Canopy surface conductance of unstressed wheat and its weather dependence

WH van Zyl*, JM de Jager, CJ Maree, and A Singels
University of the Orange Free State, PO Box 339, Bloemfontein 9300, South Africa

Abstract

The Penman-Monteith equation, together with weather data from an automatic weather station and concurrent measurements of atmospheric evaporative demand (AED) on a wheat lysimeter were used to calculate mean and median hourly values of wheat canopy conductance (ϕ_v). Mean and median hourly values were 0,08 and 0,06 m s^{-1} respectively, although the value 0,04 m s^{-1} occurred most often, i.e. 15% of the time.

Values of AED calculated from the Penman-Monteith equation, utilising ϕ_v equal to 0,08 or 0,06 m s^{-1} respectively, were compared to measured values of AED. Statistical tests yielded high index of agreement (IA) and low mean absolute difference (MAD). The IA and MAD for mean and median values of ϕ_v were 0,96; 0,07 mm h^{-1} and 0,95; 0,07 mm h^{-1} respectively.

It was shown that net radiation, wind speed, air temperature and vapour pressure deficit independently had no influence on the behaviour of ϕ_v.

List of symbols

AED	- Atmospheric evaporative demand from a wheat crop surface (mm h^{-1})
AED$_0$	- Atmospheric evaporation demand on full vegetative cover of a given crop, assuming canopy conductance (ϕ_v) equals infinity (mm h^{-1})
AED$_p$	- Atmospheric evaporative demand of full vegetative cover of a given crop, provided with adequate soil water (mm h^{-1})
C_p	- Specific heat of air (J kg^{-1} °C^{-1})
d	- Zero displacement level (m)
F	- Normalised crop factor
G	- Soil heat flux density (W m^{-2})
H	- Available energy (W m^{-2})
h	- Crop height (m)
k	- Von Karman's constant (0,41)
LAI	- Leaf area index
Q_n	- Net radiation (W m^{-2})
r_v	- Canopy resistance to water vapour exchange for a complete vegetative cover (s m^{-1})
s	- Slope of the saturated vapour pressure temperature curve (Pa °C^{-1})
S(t)	- Total radiant flux density (W m^{-2})
T_a	- Air temperature (°C)
T_c	- Canopy surface temperature (°C)
u(z)	- Wind speed at height 3,15 m above ground level (m s^{-1})
z	- Height above ground level (here 3,15) (m)
z_0	- Roughness parameter (m)
α	- Solar elevation (degree)
γ	- Psychrometric constant (Pa °C^{-1})
γ^*	- $\gamma(1 + \phi_a/\phi_v)$(P$_a$ °C^{-1})
δe	- Saturated vapour pressure deficit (Pa)
ρ	- Air density (kg m^{-3})
τ	- Transmission coefficient
ϕ_a	- Aerodynamic conductance of the atmosphere (ms^{-1})
ϕ_1	- Individual leaf stomatal conductance (m s^{-1})
ϕ_v	- Surface conductance of water vapour exchange for a complete vegetative cover (m s^{-1})

Definition

An important concept utilised 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) assuming 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 (1965) satisfactorily generalised the theory by introducing canopy surface resistance, r_v. In this study, for convenience, the term surface conductance, ϕ_v, will 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, *et al.* (1982) Bristow and Van Rooyen (1982), viz.:

$$\mathrm{AED} = F\{(sH + \rho C_p \delta_e \phi_a) / (s + \gamma^*)\} \qquad ...(1)$$

where :

$$H = Q_n - G \qquad ..(2)$$

$$\phi_a = k^2 u(z) / \{\ln(z-d)/z_o\}^2 \qquad ..(3)$$

$$\gamma^* = \gamma(1 + \phi_a / \phi_v) \qquad ..(4)$$

$$\left.\begin{aligned} d &= 0{,}63\ h & ..(5)\\ z_o &= 0{,}13\ h & ..(6)\end{aligned}\right\} \text{(Monteith, 1973)}$$

and $\phi_v = 1 / r_v$ ..(7)

---

*To whom all correspondence should be addressed.

Received 17 May 1989; accepted in revised form 19 December 1989

F, a normalised 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, and F in Eq. 1 equalled unity.

While measurement of the weather variables in Eq. 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.:

$$\phi_v = \phi_a[\{1 + (s/\gamma)\}\{(AED_o/AED_p) - 1]^{-1} \quad ..(8)$$

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 $\phi_v = 0{,}03 \text{ m s}^{-1}$, provided soil water deficit below field capacity was < 30 mm. Rate of evaporation, AED_p, was calculated from rainfall measurements and changes in soil water content measured with a neutron probe. Corrections were made for estimated drainage.

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

$$AED_p = Q_n(1 - \Gamma) - \rho C_p(T_c - T_a)\phi_a \quad ..(9)$$

Because F equalled unity and vegetation received adequate water, this value could be substituted on the left hand side of Eq. 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:

$$\Gamma = \exp(-LAI/2\sin\alpha) \quad ..(10)$$

Eq. 10 applies for canopies with randomly oriented leaves such as wheat (Denmead, 1976). The accuracy of AED_p in Eq. 9 had been tested against measurements from a 1 m² weighing lysimeter planted to wheat. Good correlation (r = 0,97) was obtained. A maximum value of $\phi_v = 0{,}03 \text{ m s}^{-1}$ for ϕ_v was reported.

Bristow (1980) measured stomatal conductance hourly on one thousand individual wheat leaves, using a non-steady state autoporometer. Reported values (Bristow, 1980 and Bristow *et al.*, 1981) were $0{,}0033 \text{ m s}^{-1}$ for wet soil conditions on sunny days at 13:00. This value remained almost constant throughout daylight. Other measurements (Van Zyl *et al.* (1987) unpublished results) of stomatal conductance of wheat leaves using steady state autoporometer yielded values of 0,001 and $0{,}005 \text{ m s}^{-1}$.

These data suggest that individual leaf measurements of stomatal conductance differ substantially from whole canopy surface conductance estimates obtained from weather measurements and Eqs. 1, 8, 9 and 10.

It is, however, logical to expect canopy conductance to relate to leaf stomatal conductance. The differences quoted here can be explained by the arrangement of leaves in the canopy, so that their combined effect realises an effective canopy conductance for the cropped surface as a whole.

Van Zyl and De Jager (1987) successfully adopted the Russell (1980) value of $\phi_v = 0{,}03 \text{ m s}^{-1}$ in validation of the Penman-Monteith equation. From tests against lysimeter measurements for a wheat crop, high index of agreement (Willmott, 1982) and mean absolute difference of 0,97 and $0{,}09 \text{ mm h}^{-1}$ respectively were obtained. This result suggested that determination of ϕ_v is possible utilising Eq. 1, lysimeter values of AED_p and meteorological measurements.

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.:

$$\phi_l = 0{,}0005 + 0{,}00002\ Q_n \ (\text{m s}^{-1}) \quad ..(11)$$

The correlation coefficient was 0,90 and standard error of estimate $0{,}0011 \text{ m s}^{-1}$. This relationship was derived using 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 objectives of the present study were:

- to determine ϕ_v for a wheat crop through the daylight period (08:00 to 17:00);
- to verify the use of these values of ϕ_v in Eq. 1; and
- 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 AED = AED_p, which means that o_v can be expressed by rearranging Eq. 1. Thus:

$$\phi_v = (\phi_a \ \gamma AED)/(sH + \rho C_p \ \delta_e \ \phi_a - AED(s + \gamma)) \quad ..(12)$$

In the present study, AED in Eq. 13 was measured in the 10 m² lysimeter on the West Campus, University of the Orange Free State. The depth and resolution thereof are 2 m and 0,07 mm respectively.

To enable use of solar, instead of net radiation measurements, the empirical equation of Van Zyl *et al.*, 1988 was used, viz.:

$$H = 0{,}75\ S(t) - 72 \text{ W m}^{-2} \quad ..(13)$$

The correlation coefficient associated with the initial development of Eq. 13 for Bloemfontein 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. Wind speed was measured at a height of 3,15 m. Measurements at this height were assumed to be representative of the boundary layer above the wheat crop. The validity of this assumption was proved by Maree (1989). Allan (1986) utilised a similar approach. Air temperature and relative humidity were measured at 1,5 m in a Stevenson screen and total radiant flux density at a height of 3 m. The latter was used to estimate available energy, H, using Eq. 13.

Experimentation proceeded from September through October 1987 on the West Campus of the University of the Orange Free State. Geographical coordinates of the site are latitude 29°6'W and longitude 26°15'S. Wheat *(Triticum vulgare)*, cultivar SST44, was studied during the time when the leaf area index increased from 3 to 8 and giving 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 proceeded as per definition of De Jager and Van Zyl (1989) at all times. Hence surface conductance, ϕ_v, was a maximum during daylight for the duration of the experiment.

TABLE 1
MEAN AND MEDIAN ϕ_v CALCULATED FROM SETS OF WEATHER DATA, LYSIMETER OBSERVATIONS AND EQ. 12.

Data sets	Canopy surface conductance, ϕ_v	
	Mean value	Median value
	(m s^{-1})	(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

Determination of ϕ_v

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 carried out separately for October and September. They are reported in Table 1. This was done in order to ascertain whether the mean and median of ϕ_v differed between tillering and soft dough growth stages.

Verification of ϕ_v values

Mean and median values of ϕ_v, determined as above, during September were each substituted into Eq. 1. The equations were then used to calculate AED from 48 hourly independent sets of weather data collected during October. Calculated AED values were then compared to lysimeter measurements of AED.

Willmott's (1982) index of agreement, mean and absolute differences were calculated together with regression constants and correlation coefficients and are reported in Table 2.

Weather influence on ϕ_v

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

Results and discussion

Mean and median ϕ_v, determined from the September and October data sets, are reported in Table 1. Clearly the mean and median values of ϕ_v remained virtually unchanged throughout both growing stages. A skewed frequency distribution (Fig. 1) 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

TABLE 2
RESULTS OF THE STATISTICAL TESTS CARRIED OUT BETWEEN AED MEASURED AND AED ESTIMATED FROM EQ. 1 USING HOURLY METEOROLOGICAL DATA FOR OCTOBER, OBTAINED FROM AN AUTOMATIC WEATHER STATION. THE CANOPY SURFACE CONDUCTANCES USED WERE ϕ_v = 0,03 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 values			
	ϕ_v = 0,03 m s^{-1}	ϕ_v = 0,04 m s^{-1}	ϕ_v0,06 m s^{-1}	ϕ_v = 0,08 m 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^{11}	0,07 mm h^{-1}	0,07 mm h^{-1}
Measured AED (x-axis)	0,59 mm h^{-1}	0,59 mm h^{-1}	0,59 mm h^{-1}	0,59 mm h^{-1}
Estimated AED (y-axis)	0,48 mm h^{-1}	0,51 mm h^{-1}	0,56 mm h^{-1}	0,59 mm h^{-1}

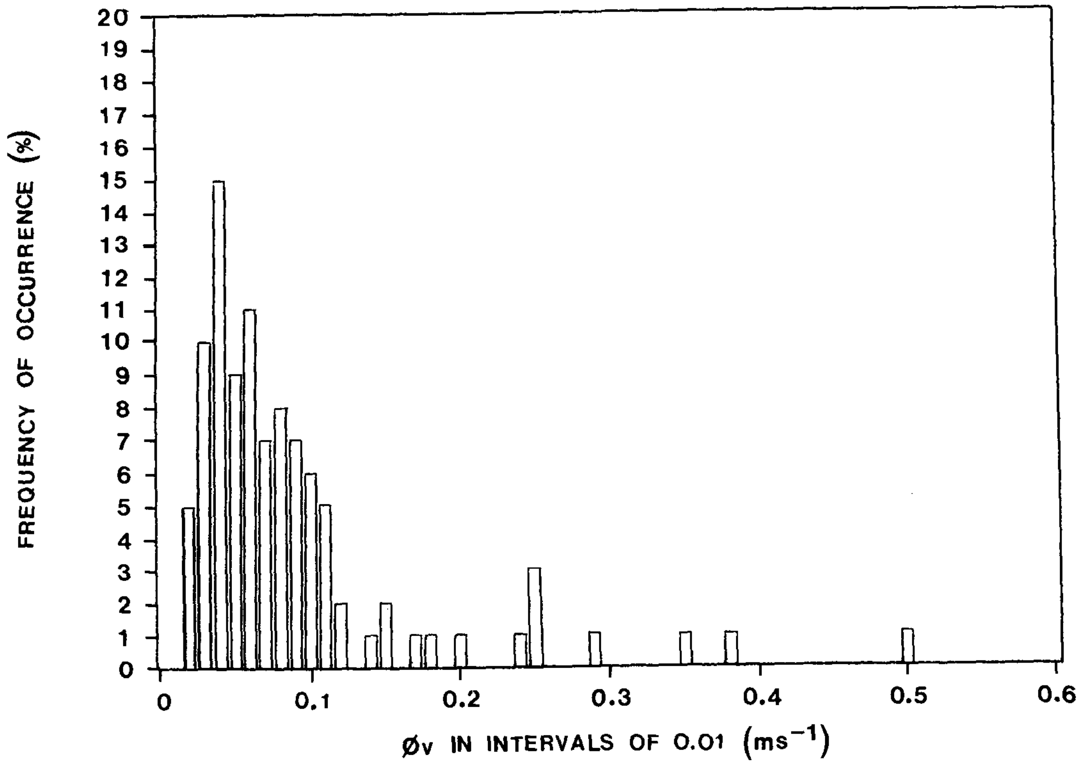

Figure 1

Frequency distribution of 100 hourly values of the canopy surface conductance, ϕ_v, calculated from Eq. 12 using all the data from September and October.

skewed pattern suggests that 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, the 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 2 compares AED measured with AED estimated for each assumption. Hourly meteorological data for October, obtained from the automatic weather station and Eq. 1 were used in these 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 using Eq. 1. Excellent agreement between AED measured and AED calculated, with ϕ_v = 0,08 m s^{-1}, is illustrated in Fig. 2.

In a similar study in 1985, Van Zyl and De Jager (1987) using ϕ_v = 0,03 m s^{-1} in Eq. 1, obtained an index of agreement between measured and calculated AED of 0,97. The slightly reduced value in the index of agreement of 0,91, reported here 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 used in this study. Furthermore, wind speed was measured above the wheat field at a height of 1,5 m above ground level in 1985. In this study wind speed was measured at a height of 3,15 m above an adjacent short grass surface. Utilisation of Eq. 1 and weather elements to estimate AED in practice for say irrigation scheduling, would demand wind speed measurements outside the boundary layer of the underlying surface. It is assumed that the latter will not influence the wind speed measured at a height of 3,15 m. This means that a single weather station could be used to cover a large region of, say, 50 km in diameter. In such case then ϕ_v = 0,08 m s^{-1}, instead of 0,03 m s^{-1}, should be used in Eq. 1 to estimate AED.

Table 3 reports results of comparisons between ϕ_v and each of the weather elements Q_n, u(z),δ_e and T_a. 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 were obtained. These suggest that ϕ_v is totally independent of these weather elements.

The relationship between o_l and Q_n found by Denmead and Millar (Eq. 11) contradicts our findings. However, the left skewed distribution of ϕ_v (Fig. 1) is possibly attributable to the combined effect of Q_n, u(z),δ_e and T_a, which were used as inputs to calculate ϕ_v.

The method of determining ϕ_v described here, 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, utilising an infrared thermometer is problematical as it is influenced by concomitant weather (Berliner *et al.*, 1984).

TABLE 3
CORRELATION OF AND REGRESSION COEFFICIENTS OBTAINED FROM COMPARISON OF MEAN HOURLY VALUES OF ϕ_v WITH MEAN HOURLY VALUES OF Q_n, u(z) δ_e and T_a RESPECTIVELY

Statistical	**Parameter value**			
	Q_n	**u(z)**	δe	**T_a**
	(W m^{-2})	(m s^{-1})	(Pa)	(°C)
n	87	87	87	87
Slope	6,3x10^{-5}	5,6x10^{-3}	-3,8x10^{-3}	-2,8x10^{-3}
Intercept	0,0605	0,0639	0,1156	0,1326
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. 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}, occurring in 15% of the cases.

Excellent agreement was obtained between AED measured and AED 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.

Variation in net radiation, wind speed, air temperature and vapour pressure deficit alone were shown to have no influence on the behaviour of ϕ_v.

These results unequivocally prove that a constant value for o_v of 0,08 m s^{-1} and measurements from an automatic weather station in the Penman-Monteith equation (Monteith, 1973) provide accurate estimates of AED for a complete wheat canopy.

Acknowledgements

Financial support from the Water Research Commission is gratefully acknowledged.

References

ALLAN, RG (1986) A Penman for all seasons. *J. Irrig. Drain. Engineers* **112** 348-368.

BERLINER, P, OOSTERHUIS, DM and GREEN, AC (1984) Evaluation of the infrared thermometer as a crop stress detector. *Agric. For. Meteorol.* **31** 219-230.

BRISTOW, KL (1980) Weather control of wheat plant water relations. M.Sc. Thesis, University of the Orange Free State. pp 146.

BRISTOW, KL, DE JAGER, JM and VAN ZYL, WH (1981) The leaf water potential - Leaf diffusive resistance relationship of a wheat crop. *Agrochemophysica* **13** 21-23.

CHOUDHURY, BJ and IDSO, SB (1985) Evaluating plant and canopy resistances of field-grown wheat from concurrent diurnal observations of leaf water potential, stomatal resistance, canopy temperature and evapotranspiration flux. *Agric. For. Meteorol.* **34** 67-76.

DE JAGER, JM, VAN ZYL, WH, BRISTOW, KL and VAN ROOYEN, A (1982) Besproeiingskedulering van koring in die besproeiingsgebied van die Vrystaatstreek. Project Report for the Water Research Commission. 125 pp.

DE JAGER, JM and VAN ZYL, WH (1989) The atmospheric evaporative demand and evaporation coefficient concepts and their application. *Water SA* **15** 103-110.

DENMEAD, OT (1976) Temperate cereals. In: JL Monteith, *Vegetation and the Atmosphere*, Vol. **2**. Academic Press, London. 1-31.

DENMEAD, OT and MILLAR, BD (1976) Field studies of the conductance of wheat leaves and transpiration. *Agronomy J.* **68** 307-311.

MONTEITH, JL (1965) Evaporation and environment. In: GE Fogg (Editor) *The State and Movement of Water in Living Organisms.* Symp. Soc. Exp. Biol. **19** 205-234. Academis Press, New York.

MONTEITH, JL (1973) *Principles of Environmental Physics.* Arnold, London, 241 pp.

MAREE, CJ (1989) Gewasfaktore van koring t.o.v. 'n verwysingsgewas.

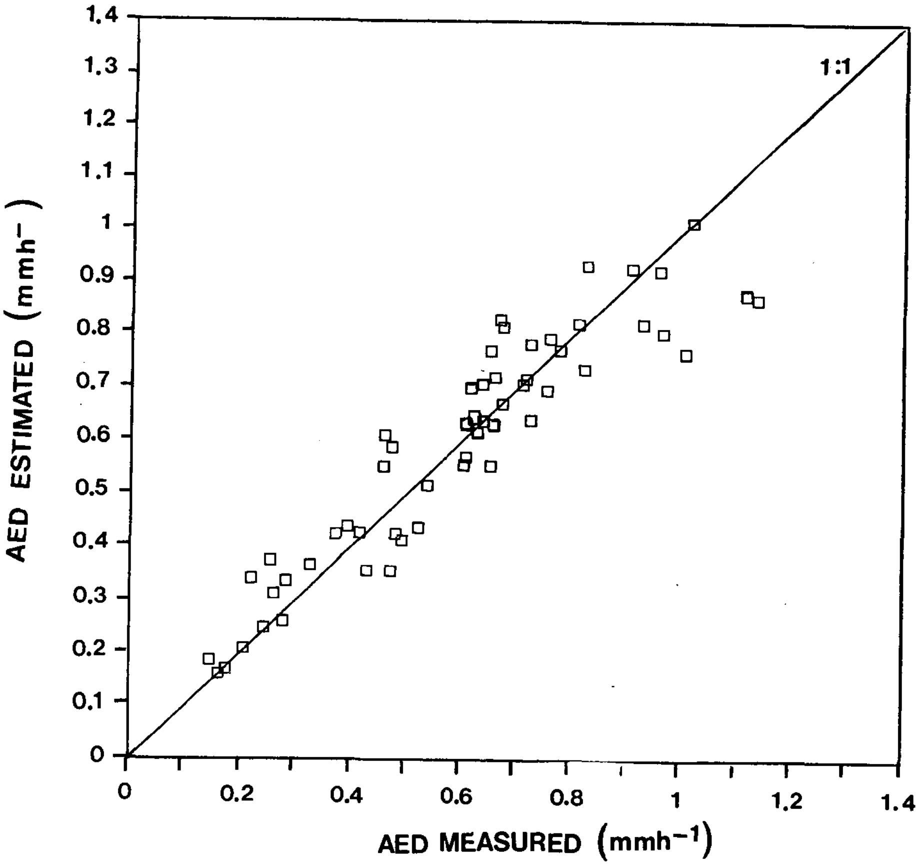

Figure 2
A comparison of AED measured with AED calculated from Eq. 1. Weather data for October from an automatic weather station and ϕ_v = 0,08 m s^{-1} were used for the calculations.

M.Sc. Agric. Thesis, University of the Orange Free State. 68. pp.

PENMAN, HL (1948) Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. London* **A193** 120-146.

RUSSELL, G (1980) Crop evaporation and surface resistance and soil water status. *Agric. Meteorol.* **21** 213-226.

VAN ZYL, WH and DE JAGER, JM (1987) Accuracy of the Penman-Monteith equation adjusted for atmospheric stability. *Agric. For. Meteorol.* **41** 57-64.

VAN ZYL, WH, DE JAGER, JM and MAREE, CJ (1988) A simple accurate method of estimating maximum total evaporation from a wheat crop during the daylight period. *SA J. Plant Soil* **5** 114-116.

WILLMOTT, CJ (1982) Some comments on the evaluation of model performance. *Bul. Am. Meteorol. Soc.* **64** 1309-1313.