Although used by many workers in the past it has never been clearly defined. Rigid conceptualization and precise definition thereof is given in Chapter 2.

The Penman-Monteith equation (Thom, 1975) was used as a basis for developing the desired correction factors. Initially, it was necessary to prove the accuracy of this formula by comparing it against measured reference (short grass) crop evaporation rate, E_o. This verification appears in Chapter 3.

Chapters 4 and 5 deal with implications of correcting Class A pan measurements utilizing the Penman-Monteith equation. In Chapter 6, evaporation from exposed, but shaded, Piché and carborundum atmometers, was empirically related to the aerodynamic component of the Penman-Monteith equation respectively. AED, estimated from the energy component of the Penman-Monteith equation plus empirically derived aerodynamic component was then shown to compare highly successfully with lysimetric measurements of atmospheric evaporative demand.

In practice, micrometeorological measurements required by this approach are not readily available. Hence it was necessary to investigate the accuracy of estimating atmospheric evaporative demand by the method explained in Chapter 6, but using empirical formulae for the energy component. This was carried out in Chapter 7.

Crop surface conductance is required when applying the Penman-Monteith equation. Since the latter was used for determining correction factors for evaporimeters, accurate estimates of crop surface conductance are necessary. Determination of crop surface conductance and its dependence upon weather is discussed in detail in Chapter 8.

Finally, atmospheric evaporative demand is given by the product of crop evaporation coefficient, k_c, and reference evaporation, E_o. The most important component in k_c is the ratio of upper limit plant evaporation to E_o. This ratio is determined in Chapter 9.

SURVEY OF LITERATURE CONCERNING ATMOSPHERIC EVAPORATIVE DEMAND AND EVAPORATION COEFFICIENTS

Estimates of crop water use are indispensable to planning and scheduling irrigation. The demand for soil water by vegetation is determined mainly by values of weather elements. This constitutes the upper limit of water loss from a natural surface. It is called the atmospheric evaporative demand, AED (see definition in Chapter 2). The latter has been termed the maximum total evaporation (E_m), potential evapotranspiration (E_p), basal evapotranspiration (E_v) or reference evapotranspiration (E_o). Each of these conceptualizations of evapotranspiration (see definitions in Chapter 2) relates however to a special case of the upper limit of water loss rate from a natural surface.

Common methods for approximating AED thus involve use of one or other evaporimeter. For example, the USWB Class A pan measures evaporation rate (E_{pan}) from a circular water surface area of 1,13 m^2. Water depth is approximately 250 mm. Approximation of AED from a given crop have been obtained using

$$AED = k_{pan}\ E_{pan} \qquad \ldots(1.1)$$

where,

k_{pan} is the appropriate evaporation coefficient. It is a function of crop growth stage and management practice.

Currently accepted k_{pan} values for use with the USWB Class A pan were published by Green (1985). Problems exist with the use of such coefficients, because k_{pan} values vary markedly from day to day, from one climatic zone to another and from season to season (Thom, Thony and Vauclin, 1981; Howell, Phene and Meek, 1983 and Du Plessis, 1989). Du Plessis (1989) reported k_{pan} values for citrus for January varied from 0,5 to 1,0 for Citrusdal and Nelspruit respectively.

Despite daily errors compensating for one another over an irrigation cycle of a week or longer, they still cause inefficient use of irrigation water (over or under irrigation) with significant financial implications.

Errors in k_{pan} values arise from failure to account for interactions between evaporimeter design and exposure (Bosman, 1987), crop architecture, atmospheric stability and the non-linear heat exchange relationships between ambient air and evaporimeter.

The lack of universality in k_e-values (i.e. ratios of AED to evaporation from evaporimeters in general), is due to the marked differences between character and architecture of growing crops and that of evaporimeters. Doorenbos and Pruitt (1983) maintain that stable coefficients result when k-values are referenced to surfaces closely resembling a growing crop. For this purpose, a short grass cover probably offers the most effective median. Numerous different k-values are relevant in this study, for example

$$E_o = k_o \, E_e \qquad \ldots(1.2)$$

and

$$E_m = k_e \, E_e \qquad \ldots(1.3)$$

E_m, E_e, E_p and E_{pan} are all measurable quantities.

Evaporation coefficients have practical value in irrigation scheduling. Because of this, an urgent need has arisen for firstly, appropriate factors which will remove most of the variance inherent, and secondly, to improve evaporimeter design.

Most discrepancies in evaporimeter (such as Class A evaporation pans) estimates of AED are probably due to evaporimeter insensitivity of the evaporation pan to solar radiation. Crop evaporation is extremely sensitive to this weather element. Correction factors for evaporation are therefore expected to be strongly dependent upon incoming solar radiation. Unfortunately few radiation stations are found in irrigation areas of southern Africa. A substantial network of sunshine duration recorders does however exist. Hence, the possibility of using sunshine duration data for correcting k values deserves attention.

This chapter reviews undermentioned topics relating to use evaporimeter use for estimating AED:

- methods of estimating E_o i.e. reference surface crop/evaporation
- review of physical characteristics and mechanisms of evaporation from existing evaporimeters, and
- utilization of sunshine duration data for purposes of this study.

ESTIMATION OF AED FROM E_o USING WEATHER VARIABLES

De Jager and Van Zyl (1989) expressed AED as follows viz.

$$AED = k_c\ E_o \qquad ..(1.4)$$

The crop evaporation coefficient, k_c, is defined by Eq. 1.4. E_o in Eq. 1.4 may be estimated using the Penman-Monteith formula (Thom, 1975). This in its simplest form is:

$$E_o = 3600/\lambda\ [sH + \rho C_p \delta_e \phi_a]\ /\ [\ (s + \gamma^*)] \qquad ..(1.5)$$

or $\quad = EC + AC \qquad ..(1.6)$

where 3600 ensured the coherency of units,

EC and AC in Eq. 1.6 represent energy and aerodynamic component respectively, given by

$$EC = 3600\ sH / \lambda(s + \gamma^*) \qquad (1.7)$$

and

$$AC = 3600\ \rho C_p \delta_e \phi_a / \lambda(s + \gamma^*) \qquad ..(1.8)$$

Furthermore

$$H = Q_n - G \qquad ..(1.9)$$

$$\gamma^* = \gamma(1 + \phi_a / \phi_v) \qquad ..(1.10)$$

and

$$\phi_a = k^2 u(z) / \{l_n(z-d)/z_o\}^2 \qquad ..(1.11)$$

In Eq. 1.12 z_o and d are 0,013 and 0,063 m respectively for a reference crop height of 0,1 m (Monteith, 1973). From the work of Russell (1980) it is assumed that ϕ_v is equal to 0,03 m s^{-1}.

Strictly these equations apply in conditions approximating neutral atmospheric stability. For stable and unstable conditions, Eq. 1.11 should be multiplied by a stability function, Φm^2. For stable conditions Lumley and Panofsky (1964), Munn (1966) and Webb (1970) developed the relationship

$$\Phi m = (1 - 5\ R_i)^{-1,0} \quad \text{for } Ri > 0 \qquad ..(1.12)$$

For unstable conditions Businger (1966) and Dyer and Hicks (1970) proposed

$$\Phi_m = (1 - 16\ R_i)^{-0,25} \quad \text{for } R_i < 0 \qquad ..(1.13)$$

The Richardson number, R_i, in Eq. 1.13 and 1.14 is given by

$$R_i = (g/\bar{T})\ (dT/dz) / (du/dz)^2 \qquad ..(1.14)$$

(see Thom, 1975)

EVAPORIMETERS

Water surfaces

Evaporation rates from water held in suitable containers (pans) are frequently used for estimating AED. At first glance accurate measurements are convenient and easy from such equipment. Unfortunately both the energy and the aerodynamic components of the Penman-Monteith equation differ comprehensively for pan evaporation and crop evaporation. These differences are the major source for the problems associated with the use of evaporimeters for estimating AED. A comprehensive survey was conducted by Doorenbos and Pruitt (1983). Attention was given to the various factors affecting water loss from pans and vegetation. These authors pointed out that evaporation pans and vegetation respond differently to the same set of climatic conditions, particularly with regard to the following:

The reflection of solar radiation from a water surface is approximately 6% compared to 20% for most vegetative surfaces. Furthermore, water transmits 80 % of incident solar radiation to a depth of 0,3 m, whereas dense crops absorb virtually all radiation which is not reflected.

Heat storage within the water in the pan can be appreciable. This induces additional evaporation during daytime and particularly at night. Most crops naturally transpire little at night due to stomatal closure.

Creation of a markedly different turbulent temperature and humidity regimes in air immediately above different surfaces (Thom, et al., 1981),

Lateral heat transfer through pan walls, may be considerable (Thom, et al., 1981) but could be insignificant in field crops.

Furthermore large errors can be introduced should water levels in the pans not be kept between 50 and 75 mm below the rim of the pan. These errors can be as much as 15 %. Wire screens (0,1mm in diameter by 50mm mesh), while reducing evaporation by approximately 10 %, should be employed in practice to prevent water consumption by animals. Turbidity in the water could also effect evaporation by 5 % or more.

Pans installed surrounded by poor grass cover, dry bare soil or, most undesirably, concrete or asphalt experience air temperatures at pan level, up to 5^{o}C higher and relative humidities 20 - 30 % lower than suitably exposed pans (Doorenbos *et al*, 1983). It is thus apparent that observations from pans so exposed would require marked corrections to k-values. Reductions in evaporation rate of up to 20 % are frequently necessary. Doorenbos *et al* (1983) stated that for areas with moderate levels of wind, temperature and relative humidity, reductions of the order of 5 - 10 % are necessary. Small reductions in k-values are required in humid, cool conditions. Where pans are placed in small enclosures surrounded by tall crops (for example, maize 2,5 m in height) coefficients need to be increased by up to 30 % for dry, windy climates, whereas only 5 - 10 % increases are required for calm, humid conditions.

Doorenbos *et al* (1983) reported k-values at given windspeed, but at various relative humidities. These remained unchanged for sunken Colorado pans sited in short green cropped areas. For the same conditions, k-values however, varied between 14 - 22 % for A pans. On the other hand, the variation in k-values for Colorado sunken pan at a specific relative humidity was twice that of the A pan for a change in windspeed from 1,5 m s^{-1} to approximately 5 m s^{-1}.

Aerodynamic, empirical Dalton equations, viz.

$$E = F(u)(C_s - C_z) \qquad ..(1.15)$$

have been used extensively for estimating bulk evaporation from natural water bodies. In spite of an obvious urgent requirement for such relationships, no single universally accepted equation has emerged. Sill (1983) found approximately 100 different equations in the literature. He examined effects of free and forced convection upon evaporation rate from seven open water bodies. Six "normal" size lakes and a 60 m x 60 m pond were investigated. Analogies between forced convective evaporative transport and momentum, heat and mass transfer from flat surfaces were used to develop new Dalton type equations, viz.

$$E = CD\ u(z)(1 + 0{,}73\ CR^2)(C_s - C_z) \text{ for } CR < 1{,}37 \qquad ..(1.16)$$

and

$$E = CD\ u(z)(1 + CR)(C_s - C_z) \text{ for } CR > 1{,}37 \qquad ..(1.17)$$

Thom, *et al.* (1981) developed an alternative method for calculating evaporation from an open water body. This method utilizes measurements available on country-wide meteorological networks. Hence, it offers greater potential for irrigation scheduling than does Dalton types. The equation is developed from the original Penman equation (1948). It yields estimates of evaporation from the A pan. The equation is given by:

$$E_{pan} = \{s(aQ_n - S_p) + b\gamma\ f_{vp}(u)\delta_e\}/(s + c^*\gamma) \qquad ..(1.18)$$

where,

$$a = Q_{nc}/Q_n, \qquad ..(1.19)$$

$$b = c^* \text{ x } d^* \qquad ..(1.20)$$

$$x = f_{vc}(u_c)/(f_{vp}(u), \text{ and} \qquad ..(1.21)$$

$$d^* = (\delta_e)_c/\delta_e \qquad ..(1.22)$$

The parameter a, is obtained by comparison of simultaneous measurements of net radiation above the A pan (Q_{nc}) and the vegetation (Q_n).

The parameter c, accounts for sensible heat exchange. It is the ratio of the area of water surface plus A pan wall plus a suitably weighted pan basal area to area of surface water exposed to ambient air.

Sensible heat exchange from the pan wall was assumed by Thom *et al* (1981) to be the same as that from the water surface. Since 50% of the base area of the pan rests upon wooden beams, he further assumed that no sensible heat exchange takes place through this area. From the remaining 50% of the base, sensible heat exchange proceeds at 50% of that from the water surface. Hence assuming unit sensible heat exchange per unit surface area from the water surface, it follows that

$$c^{*} = (\pi r^2 + 2\ \pi r\ h + 0{,}25\ \pi r^2)\ /\ \pi r^2 \qquad ..(1.23)$$

Since r and h (A pan radius and depth of water in pan) are 0,6 and 0,25m respectively, $c^{*} = 2{,}1$.

The value $d^{*} = 1$ was used at all times by Thom *et al.* (1981). The site surrounding the experiment consisted essentially of freely transpiring, non-irrigated, grass cover. For hourly analysis of certain nocturnal data however, when the grass had been wetted by dew deposition, d^{*} was equated to 0,73. The vapour pressure deficits, δ_e and $(\delta_e)_c$ were obtained at heights of 0,4 and 2 m respectively.

For pan evaporation, wind function, $f_{vc}(u_c)$ was obtained from appropriate Nusselt and Sherwood numbers. Reference dimension for pan diameter of 1,21 m was adopted (Monteith, 1973). Thus for forced convection, with windspeed measured at a height of 2 m.

$$f_{vc} = 0{,}26\ u_c^{0{,}8} \qquad ..(1.24)$$

and for free convection

$$f_{vc} = 0,105(T_s - T_c)^{0,33} \qquad ..(1.25)$$

For vegetation Penman's wind function (Penman, 1948) was employed, viz.

$$f_{vp}(u) = 0,26(1 + 0,54\ u) \qquad ..(1.26)$$

Study of the behaviour of the parameters a, b and c* will enable the climatological dependence of relationships between AED and E_{pan} to be determined.

Piché evaporimeter

Much analysis thereof, one century after its invention by Jelinek and Hann (1883), has since been done (see Stanhill, 1962; Heine, 1981; Kyaw Tha Paw U and Massamba Gueye, 1983; Jacobs and Linclaen Arriëns-Bekker, 1983; Stigter and Uiso, 1981).

Peculiar shape and exposure requirements, make it difficult to relate Piché evaporation rate to evaporation rates from natural surfaces. Usually instruments are placed in a shelter, shielded from solar radiation. Hence, evaporation is primarily in response to atmospheric humidity deficit and to lesser extent, wind velocity. It might be expected that this instrument would provide readings relatable to shaded leaves, rather than either open water surfaces or luxuriant vegetation exposed to solar radiation.

Kyaw and Gueye (1983) developed a model simulating evaporation from a single broad leaf. The linearised energy budget for the leaf was used to predict daily evaporation from an exposed Piché atmograph. This approach yielded a 1:1 relationship for modelled hourly leaf evaporation to observed hourly Piché evaporation and accounted for 70 - 90 % of the variance observed.

Jacobs *et. al.*, (1983) used the energy balance model of De Vries and Venema (1953) and the aerodynamic model of Stigter and Uiso (1981) to obtain a better understanding of the physical behaviour of the Piché. The model is given by

$$E_{p1} = \{s/s+\gamma\}\{q_d/\rho_w\lambda\} + \{1/s+\gamma\}\{h_w/\rho_w\lambda\}\{\delta_e\} \quad ..(1.27)$$

The latter model is given by

$$E_{p2} = 0,12 \times 10^{-3} D\{u(z)^{\frac{1}{2}/\nu d}\}\{e_s/T_s - e_a/T_a\} \quad ..(1.28)$$

The first model simulates the entire energy balance. Model of measurement comparison produced a slope of 1,09 and intercept of 0,59mm and correlation coefficient of r = 0,98 for the regression. Seven-hourly values of E_p were compared to actual measurements and overestimation by approximately 30 % resulted. The second model simulated only the aerodynamic component. Comparisons with actual measurements resulted in regression coefficients a = 1,23, c = -0,127 mm and a correlation coefficient of r = 0,98. Jacobs *et. al.* (1983) concluded that the underestimation of approximately 15 % by the second model was probably due to omitting an energy component. The model of Stigter and Uiso (1981) had been developed for an evaporimeter within a screen. Jacobs, *et al.* (1983) however, applied it out in the open. Their reason for so doing was to confirm that natural evaporation is strongly influenced by radiation and wind effects.

Stanhill (1962) compared daily evaporation from Piché atmometer (E_{ps}) installed at a height of 2 m, in double-louvered thermometer screen with the aerodynamic term of Penman's formula (E_a), viz.

$$E_a = 0,35(\delta_e)(0,5 + u(z)/100)A' \text{ (mm d}^{-1}) \quad ..(1.29)$$

The line of best fit found was

$$E_a = 0,1469\ E_{ps} + 0,1118 \quad (\text{mm d}^{-1}) \quad ..(1.30)$$

The mean standard error of estimate was approximately 0,146 (mm d^{-1}) (15 % of E_a) and the regression accounted for 79 % of the variance. He also compared estimated evaporation (Epse) using Piché evaporation for the aerodynamic term plus a regional value for the energy component with estimated values obtained from the complete Penman formula, (E_{pen}) (1956). From the graphical comparison presented (no regression analyses were carried out), he derived the following relationship:

$$E_{pen} = 0,81\ E_{pse} + 0,7 \quad (\text{mm d}^{-1}) \quad ..(1.31)$$

Carborundum Evaporimeter

Wilcox (1976) utilized a 40 mm diameter porous carborundum block as an evaporating surface. Evaporation of a mixture of 22 % methanol and 78 % distilled water by mass was measured. This solution has a freezing point well below temperatures normally encountered in nature. The liquid moves to the evaporating surface in response to matric suction gradients similar to those occurring in the Piché evaporimeter.

Portable capillary evaporimeter

Williams, Zangvil and Karnieli (1984) developed and tested a portable evaporimeter constructed from precision bore glass capillary tubing joined to a round plate covered by water saturated filter paper. Water lost by evaporation from the paper surface is replaced by capillary action in the tube. Comparison between quantity of water lost from the evaporimeter, E_c, and A pan evaporation , E_{pan}, yielded the following relationship:

$$E_{pan} = -0{,}297 + 0{,}678\, E_c \quad (\text{mm h}^{-1}) \qquad ..(1.32)$$

The correlation coefficient found was 0,80 with probability less than 10 % that correlation occurred by chance.

A method for estimating the energy component in the Penman formula using this instrument was proposed. Although no results were reported, good agreement is claimed by Williams *et al.* (1984).

SOLAR RADIATION FROM SUNSHINE DURATION DATA

The aerodynamic component of the Penman formula (Stanhill, 1962) alone cannot be used to estimate AED from a vegetative surface. Reliable estimates of AED are obtained by adding to the aerodynamic component either actual measurements of $(Qn - G)/(s + \gamma)$, or EC estimated from total solar radiation, S_t

The following reviews a possible empirical relationship for estimating S_t.

<u>Cloudless atmosphere</u>

Direct and diffuse components of S_t, solar radiation, exist. The vertical component of direct solar radiant flux density upon a horizontal surface at the outer limit of the atmosphere is given (Maaren,1976) by

$$I_v(h') = I_o/r_v \quad \sin(h') \qquad ..(1.33)$$

From this equation the direct component reaching the horizontal plane at the earth's surface is given by

$$S_v(h') = a(h')I_v(h') \qquad ..(1.34)$$

where a(h'), the atmospheric transmissivity for direct radiation developed by Brookes (1959) and re-written by Gates (1962) takes the form

$$a(h') = \text{Exp} - \{0{,}089(p.m'/1013)^{0{,}75} + 0{,}174(w.m'/20)^{0{,}6} + 0{,}083(d_p.m')^{0{,}9}\} \quad ..(1.35)$$

In agricultural areas, aerosol effects are minimal. The most important and variable factor affecting transmission is absorption of solar radiation by atmospheric water vapour. Under normal circumstances precipitable water, w, has to be estimated from surface humidity conditions. McGee (1974) empirically related w to T_d (surface dewpoint temperature). He obtained a correlation coefficient of r = 0,97 and the regression equation

$$w = 10(\ln 0{,}0845 - T_d - 0{,}236) \quad ..(1.36)$$

An empirical relationship for $S_v(h')$ for southern Africa was developed by Archer (1964), viz.

$$S_v(h') = 1127 \sin h' \; 0{,}888^{\text{cosec } h'} \quad ..(1.37)$$

The same author related diffuse radiation to solar elevation obtaining:

$$q(h') = 94{,}23(\sin(h'))^{0{,}5} \quad ..(1.38)$$

Total radiation on a cloudless day is given by

$$S_t(h') = S_v(h') + q(h') \quad ..(1.39)$$

Cloudiness effects

Schulze (1976) developed a sunshine duration model over a period of one year. Observations from a Campbell-Stokes sunshine recorder and Kipp solarimeter were compared. Hours were divided into three 20 minute periods. The latter were presented as either cloudless or cloudy and the model tested. For overcast conditions a transmissivity of 0,24 was assumed. Using latitude, pressure and dew point values for Pietermaritzburg, $I_v(h)$ for each 20 minute period was calculated at the top of the atmosphere. The total incoming radiation was estimated taking into account Eq. 1.35, 1.36 and 1.38. Good agreement was obtained between solar radiation as simulated and observed on the Kipp solarimeter. The correlation coefficient exceeded 0,992 in most cases. It never dropped below 0,965.

CONCLUSION AND SUMMARY

The most suitable evaporating surface to which crop evaporation can be consistently referenced, appears to be short grass cover. Reasons for this include its slow changing, homogeneous vegetative character and the similarity in the energy balance at its surface and that found in field crops. Although soil characteristics and soil climate differ from those of field crops, they certainly approximate field conditions more closely than does water body. During early crop growth stages, incomplete cover prevails. Hence at this time, a factor compensating for leaf cover is imperative for accurate determination of actual evaporation. This aspect is most important when scheduling irrigation, as accurate scheduling leads to water saving.

Unreliability and poor repeatability is inherent to evaporimeter estimates of AED. These stem from inadequate compensation for the different energy balances existing in evaporimeters and natural surfaces. Appropriate corrections to evaporation coefficients can only be achieved by careful accounting of these energy balances. Complete understanding of the complex mechanisms governing both transpiration and evaporation is of the utmost importance. Surface temperature and heat conduction away from the surface (into the body of the evaporimeter) appear to be extremely significant. At this stage, it seems greatest advances in knowledge will result from simultaneously measuring evaporation from a grass lysimeter, E_o, and from cropped observations in lysimeters, AED. Alternatively, E_o observations could be replaced by suitably corrected evaporimeter measurements. The results need always to be interpreted in terms of available theoretical models.

The literature offers little guidance regarding the most reliable evaporimeter for southern Africa, or elsewhere. The USWB Class A pan is the most widely used instrument in the RSA. It appears (Thom *et al.*, 1981) that this pan holds promise for measurement of both the energy and the aerodynamic component in the Penman equation. However its use in estimating AED directly is problematical.

Piché evaporimeters have been shown to be most accurate when determining only the aerodynamic component in Penman equations. Correct exposure of Piché evaporimeters, inside or outside screens, is still uncertain. When, however, it is employed to measure the aerodynamic component, it should be exposed directly in the atmosphere, but shielded from long and short direct radiation. In this manner, diffuse radiation intercepted by the sensing surface during most of the day is small in comparison to wind and water vapour deficit effects.

A portable capillary evaporimeter holds promise, but has not been compared to actual measurements of either E_o or AED. Its use is limited by the length of the capillary tube utilized.

Finally, it appears that evaporation coefficients, k-values, used with A pans require complex correction factors for estimating E_o or AED. A suitably exposed Piché evaporimeter to estimate aerodynamic evaporation component together with accurate estimates of hourly sunshine duration probably offer the most convenient and accurate method of determining AED or E_o. Main advantages of such approach are low capital outlay, ease of installation, convenient, expedient and simple operation and low running costs.

<u>Experimental site</u>

Experiments were carried out during 1985, 1986, 1987 and 1988 on the experimental terrain, (Fig. 1.1) West Campus, University of the Orange Free State. The site, situated 29°6'S latitude and 26°15'W longitude, is characterized by cold, dry winters and hot, moist summers. Precipitation and daily maximum and minimum temperature for winter are typically 50 mm, 15°C and 0°C respectively. Corresponding climatic characteristics for summer are typically 500mm, 25°C and 10°C.

The site supports a short grass surface, 0,5ha in size and 3 ha planted to SST44 spring wheat, under irrigation. Both sections were supplied with adequate water to ensure maximum evaporation during experiments.

The grass site was equipped with an automatic weather station, micrometeorological instrumentation, A pan and a grass lysimeter. A large lysimeter was installed in the centre of the wheat plot.

A detailed description of the wheat lysimeter is given in De Jager, Van Zyl, Kelbe and Singels, 1987. Physical characteristics of the grass lysimeter is given in Chapter 3.

The experimental site and micro-meteorological instrumentation used in this study is fully discussed by Maree (1989).

Micro-meteorological instrumentation installed on the grass site constituted

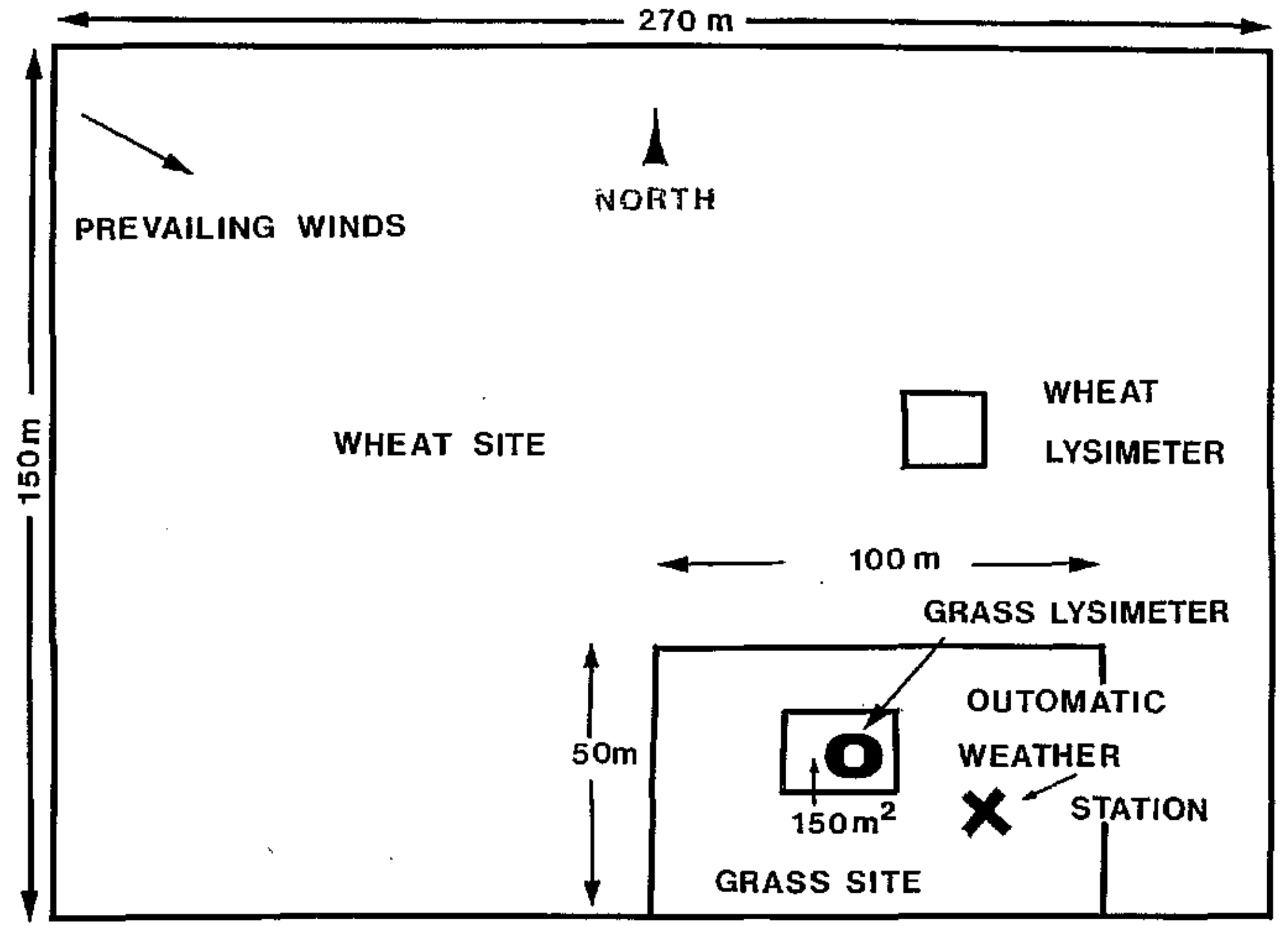

FIG. 1.1 - Schematic outlay of the experimental plot.

- net radiometer at a height of 1,5 m above grass level,
- soil heat flux sensors imbedded 20 mm below grass surface,
- three anemometers at heights 0,5, 1,0 and 2 m above grass level, and
- three ventilated psychrometers at corresponding heights as the anemometers.

CHAPTER 2

ATMOSPHERIC EVAPORATIVE DEMAND AND EVAPORATION COEFFICIENT CONCEPTS

Atmospheric conditions create demand for water from soil and vegetative surfaces. This demand, modified by existing surface conditions, finally determines the actual rate of water vapour exchange between the given surface and the atmosphere. This, in turn, represents the water used by the crop.

When plant roots have an adequate supply of water, there exists an upper limit to the rate of water vapour exchange between atmosphere and vegetation. This upper limit is determined primarily by atmospheric conditions and is a significant and useful entity which deserves precise definition.

Crop growth is a dynamic process. Crop architecture, percentage of the soil surface covered by vegetation and the water status of the soil surface change continually. For practical scheduling of irrigation and theoretical modeling of vegetation hydrology, crop growth and crop development, it is important that the upper limit of the rate of water loss required from a natural vegetative surface be known, or calculable, at all times throughout the growing season. As will be shown, no clear conceptualization of this entity, applicable at all times, for all conditions, exists at present.

An improved, generally applicable and fundamental definition of the upper limit to the rate of evaporation created by atmospheric driving forces is required. Relevant driving forces are radiation, wind and atmospheric temperature and humidity. This definition is the objective of the work reported in Chapter 2. The new entity defined will be called *atmospheric evaporative demand.* How it is determined for practical and modeling purposes will be described.

A NEW TERMINOLOGY

While streamlining evaporation concepts involved, it was felt that something can be done to improve the terminology employed. Hence a new system will be developed. Proposals contained therein stem from the excellent suggestions of Monteith (1985).

Evaporation from a vegetated surface is the sum of evaporation from water, soil, leaf cuticle and sub-stomatal cavity surfaces. Monteith (1985) named this process, total evaporation. It is true that purely a single exchange process, namely evaporation, is involved. Matters are therefore simplified if the term *evaporation* is employed. Evaporation is defined in the Glossary of Meteorology (Huschke, 1959) as *the physical process by which a liquid or solid is transferred to the gaseous state.* This definition includes what is commonly referred to as vaporization, which takes place due to molecular escape without a change in temperature.

For this study and hopefully other agrometeorological investigations a definition of evaporation will be collated from the definition of Huschke(1959) and the description of the evaporative process made by Monteith (1981) - here quoted in inverted commas. Thus, *Evaporation* is defined as *the physical process by which liquid is transferred to the gaseous phase "at the interface between a surface and the atmosphere such that the temperature at each point on the surface tends to an equilibrium value at which the local loss of latent heat is balanced by the net supply of heat by processes such as radiation, convection and conduction."*

Latent heat of vaporization refers to the energy required to be added to liquid (or solid) water to compensate kinetic energy lost when molecules escape through the surface i.e. the energy required to maintain water temperature constant. The coefficient of latent heat of vaporization is thus temperature dependent. It is not strictly applicable to the definition of evaporation adopted here. We will use the value = 2,45 MJ kg^{-1} which corresponds to 20°C. This approximate values for temperatures between 0°C and 40°C to within 2%.

Monteith (1985) suggested that, when describing water vapour exchange from natural surfaces, the multi-lettered *evapotranspiration*, be replaced simply by *total evaporation*.

For convenience, *plant evaporation* will be defined as *evaporation of water which takes place, from vegetation, through the stoma from cell walls in sub-stomatal cavities* and *through the cuticle.*

Then, symbolically, the entire evaporation process from a vegetated surface may be described by

$$E = E_v + E_s \qquad ..(2.1)$$

Thus subscripts "v" and "s" in Eq. 2.1 denote vegetation and soil respectively.

In the ensuing discussion this terminology with appropriate subscripts will be used. It is stressed that for natural vegetated surfaces, the terms evapotranspiration and total evaporation are totally synonymous.

PRESENT DAY CONCEPTS

Total evaporation

Total evaporation, E, or the old "evapotranspiration", is described by Rosenberg, Blad and Verma (1983) as the *total process of water transfer into the atmosphere from vegetated land surfaces.*

Potential total evaporation

Penman (1963) provided evidence to support his hypothesis that vegetation with its roots in soil with water content at field capacity and with leaves forming a complete canopy transpires at a maximum, or potential, rate determined primarily by weather. This led to the definition by Rosenberg *et al.* (1983) of *potential total evaporation*, E_p, as *the evaporation from an extended surface of crop cover which fully shades the ground, exerts negligible resistance to the flow of water and for which the soil surrounding the roots is maintained at field capacity.*

Reference total evaporation

Penman (1963) probably believed that the upper limit of atmospheric evaporative demand might well consistently be related to the evaporation rate from some standard or reference surface such as open water or short vegetation and hence his preoccupation with both. This belief led to coining of the term *reference total evaporation*, E_o, by Doorenbos and Pruitt (1977). A concept they defined as *the rate of total evaporation of an extended surface of an 80 mm to 150 mm tall grass cover of uniform height actively growing, completely shading the ground and not deficient of water or nutrients.*

Maximal total evaporation

The concepts, reference and potential total evaporation, however, do not apply to all cases found in nature. Natural dynamic changes in crop cover and soil surface water content throughout a growing season result in perplexities particularly relevant for irrigation managers. In an attempt to circumvent these problems, Bouchet and Robelin (1969) introduced a "special case" of actual total evaporation. This they called maximum total evaporation, E_m. In so doing, Bouchet and Robelin (1969), and later Wright (1981), recognized that atmospheric evaporative demand has inherently to be surface (i.e. crop) specific. Their concept however applies only to the crop plus saturated soil surface situation.

Maximum evaporation, E_m, is here re-defined as *the rate of evaporation from an actively growing incomplete vegetative cover under which the root zone soil water content corresponds to field capacity or greater and the soil surface is wet.*

For a given crop growth stage, this entity is deemed by Rosenberg *et al.* (1983) to be governed entirely by atmospheric driving forces.

Doorenbos and Kassam (1979) have defined E_m as the rate of *maximum total evaporation of an actively growing crop, in large fields under optimum agronomic and irrigation management.* Because it makes direct reference to soil surface water content, the former definition is preferable. Also, optimum agronomic and irrigation management are ill-defined by the second definition.

Basal plant evaporation

The definition of *basal plant evaporation*, E_{vm}, implied from the work of Wright (1981), is *the rate of water loss from an incomplete, or complete, ($E_{vm} = E_v = E_p$) vegetation cover with its roots growing in soil not deficient in nutrients and water content at field capacity, but for which the soil surface is dry so that comparatively insignificant soil evaporation occurs.*

Here, it is again evident that this definition covers specific cases not generally applicable in all sets of conditions.

From this definition it is apparent that basal evaporation is equivalent to maximal evaporation from only the vegetative component of a natural surface. Hence the symbol E_{vm} is used.

The pan coefficient concept

Many workers have attempted to estimate reference total evaporation, E_o, using the American Class A pan. For this the so-called pan coefficient is required. Doorenbos and Kassam (1979) defined the *pan coefficient*, k_{pan}, as

$$k_{pan} = E_o/E_{pan} \qquad ..(2.2)$$

where, E_{pan} is the rate of evaporation from the Class A pan.

<u>The crop coefficient concept</u>

An evaporation coefficient has also been used to relate maximum total evaporation to reference total evaporation. Doorenbos and Kassam (1979) proposed defining the *crop coefficient*, k_m, as

$$k_m = E_m/E_o \qquad ..(2.3)$$

Here, experimentally determined crop evaporation coefficients, k_m, can be used to relate maximum evaporation, E_m, to reference evaporation, E_o. Unfortunately, managers erroneously apply this coefficient for scheduling irrigation irrespective of soil surface wetness condition.

To circumvent the problems of partial vegetative cover and wet, dry or partially dry soil surface, Wright (1981) defined *basal crop coefficients*, k_{vm}, pertaining specifically to dry soil surface conditions. Thus,

$$k_{vm} = E_{vm}/E_o \qquad ..(2.4)$$

He further developed formulae whereby crop coefficients intermediate between k_m and k_{vm} can be calculated.

Doorenbos and Kassam (1979) offer three methods of calculating E_o from reliable meteorological data obtained in a representative agricultural environment. The methods concerned are the Penman combination, the radiation and the pan evaporation methods. All three methods require adjustments for prevailing climate, as will be shown later.

UPPER LIMITS TO EVAPORATION RATE

Complete vegetative cover

The Penman equation is possibly the most significant scientific advance in environmental science this century. Penman (1948) perfected a combination equation consisting of an energy budget and an aerodynamic component. Estimating the upper limit of evaporative demand from natural surfaces, supplied with adequate water and having a complete vegetative cover is possible with this equation. It operates using weekly, or longer, mean values of meteorological data.

For completeness, the form of the Penman Equation as applied by Doorenbos and Kassam (1979) who used it to determine reference evaporation, E_o, will be quoted here.

The Penman equation is:

$$E = E_o = c\ [WQ_n + (1-W)\ \ f(u(z))\ \ (e_s(T) - e)] \quad ..(2.5)$$

where

$$Q_n = 0,75[(0,25 + 0,50\ n/N)S_t] - [\sigma T^4(0,34 - 0,44\ \delta_e)(0,1 + 0,9\ n/N)] \quad ..(2.6)$$

σ is the Stefan-Boltzmann constant (2×10^{-9}mm d^{-1} K^{-4})

and

$$f(u(z)) = 0,27(1 + u(z)/100) \quad ..(2.7)$$

Values of Q_o, N, W and c are available from tables in Doorenbos and Kassam (1979) who maintain that correct implementation of this equation will probably limit errors in estimated E_o to between 10% and 20% of measured values. Poorest estimates are usually obtained under low evaporative conditions.

Monteith (1965) modified Penman's original theory to account for the effects of the vegetation. This he accomplished by introducing terms for surface resistance (the reciprocal of conductance) to gaseous water exchange. Covey (1959) may have been the first to evaluate surface resistances for vegetation. The new equation operated best with hourly values of the weather variables. This modified form has become known as the Penman-Monteith equation (Thom, 1975).

When considering complete vegetative cover for which root zone water content is at field capacity, it is permissible to assume that gaseous water exchange to the atmosphere proceeds virtually entirely by means of plant evaporation, i.e. the term E_s in Eq. (2.1) is negligibly small. Thus, for this case

$$E = E_p = E_{vm} = E_m$$

Given the coefficient of specific latent heat of vaporization (2,45 MJ kg^{-1} at 20^oC), the slope of the saturated vapour pressure versus temperature curve (at ambient temperature, T), s, soil heat flux density, G, the psychrometric constant, γ, and density, , and specific heat of air, c_p, the Penman-Monteith equation reduces to

$$E = E_p = [s(Q_n-G) + C_p(e_s(T)-e)\phi_a]/[s+\gamma(1 + \phi_a/\phi_v)] \quad ..(2.8)$$

where ϕ_a, the atmospheric conductance to gaseous exchange, is a function of windspeed, u(z), and crop height, h (see Van Zyl and De Jager (1987a)):

$$\phi_a = f(u,h) \quad ..(2.9)$$

According to Eq. (2.5) the atmospheric determinants of evaporative demand upon a complete vegetative cover are net irradiance, Q_n, soil heat flux density, G, daily windrun, u, air temperature T, and water vapour pressure deficit ($e_s(T) - e$). The major physical characteristics of vegetation which modify these atmospheric driving forces are the conductance of the entire vegetative surface to gaseous water diffusion, ϕ_v, vegetation height, h, and the slope of the surface. The latter two influence ϕ_a, atmospheric conductance to gaseous exchange. Vegetative surface conductance, ϕ_v, seems (see Russell, 1980 and Van Zyl and De Jager, 1987a and Chapter 8) to maintain a constant value for wet soil for many agronomic crops. From these facts we may conclude that the upper limit to the demand for water (vapour) from a natural surface is overwhelmingly determined by the atmospheric elements. But, it is also, albeit to small extent, inherently dependent upon nature and height of the vegetation. Failure to account for the latter two could cause problems.

Thus, it is not possible, completely to characterise atmospheric evaporative demand, even on well-watered complete vegetative cover, in terms of exclusively atmospheric variables. The next best thing would be to do so for a standard vegetated surface. This resulted in conceptualization of reference evaporation which applies to a standard vegetation type and its height.

Upper limit evaporation rate from a reference surface finds application in:

(i) climatological comparisons between regions, and

(ii) providing a basis from which evaporation rates from natural surfaces may be estimated for surfaces with both full and incomplete cover.

We see therefore that, whereas reference evaporation varies only with atmospheric conditions, potential evaporation from a full cover vegetated surface varies to a certain extent with vegetation type and crop height.

<u>Open water surfaces</u>

The use of a free water surface to provide estimates of the upper limit of evaporation rate has been attempted. Initially, Rosenberg *et al.* (1983) believed that potential total evaporation cannot exceed free water evaporation under the same weather conditions. Rosenberg and Powers (1970), however, illustrated that in a dry climate daily evaporation from class A evaporation pans, with either land or lake exposures, was smaller than the evaporation rate measured lysimetrically in irrigated lucerne. Rosenberg *et al.*

(1983) concluded, from this, as well as other evidence, that so-called free water evaporation need not always indicate the maximum evaporation rate in sub-humid and arid regions as it apparently does in humid regions. Loose reference to evaporation from pans as free water evaporation can be misleading. The former should not be confused with evaporation from an extended water surface, which could well be used as a form of reference evaporation.

Incomplete vegetative cover

For a natural surface, the degree of vegetative cover affects the energy budget and hence rate of evaporation from that surface.

The physical laws governing the evaporation process are contained in the surface energy budget described by Eq. 2.5 and 2.8. Now, apart from atmospheric influences, the following surface aspects become important:

: surface temperature which determines the saturated water vapour pressure density at the surface and, in part, the net irradiancy (see Monteith, 1981),
: sub-surface temperature and soil physical composition which regulate the soil heat flux density,
: the degree of vegetative cover which determines the relative proportions of plant and soil evaporation, and
: soil surface water content which regulates soil evaporation rate which, in turn, could influence the vapour pressure immediately above the surface.

For both practical (irrigation scheduling) and theoretical (hydrological and crop growth modeling) purposes, it would prove most convenient if it were true that a given set of atmospheric conditions exerted an identical demand for water upon all natural surfaces. From the foregoing, however, it is evident that it would be illogical to expect this.

The immediate need, at least, to approximate the maximum demand by the atmosphere for water from natural surfaces, however, led to the conceptualization of terms such as maximum total evaporation (Bouchet and Robelin, 1969) and basal evaporation (Wright, 1981). E_m and E_{vm} represent the upper limit of the rate of water loss from an incomplete canopy cover with a wet soil surface and from incomplete cover over a dry soil surface respectively. Neither explicitly accounts for incomplete vegetative cover over partially dry soil surfaces. Application of either E_m or E_{vm} throughout an entire growing season, however, is incorrect. This is so, because each has to be adjusted to account for partially wet soil surface condition experienced during the many drying cycles which occur.

THE CROP AND PAN COEFFICIENT CONCEPTS

Crop and pan coefficients evolved as an expedient, but approximate method, for estimating the atmosphere's demand for water. The crop and pan coefficient concepts may be tested by analyzing the energy budgets of evaporating surfaces.

Consider a given surface. The energy balance is described by:

$$Q_n + E + G + C = 0 \qquad ..(2.10)$$

Eq. 2.10 may be written:

$$E = -Q_n - G - C \qquad ..(2.11)$$

Using the subscript "$_o$" to denote conditions appropriate to a reference surface, this becomes

$$E_o = -Q_{no} - G_o - C_o \qquad ..(2.12)$$

In the past, a mean crop coefficient, k_c, intended to cover all degrees of soil surface wetness has been defined using

$$E = k_c E_o \qquad ..(2.13)$$

Here, E represents total evaporation rate from the natural surface in question, irrespective of soil surface wetness condition.

Because of the surface wetness problem outlined above, it is difficult, to accurately determine, and even more difficult to apply, the k_c in Eq. 2.13. Instead, two alternative types of crop coefficient have evolved. The basal crop coefficient of Wright (1981),

$$k_{vm} = E_{vm}/E_o \qquad ..(2.14)$$

and

what is actually a "maximum" crop coefficient of Doorenbos and Kassam (1979)

$$k_m = E_m/E_o \qquad ..(2.15)$$

On the other hand the pan coefficient can be determined experimentally using:

$$k_{pan} = E_{pan} / E_o \qquad ..(2.16)$$

CLIMATE DEPENDENCE OF k-VALUES

It will be shown that all evaporation coefficients (k-values) are influenced by prevailing climate. Let k represent any type of evaporation coefficient, i.e. any crop or pan coefficient. Substituting Eq. 2.11 and Eq. 2.12 in Eq. 2.13, for a specific site, then over a given period, k will be given by

$$k = (-Q_n - G - C) / (-Q_{no} - G_o - C_o) \qquad ..(2.17)$$

At a second site denoted by "'" a different k would pertain, thus

$$k' = (-Q_n' - G' - C') / (-Q_{no}' - G_o' - C_o') \qquad ..(2.18)$$

The application of coefficient theory to diverse sites is thus based upon the assumption that

$$k = k' \qquad ..(2.19)$$

The only way the assumption expressed by Eq. 2.19 could be true, would be for the ratio on the right hand sides of Eq. 2.17 and Eq. 2.18 to be equal. The individual terms on the right hand side of these equations are never equal. It is thus impossible for the *a priori* assumption, i.e., Eq. 2.19, ever strictly to be valid. This is so, because Eq. 2.10 is an implicit equation. Monteith (1981) showed that a small change in any one driving force will directly influence the other terms in a manner dictated by, to a large extent, the conditions prevailing in the top layer of the soil and by the type of vegetation.

It might be argued that soil heat flux terms are so small that they have negligible effect. But, to expect the Q_n and C terms to vary compensatorily from hot to cold, damp to dry, or sunny to cloudy climates is illogical. In any event, the contrary can only be proven by interesting future research.

For certain practical applications to crop situations, where reasonably large inaccuracies can perhaps be accommodated, the statement $k_c = k_c'$ has been tolerated.

In summary then, the crop coefficient concept represents, at best, but a poor approximative method containing inherent errors. Doorenbos and Kassam (1979) state that the magnitude of such errors varies between 10% and 20%. For example, Meyer and Green (1981) reported for the identical site, wheat growth stage and cultivation practices, mean k_c values of 1,29 and 1,11 for 1978 and 1979 respectively. They explained this 16% difference as being due to advection and a lower plant population. The former supports the argument that crop coefficients are climate dependent. The latter however, should not have been a significant factor at the high planting densities used. Measured daily deviations from mean k_c can exceed 40% (see Meyer *et al.* 1979). Van Zyl, De Jager and Van Rooyen (1981) found daily variations of up to 80% in k_{pan} calculated from measured pan evaporation and wheat crop evaporation computed using the Penman-Monteith equation.

Wright (1981) stated that the errors incurred when applying the crop evaporation coefficient concept, are due to lack of attention to detail in the methods used when deriving k_c. He stipulated that the same method of estimating E_o should be used as had been used to determine k_c originally. And, that the time scale should be similar. Careful adherence to mentioned procedures and precautions could perhaps limit errors to a level acceptable for practical purposes, say 10% (Wright, 1981).

Although they found high correlation coefficients between E_o and E_{pan} at a given site, Pruitt and Doorenbos (1977) conclusively demonstrated that k_{pan} varied by 143% with changing climate and pan exposure. Hence estimates of potential evaporation from short vegetation with injudicious choice of k_{pan} reflect discrepancies of this magnitude. It is conceivable that even larger inaccuracies will occur when pan values are incorrectly applied to obtain estimates of E_p for tall crops.

THE DRYING SOIL SURFACE PROBLEM

The problem of a partially wet surface was addressed amongst others by Bouchet and Robelin (1969), De Jager *et al.* (1981) and Wright (1981). Model solutions by the first authors involved E_m, maximum, and in the latter two papers E_v, the basal evaporation. To be viable, evaporation coefficient theory must adequately account for soil wetness situations occurring between these two special cases (see De Jager *et al.*, 1981 and Wright, 1981). Burgers (1982) and Doorenbos and Kassam (1977) tried to solve the problem by approximating average soil surface wetness.

It is therefore evident that crop coefficients require to be modified in such manner as to accommodate partially wet soil surface situation.

This is achieved starting from Eq. (2.1), viz.

$$E = E_v + E_s \qquad ..(2.1)$$

Applying evaporation coefficient theory to the individual terms on the right hand side, we may write

$$E_v = k_v E_o \qquad ..(2.20)$$

and

$$E_s = k_s E_o \qquad ..(2.21)$$

Where, k_v and k_s are evaporation coefficients defined as fraction of reference evaporation supplied by plant evaporation and soil evaporation respectively.

Individual evaporation coefficients may be expressed in terms of the normalized crop factors F_h, F_l and F_g of De Jager *et al.* (1981) and incorporating the concepts k_{vm} and k_{vs}, which are defined as

$$k_{vm} = E_{vm}/E_o \qquad ..(2.22)$$

$$k_{sm} = E_{sm}/E_o \qquad ..(2.23)$$

Here, E_{vm} and E_{sm} represent upper limit plant and upper limit soil evaporation rates respectively for the current growth stage.

Now, by definition,

$$k_v = k_{vm} F_l F_h \qquad ..(2.24)$$

$$k_s = k_{sm} F_g(1 - F_l) \qquad ..(2.25)$$

For these equations the following boundary conditions apply:

$0 \leq F_h \leq 1$ $\quad$ $0 \leq F_l \leq 1$ $\quad$ $0 \leq F_g \leq 1$

and $\quad 0 \leq k_s \leq k_{sm}$

$0 \leq k_v \leq k_{vm}$

The physiological factor, F_h, reflects limitation on plant evaporation due to plant water stress. It represents the ratio of actual to possible plant evaporation rate for a natural vegetative surface. De Jager *et al.* (1981) expressed F_h as the ratio of actual conductance of the vegetation surface to water vapour diffusion, ϕ_v, to its maximum value, ϕ_{vo}. F_l is a normalized factor reflecting the degree of foliage cover. It is a function of leaf area index, LAI.

Furthermore, F_g is the fraction of E_{sm} permitted by soil surface wetness status.

Several expressions for F_l and F_g appear in the literature (Ritchie, 1972; Monteith, 1981; Wright, 1981; De Jager *et al.*, 1981; Hanks and Hill, 1980 and Campbell and Diaz, 1989).

Substituting Eq. 2.20 and Eq. 2.21 into Eq. 2.1 yields

$$E = [k_v + k_s]E_o \qquad ..(2.26)$$

From which the crop evaporation coefficient, k_c, may be defined as follows

$$E = k_c \ E_o \qquad ..(2.27)$$

where

$$k_c = k_v + k_s \qquad ..(2.28)$$

Substitution of Eq. 2.24 and 2.25 produces

$$k_c = k_{vm} \ F_l \ F_h + k_{sm} \ F_g(1-F_l) \qquad ..(2.29)$$

When maximum total evaporation is under consideration $F_h = F_g = 1$ and thus Eq. 2.15 becomes

$$E_m = [k_{vm} \ F_l + k_{sm}(1-F_l)]E_o \qquad ..(2.30)$$

For the basal evaporation case, $F_h = 1$ and $F_g = 0$, and Eq. 2.14 becomes

$$E_{vm} = k_{vm} \ F_l \ E_o \qquad ..(2.31)$$

It is therefore evident that a completely general evaporation coefficient concept can be described only by using two defining equations, viz.

$$E = k_c E_o \qquad ..(2.32)$$

and either $$k_c = k_v + k_s \qquad ..(2.33)$$

or $$k_c = k_{vm} F_l F_h + k_{sm} F_g(1-F_l) \qquad ..(2.34)$$

Maximum values of k_v and k_s exist. These, denoted k_{vm} and k_{sm} respectively, depend upon crop architecture and soil character. They are empirically determined.

For the special case where the root zone is at field capacity; upper limit plant evaporation rate is maintained (i.e. $F_h = 1$) irrespective of soil evaporation rate. This situation we will soon be defined as atmospheric evaporative demand (AED). Then,

$$k_c = k_{vm} F_l + k_{sm} F_g(1-F_l) \qquad ..(2.35)$$

Here, the value of k_c will vary between a minimum when $F_g = 0$ and k_v takes its prevailing value and a maximum value given by Eq. 2.35 with $F_g = 1$ and $k_v = k_{vm}$ i.e. maximum total evaporation E_m (see Eq. 2.30). Thus

$$k_{vm} F_l \leq k_c \leq k_{vm} F_l + k_{sm} (1-F_l) \qquad ..(2.36)$$

For interest, pan evaporation $F_g = 1$ and $F_l = 0$ and $k_c = k_s = k_{pan}$. Here, k_{pan} is an empirical parameter varying with climate and pan exposure.

It is thus evident that the major problems encountered with use of the crop coefficient concept stem from failure to account for variation in k_c due to variation in k_s as soil surfaces dry. In a later section, suggestions on how to overcome this problem in practice will be offered. For the present, suffice it to report that experimental relationships have been determined for this purpose, viz

$k_c = k_m$ = f(crop growth stage, i.e. time) - this is a poor approximation (see Doorenbos and Pruitt, 1977), or

$k_c = k_c$ = f(crop growth stage) - a poor assumption because k_c is dependent upon irrigation frequency and irrigation system.

k_v = f(Leaf Area Index) - for k_{vm} assumed unity (see Ritchie, 1972 and De Jager *et al.*, 1987) and

k_s = f(time since latest wetting event) (see Hanks and Hill, 1980 and De Jager *et al.*, 1981) (for both k_{sm} was assumed unity), (Wright, 1981 and Monteith, 1981), or

k_s = f(water deficit below field capacity in the top soil layer) - for k_{sm} assumed unity (see De Jager *et al.*, 1987).

It is here emphasized that it is imperative to make use of functions such as these for k_v and k_s when evaluating k_c. Little information regarding k_{vm} and k_{sm} is available in the literature.

THE CONCEPT ATMOSPHERIC EVAPORATIVE DEMAND

In summary therefore it may be stated that, in use at present, are at least four conceptualizations of upper limit evaporation rate from natural surfaces, viz. E_o, E_p, E_m and E_{vm}. Each of these relates to only a special case of the upper limit of water loss rate from a natural surface.

Furthermore, in strict scientific terms, the basic assumption upon which crop and pan coefficient concepts are based, is invalid. Their practical application too, is fraught with restrictive precautions and procedural requirements.

Shortcomings in the conceptualization of both upper limit evaporation rate and evaporation coefficient lead to confusion, errors and anomalies. Many of these problems could be removed by a new definition and conceptualization of this upper limit.

The term atmospheric evaporative demand has been used in numerous scientific articles. Yet, no where has it been adequately defined. Because of its overpowering influence on microclimate, and particularly water use by crops, the concept most certainly deserves rigid formulation. From the previous discussion too, it has become apparent that a general definition, applicable at all times, when roots provide adequate water for unhindered plant evaporation is required.

It is evident from Eq. 2.8 that atmospheric evaporative demand is primarily the resultant of atmospheric driving forces acting upon a natural surface. The major emphasis in name therefore deserves to be the atmosphere. As explained, however, it must also be defined in terms of the surface with which the atmospheric elements interact.

To meet all these requirements, it is here proposed that the upper limit of the atmospheric demand for water from a natural surface be named *atmospheric evaporative demand*, AED, and, that it be defined as *the water vapour transfer to the atmosphere required to sustain the energy balance of a given vegetative surface (crop), in its present growth stage, when the water status of its root zone permits unhindered plant evaporation and the water status of the top 150mm of soil equals its current value.*

Mathematically this definition entails replacing E by AED in Eq. 2.26 and using Eq. 2.35 to evaluate k_c.

It is important to note that this definition

(i) acknowledges the dominant influence of atmospheric conditions, but

(ii) basically accounts for crop type, crop growth stage and soil surface water content.

Major differences between this definition of AED and present day definitions E_o, E_p, E_m and E_{vm} are appearance of "*sustain* the energy balance of a *given* vegetative surface in its present growth stage" and "water status of the top 150 mm of soil equals its *current value*". These ensure temporal and crop specificity required under (ii). Their inclusion means, however, that this definition of AED is completely general and applicable in all possible situations. It furthermore covers all the special cases epitomized by E_o, E_m, E_p and E_{vm}. Its main advantage lies in precise quantification of true water requirement of irrigated crops in given climates.

Hopefully, this definition of AED and the streamlined, scientifically rigorous proposed terminology will simplify understanding the processes, regularize the reporting of results and facilitate the exchange of ideas on evaporation from natural surfaces.

DETERMINATION OF AED

For practical irrigation scheduling and hydrological and crop growth modeling AED has special significance. It represents true water consumption by a cropped surface which has not experienced yield losses due to water deficiency.

The problem arises of how to evaluate AED accurately. In practice, three methods of determining AED pertain, viz.

- direct measurement of AED using a lysimeter. This has been the subject of many studies (Pruitt and Angus, 1960; King, Tanner and Suomi, 1956; Ritchie and Burnett, 1968; Pruitt and Lourence, 1985 and Rosenberg *et al.*, 1983). The technique is well perfected, but extremely expensive. No further discussion thereof is warranted here;

- indirect measurements using evaporimeters, and

- estimation, or calculation, of special case AED called E_o and multiplication thereof by an appropriate crop coefficient. Thus,

$$AED = k_c \; E_o \qquad ..(2.37)$$

The latter method will now be discussed.

De Jager (1984) suggested that the Penman-Monteith equation (Eq. 1.5) provides the best method of determining both E_p, potential evaporation and E_o, reference evaporation. This equation however requires an estimate of crop surface conductance. Slabbers (1977), Feddes (1971) Allen (1986), Van Zyl and De Jager (1987a) and De Jager *et al.* (1987) have demonstrated the accuracy of using this equation with hourly mean values of relevant weather variables. The latter experiments were conducted on wheat with $3 < LAI < 8$. A surface conductance equal to 0,03 m s^{-1} (Russell, 1980) was assumed and in some cases crop height was varied according to age. Allen (1986) also obtained accurate daily estimates of reference total evaporation, E_o, using Eq. 1.5. They found values of ϕ_v varying between 0,013 m s^{-1} and 0,03 m s^{-1} provided the most accurate results. In both USA and South

Africa, automatic weather station observations produced reliable estimates of E_o.

It warrants emphasizing that the Penman-Monteith method is absolutely fundamental and not subject to the errors due to empirical approximations found in the Penman method (1948).

The objective of Penman (1948) was to develop a theoretical equation with which routine daily meteorological data could be used to estimate weekly, or longer, open water evaporation. Of necessity, this equation contains certain empirical relationships which make it climate and site specific. Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979) describe empirical adjustments to the Penman equation which correct it for climate influence. The Penman estimate was multiplied by the factor 'c' which adjusted it for the ratio of day to nighttime wind, relative humidity, solar radiation and windspeed. Application of the Penman equation in different climates without these corrections is dangerous. Pruitt and Doorenbos (1977) showed that interaction between input variables and climate can produce 20% underpredictions and overpredictions exceeding 300% in Penman estimates of reference evaporation. For example, an error of 470% would result if the value of c = 0,27 which is relevant to a climate with mean daily windspeed of 9 m s^{-1}; a ratio of day to night wind of 1,0; radiation equivalent to 3 mm d^{-1}; mean daily temperature of 20^{o}C and mean maximum vapour pressure of 0,7 kPa were used in a climate where the corresponding values of these variables are 6 m s^{-1}; 4,0; 12 mm d^{-1}, 20^{o}C and 2,1 kPa respectively.

Application of the factor "c" effectively compensates for changes in the magnitude of the various empirical constants employed in the Penman equation when used in differing climates. Essentially, these adjustments compensate for altered mean energy balance under different climates. Use of the Penman equation for estimating E_o is therefore subject to errors, inconvenience and certain prerequisites.

A pan evaporation

For a given site, Pruitt and Doorenbos (1977) report high correlation between reference and pan evaporation. However, evaporation pans can only reliably be employed with knowledge of daily windrun, relative humidity and fetch (Doorenbos and Kassam, 1979). Climatic variables are seldom recorded together with A pan readings. The pan factor, k_{pan}, is highly sensitive to these variables which can cause up to 143% variation in k_{pan} (0,35 to 0,85). This range could be limited to 0,45 to 0,8 by ensuring say a short grass fetch of at least 10 m in all directions. Failure to document pan exposure at the time of observation will require a subjective choice of k_{pan} when these measurements are applied at a future date. Hence, use of Eq. 2.2 under such circumstances cannot be recommended at this stage. Application of pan factors without the corrections suggested by Doorenbos and Kassam (1979) would result in large errors. Furthermore, since relative humidity and windrun are required in any event to correct the pan estimates, the fundamentally sound Penman-Monteith, or even Penman, equation might just as well be used. Use of A pan for estimating E_o is therefore problematical.

Determining the crop coefficients

The use of crop coefficients to estimate AED is based upon the incorrect assumption that evaporation coefficients are independent of climatic conditions. This is not so. Determining crop coefficients in different climate conditions will change values of terms in either, or both, numerator and denominator of Eq. 2.15. Climatic independence presupposes such change in one will be exactly compensated for by change in the other terms thereby ensuring that k = k' in the new climate situation. This will occur fortuitously on only the rarest occasions.

From Eq. 2.10 and Eq. 2.27 atmospheric evaporative demand may be calculated using

$$AED = k_c \ E_o \qquad ..(2.38)$$

The value of k_c adopted must pertain to the current crop growth stage and soil surface wetness. The values of k_{sm}, k_{vm}, F_l and F_g used in Eq. 2.35 must be determined for the relevant crop and cultivation practices. For example, this was achieved by De Jager *et al.* (1987), for irrigated wheat with the expressions:

$$F_g = EXP[0,03(V_m-V)] \qquad ..(2.39)$$

$$F_l = 0,186 \ LAI \qquad ..(2.40)$$

where, V_m and V denote volumetric water content (mm m^{-1}) in the top 150 mm of soil at field capacity and the current value respectively.

Eq. 2.38, Eq. 2.39 and Eq. 2.40 are subject to the same criticisms of evaporation coefficients mentioned earlier regarding sensitivity to changed climate. Application of the coefficient concept in the manner here suggested will, however, minimize errors.

When determining the coefficients k_v and k_s, the precautions suggested by Wright (1981) should always be adhered to, viz.

(i) the same method of estimating E_o as had been used to determine k_v or k_s originally must be used when applying the coefficients in practice,

(ii) where possible, the coefficients should be experimentally determined for the climates in which they are to be applied, and

(iii) the determinations should be carried out using daily, or shorter, measurements.

The relationship between the various crop coefficients and climate deserves to be researched. Quantification of the dependence of evaporation coefficients upon say net irradiance, soil temperature profile, soil heat flux density and atmospheric vapour pressure and temperature will minimize errors incurred when applying crop coefficient theory. This is particularly true of the response in the ratio E_p/E_o to change in climate. There is no evidence supporting the present contention that this ratio is independent of climate.

SUMMARY

Four different definitions of upper limit of evaporation rate from vegetation in use at present were described and analysed. Their fundamental differences were outlined. It was furthermore shown that the basic tenet of evaporation coefficient theory is invalid.

A new definition of upper limit evaporation is proposed. This new concept is termed atmospheric evaporative demand. It applies to any cultivation practice, crop and growth stage. It is therefore completely general in contrast to present definitions which apply only to special cases of upper limit evaporation. It accords atmospheric influences their rightful emphasis and minimizes the errors inherent in the evaporation coefficient concept.

It was shown that it is incorrect to utilize a single crop coefficient. Two coefficients are required, viz k_s, reflecting soil surface drying and k_v accounting for the degree of vegetative cover and the ratio of maximum plant evaporation from the crop in question to reference evaporation.

Directions for how correctly to apply these new concepts and what precautions are necessary when determining evaporation coefficients were given.

Indications of avenues of interesting future research were outlined.

CHAPTER 3

ACCURACY OF PENMAN-MONTEITH EQUATION FOR ESTIMATING REFERENCE EVAPORATION

INTRODUCTION

In this study, accurate determination of reference surface evaporation E_o is required.

The objective in Chapter 3 is thus to demonstrate the accuracy of the Penman-Monteith equation for reliably estimating reference crop evaporation, E_o.

Atmospheric stability

The influence of atmospheric stability upon the Penman-Monteith equation when estimating maximum evapotranspiration from a whole wheat crop was investigated by Van Zyl and De Jager (1987a). A stability function based upon the Richardson number was used (see Chapter 1). It was measured over a short green grass surface and over wheat.

Lysimetric observations of evapotranspiration were compared with estimated maximum evapotranspiration found using

(i) the Penman-Monteith equation unadjusted for atmospheric stability;

(ii) the same equation, but adjusted for atmospheric stability as measured over the grass; and

(iii) the same equation adjusted for atmospheric stability as measured over wheat.

The comparisons under (i) yielded an index of agreement, correlation coefficient, slope intercept and a mean absolute difference of 0,97, 0,91, 0,97, 0,05 mm h^{-1} and 0,09 mm h^{-1}, respectively. The corresponding coefficients for comparisons (ii) and (iii) were 0,94, 0,89, 0,88, 0,11 and 0,10 mm h^{-1} and 0,94, 0,88, 0,90, 0,07 mm h^{-1} and 0,10 mm h^{-1}, respectively.

These results substantiated the accuracy of the Penman-Monteith equation for estimating maximum evapotranspiration. It could thus be expected to provide accurate simulation of E_o. Furthermore, accuracy of estimate was not improved by adjusting the Penman-Monteith equation for atmospheric stability. This was so, irrespective of whether stability measurements were conducted over either grass or the wheat.

MATERIALS AND METHODS

The Penman-Monteith equation, Eq. 1.5 (Thom, 1975),with assumed surface conductances of either ϕ_v = 0,04 m s^{-1} or ϕ_v = 0,08 m s^{-1} (see Chapter 8) was used to simulate reference evaporation, E_o. One hundred hourly micrometeorological observations were collected at the experimental site on West Campus (described in Chapter 1) for this purpose. Simultaneously E_0 was measured in the grass lysimeter (Fig. 3.1). Measured and calculated E_0 were compared using index of agreement (Willmott, 1982) and normal statistical tests. Results are reported in Table 3.1 and Fig. 3.2.

Micrometeorological measurements included

- net radiation 1,5 m above grass surface,
- soil heat flux density 0,01 m beneath soil surface under short grass,
- windspeed at 0,5; 1,5 and 2,0 m above short grass, and
- dry and wet bulb temperature at 0,5; 1,5 and 2,0 m above short grass.

Micrometeorological instrumentation used in this study is fully described by Maree (1989).

The container of the weighing grass lysimeter used to measure E_0 was constructed from galvanized iron, circular in shape. The container, with an area and depth of 5 m^2 and 0,6 m respectively, was installed on a stainless steel platform scale, with a total capacity of 6000 kg. The scale was equipped with four load cells, each having a capacity of 1500 kg. A digital indicator registered mass changes.

The resolution and accuracy of the system was 0,04 mm and ±0,016 mm respectively (Maree, 1989).

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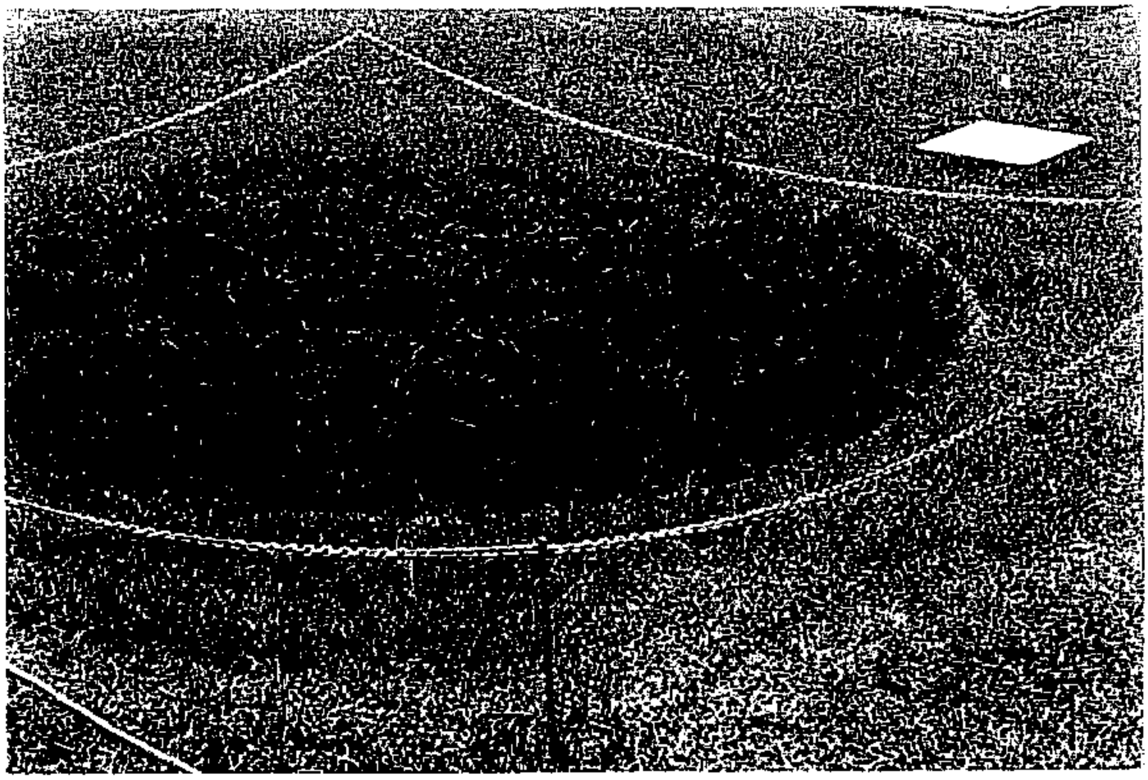

FIG. 3.1 - The grass lysimeter installed centrally on the grass site. The photo was taken prior to commencement of observations. During the measurement period however, the area surrounding the lysimeter was completely covered with grass with height equal to the height of the grass in the lysimeter.

TABLE 3.1 - Results of statistical tests carried out between E_o measured and E_o calculated during 1987. Canopy surface conductances utilized were ϕ_s = 0,08 m s^{-1} and ϕ_s = 0,04 m s^{-1}. Windspeed was measured at 0,5; 1,5 and 2 m.

STATISTICAL TEST PARAMETERS	PARAMETER VALUES				
	HOURLY				DAILY
	z = 0,5m ϕ_v = 0,04m s^{-1}	z = 0,5m ϕ_v = 0,08m s^{-1}	z = 1,5m ϕ_v = 0,08m s^{-1}	z = 2m ϕ_v = 0,08m s^{-1}	z = 0,5m ϕ_v = 0,08m s^{-1}
Slope	0,83	1,01	0,93	0,92	0,88
Intercept	0,01 mm h^{-1}	0,01 mm h^{-1}	0,03 mm h^{-1}	0,03 mm h^{-1}	0,49 mm d^{-1}
Correlation coefficient	0,93	0,93	0,93	0,94	0,95
Index of Agreement	0,92	0,96	0,96	0,97	0,97
Mean difference	0,06 mm h^{-1}	0,01 mm h^{-1}	0,01 mm h^{-1}	0,01 mm h^{-1}	0,09 mm d^{-1}
Mean absolute difference	0,08 mm h^{-1}	0,06 mm h^{-1}	0,05 mm h^{-1}	0,05 mm h^{-1}	0,42 mm d^{-1}
X-axis: Mean measured E_o	0,48 mm h^{-1}	0,48 mm h^{-1}	0,48 mm h^{-1}	0,48 mm h^{-1}	4,53 mm d^{-1}
Y-axis: Mean estimated E_o	0,41 mm h^{-1}	0,49 mm h^{-1}	0,47 mm h^{-1}	0,47 mm h^{-1}	4,62 mm d^{-1}

* Daily values of E_o measured and calculated were obtained from integrating hourly values.

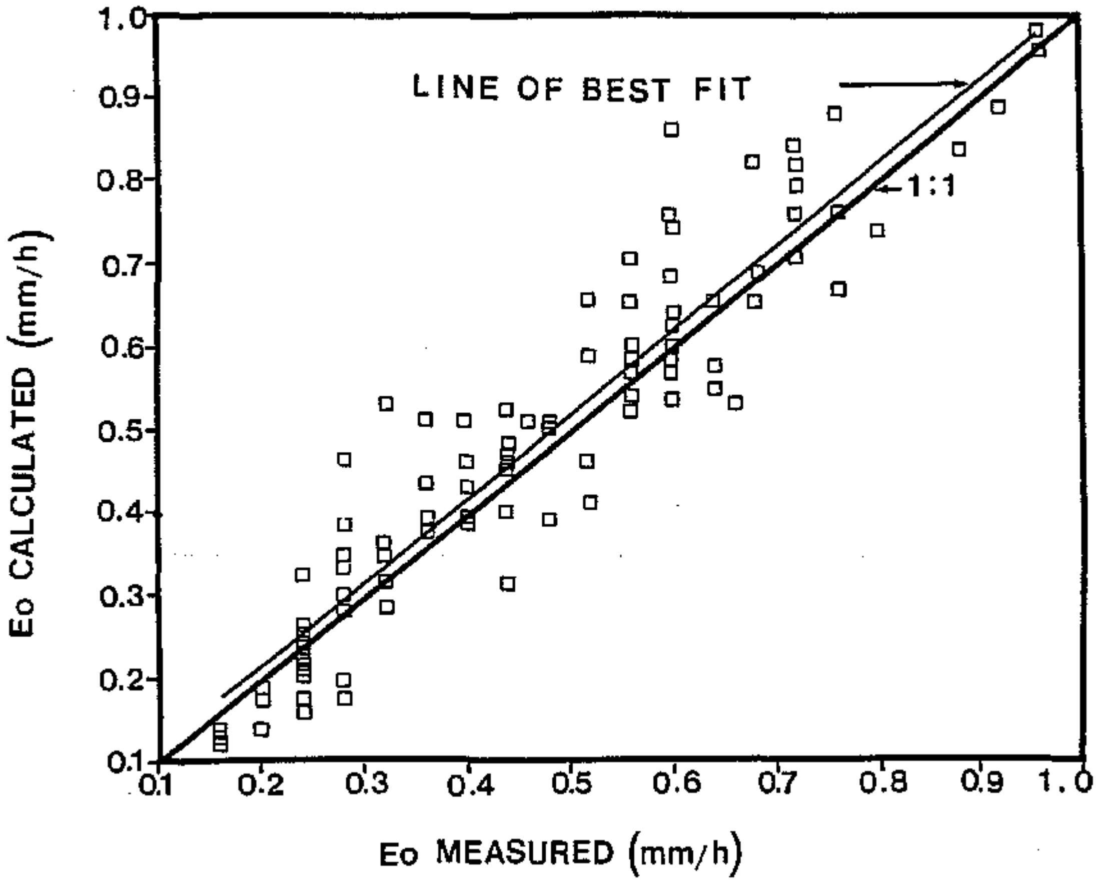

FIG. 3.2 - Comparison between Penman-Monteith estimates of E_o and E_o measured in a lysimeter for ϕ_v = 0,08 m s^{-1} and z = 0,5 m.

RESULTS AND DISCUSSION

The good comparison between E_o measured and E_o calculated, for both hourly and daily observations with ϕ_v = 0,08 m s^{-1} is indicated in Table 3.1 and Fig. 3.2, The good relationship implies that the windspeed measured at a height of 0,5 m, was within the internal boundary layer of the reference crop. This result corresponds with the work of Allen (1986). He utilized the Penman-Monteith equation (Thom, 1975) to calculate daily evaporation from a reference crop. A constant ϕ_v was used, while the windspeed was measured at height 3,7 m. Seasonal correspondence between evaporation, measured and calculated, was good. They reported a slope and correlation coefficient of 0,98 and 0,86 respectively.

Results (Table 3.1) indicated a weaker relationship between E_o measured and E_o estimated for ϕ_v = 0,04 m s^{-1} and windspeed measured at 0,5 m.

Windspeed measured at three different heights, i.e. 0,5; 1,5 and 2,0 m for ϕ_v = 0,08 m s^{-1} virtually did not affect the relationship between E_o measured and E_o estimated. This suggests that windspeed measured at 2 m height was also within the internal boundary layer of the reference crop.

CONCLUSION

Penman-Monteith equation (Thom, 1975) and micrometeorological measurements provided accurate estimates of reference crop evaporation.

CHAPTER 4

ESTIMATION OF CROP EVAPORATION USING CLASS A PAN MEASUREMENTS

INTRODUCTION

Practical irrigation scheduling requires daily estimates of total water consumption by crops. The ratios reference evaporation to pan evaporation, k_{pan}, and atmospheric evaporative demand, AED, to reference evaporation, k_c, are at present utilized to estimate the upper limit of water use, by the crop.

Use of pan measurements and k_{pan} however produce unreliable estimates of AED. This is mainly attributable to the large variations in k_{pan} values. These variations are fully discussed in Chapters 1 and 2.

The objective in Chapter 4 was to verify previously reported methods.

Comparisons conducted were:

- AED measured versus A-pan measurements over 24 hour periods i.e. from 08h00 to 08h00 on consecutive days.
- E_o measured versus A pan measured simultaneously.

MATERIALS AND METHODS

Thirty-eight daily (08h00 to 08h00) data sets of measured AED and measured E_{pan} were obtained during spring of 1985, 1986 and 1987 at a stage when leaf area index of the wheat crop was > 3. AED was measured with a wheat lysimeter (Fig. 4.1). The USWB A pan is shown in Fig. 4.2.

Furthermore, fifty-one daily data sets of measured E_o and E_{pan} measurements were obtained during the wheat growing season of 1987 and 1988.

Measured AED was compared with A pan measured using statistical analyses and index of agreement (Willmott, 1982). Measured E_o and A pan measured were similarly compared.

RESULTS AND DISCUSSION

Relationship between measured AED and measured E_{pan}

Wide scatter between measured AED and measured A pan is illustrated in Fig 4.3. This is also reflected in results reported in Table 4.1. The slope through the origin was 1,03. This value represents the so called pan factor, k_{pan}.

Although a relatively high index of agreement (Willmott, 1982) was obtained, mean absolute difference was high at 1,03 mm d^{-1}, which is equivalent to 7 mm over a 7 day interval. These results were obtained from combining 1985, 1986 and 1987 measurements for a specific site. The surface area surrounding the A pan were the same for all three seasons.

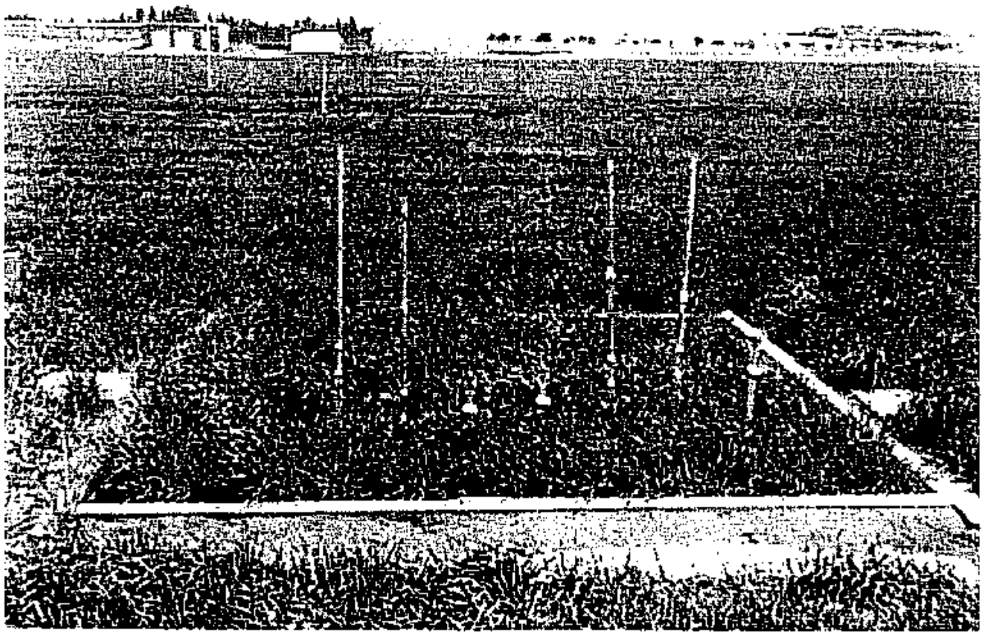

FIG. 4.1 - Wheat lysimeter installed centrally in the 4 ha wheat plot.

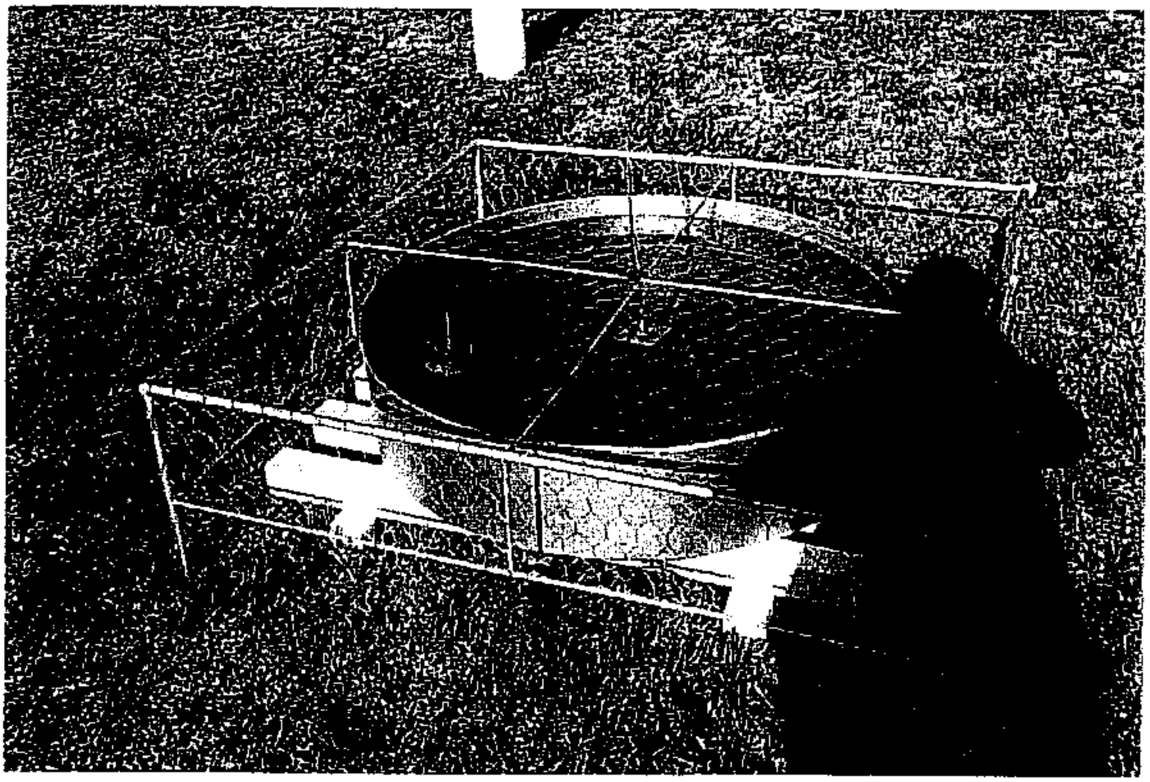

FIG. 4.2 - USWB A pan installed on the 0,5 ha a grass site adjacent to the wheat plot.

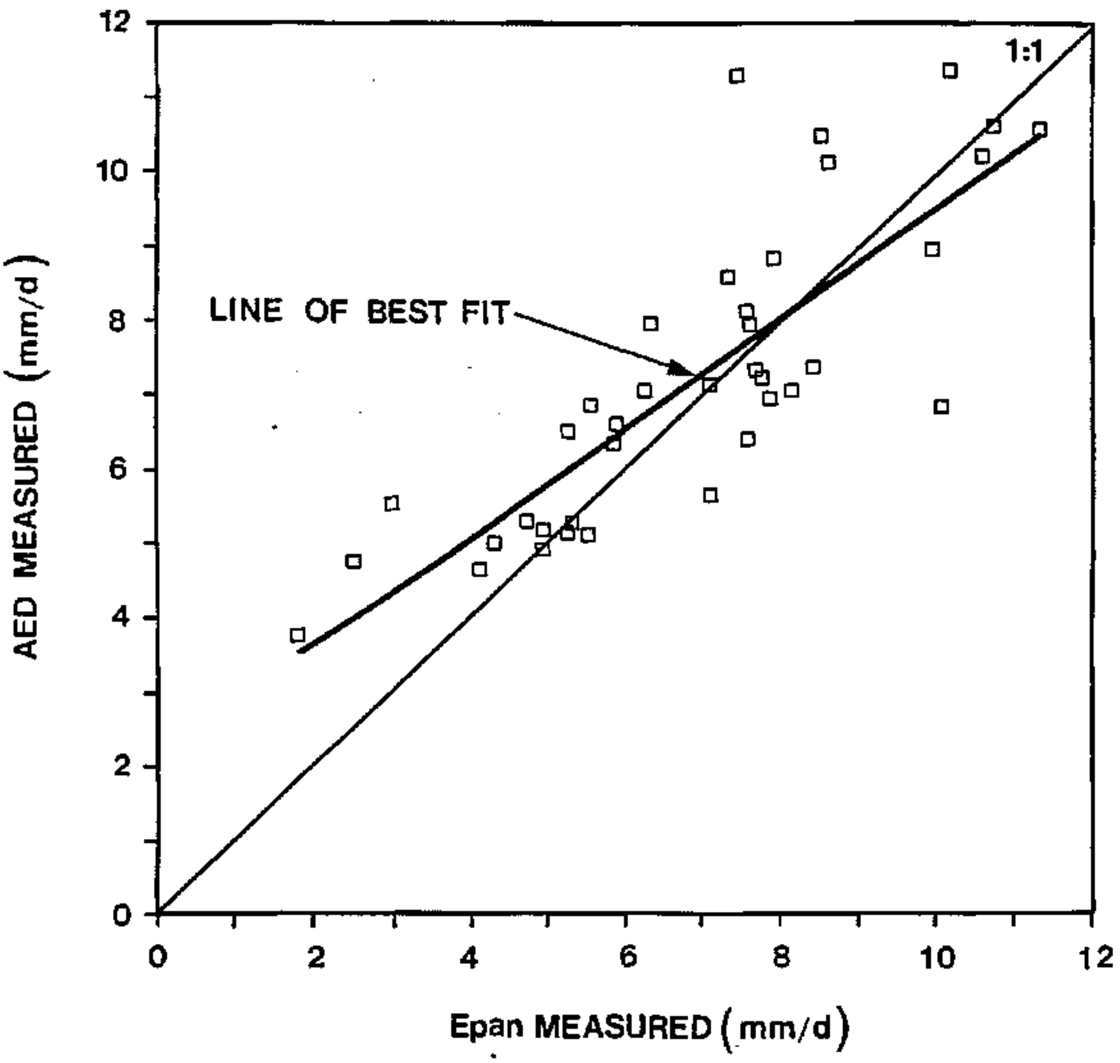

FIG. 4.3 - Comparison between measured AED and measured E_{pan}. Data sets of 1985, 1986 and 1987 were used. The LAI was >3.

TABLE 4.1 - Results of statistical tests comparing AED measured in the wheat lysimeter during 1985, 1986 and 1987 with measured pan evaporation.

STATISTICAL TEST PARAMETER	PARAMETER VALUE
n	38
Slope	0,75
Slope through origin	1,03
Intercept	2,13 mm d^{-1}
Correlation coefficient	0,83
Index of Agreement	0,89
Mean difference	0,91 mm d^{-1}
Mean of the absolute difference	1,03 mm d^{-1}
X-axis: Mean measured E_{pan}	6,84 mm d^{-1}
Y-axis: Mean measured AED	7,25 mm d^{-1}

From cited literature (see Chapters 1 and 2) it is expected that these results would differ substantially for climatic zones and pan exposures differing from those of the present study.

<u>Relationship between measured Eo and measured A pan</u>

Fig 4.4 and Table 4.2 compare E_o measured with E_{pan} measurements. Data sets of 1987 and 1988 were used. Once again wide scatter is evident. Pan measurements over estimate reference evaporation by 1,30 mm d^{-1} . The slope through the origin, representing k_{pan} (E_o/E_{pan}) is 0,69.

CONCLUSIONS

A comparison between AED measured in a wheat lysimeter and measured evaporation from A pan, for a LAI >3 yielded an index of agreement (Willmott, 1982) of 0,89 and mean absolute difference of 1,03 mm d^{-1}. These figures are significantly poorer when compare to Piché estimates (see Chapter 7) of AED. Preference should therefore be given to the latter technique, especially when AED is needed for experimental purposes.

The pan factor, k_{pan} , obtained from the ratio of measured E_o to E_{pan} measurements was 0,69 ±0,08. A pan measurements over estimate E_o by 1,30 mm d^{-1}.

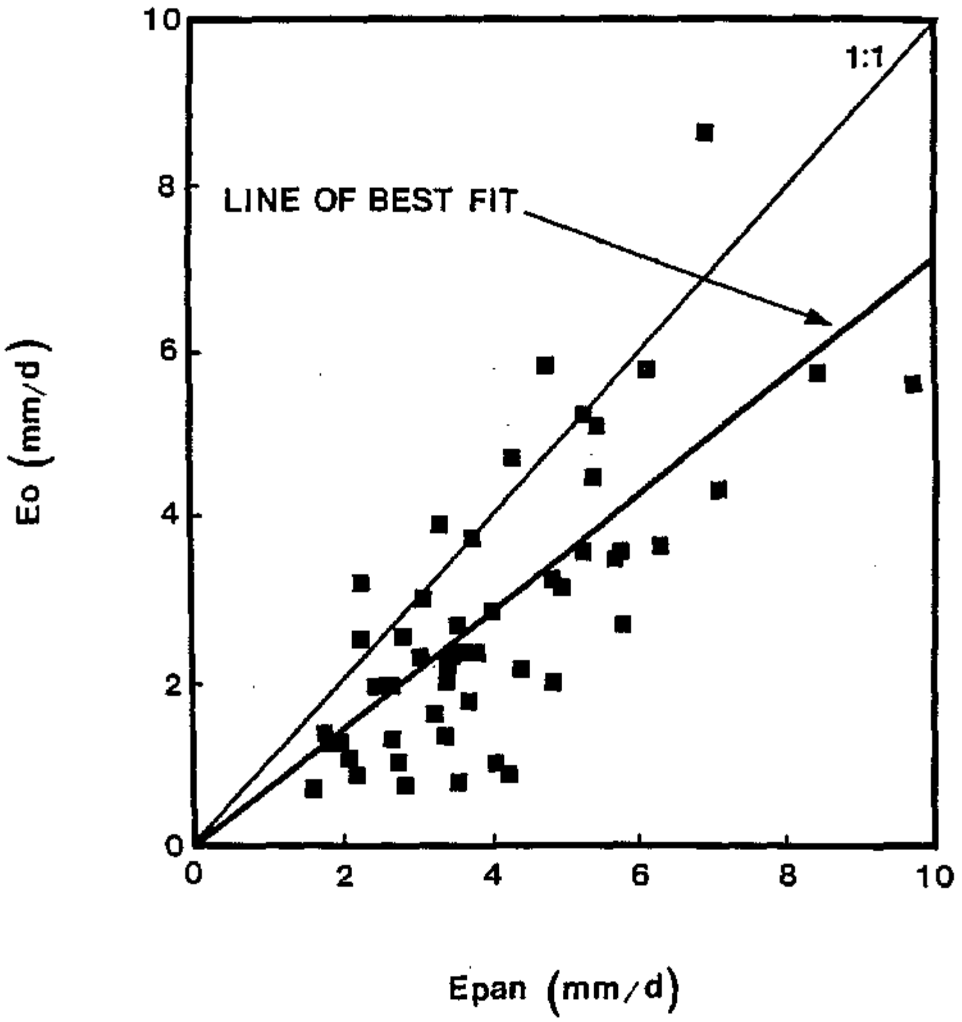

FIG. 4.4 - Comparison between measured E_{pan} and measured E_o. Data sets of 1987 and 1988 were used.

TABLE 4.2 - Results of statistical tests comparing daily measured reference evaporation, E_o, with E_{pan} measurements during 1987 and 1988.

STATISTICAL TEST PARAMETERS	PARAMETER VALUE
n	51
Slope	0,72
Slope through origin	0,69
Intercept	-0,17 mm d^{-1}
Correlation coefficient	0,74
Index of Agreement	0,74
Mean difference	1,30 mm d^{-1}
Mean of the absolute difference	1,49 mm d^{-1}
X-axis: mean measured A pan	4,09 mm d^{-1}
Y-axis: mean measured E_o	2,79 mm d^{-1}

It is believed that the latter comparison can be improved by applying appropriate correction factors to E_{pan}. This will be discussed in Chapter 5.

CHAPTER 5

RELATIONSHIP BETWEEN DAYLIGHT EVAPORATION FROM SHORT VEGETATION AND A PAN

INTRODUCTION

Measurements of evaporation from short vegetation, E_o, have become important and useful in irrigation scheduling. This is so, because of its approximately constant relationship to atmospheric evaporative demand, AED. Doorenbos and Kassam (1979) have used this to advantage. In addition Maree (1989) found AED = 1,10 E_o for wheat in Bloemfontein during 1987. One hundred hourly measurements of AED and E_o using appropriate lysimeters were analysed. An accurate method estimating E_o from A pan measurements would therefore represent an important advance in practical irrigation scheduling. Chapter 2 however, described errors inherent in pan factors. The overall objective of Chapter 5 will therefore be to develop factors whereby A pan measurements may be transformed to yield accurate estimates of E_o. In order to do this the mechanism of water evaporation from the A pan will have to be carefully analysed and methodically modelled.

It has been shown that use of A pan to estimate AED induces marked errors, particularly on a daily basis (Thom, Thony and Vauclin, 1981; Doorenbos and Pruitt, 1977; Shouse, Jury and Stolzy, 1980; Van Zyl, De Jager and Van Rooyen, 1981; Howell, Phene and Meek, 1983 and Bosman, 1987). Similar inconsistencies may be expected when estimating E_o from A pan measurements. These anomalies are due to the failure to correctly account for:

a) influence of exposure upon A pan energy balance, and
b) effect of crop architecture upon crop evaporation, which effect is non-existent for A pan evaporation.

While much work has been done on the mechanism of evaporation from crops (Slabbers, 1977; Hatfield, Reginato and Idso, 1984; Choudhury, Reginato and Idso, 1986; Van Zyl and De Jager, 1987), little is known of mechanisms of A pan evaporation and relationship to AED (Thom *et al.*, 1981, Van Zyl and De Jager, 1987a and Primault, 1985 and 1961).

It has therefore become imperative to completely understand the mechanism whereby water evaporates from the A pan and to use this knowledge to eliminate anomalies found when estimating E_o from A pan measurements (Primault, 1963).

Specific objectives of this study were to:

(i) Formulate the mechanism of evaporation during daytime from the A pan, protected within wire mesh.

(ii) Test the accuracy of a combination equation (Thom *et al.*, 1981) for calculating daylight E_{pan}.

(iii) Transform A pan measurements to provide accurate estimates of evaporation from short vegetation, E_o.

(iv) Compare transformed and untransformed E_{pan} measurements to E_o for daylight periods.

MATERIALS AND METHODS

Combination equation for calculating A pan evaporation

Evaporation losses over a 24-hour period from a A pan are explained by a Penman type formula by Thom *et al.* (1981) as follows:

$$E_{pan} = [(3600\ t\ /\lambda\ )(s(Qnp - Sp) + c^{*}\gamma fp(u)\ \delta e]\ /\ (s + c^{*}\gamma) \quad ..(5.1)$$

where 3600 s h^{-1} ensures coherence of units and c^{*} = 2,1 (see Chapter 1).

In Eq. 5.1 fp(u) is the windspeed function for a full day, i.e. a 24-hour period measured at 2 m.

The following expression was used to describe the thermal energy storage in the body of water viz:

$$S_p = (m\ .\ S_w\ /\ 3600\ .\ A)(\pm \Delta T/t) \quad ..(5.2)$$

where

m = the mass of the water contained in the A pan (= 230 kg)

ΔT = the change in water temperature between X and Y or Y, and Z (Fig. 5.1)

A = the cross sectional area of the A pan (1,13 m^2)

t = the appropriate period over which S_p was determined.

The factor 3600 s h^{-1} converts hours to seconds.

Total S_p for the daylight period was obtained by summing positive and negative values of S_p.

Convective aerodynamic heat transfer from the A pan, expressed by $f_p(u)$, involves both forced and free convection. It was therefore necessary to decide which form dominated for windspeeds and the temperature differences between water and air (T_s- T_a), occurring during this experiment. Given the relationship (Thom *et al.*, 1981) between $f_p(u)$ and windspeed measured at 2 m and that mean daylight windspeed never dropped below 1,2 m s^{-1} during this experiment, it was assumed that forced convection dominated.

The wind function for the daylight period, when forced convection prevailed, was derived from appropriate dimensionless parameters (Monteith, 1973) with a reference dimension of 1,21m (pan diameter). The wind function so obtained was

$$f_p(u) = a\ u^{0,8} \qquad ..(5.3)$$

According to Monteith (1973) parameter 0,8 is appropriate for Reynold's numbers $4x10^4 \leq Re \leq 4x10^5$. Empirical parame-

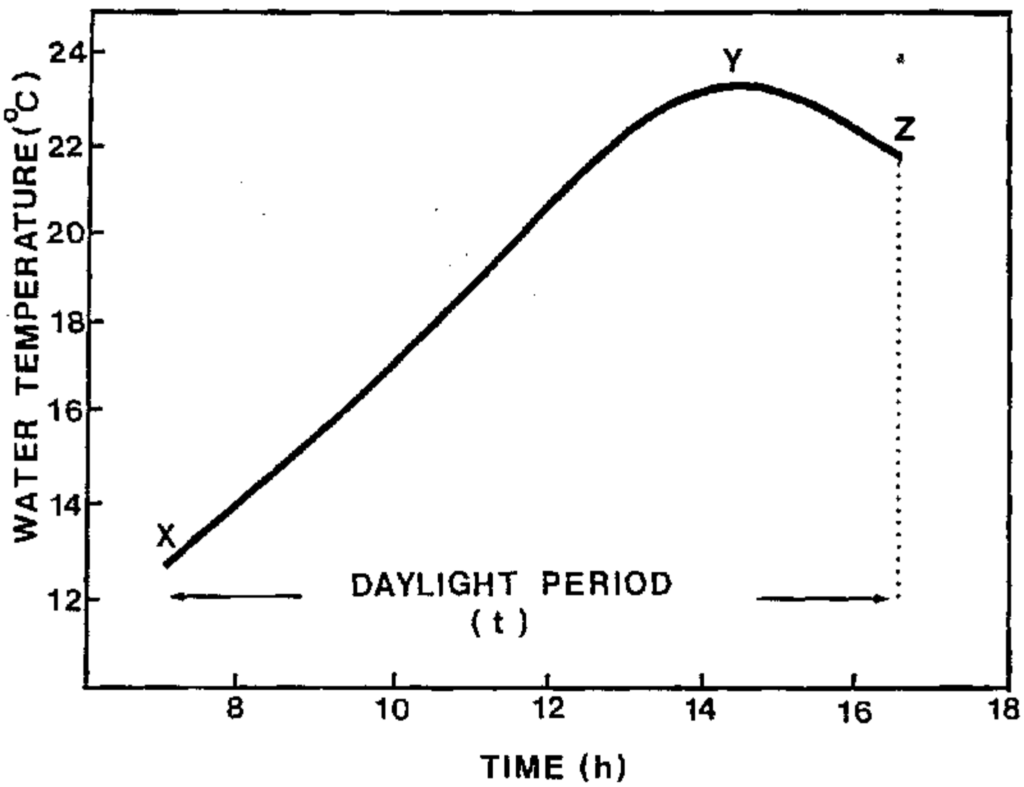

FIG. 5.1 - Diurnal variation of the water temperature at 150 mm in the water depth in the class A pan. This pattern is typical for the daylight period from mid-July through end October.

ter a was evaluated from twelve meteorological data sets using Eq. 5.1 in the form

$$a = \{E_{pan} + [3600t(Q_{np}-S_p)/(\lambda(s+c^*\gamma))\}\{(s+c^*\gamma)/c^*\gamma u^{0,8}\delta e\} \quad ..(5.4)$$

In Eq. 5.4, E_{pan} denotes measured values of daylight pan evaporation.

The aerodynamic effects of wire mesh enclosure upon evaporation are minimal (<3%) (Howell, *et al*, 1983). It was therefore decided to apply Eqs. 5.3 and 5.4, valid for an unscreened pan, in Eq. 5.1. Howell *et al.* (1983) found that the overall effect of such covers is to reduce evaporation by <10%. In this experiment net radiation was measured with the cover in position. This took any radiative effects into account.

Reference evaporation

According to Thom (1975), the combination equation for Eo may be written

$$E_o = 3600\ /\lambda[s(Q_n-G)/(s+\gamma^*) + \int C_p\phi_a\delta_e/(s+\gamma^*)] \quad ..(5.5)$$

or assuming $G \ll Q_n$ ($G = 0{,}002\ Q_n$ for full vegetative cover (Van Zyl and De Jager, unpublished results)

$$E_o = 3600/\lambda[sQ_n/(s+\gamma^*) + \int C_p\phi_a\delta_e/s+\gamma^*] \quad ..(5.6)$$

For a reference crop of height $h = 0,1m$, approximate values of z_o and d are given by

$z_o = 0,13\ h = 0,013m$ and
$d = 0,63\ h = 0,063m$ (Monteith, 1973)

Because $d \ll z$, Eq. 1.11 reduces to

$$\phi_a = k\ u(z)^2 / (\ln z/z_o)^2 \qquad ..(5.7)$$

Surface conductance, ϕ_v, is equal to 0,03 m s^{-1} (Russell, 1980).

<u>Relationship between E_{pan} and E_o</u>

The relationship between E_o and E_{pan} is expressed as

$$E_o = (E_{pan} + TF) \qquad ..(5.8)$$

In Eq. 5.8, E_{pan} represents measured values of A pan evaporation. Function, TF, compensates for anomalies between pan and crop evaporation described earlier. Since it basically transforms pan measurements equitable to E_o, it will henceforward be called the transformation function.

Eq. 5.1 can be resolved into the following components viz:

$$TF_1 = 3600t/\lambda\ [s\ Q_{np}/(s+c^*\gamma) + c^*\gamma a u^{0,8} \delta e/(s+c^*\gamma)] \qquad ..(5.9)$$

and

$$TF_2 = (3600t\ /\lambda)s\ S_p/(s+c^*\gamma) \qquad ..(5.10)$$

The transformation function TF in Eq. 5.8 can now be defined in terms of two functions TF_1, TF_2 and E_o, for a strictly complete transformation

$$E_o = TF_1 - TF2 + TF \qquad ..(5.11)$$

Simple, but partial transformation, which nonetheless has valuable practical application, may be obtained by assuming $TF_1 = E_o$. This is equivalent to equating Eq. 5.9 to Eq. 5.6 making the assumption

$$s\ Q_n/s+\gamma^*) = s\ Q_{np}/(s+c^*\gamma) \quad \text{and}$$
$$\rho\ C_p\phi_a\delta_e/(s+\gamma^*) = c^*\gamma a u^{0,8}\delta_e/s+c^*\gamma)$$

This assumption is valid for daylight only.

With these assumptions Eq. 5.11 reduces to

$$TF = TF_2 = (3600t/\lambda)s\ S_p/(s+{}^{c}*\gamma) \qquad ..(5.12)$$

Thus, for this *partial* transformation

$$E_o = E_{pan} + TF_2 \qquad ..(5.13)$$

<u>Experimental procedures</u>

Hourly measurements were made in the centre of 0,4 ha of well irrigated short grass. Included were:

- Net radiation, 12mm above the water surface in the A pan, using a miniature net radiometer.

- Net radiation, 1,5 m above the grass surface.

- Windspeed at a height of 2m above the grass surface.

- Wet and dry bulb temperatures using an aspirated psychrometer installed at a height 2,0 m above the grass surface.

- Temperature of the water, measured mid-way between the surface and the bottom of the A pan. Van Zyl and De Jager (unpublished data) demonstrated that experimentally single measurements at this depth accurately reflect mean pan water temperature. Small vertical temperature gradients < 1,0 $^{o}C\ m^{-1}$ were found to exist during daylight from 08h00 - 17h00.

- Total daylight evaporation from the A pan was obtained between 8h00 and 17h00 using a hook gauge.

A pan evaporation was estimated from Eq. 5.1 using daylight totals of Q_{np} and S_p, mean daylight values of windspeed, mean wet and dry bulb temperatures and hourly measurements of A pan water temperature. Daylight totals of E_o were obtained from hourly estimates of E_o using Eq. 5.6.

Forty-four daylight totals were obtained during 1986. Twelve data sets were used to determine a in Eq. 5.3, while the remainder was used to compare measured and calculated daylight totals of E_{pan}.

Comparisons carried out included:

(i) calculated versus measured daylight totals of E_{pan}. This tested the accuracy of Eq. 5.1. Results are presented in Table 5.1,

(ii) daylight totals of E_o estimated using Eq. 4.6 versus measured E_{pan}. Results here, reported in Table 5.2 tested whether transformation was necessary. Forty-four data sets were used,

(iii) daylight totals of E_o estimated using Eq. 5.6 versus measured E_{pan} partially transformed using Eq. 5.12 and 5.13, and

(iv) for interest, the same comparison was carried out using fully transformed (Eq. 5.8, 5.9, 5.10 and 5.11) values of E_{pan}. This approach offers little practical use, because having made all the meteorological measurements it would be better to simply estimate E_o using Eq. 5.6.

Normal statistical analyses and model performance tests (Willmott, 1982) were applied.

TABLE 5.1 - Comparison between E_{pan} calculated and E_{pan} measured for the daylight period.

STATISTICAL PARAMETERS	PARAMETER VALUE
n	32
Slope	0,70
Intercept	0,87 mm
Correlation Coefficient	0,88
Index of agreement	0,92
Systematic error	0,57 mm
Unsystematic error	0,73 mm
Mean difference	0,06 mm
Mean absolute difference	0,76 mm
Maximum absolute difference	1,84 mm
Mean of E_{pan} measurements	2,74 mm
Mean of E_{pan} estimates	2,80 mm

TABLE 5.2 - Comparison between E_o estimated using Eq. 5.6 and fully transformed (Eq. 5.11) E_{pan}, partially transformed E_{pan} (Eq. 5.13) and untransformed E_{pan} values for the daylight period.

STATISTICAL PARAMETER	PARAMETER VALUE		
	TRANSFORMED		UNTRANSFORMED
	FULLY	PARTIALLY	
n	44	44	44
Slope	1,09	1,05	0,78
Intercept	-0,42 mm	-0,35 mm	-0,89 mm
Correlation Coefficient	0,90	0,80	0,71
Index of agreement	0,94	0,88	0,64
Systematic error	0,14 mm	0,13 mm	2,05 mm
Unsystematic error	0,85 mm	1,22 mm	1,29 mm
Mean difference	0,01 mm	0,10 mm	2,01 mm
Mean absolute difference	0,70 mm	1,00 mm	2,06 mm
Maximum absolute difference	1,84 mm	3,60 mm	5,84 mm
Mean of E_o estimated	4,87 mm	4,87 mm	4,87 mm
Mean of E_{pan} measured	4,89 mm	4,77 mm	2,97 mm

RESULTS AND DISCUSSION

Empirical constant a, used in Eq. 5.3, as determined from Eq. 5.4, was found to be 0,17 from twelve meteorological data sets. The coefficient of variation was 23%. This value differed from the value of 0,26, reported by Thom *et al.* (1981). A possible explanation for the difference is that Thom *et al.* (1981) developed his formula over a 24 hour period. Here weather data for the daylight period alone were used.

Table 5.1 and Fig. 5.2 compare E_{pan} measured with E_{pan} calculated, using Eq. 5.1 for the daylight period. The high index of agreement of 0,92 and relatively low mean absolute difference, MAD, of 0,76 mm prove that this equation may be used to explain the mechanism of A pan evaporation.

Good agreement between simulated and measured A pan evaporation furthermore justifies use of Eq. 5.1 through 5.4 for wire mesh enclosures.

The thermal energy storage term has a major influence upon evaporation from the A pan. The mean of 44 daylight mean values of S_p and Q_{np} were 378 and 278 W m^{-2} respectively. The correlation coefficient of 0,30, high maximum absolute difference of 352 W m^{-2} and the fact that S_p approximated Q_{np} in only fourteen of the forty-four days indicated poor correspondence between S_p and Q_{np}. Thom *et al.* (1981) using

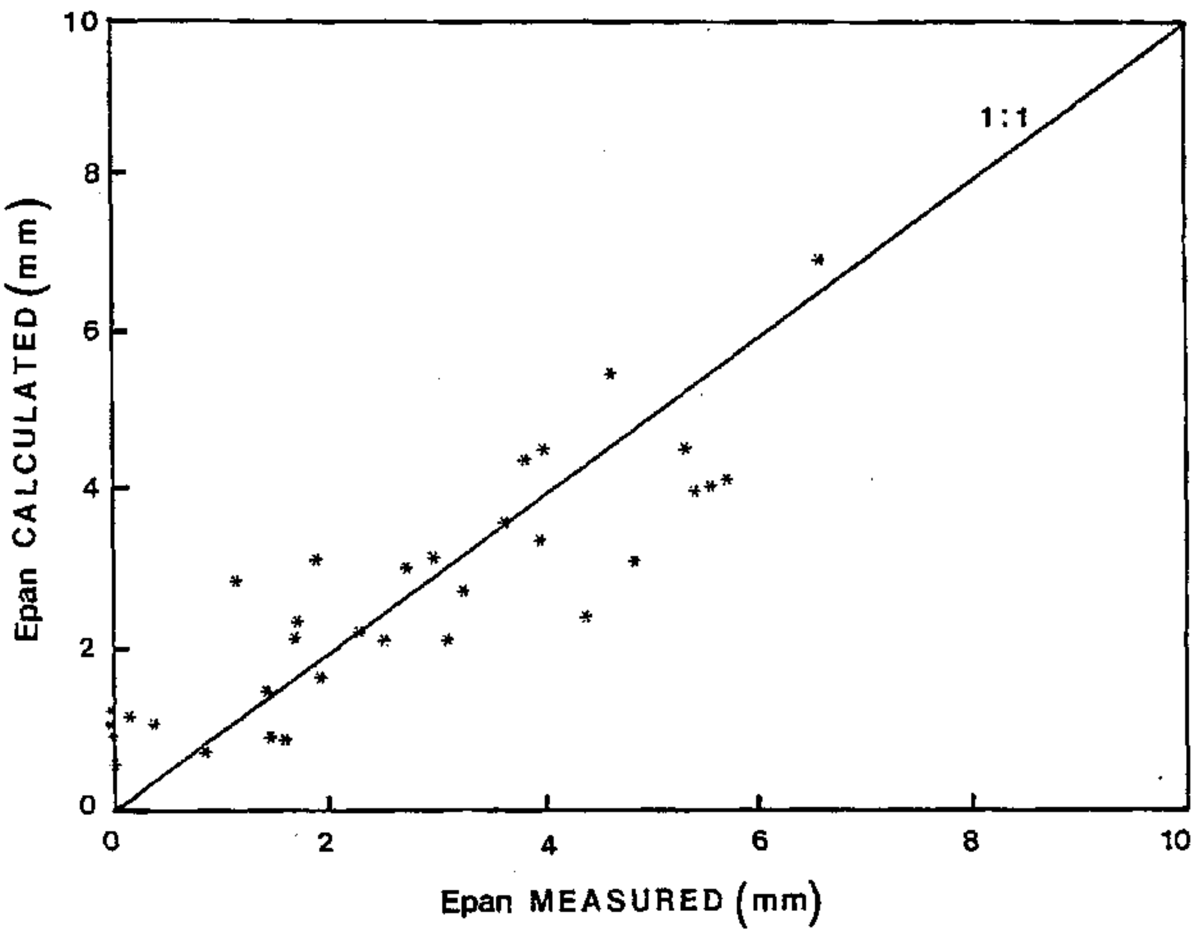

FIG. 5.2 - Comparison between E_{pan} calculated using Eq. 5.1 and E_{pan} measured for the daylight period.

hourly data sets taken over four days at Grenoble contended that $S_p = 0,75\ Q_{np}$. He provided no indication as to how S_p was obtained however.

Table 5.2 compares E_o calculated with E_{pan} measured for fully transformed, partially transformed, or simple untransformed measured values of E_{pan} for the daylight period. The poor relationship between E_o and untransformed measured values of E_{pan} is self-evident. The index of agreement and mean absolute difference were 0,64 and 2,06 mm for the daylight period respectively. Superiority of partially transformed E_{pan} measurements over untransformed E_{pan} measurements is clearly demonstrated in Table 5.2.

A typical diurnal variation of E_o, partially transformed and untransformed pan measurements is shown in Fig. 5.3. The improvement resulted by adding Eq. 4.12 to pan measurements is clearly demonstrated.

Fully transformed E_{pan} measurements using Eq. 5.11 are of no practical significance, because they require measurements of all the applicable weather elements. Should these be available, it would be preferable simply to calculate E_o using the combination equation, Eq. 5.6.

It must be emphasized that these results pertain to the daylight period. When 24 hour or say weekly periods are considered, nighttime compensation could occur. The latter, while fortuitous, could improve untransformed A pan estimates of AED.

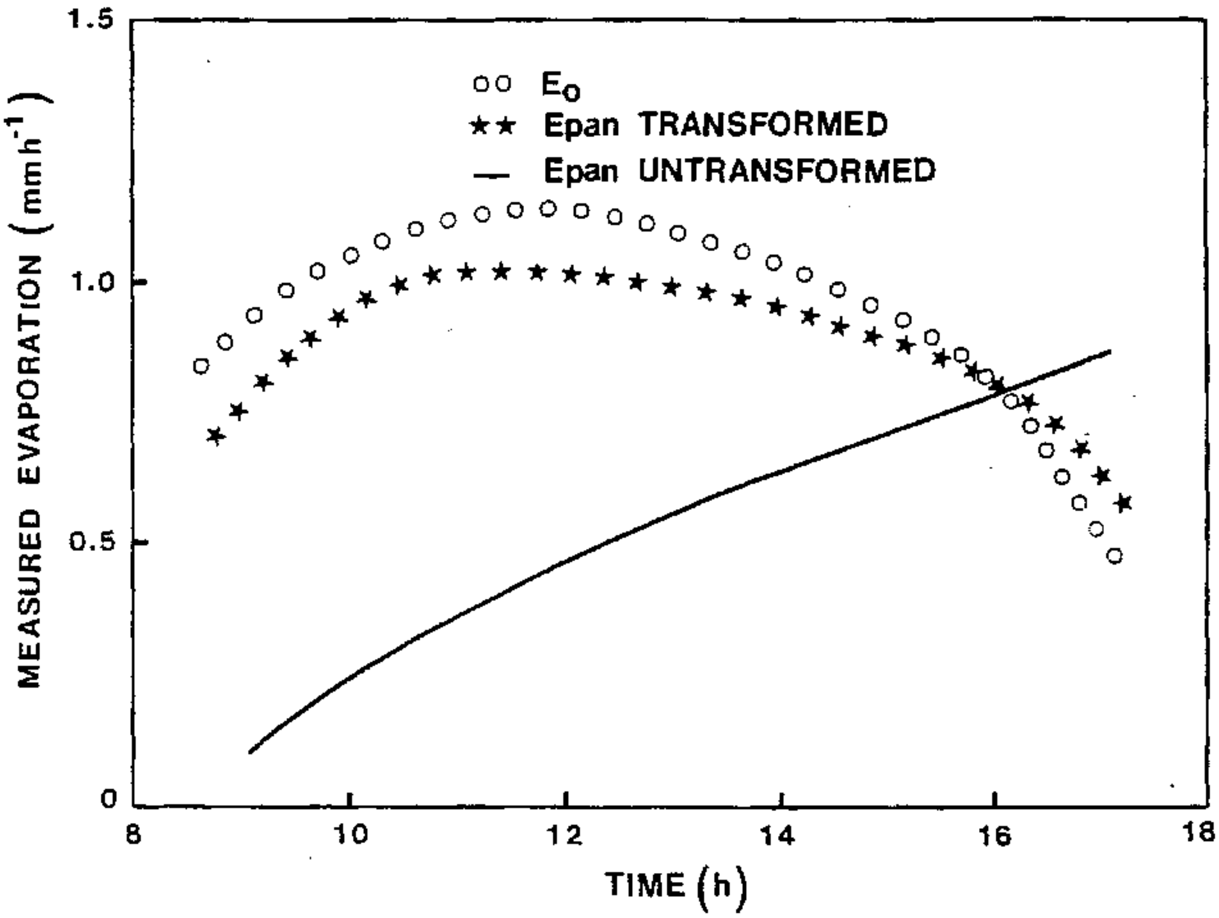

FIG. 5.3 - Typical diurnal variation of reference evaporation, E_o, partially transformed and untransformed pan evaporation.

The importance of maintaining a constant water level in an evaporation pan is reiterated. The volume of water in the container regulates directly the amount of energy stored and hence water temperature fluctuations.

CONCLUSION

A good relationship between E_{pan} measured and calculated was obtained from the combination equation of Thom *et al.* (1981). A wind function derived for the daylight period only, together with a parameter accounting for sensible heat exchange were used.

Large amounts of thermal energy is stored in the water body during daylight. The magnitude thereof was comparable to the net radiation measured above the A pan during daylight. Stored energy, in conjunction with the low windspeed and relatively small vapour pressure deficit normally experienced during the night, induced evaporation from the A pan in the late afternoon and at night.

Partial transformation of A pan measurements for purposes of estimating E_o, require little effort. All that is needed are pan measurements, hourly water and air temperatures. The latter are necessary to calculate s in Eq. 5.10. Hence A pan values partially transformed, as here described, offer an accurate practical technique for estimating AED. This partial transformation function (TF_2 in Eq. 5.12) therefore represents the correction factor required to be applied to daylight A pan observation in order to estimate reference surface evaporation.

The analysis in Table 5.2 includes a mirror correlation for the fully transformed case. The first term in estimated E_o (Eq. 5.6) is also the first term in TF_1, because it was assumed that $Q_n = Q_{np}$. This however could not be responsible entirely for the good agreement reported in Table 4.2. It would have been better to compare measured E_o against Eq. 5.11. Unfortunately such observations were not available. The good agreement between E_o measured and E_o calculated is well documented in Chapter 3.

CHAPTER 6

ESTIMATING HOURLY ATMOSPHERIC EVAPORATIVE DEMAND FROM WHEAT USING WEATHER MEASUREMENTS AND CARBORUNDUM OR PICHé ATMOMETER

Van Zyl and De Jager (1987b) have shown that neither carborundum (Wilcox, 1976) nor Piché atmometer (Jelinek and Hann, 1983) can accurately be related to measured maximum total evaporation. Comparison between evaporation from a Piché atmometer inside a Stevenson screen with lysimeter observations yielded a correlation coefficient (r) of 0,50. Corresponding values for Piché and carborundum atmometers shaded from long and short wave radiations were 0,60 and 0,69 respectively. Indeed, the Piché atmometer has in the past never successfully been applied for this purpose. It is therefore apparent that some form of transformation of atmometer values is necessary for the purpose at hand. Using Penman-Monteith equation (Thom, 1975) as a basis for this was investigated.

There is however a distinct possibility (Stanhill, 1962) of determining the aerodynamic term for the Penman-Monteith formula (Thom, 1975) using an atmometer. Such procedure offers a convenient, practical alternative for estimating maximum total evaporation. Now a single evaporation measurement would replace the measurement of windspeed and atmospheric water vapour in the aerodynamic term. Stanhill

(1962) found a high correlation between the aerodynamic component as calculated in the Penman formula and Piché observations. The standard error of the estimate was $\pm0,146$ mm d^{-1} or 15 percent of the mean calculated aerodynamic component. He found no significant changes in the relationship between two regions in Israel.

The first, or thermal energy component, of the Penman-Monteith equation (Thom, 1975) can easily be determined with present day equipment. In order to perfect the suggested technique, it was necessary first to find the most suitable evaporimeter for estimating this aerodynamic component and thereafter to test the accuracy thereof using a form of Penman-Monteith equation (Thom, 1975) which included evaporimeter estimates of the aerodynamic term.

With a view to converting atmometer readings to accurately estimate AED, detailed objectives of Chapter 6 were therefore to

(i) compare measurements made with a Piché in a Stevenson screen, exposed but shaded Piché and exposed but shaded carborundum atmometers in order to ascertain which was most sensitive and whether exposure influences consistency of results in any way,

(ii) develop the relationship between hourly estimates of the aerodynamic component in the Penman-Monteith equation (Thom, 1975) and evaporation from each of the three atmometers exposed as described in (i) above, and

(iii) test the accuracy of estimates of AED obtained by combining the energy component in the Penman-Monteith equation (Thom, 1975) with an aerodynamic component derived from the atmometers, against AED measured in a wheat lysimeter.

MATERIALS AND METHODS

The method of exposure of atmometers is critical. Three arrangements were examined:

- a Piché atmometer installed in the Stevenson screen (E_{psc}),
- a Piché atmometer (E_{ps}) exposed outside the Stevenson screen, but shaded from direct short wave radiation, and
- a carborundum atmometer (E_{cs}) exposed outside but similarly shaded.

The investigation was carried out on the agrometeorological experimental site at the West Campus of the University of the Orange Free State. Both sections (grass and wheat) were supplied with adequate water to ensure E_o and AED at all times. The leaf area index, LAI, of the wheat was greater than 3 during the experiments. The crop height varied from

0,15 to 0,7m. Hence soil water and leaf cover justified use of the Penman-Monteith equation (Thom, 1975).

A Piché atmometer (Jelinek and Hann, 1883) was mounted within a Stevenson screen. The exposed, hereafter called shaded, Piché and carborundum (Wilcox, 1976) atmometers were each provided with white circular perspex shields, to intercept direct short wave radiation (see Fig. 6.1 and 6.2). The instruments were installed at a height of 1m above grass surface which was 0,5 ha in extent. The effective evaporating surfaces of the Piché and carborundum evaporimeters were 3820 mm^2 and 4125 mm^2, respectively. The diameter of water feed tubes was 12mm for both types of evaporimeter. The graduation intervals on the Piché tube were 0,86 mm. Carborundum graduations were 1 mm apart.

All three instruments were read at hourly intervals during daytime.

Evaluation of the aerodynamic component, AC, Eq. 1.8 required measurements of windspeed, water vapour pressure deficit and air temperature at one level above wheat. The energy component, EC, involves measurements of net radiation, soil heat flux density, air temperature and windspeed.

The objective was to find a model for AC in terms of evaporimeter evaporation which would provide accurate measurements of AED. Instead of Eq. 1.8 a simple linear model was developed viz:

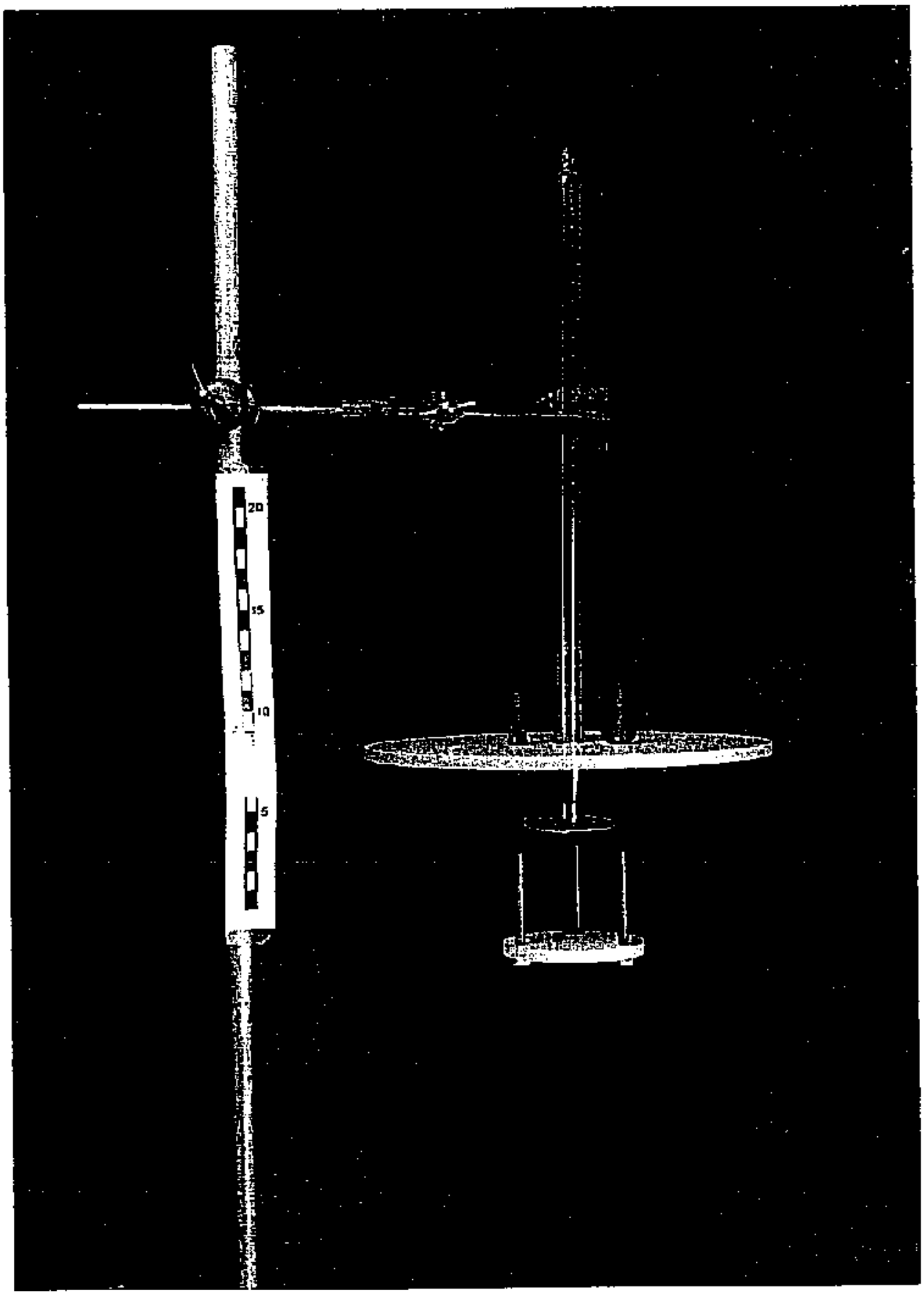

FIG. 6.1 - View of the shaded Piché atmometer.

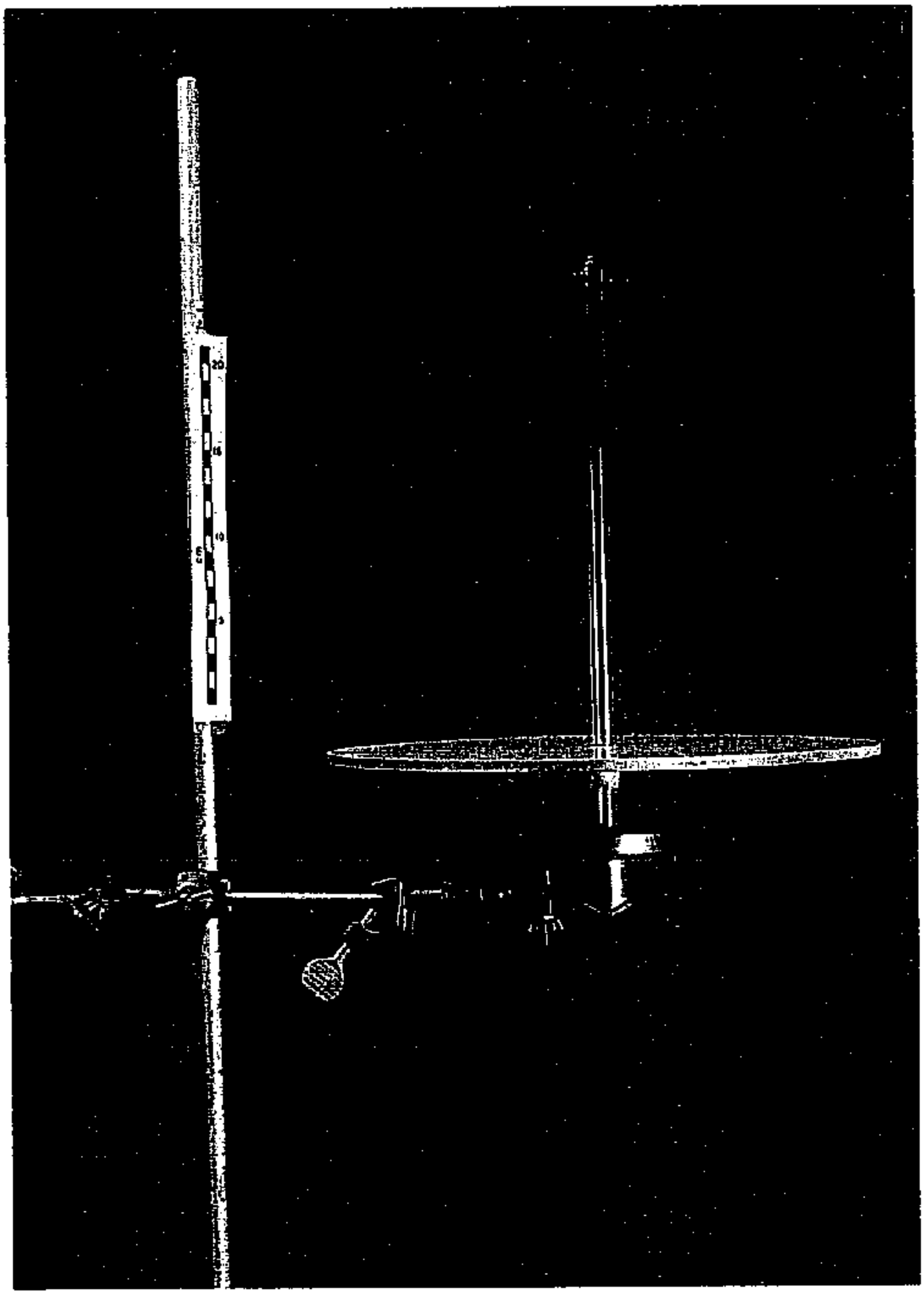

FIG. 6.2 - View of the shaded carborundum atmometer.

50 %

$$AC = a\,E + b \qquad ..(6.1)$$

where, a and b are regression constants.

The AED model tested therefore reads

$$AED = 3600/\lambda[s(Qn - G)] \,/\, (s + \gamma^*)] + (aE + b) \qquad ..(6.2)$$

To make possible the necessary model development and testing, the following measurements were made hourly in the wheat:

- windspeed using a three-cup anemometer at a level of 1,0 meter above ground surface,

- dry and wet bulb temperatures at a level of 1,0m above ground surface, utilizing aspirated psychrometer,

- net radiation at a level of 1,5m above ground surface using a net radiometer, and

- soil heat flux density using three soil heat flux sensors imbedded 5mm below the soil surface.

Furthermore, hourly evaporation was measured concurrently by three atmometers exposed as described.

Hourly measurements of AED were obtained from the lysimeter installed in the centre of the wheat plot.

In 1985 eighty data sets were collected. Of these, forty alternate sets were used to develop an empirical relationship between evaporation from the atmometers and the aerodynamic component in the Penman-Monteith equation (Thom, 1975). While problems of auto-correlation might have occurred, it is true that diurnal variation in evaporation takes place normally in nature, and it was furthermore necessary to ensure that the full range of hourly values was considered. Use of alternate data sets ensured an even spread of high and low values in the comparisons. Simple linear regression was applied. The remaining forty data sets were then used to test the accuracy of combining energy component with empirical relationship for the aerodynamic component as in Eq. 6.2. Estimated AED values were compared against lysimeter observations.

Further validation of the empirical relationship obtained between evaporation from the carborundum atmometer and the aerodynamic component in 1985 was carried out in 1986. In the latter year, 70 independent data sets were collected and used. They were obtained in a manner similar to that of 1985. Once again, estimated AED (Eq.6.2) was tested against lysimeter observations.

The empirical relationship between evaporation from the Piché atmometer and the aerodynamic component in the Penman-Monteith equation (Thom, 1975) was verified during the summer of 1988/89.

Normal statistical tests were applied and the index of agreement of Willmott (1982) determined.

RESULTS AND DISCUSSION

Fig. 6.3 illustrates the agreement between evaporation from the shaded Piché and the Piché inside the Stevenson screen. A correlation coefficient of r = 0,97 significant at p = 0,01 was found. Fig. 6.4 shows the agreement between evaporation from the shaded Piché and shaded carborundum atmometers. Here again a highly significant correlation coefficient of r = 0,97 at p = 0,01 was obtained. The coherent response resulting from these two comparisons demonstrates the consistent linear response of all three atmometers to atmospheric driving forces.

The values observed on the Piché atmometer outside the Stevenson screen were, in general, 1,4 times higher than those inside. This may be ascribed to the increased ventilation to which the latter is subjected. The carborundum evaporimeter was approximately 1,6 times more sensitive than the shaded Piché evaporimeter. This was probably attributable to the larger area of carborundum.

The empirical models developed for the aerodynamic component (AC) for the different evaporimeters using 40 sets of data in 1985 were:

$$AC = 0,018\ (E_{psc}) + 0,09\ (\text{mm h}^{-1}) \quad ..(6.3)$$

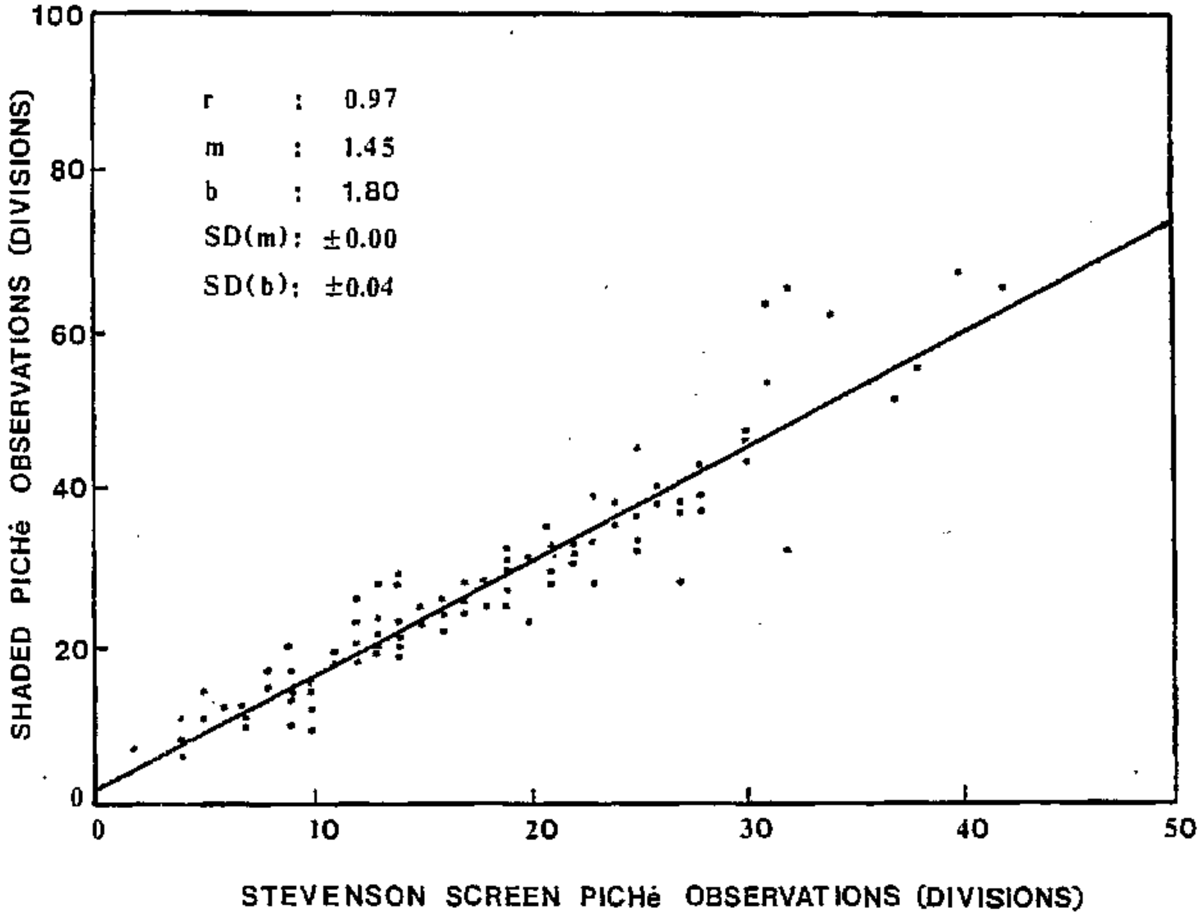

FIG. 6.3 - A comparison between hourly evaporation from the shaded Piché atmometer and the Piché inside the Stevenson screen.

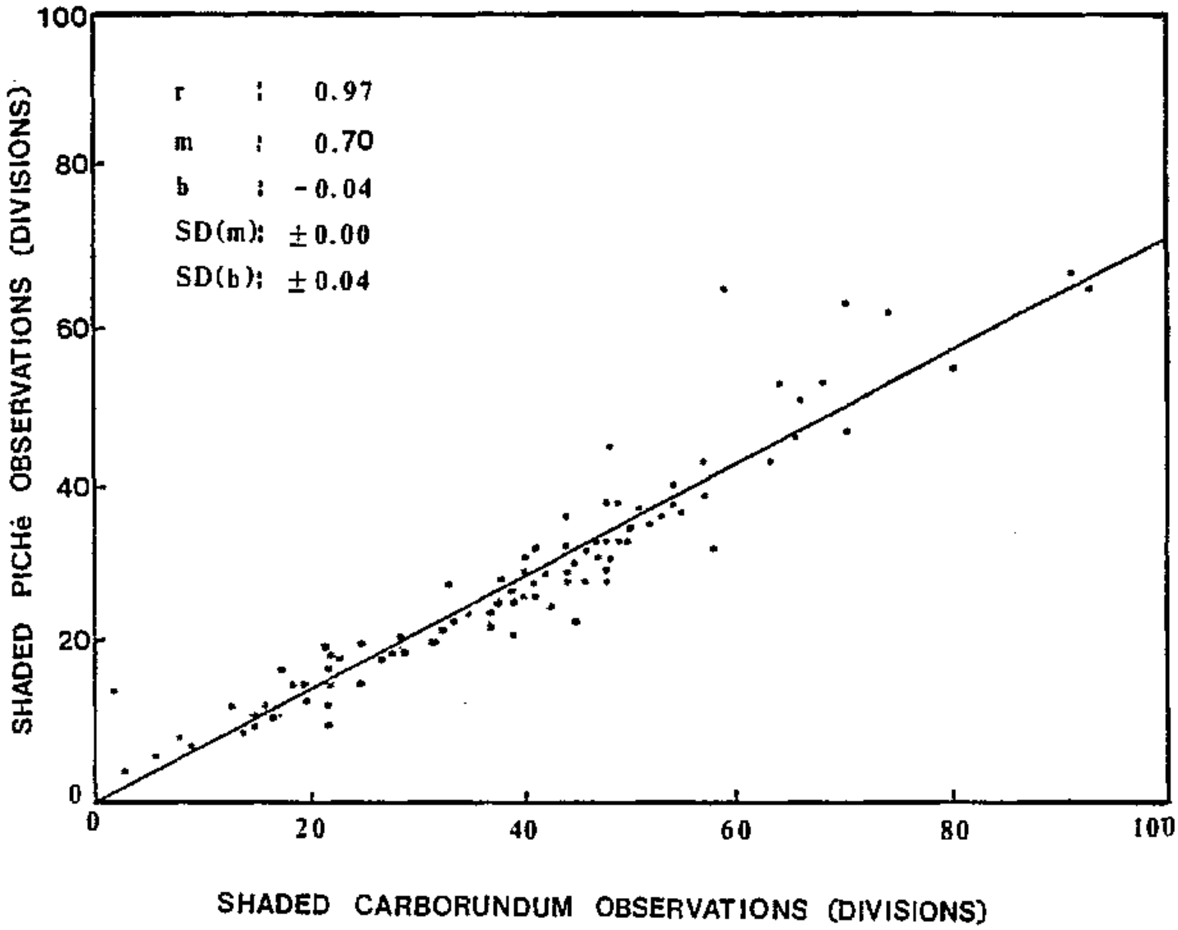

FIG. 6.4 - A comparison between hourly evaporation from the shaded Piché and carborundum atmometers. The size of the column divisions are given in the text.

$$AC = 0,014\ (E_{ps}) + 0,05\ (mm\ h^{-1}) \quad ..(6.4)$$

$$AC = 0,008\ (E_{pcs}) + 0,06\ (mm\ h^{-1}) \quad ..(6.5)$$

Correlation coefficients (r) for these comparisons on n = 40 sets of data were 0,95, 0,96 and 0,95 respectively. The intercepts were not significantly different from zero at the p = 0,01 level.

The empirical relationship obtained between AC and E_{psc} during the summer of 1988/89 was

$$AC = 0,018(E_{psc}) - 0,03\ (mm\ h^{-1}) \quad ..(6.6)$$

The correlation coefficient was 0,92 for 71 hourly data sets. The good comparison between Eq. 6.3 and Eq. 6.6 is once again a proof of the repeatability of this method.

It is suggested that the regression coefficients in these equations account for crop surface roughness, canopy conductance, atmospheric water vapour, air temperature and windspeed. Since the former two are almost certainly a function of leaf area index, similar relationships should be determined for other crop growth stages.

Stanhill (1962) compared estimates of the aerodynamic component, AC, of the Penman formula (1948) with evaporation from a Piché evaporimeter in a Stevenson screen. He obtained the regression equation.

$$AC = 0,15\ (E_{psc}) + 0,11\ (mm\ d^{-1}) \qquad ..(6.7)$$

The accuracy of use of Eq. 6.3, 6.4 or 6.5 in Eq. 6.2 to estimate AED was verified using the remaining 40 data sets in 1985. Results of the statistical tests applied are reported in Table 6.1.

High index of agreement of 0,94, 0,95 and 0,97 when E_{psc}, E_{ps} and E_{cs} were used respectively, indicate high model reliability, as do the low mean differences of 0,02, 0,01 and 0,02 mm h^{-1} respectively.

Fig. 6.5 illustrates the agreement between AED estimated according to the method utilizing the energy component plus Eq. 6.5 and AED measured in the lysimeter. The good agreement is self-evident.

From Table 6.1 the statistical tests and the almost equal indices of agreement (0,94 to 0,95) prove that there is little to choose between the three atmometers.

Fig. 6.6 is a comparison of AED estimated using the empirical relationship developed for the carborundum evaporimeter in 1985 (Eq. 6.5) and independent field data from 1986. The good relationship obtained is once again self-evident. The statistical tests (index of agreement = 0,92 and mean difference of 0,01 mm h^{-1}) listed in column 4 of Table 6.1 demonstrate the good accuracy and high degree of repeatability of the model.

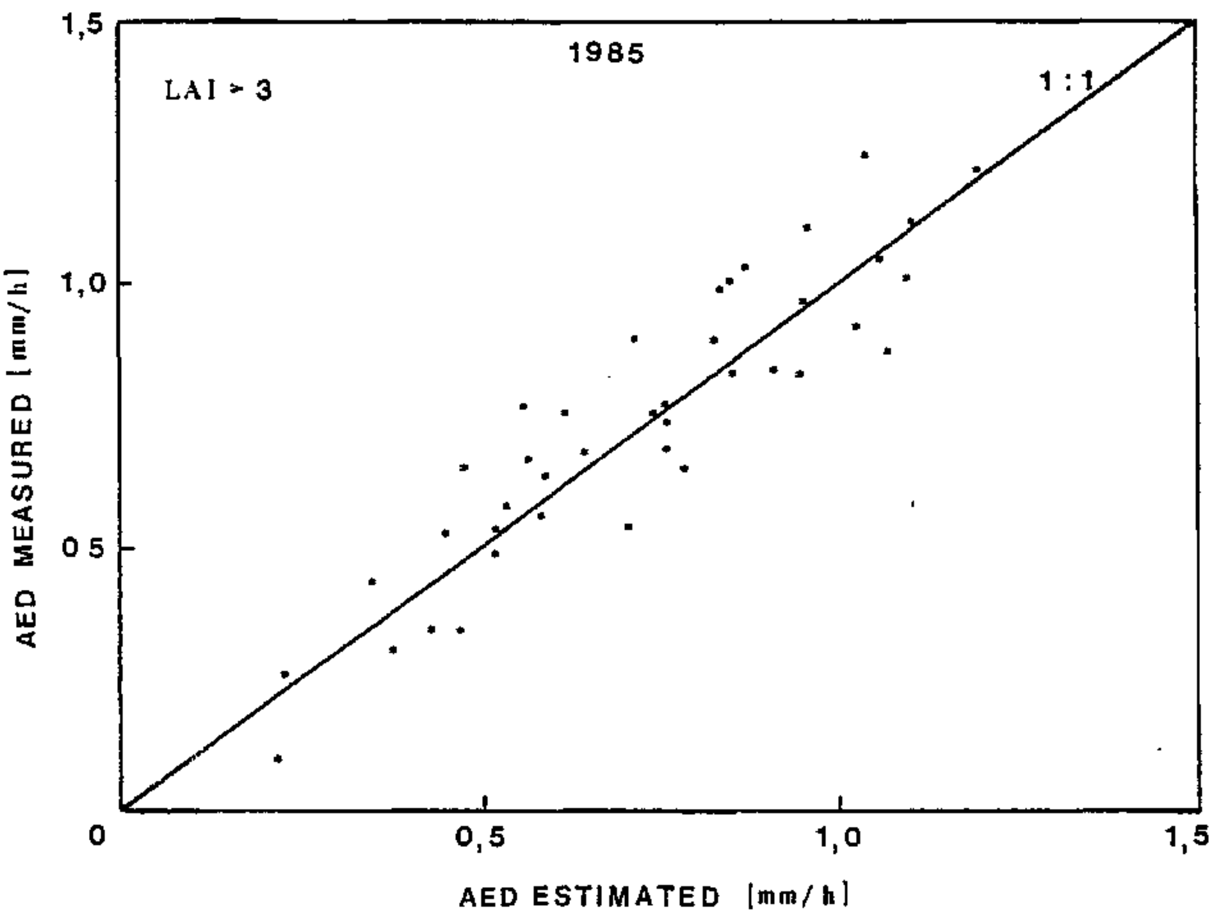

FIG. 6.5 - Relationship between AED measured in a wheat lysimeter and AED estimated by combining the energy component in the Penman-Monteith equation (Thom, 1975) and the aerodynamic component from the carborundum atmometer using 1985 field data.

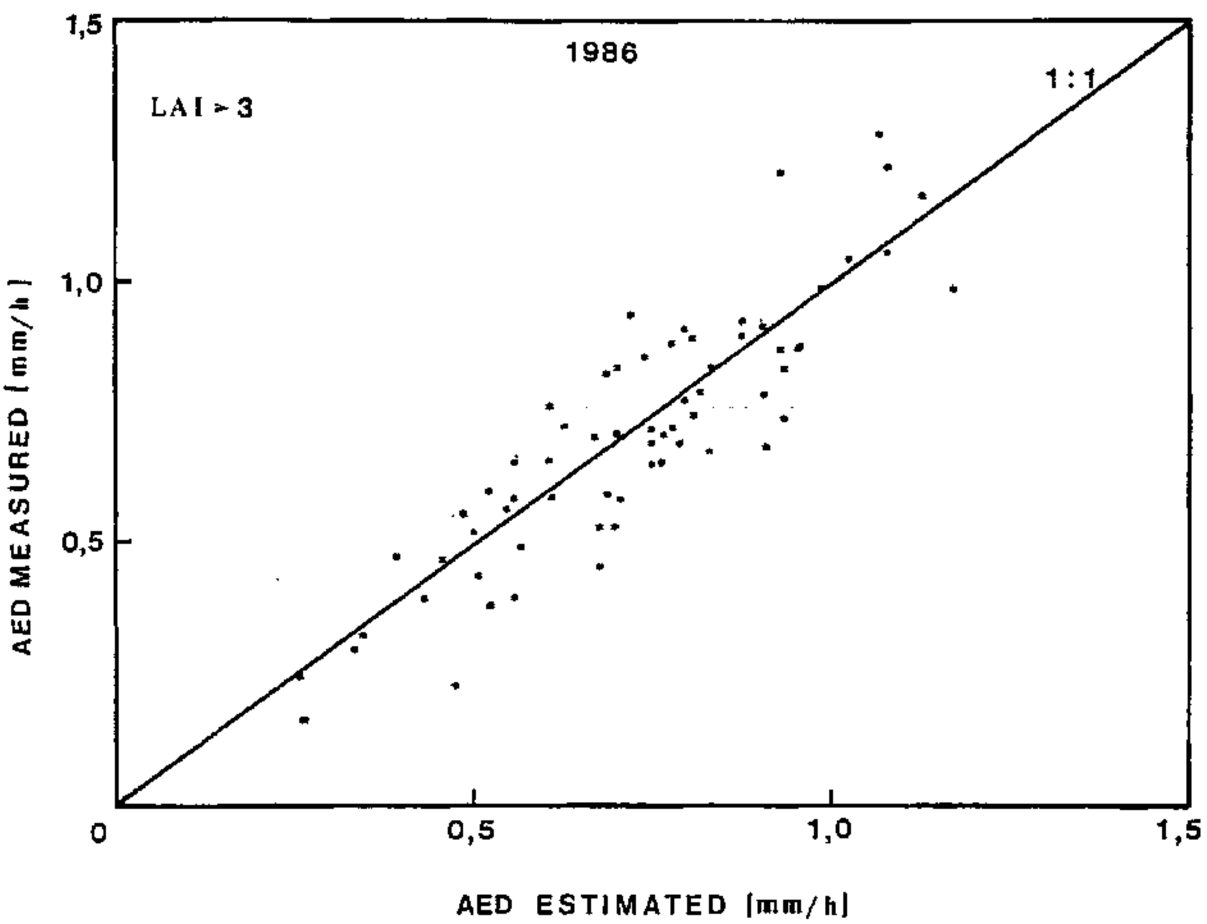

FIG. 6.6 - Relationship between AED measured in a wheat lysimeter and AED estimated using the method developed in 1985 for a carborundum atmometer and 1986 field data.

TABLE 6.1 - Statistical tests on comparison of the estimates obtained using Eq. 6.2 and lysimetrically measured AED.

STATISTICAL PARAMETERS	ATMOMETERS			
	SCREEN Piché	SHADED Piché	SHADED CARBORUNDUM	
			1985	1986
	1	2	3	4
n	40	40	40	70
Slope	1,00	0,96	0,98	1,06
Intercept	0,02mm h^{-1}	0,04mm h^{-1}	0,04mm h^{-1}	-0,04mm h^{-1}
Correlation Coefficient (r)	0,90	0,90	0,92	0,87
Index of agreement	0,94	0,95	0,95	0,92
Systematic error	0,02mm h^{-1}	0,02mm h^{-1}	0,03mm h^{-1}	0,0 mm h^{-1}
Unsystematic error	0,12mm h^{-1}	0,11mm h^{-1}	0,11mm h^{-1}	0,12mm h^{-1}
Mean residual	0,10mm h^{-1}	0,09mm h^{-1}	0,09mm h^{-1}	0,09mm h^{-1}
Mean absolute difference (MAD)	0,10mm h^{-1}	0,09mm h^{-1}	0,09mm h^{-1}	0,09mm h^{-1}
X-axis: Mean AED estimated (y)	0,71mm h^{-1}	0,72mm h^{-1}	0,70mm h^{-1}	0,73mm h^{-1}
Mean AED measured (x)	0,73mm h^{-1}	0,73mm h^{-1}	0,73mm h^{-1}	0,73mm h^{-1}

Substitution of γ^* by γ in Eq. 6.2 has been shown elsewhere to have virtually no affect upon final estimates of AED (Van Zyl and De Jager, 1986, unpublished data). This obviates the necessity for measuring windspeed in the proposed model, and makes Eq. 6.2 an extremely simple and convenient model for estimating AED.

Regarding the overall purpose of this study; it is thus evident that the best correction factor for an atmometer results from using it in Penman-Monteith equation (Thom, 1975). Atmometer correction factors are therefore the slope and intercept of AC-atmometer evaporation relationships, (see Eq. 6.3 through 6.5) in the Penman-Monteith equation (Thom, 1975).

CONCLUSION

The shaded carborundum atmometer exhibited a sensitivity 1,6 times that of the shaded Piché atmometer. The latter in turn was 1,4 times as sensitive to atmospheric driving forces as the Piché atmometer in the Stevenson screen.

Furthermore, reliable estimates of the aerodynamic component in the Penman-Monteith equation (Thom, 1975) are obtainable from any one of the atmometers. Each atmometer varied consistently and linearly with atmospheric driving forces.

Use of the Penman-Monteith equation (Thom, 1975) utilizing atmometer derived values for the aerodynamic component provide estimates of AED from a wheat crop with complete vegetation cover with a mean accuracy of $\pm 0{,}09$ mm h^{-1}.

CHAPTER 7

ESTIMATING DAYLIGHT AED FROM WHEAT USING EMPIRICAL RELATIONSHIPS FOR ENERGY AND AERODYNAMIC COMPONENTS IN THE PENMAN-MONTEITH EQUATION

INTRODUCTION

The Penman-Monteith equation (Thom, 1975) has been proved to be highly accurate for estimating AED from a wheat crop (van Zyl and De Jager, 1987). Application of this equation to estimate crop evaporation however involves expensive and sophisticated sensors, a data logger and computer system.

In Chapter 6, (see also Van Zyl and De Jager, 1987b) a simplified technique, whereby the Penman-Monteith equation (Thom, 1975) may be applied to estimate AED for a wheat crop was developed by estimating hourly aerodynamic components from evaporation from a Piché atmometer exposed in a Stevenson screen. The main advantage of this method is that it removes the need to measure relative humidity and windspeed.

The objective of Chapter 7 was to develop and verify this approach for daylight periods, utilizing an empirical relationship for energy and aerodynamic components.

MATERIALS AND METHOD

The empirical equation to estimate AED over the daylight period, based on the Penman-Monteith equation (Thom, 1975), is given here by the sum of the empirical energy component (Eq. 1.7) and the empirical aerodynamic component (Eq. 1.8). Hence,

$$AED = \{ \{ (s/(s+ \quad) \sum_{t=08h00}^{t=17h00} (0,75\ St(t)-72)\delta t\} + (0,0189\ Eps + 0,2268)\}k_c \quad ..(7.1)$$

It was assumed that whole crop surface conductance ϕ_v equals infinity.

In Eq. 7.1 δt (= 1h, which needs to be converted to seconds by multiplying by 3600 s h^{-1}) is the time interval between measurements. Here the daylight period was assumed to stretch from 08h00 to 17h00. De Jager *et al.* (1982) showed that wheat stomates were closed outside this period for this locality.

In the energy balance term total radiation, St, may either be measured or calculated from the formulae of Archer (1964) or Reid and De Jager (1989).

The regression constants 0,75 and -72 W m^{-2} in Eq. 7.1, for the slope and intercept respectively, were determined by comparing hourly measurements of available energy (Qn - G) with measured total radiation (De Jager *et al*, 1987). The correlation coefficient was 0,96 for 96 data sets. When Archer (1964) estimates of St were regressed against measured total radiation a slope of 0,97 and intercept of -32 W m^{-2} were found (Van Zyl, *et al*, unpublished results). The regression coefficient, index of agreement (Willmott, 1982) and mean absolute difference were 0,97; 0,97 and 61 W m^{-2} for 200 hourly data sets respectively.

Empirical expression described by Eq. 6.4, for estimating the aerodynamic component from Piché evaporimeter measurements, was obtained from hourly measurements for LAI > 3 (Van Zyl and De Jager, 1987b and Chapter 6). However, for the daylight totals relationship 0,0189Eps + 0,2268 mm was found to be accurate (Van Zyl *et al*, unpublished results). The relevant correlation coefficient was 0,80 with the error estimate of the regression of 0,84 mm $daylight^{-1}$.

The crop coefficient, k_c, (De Jager and Van Zyl, 1989; see also Chapter 2) was used to account for the change in the LAI and soil water content over the growing season. It was assumed in this chapter that $k_{vm} = k_{sm} = 1$. Hence, Eq. 2.29 reduces to the form

$$k_c = F_h F_l + F_g(1 - F_l) \qquad ..(7.2)$$

In Eq. 7.2, F_h is the relative transpiration rate and F_g. Relative soil surface evaporation rate is given by

$$F_g = e^{-0,4D} \qquad ..(7.3)$$

D, in Eq. 7.3, is the time in days since the previous irrigation or rainfall in excess of 5 mm.

According to Ritchie (1972), the factor accounting for variation in vegetative cover, F_l, is described by the relationship

$$F_l = -0,2 + 0,7\ LAI^{0,5} \qquad ..(7.4)$$

which is valid for $0,2 \leq LAI \leq 2,9$. It is assumed that F_l equals 0,1 and 1,0 for LAI < 0,2 and LAI > 2,9 respectively.

For optimal water supply relative transpiration rate, Fh, is equal to one. Hence Eq. 7.2 now reads

$$k_c = F_l + F_g\ (1 - F_l) \qquad ..(7.5)$$

The validation of Eq. 7. 1 was carried out between mid-July 1986 and the end of October 1986 on the West Campus of the University of the Orange Free State.

Hourly solar radiant flux density, S_t (measured by automatic weather station or estimated) and mean hourly screen temperature, T, were used to calculate the energy component of Eq. 7.1. The aerodynamic component was calculated using total daylight (08h00-17h00) evaporation from a Piché atmometer exposed in a Stevenson screen.

Estimated values of AED accumulated over the daylight period were compared against corresponding values measured using the lysimeter. The comparisons were carried out over a period when LAI increased from 0,2 to 7. The index of agreement (Willmott, 1982) and normal statistical tests were applied.

The results of these tests, (for St measured and estimated from the Archer (1964) model) are shown in Table 7.1. Fig. 7.1 illustrates the relationship between AED estimated (for S_t measured) and AED measured lysimetrically.

RESULTS AND DISCUSSION

Excellent agreement between AED measured and estimated, was obtained. However, use of Eq. 7.1 results in an overestimation of AED by 0,26 and 0,45 mm for S_t measured and estimated respectively. This corresponds to approximately 1,8 and 3,2 mm over a seven day cycle.

These results demonstrate the reliability of using empirical approximations for the energy and aerodynamic components of the Penman-Monteith equation (Thom, 1975). Such techniques are of considerable significance because they eliminate the sophisticated instrumentation and computers usually required when applying evaporation theory. By installing a radiometer (or, alternatively, a sunshine recorder and estimating S_t values for the site latitude), a thermometer and Piché atmometer exposed in a screen, farmers could practice sound irrigation scheduling.

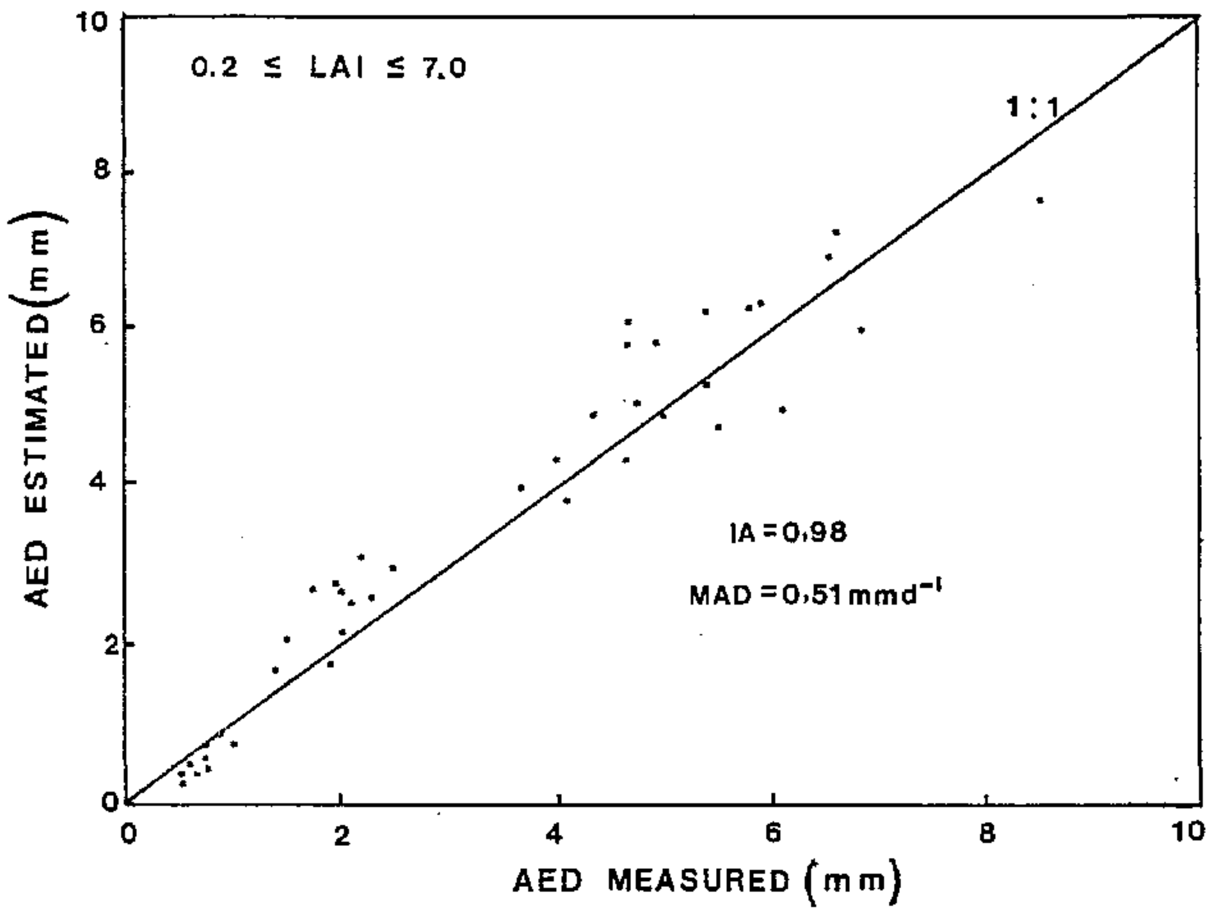

FIG. 7.1 - Comparison between AED estimated with *St* measured from Eq. 7.1, and AED measured lysimetrically, for the daylight period.

TABLE 7.1 - Comparison between AED estimated with S_t either measured or estimated respectively estimated using Eq. 7.1, and AED measured lysimetrically for the daylight period.

STATISTICAL TEST PARAMETER	PARAMETER VALUE	
	S_t measured	S_t estimated
n	42	38
Slope	1,01	1,07
Intercept	0,24 mm	0,21 mm
Correlation coefficient	0,97	0,98
Index of agreement	0,98	0,98
Model estimate error	0,63 mm	0,70 mm
Systematic error	0,25 mm	0,48 mm
Unsystematic error	0,57 mm	0,51 mm
Mean difference	0,26 mm	0,45 mm
Mean absolute difference	0,51 mm	0,57 mm
Maximum absolute difference	1,56 mm	1,37 mm
Mean measured AED (x)	3,32 mm	3,16 mm
Mean estimated AED (y)	3,58 mm	3,50 mm

CONCLUSION

This chapter thus shows that for determining correction factors for atmometers by the method suggested in Chapter 6, sophisticated meteorological observations in Penman-Monteith equation (Thom, 1975) may be successfully replaced by empirical estimates of thermal energy input obtained from solar radiation or sunshine duration measurements.

CHAPTER 8

CANOPY SURFACE CONDUCTANCE OF UNSTRESSED WHEAT AND ITS WEATHER DEPENDENCE

DEFINITION:

An important concept utilized in this paper is atmospheric evaporative demand, AED.

> De Jager and van Zyl (1989) defined AED as the water vapour transfer to the atmosphere, required to sustain the energy balance of a given vegetative surface (crop) in its present growth stage, when its roots are supplied with adequate soil water and the water status of the soil surface equals its current value.

INTRODUCTION

A combination equation explaining evaporation from short green vegetation was established by Penman (1948). He assumed that leaf stomates exerted zero resistance to water vapour exchange. The lack of generality in the original equation was fully appreciated by Penman (1948). Monteith (1964) satisfactorily generalised the theory. He introduced canopy surface resistance. For convenience, the term surface conductance, ϕ_V, will here be preferred to its reciprocal, surface resistance. The resultant equation is valid for a non-stressed, full vegetative cover of any type.

Using the new definition of AED and symbols (De Jager and Van Zyl, 1989) and the Monteith (1973) equation, a universal evaporation equation was constructed (De Jager, Van Zyl, Bristow and Van Rooyen (1982), viz:

$$AED = F\{(sH + \rho C_p \, \delta_e \, \phi_a) \, / \, (s + \gamma^*)\}3600/\lambda \qquad ..(8.1)$$

where

$$H = Q_n - G \qquad ..(8.2)$$

$$\phi_a = k^2u(z) \, / \, \{\ln(z-d)/z_o\}^2 \qquad ..(8.3)$$

$$\gamma^* = (1 + \phi_a \, / \, \phi_v) \qquad ..(8.4)$$

$$d = 0,63 \ h \qquad) \qquad ..(8.5)$$

) (Monteith, 1973)

$$z_o = 0,13 \ h \qquad) \qquad ..(8.6)$$

and

$$\phi_v = 1 \, / \, r_v \qquad ..(8.7)$$

The factor 3600/λ converts W m^{-2} to mm h^{-1}.

F, a normalized crop factor, is fully discussed by De Jager *et al*, (1982). The present study was carried out during a period when the leaf area index, LAI, was greater than 3. This implies that F in Eq. 8.1 is equal to unity.

While measurement of the weather variables in Eq. 8.1 is possible, accurate values of canopy surface conductance are not readily available.

Russell (1980) calculated canopy surface conductance for full vegetative cover from the following expression viz.

$$\phi_v = \phi_a[\{1 + (s/\ )\}\{(AED_o/AED_p) - 1]^{-1} \quad ..(8.8)$$

where AED_o represents the special case of AED with F = 1 and ϕ_v equal to infinity.

Russell (1980) found the mean canopy resistance for non-stressed barley to be equivalent to ϕ_v = 0,03 m s^{-1}, provided soil water deficit below field capacity was < 30 mm. Rate of evaporation, AED_p, was calculated from rainfall measurements and changes of soil water content measured with a neutron probe. Corrections were made for drainage.

Choudhury and Idso (1985) used a different method to determine ϕ_v from weather measurements. Here, for a full canopy, AED_p from irrigated wheat was calculated from an energy-aerodynamic equation viz.

$$AED_p = Q_n(1 - \Gamma) - C_p(T_c - T_a)\phi_a \quad ..(8.9)$$

Because F equalled unity and vegetation received adequate water, this value could be substituted on the left hand side of Eq. 8.1 which was then solved for ϕ_v.

The canopy surface temperature, T_c, was measured with an infra-red thermometer. The transmission coefficient, Γ, was determined from

$$\Gamma = \exp(-LAI/2\sin\alpha) \quad ..(8.10)$$

Eq. 8.10 applies for canopies with randomly oriented wheat leaves (Denmead, 1976). The accuracy of AED_p in Eq. 8.9 had been tested against measurements from a 1 m^2 wheat lysimeter. Good correlation (r = 0,97) was obtained. A maximum value of ϕ_v = 0,03 m s^{-1} for ϕ_v was reported.

Bristow (1980) measured stomatal resistance hourly on a thousand individual wheat leaves, using a non-steady state autoporometer. Reported values (Bristow, 1980 and Bristow, de Jager and van Zyl, 1981) were 300 s m^{-1} for wet soil conditions on a sunny day at 13h00. This value remained constant throughout daylight. Other measurements (van Zyl, de Jager, Maree, 1987 unpublished results) of stomatal resistance of wheat leaves using a steady state autoporometer yielded values of 100 and 200 s m^{-1}. This implies that single leaf measurements of stomatal conductance obtained using autoporometers differed by less than one-sixth from canopy surface conductance, estimates obtained from weather measurements and Eq. 8.8. Choudhury and Idso (1985) reported a stomatal/canopy resistance ratio of approximately three.

It is logical to expect canopy conductance to depend upon leaf stomatal conductance. The large differences here quoted can be explained by the arrangement of leaves in the canopy. Their combined effect realizes an effective canopy conductance for the cropped surface as a whole.

Van Zyl and de Jager (1987) with success adopted the Russell (1980) value of ϕ_v = 0,03 m s^{-1} to validate the Penman-Monteith equation. Tested against lysimeter measurements for a wheat crop, a high index of agreement (see Willmott, 1982) and mean absolute difference of 0,97 and 0,09 mm h^{-1} respectively were obtained. This excellent result suggested that determination of ϕ_v is possible utilizing Eq. 8.1, lysimeter values of AED and meteorological measurements.

For wheat canopies Allen (1986) found ϕ_v to approximate 0,025 m s^{-1}. Values varied with LAI and daily net radiation.

Some weather dependance of ϕ_v was demonstrated by Denmead and Millar (1976). They found a linear relationship between individual leaf conductance, ϕ_l, and net radiation, Q_n, viz.

$$\phi_l = 0,05 + 0,0020\ Q_n \quad (\text{cm s}^{-1}) \qquad ..(8.11)$$

The correlation coefficient was 0,90 and standard error of estimate 0,11 cm s^{-1}. This relationship applied to green leaves at all stem positions in the canopy for values of Q_n up to 500 Wm^{-2}. Measurements were made with a diffusion porometer.

The objective of the present study was

(i) to determine ϕ_v for a wheat crop through the daylight period (08h00 - 17h00),

(ii) to verify use of these values of ϕ_v in Eq. 8.1, and

(iii) to investigate the influence of weather variables on ϕ_v.

MATERIALS AND METHODS

Measurements

For a complete vegetative cover (LAI>3), not subject to water stress, ϕ_v can be expressed by rearranging Eq. 8.1. Thus

$$\phi_v = (\phi_a\ \gamma AED_p)\ /\ (sH + \rho C_p\ \delta_e\ \phi_a - AED_p(s + \gamma)) \quad ..(8.12)$$

In the present study AED_p in Eq. 8.12 was measured in the 10 m^2 lysimeter on West Campus, University of the Orange Free State. The depth and resolution thereof are 2m and 0,07 mm respectively.

To enable use of solar, instead of net radiation measurements, the empirical equation of van Zyl, de Jager and Maree (1988) was used, viz.

$$H = 0,75\ S(t) - 72\ W\ m^{-2} \quad ..(8.13)$$

The correlation coefficient associated with the initial development of Eq. 8.13 was 0,99 for 200 hourly values.

Hourly meteorological measurements were carried out using an automatic weather station installed centrally in a 0,5 ha short grass site, adjacent to a 4 ha wheat field (Fig. 8.1). Windspeed was measured at a height of 3,15 m. Measurements

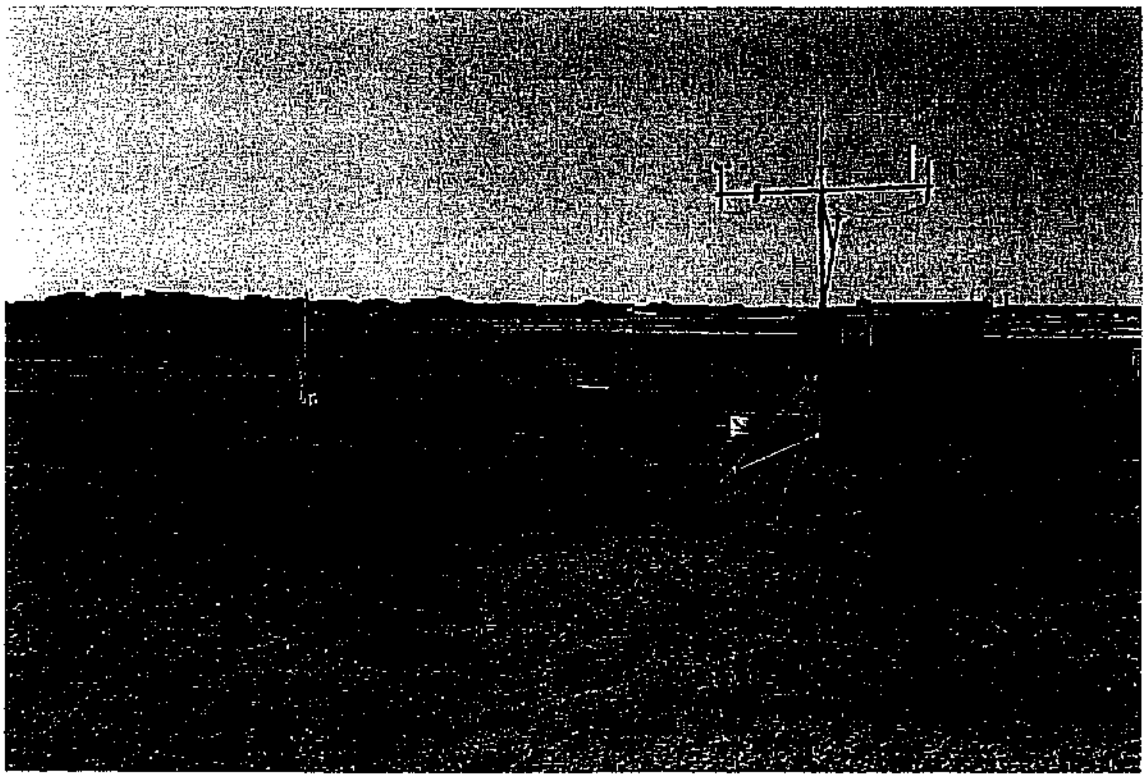

FIG. 8.1 - Automatic weather station installed on the grass site.

at this height were assumed representative of the boundary layer above the wheat crop. The validity of this assumption was proved by Maree (1989). Allen (1986) utilized a similar approach. Air temperature and relative humidity were measured at 1,5 m in a Stevenson screen and total radiant flux density at 3m height. The latter was used to estimate available energy, H, using Eq. 8.13.

Experimentation proceeded from September through October 1987 on the West Campus of the University of the Orange Free State. Wheat cultivar SST44 was used. Over the entire study period leaf area index increased from 3 to 8 by end October. For LAI>3 this wheat crop offered 100% ground cover. Hence all observations were conducted over complete vegetative cover. The wheat plot, lysimeter and grass site were irrigated frequently to prevent moisture stress. These conditions ensured that potential evaporation proceeds as per definition (De Jager and Van Zyl, 1989) at all times. Hence, surface conductance, ϕ_v, was a maximum during all daylight periods for the duration of the experiment.

<u>Determination of ϕv</u>

One hundred hourly weather and lysimeter data sets, evenly distributed throughout September and October, were collected. The majority (98%) of the randomly selected days were cloudless. Hourly determinations of ϕ_v were made from Eq. 8.12 throughout the daylight period, from 08h00 to 17h00. Calculations of mean and median hourly ϕ_v were carried out separately for October and September. They are reported in Table 8.1. This was done in order to ascertain whether the mean and median of ϕ_v differed between tillering and soft dough growth.

<u>Verification of ϕv values</u>

Mean and median values of ϕ_v, determined as above, during September were each substituted into Eq. 8.1. The equations were then used to calculate AED_p from 48 hourly independent sets of weather data collected during October. Calculated AED_p values were then compared to lysimeter measurements of AED_p.

Willmott (1982) index of agreement, mean and absolute differences were calculated together with regression constants and correlation coefficients and are reported in Table 8.2.

<u>Weather control of ϕv</u>

The influence of weather variables, such as net radiation, Q_n, windspeed, u(z), vapour pressure deficit, δe, and air temperature, T_a, on ϕ_v was investigated by correlating diurnal variations of the latter with each of abovementioned weather element separately. Eighty-seven values of Q_n, u(z), δ_e and T_a and ϕ_v collected over nine days in September and October were used in the comparisons.

TABLE 8.1 - Mean and median ϕ_v calculated from sets of weather data, lysimeter observations and Eq. 8.12.

DATA SETS	CANOPY SURFACE CONDUCTANCE, ϕv	
	MEAN VALUE ($m\ s^{-1}$)	MEDIAN VALUE ($m\ s^{-1}$)
Full data set (Sept. plus Oct.) n = 100	0,09	0,06
September n = 52	0,08	0,06
October n = 48	0,09	0,06

TABLE 8.2 - Results of the statistical tests carried out between AED_p measured and AED_p estimated from Eq. 8.1 and hourly meteorological data for October, obtained from an automatic weather station. The canopy surface conductances used were ϕ_v = 0,3 m s^{-1}, ϕ_v = 0,04 m s^{-1}, ϕ_v = 0,06 m s^{-1} and ϕ_v = 0,08 m s^{-1}, respectively. Comparisons were conducted on 48 data sets.

STATISTICAL PARAMETERS	PARAMETERS VALUES			
	ϕ_v = 0,03m s^{-1}	ϕ_v = 0,04m s^{-1}	ϕ_v = 0,06m s^{-1}	ϕ_v = 0,08m s^{-1}
Index of agreement (Willmott, 1982)	0,91	0,92	0,95	0,96
Mean difference	0,11 mm h^{-1}	0,08 mm h^{-1}	0,03 mm h^{-1}	0,00 mm h^{-1}
Mean absolute difference	0,11 mm h^{-1}	0,09 mm h^{-1}	0,07 mm h^{-1}	0,07 mm h^{-1}
Measured AED_p (x-axis)	0,59 mm h^{-1}	0,59 mm h^{-1}	0,59 mm h^{-1}	0,59 mm h^{-1}
Estimated AED_p (y-axis) mm h^{-1}	0,48 mm h^{-1}	0,51 mm h^{-1}	0,56 mm h^{-1}	0,59

RESULTS AND DISCUSSION

Mean and median ϕ_v , determined from the September and October data sets separately are reported in Table 8.1. Clearly the mean and median values of ϕ_v remained virtually unchanged throughout both growing stages.

A skewed frequency distribution (Fig. 8.2) pertained when all data sets i.e. September plus October, were considered.

A value of ϕ_v approximately equal to 0,04 m s^{-1} was found to occur most frequently (15% of values). This together with the skewed pattern suggests Van Zyl and de Jager (1987) were justified in adopting the value of ϕ_v of 0,03 m s^{-1} found by Russell (1980).

Next, consequences of adopting one of ϕ_v = 0,03 m s^{-1}, ϕ_v = 0,04 m s^{-1} or ϕ_v = 0,06 m s^{-1} or ϕ_v = 0,08 m s^{-1} were investigated. Table 8.2 compares AED_p measured with AED_p estimated for each assumption. Hourly meteorological data for October, obtained from the automatic weather station and Eq. 8.1 were used is the calculations. The accuracy obtained with both median (0,06 m s^{-1}) and mean (0,08 m s^{-1}) was superior to that found when using ϕ_v = 0,03 m s^{-1} and ϕ_v = 0,04 m s^{-1} when calculating AED_p using Eq. 8.1. Excellent agreement between AED_p measured and AED_p calculated, with ϕ_v = 0,08 m s^{-1}, is illustrated in Fig. 8.3.

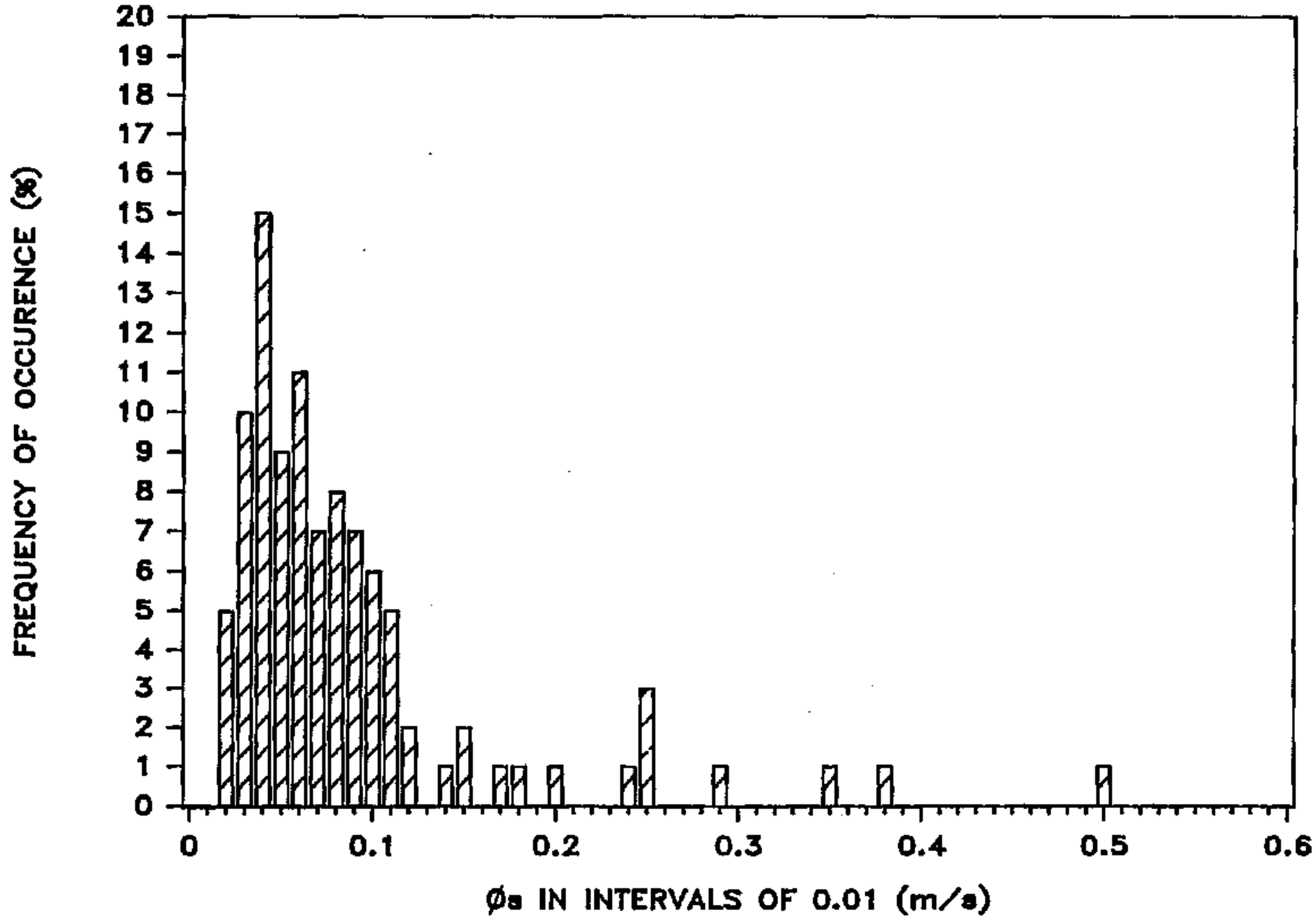

FIG. 8.2 - Frequency distribution of the 100 hourly values of the canopy surface conductance, ϕ_v, calculated from Eq. 8.12 using all the data from September and October

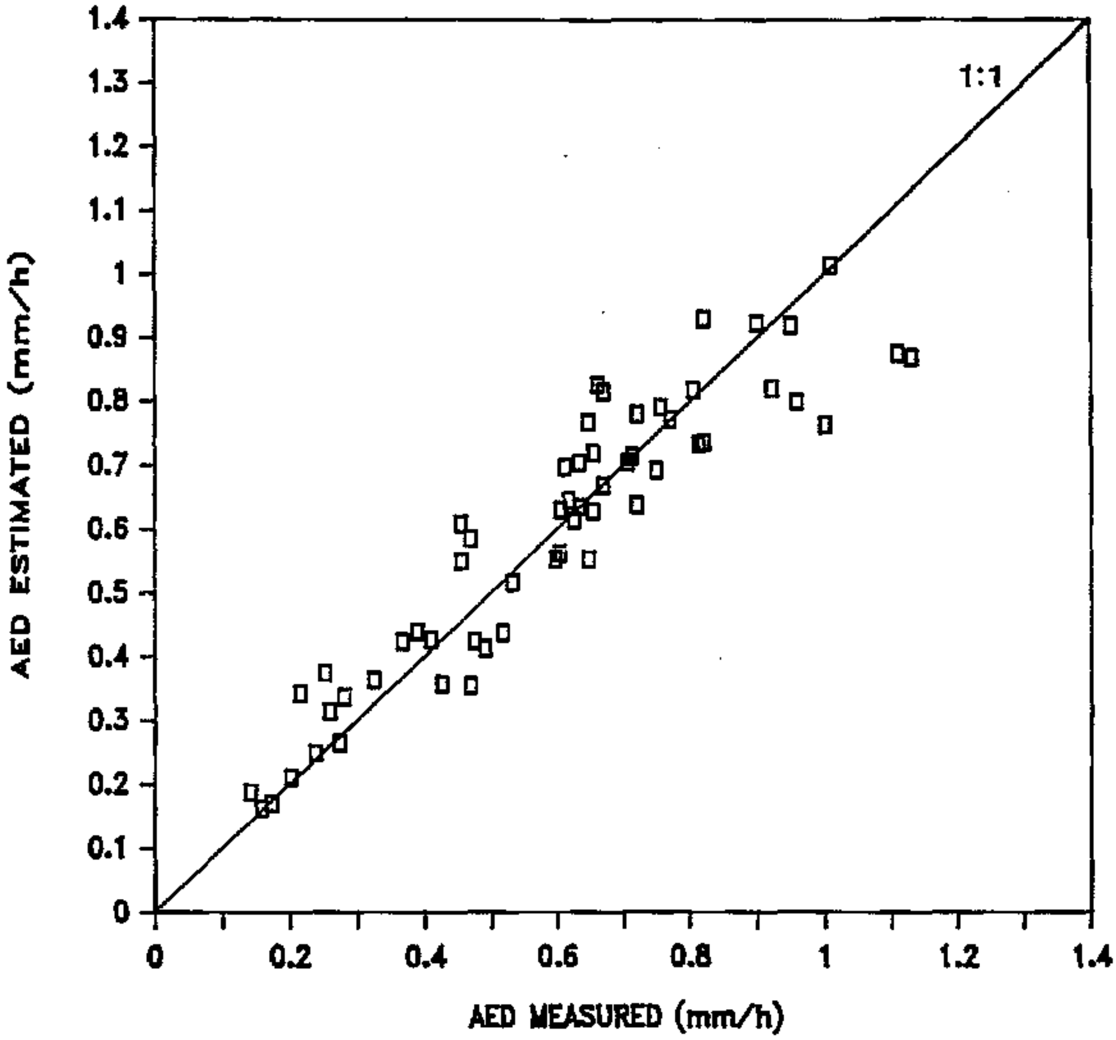

FIG. 8.3 - A comparison of AED_p measured with AED_p calculated from Eq. 8.1. Weather data from an automatic weather station and ϕ_v = 0,08 m s^{-1} were used for the calculations.

In the 1985 study, Van Zyl and De Jager (1987) using ϕ_v = 0,03 m s^{-1} in Eq. 8.1, obtained an index of agreement between measured and calculated AED_p of 0,97. The slightly reduced value in the index of agreement of 0,91, here reported for ϕ_v = 0,03 m s^{-1}, is explained by use of micrometeorological data during 1985 as opposed to data from the automatic weather station in this study. Furthermore, windspeed was measured within the wheat field at a height of 1,5 m above ground level in 1985. In this study windspeed was measured at a height of 3,15 m above an adjacent short grass surface.

Table 8.3 reports results of comparisons between ϕ_v and each of the weather elements Q_n, u(z), δ_e and T_a.

The low, statistically insignificant correlation coefficients (r) between ϕ_v and Q_n, u(z), δ_e and T_a of 0,13; 0,07; -0,16 and -0,12 respectively suggest that ϕ_v is totally independent of these weather elements.

The method of determining ϕ_v here described, is preferred to that outlined by Choudhury and Idso (1985), because it eliminates the need to measure canopy surface temperature, T_c. Measurement of T_c, utilizing an infra-red thermometer is always difficult as it is influenced by concomitant weather (Berliner, Oosterhuis and Green (1984).

TABLE 8.3 - Correlation of mean hourly values of ϕ_v and mean hourly values of Q_n, $u(z)$, δ_e and T_a respectively.

STATISTICAL PARAMETERS	PARAMETER VALUE			
	Q_n	$u(z)$	δ_e	T_a
	($W\ m^{-2}$)	($m\ s^{-1}$)	(Pa)	(^oC)
n	87	87	87	87
Correlation coefficient (r)	0,13	0,07	-0,16	-0,12

CONCLUSIONS

Canopy surface conductance, ϕ_v, for a wheat crop was determined using the Penman-Monteith equation (Monteith, 1973), hourly values of the necessary weather elements and simultaneous lysimetric measurements of AED_p. Mean and median ϕ_v calculated from 100 determinations were 0,09 and 0,06 m s^{-1} respectively. A left skewed frequency distribution of ϕ_v was obtained. The most frequent ϕ_v was 0,04 m s^{-1}. It occurred in 15% of the cases.

Excellent agreement was obtained between AED_p measured and AED_p estimated, using the Penman-Monteith formula (Monteith, 1973), weather data from an automatic weather station and either ϕ_v = 0,08 m s^{-1} or ϕ_v = 0,06 m s^{-1}. Weather data used in this test were collected in October.

Net radiation, windspeed, air temperature and vapour pressure deficit were shown to have no influence on the behaviour of ϕ_v.

These results proved that a constant value for ϕ_v and measurements from an automatic weather station in the Penman-Monteith equation (Monteith, 1973) provide accurate estimates of AED for a complete wheat canopy.

CHAPTER 9

DETERMINATION OF THE RATIO OF UPPER LIMIT PLANT EVAPORATION RATE TO E_o

An interesting and useful new conceptualization of AED has evolved from this study. AED for a natural vegetation surface in its current state has been defined and determined in previous chapters. The ratio of upper limit plant evaporation to E_o (k_{vm}) is an important component of AED. Accurate determination thereof is therefore imperative.

According to De Jager and Van Zyl (1989) (See also Chapter 2) AED is given mathematically by

$$AED = k_c\ E_o \qquad ..(9.1)$$

where

$$k_c = k_{vm}\ F_h\ F_l + k_{sm}\ F_g\ (1-F_l) \qquad ..(9.2)$$

Assuming that $k_{vm} = k_{sm}$ and $F_h = 1$ for optimal water supply Eq. 9.2 reduces to

$$k_c = (F_l + F_g(1 - F_l))\ k_{vm} \qquad ..(9.3)$$

or

$$k_c = F\ k_{vm} \qquad ..(9.4\ )$$

where

$$F = F_l + F_g(1 - F_l) \qquad ..(9.5)$$

Eq 9.1 can now be rewritten as

$$k_{vm} = AED/FE_o \qquad ..(9.6)$$

The objective of this study was to determine k_{vm}, the ratio of upper limit plant evaporation rate to E_o, from an incomplete wheat cover. A range of LAI of 0,2 through 3,0 was investigated.

MATERIALS AND METHODS

In Eq 9.6 AED and E_o were measured daily in lysimeters. F was calculated from Eq 9.5 using procedures described below.

F_g in Eq 9.5 was determined from

$$Fg = e^{-0,4D} \qquad ..(9.7)$$

where D is the time elapsed in days since the previous irrigation or rainfall > 5 mm (De Jager *et al*, 1982).

F_l in Eq 9.5 was calculated from values of leaf area index, LAI, measured viz.

$$F_l = 0,186\ \text{LAI} \quad \text{(De Jager } et\ al\text{, 1987)} \qquad ..(9.8)$$

It was assumed here that $F_l = 0,1$ for LAI < 0,2 and $F_l = 1$ for LAI > 5

The study was carried out during 1988 on the experimental plot on West Campus of the University of the Orange Free State. The entire of the experimental plot was supplied with adequate water to ensure maximum evaporation rate. Thirty-one data sets of measured AED and measured E_o were used. The study was terminated when LAI = 2,7, because rot developed in the wheat lysimeter.

The slope of the straight line (forced through zero) resulting from regression of AED against FE_o was determined. The slope represents k_{vm}.

RESULTS AND DISCUSSION

A correlation coefficient of 0,85 between AED and FE_o was obtained. The slope through the origin (forced through origin), representing k_{vm}, was 1,11. Maree (1989) reported a value of 1,10 ±0,13 for k_c for complete wheat cover. In latter case $k_c = k_{vm}$. Hence the two experiments support a hypothesis for constant k_{vm} throughout the early and mid-growing season. This value 1,10 ±0,13 was obtained from the ratio of hourly measured AED to hourly measured E_o.

CONCLUSION

The ratio of upper limit plant evaporation to E_o was found to be 1,11 for incomplete wheat cover.

The equality of k_{vm} here (1,11 and 1,01 ±0,13) suggests that k_{vm} is constant through the whole of the growing season.

CHAPTER 10

SUMMARY AND CONCLUSIONS

This study commenced with theoretical analysis of factors influencing evaporation from natural and artificial surfaces.

It was shown in Chapter 2 that utilization of a single crop evaporation coefficient is incorrect. Two coefficients are required, viz. a coefficient reflecting soil surface drying and a coefficient accounting for degree of vegetative cover. The sum of these two coefficients multiplied by evaporation from a reference crop leads to a new concept of upper limit evaporation viz. atmospheric evaporative demand, AED. This concept as defined here is completely general and physically determined by atmospheric, plant and soil factors. All previously used concepts such as total evaporation, potential total evaporation, reference total evaporation, maximum total evaporation and basal plant evaporation are accounted for.

For practical application of this AED concept, reliable estimates of evaporation from a reference crop short grass surface, E_o, are required. Accurately simulations of E_o were shown to be possible using the Penman-Monteith equation, micrometeorological weather data and a canopy surface conductance of 0,08 m s^{-1}. The index of agreement, mean absolute difference and mean difference between simulated and measured E_o was 0,97; 0,05 mm h^{-1} and 0,01 mm h^{-1} respectively.

The possibility of estimating E_o from American Class A pan evaporimeter was tested. Calculating AED or E_o from daily A pan measurements, E_{pan}, was shown to be inaccurate. Pan measurements compared to measured AED for a LAI > 3 yielded an index of agreement and mean absolute difference of 0,89 and 1,03 mm d^{-1} respectively. Corresponding values between E_{pan} measured and E_o measured was 0,74 and 1,49 mm d^{-1}. These results together with theoretical evidence outlined in Chapters 1 and 2, suggest that uncorrected pan measurements should not be used as a measure for AED, especially for experimental purposes.

Poor correspondence between pan and E_o estimates is largely attributable to heat stored in the A pan during daylight. Correcting for this, significantly improved the relationship. Index of agreement of 0,88 and a mean absolute difference of 1,00 mm were found. Application of this correction factor requires two A pan readings daily. Firstly, in the morning, when stomates of the crop under consideration open, and secondly, in late afternoon when closure of the stomates occurs. In addition air and water temperature need to be monitored continuously. These temperatures are needed to calculate the slope of the saturated water vapour density temperature curve and the energy stored in the A pan. It is emphasized that this correction is only valid for daylight conditions which may be conveniently applied.

Atmometers are evaporimeters in practice. It was found that Piché and carborundum atmometer, properly shielded from long and short wave radiation, can be used with confidence to measure the aerodynamic component (AC) in the Penman-Monteith equation.

Furthermore empirically derived expression for AC, utilizing these atmometers and estimates of the energy component in the Penman-Monteith equation can be used to accurately estimate daily AED. The index of agreement and mean absolute difference between daily AED measured and AED estimated, was 0,98 and 0,51 mm respectively. Of major significance is the fact that use of atmometers obviates measurements of windspeed and vapour pressure deficit.

It was decided that the reliable relationship found to exist between E_o estimated by Penman-Monteith equation and atmometer and actual E_o (see Chapter 3) provided the best means of constructing correction factors for atmometers. This technique requires accurate estimates of a canopy surface conductance, for complete vegetation, ϕ_v. Penman-Monteith equation weather data from an automatic weather station and a lysimeter were used for this purpose. Results originating from this work indicated that the value $\phi_v = 0{,}08\ m\ s^{-1}$ can be used with confidence in the Penman-Monteith equation together with weather data from an automatic weather station to estimate AED.

The ratio of upper limit plant evaporation to reference crop evaporation, k_{vm}, (as defined in Chapter 2) was determined for incomplete wheat crop cover. The value k_{vm} = 1,11 determined in Chapter 9 excellently agrees with the value of 1,10 ±0,13 determined by Maree (1989) for complete wheat cover. These results imply that k_{vm} is a constant over the entire wheat growing season.

Finally, and briefly:

- It was once again proved that, with regard to accuracy and scientific finesse, Penman-Monteith equation and weather data from automatic weather station is the ultimate technique for estimating reference crop evaporation.

- A pan evaporation, measured daily, is an unreliable estimator of both E_o and AED.

- For daylight, A pan measurements can be corrected to estimate E_o, with acceptable accuracy. However, measurements of pan water temperature and air temperature, are needed to calculate the correction factor. A comprehensive correction factor for A pan observations thus requires extensive micrometeorological measurements. Instead E_o could more accurately be estimated using Penman-Monteith equation and weather data from automatic weather station.

- Substitution of energy and aerodynamic components in the Penman-Monteith equation by empirical derived equations was shown to estimate E_o with the same degree of accuracy as did the Penman-Monteith equation (Thom, 1975). In the energy component (Q_n - G) was substituted by aS(t)+b while the aerodynamic component was replaced by cE + d. S(t), E, a, b, c and d represent total radiation flux density, free water evaporation from atmometer surfaces and appropriate regression constants respectively. Hence, atmometer correction factors produced by this study constitute substitution of empirical relationship for energy component, and transformed atmometer reading for aerodynamic component in the Penman-Monteith equation.

- A crop surface conductance is required in the correction factor for use with evaporimeters. A value equal to 0,08 m s^{-1} was shown to provide acceptable accuracy.

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Members :	Dr	G C Green	Water Research Commission
	Mr	D S van der Merwe	Water Research Commission
	Dr	A L du Pisani	S.A. Weather Bureau
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