Use of evaporimeters for estimating maximum total evaporation

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Abstract

This study reviews the theory of evaporation from evaporimeters and its relationship to maximum total evaporation, Em.

A Penman type mathematical model comprising both an energy and an aerodynamic component is proposed to explain the mechanism of evaporation from the A-pan and evaporation from a reference crop (Er).

The use of a Piché evaporimeter or an evaporating carborundum surface to simulate the aerodynamic component in the Penman-Monteith equation seems a most promising alternative. This together with the evaluation of the energy term, using sunshine duration and air temperature data could result in reliable estimation of Em.

Favourable comparison between one or both of these techniques with Em should inevitably lead to better planning and management for irrigation scheduling.

List of symbols

Em	–	Maximum total evaporation from an infinitely large wheat crop surface (mm/h)
Er	–	Maximum total evaporation from a reference crop supplied with adequate water (mm/h)
Ep	–	Evaporation from the American Class A-pan (mm/d)
Ee	–	Evaporation from an artificial evaporimeter (mm/d)
Ec	–	Evaporation from a capillary evaporimeter (mm)
kp	–	The ratio of Em to Ep (Em/Ep)
ke	–	The ratio of Em to Ee (Em/Ee)
kr	–	The ratio of Er to Ee (Er/Ee)
s	–	Slope of the saturated water vapour density-temperature curve (mbar/°C)
γ	–	Psychrometric constant (mbar/°C)
ρ	–	Density of air (kg/m^3)
Cp	–	Specific heat of air (J/kg.°C)
Qn	–	Net radiation over vegetation (W/m^2)
G	–	Soil heat flux density (W/m^2)
δe	–	Vapour pressure deficit (mbar)
λ	–	Latent heat of evaporation (J/kg)
Øa	–	Aerodynamic conductance of the atmosphere (m/s)
Øs	–	Whole crop surface conductance for water vapour exchange (m/s)
ra	–	Aerodynamic resistance of the atmosphere (s/m)
zo	–	Surface roughness parameter (m)
d	–	Displacement level (m)
k	–	Von Karman's constant
u(z)	–	Windspeed at height z (m/s)
Φ	–	Atmospheric stability function
Ri	–	Richardson number
FT	–	First term or energy component in the Penman-Monteith equation (W/m^2)
ST	–	Second term or aerodynamic component in the Penman-Monteith equation (W/m^2)
F	–	The crop evapotranspiration coefficient
Fl	–	Component in F accounting for the leaf area index
Fg	–	Component in F accounting for evaporation of water from the soil surface
Fh	–	Component in F accounting for the plant water status
f(u)	–	A wind function (mm/d.mbar)
Cs	–	Saturated water vapour density at surface temperature (kg/m^3)
Cz	–	Ambient water vapour density at height Z (kg/m^3)
CD	–	Drag coefficient
CR	–	Convection ratio
Qnc	–	Net radiation over the pan (mm/d)
S	–	Rate of heat storage in the pan (mm/d)
fvp(u)	–	Penman's wind speed function for vegetation (mm/(d mbar))
fvc(uc)	–	Penman's wind speed function for the A-pan (mm/d.mbar)
(δe)c	–	Vapour pressure deficit just above the pan water level (mbar)
Ts	–	Pan surface temperature (°C)
Tc	–	Air temperature at pan water surface level (°C)
Ep1	–	Estimated evaporation using the model of De Vries and Venema (1953) (mm/7h)
Ep2	–	Estimated evaporation using the model of Stigter and Uiso (1983) (mm/7h)
qd	–	Energy supply to the disc of the Piché atmometer (W/m^2)
ρw	–	Specific mass of water (kg/m^3)
λ	–	Latent heat of evaporation (J/kg)
hw	–	Heat transfer coefficient of water (W/m^2.°K)
D	–	Diffusivity of still air (m/s)
ν	–	Kinematic viscosity of air (m/s)
d'	–	Length scale of Piché disk evaporimeter (m)
ea	–	Vapour pressure of air (mbar)
es	–	Vapour pressure of air in contact with Piché surface (mbar)
Ta	–	Air temperature (°C)
Eps	–	Evaporation from a screen Piché atmometer (divisions)
Ea	–	Aerodynamic term in Penman's formula (mm/d)
Epse	–	Estimates of Em using Eps 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
Epen	–	Estimated evaporation using Penman's formula (mm/d)
Ec	–	Evaporation from the capillary evaporimeter (mm)
To	–	Surface temperature of vegetation (°C)
Iv(h)	–	Extra-terrestrial radiation flux density for a solar elevation h (W/m^2)
h	–	Solar elevation (degrees)

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Io	–	Solar constant (W/m^2)
rv	–	Earth to sun radius vector
a(h)	–	Atmospheric transmissivity for direct radiation
p	–	Atmospheric pressure (mbar)
w	–	Precipitable water in the atmosphere in zenithal direction (mm)
td	–	Surface dewpoint temperature (°C)
dp	–	Dimensionless dust parameter
m	–	Optical air path, generally equal to cosec h, where h exceeds 10°
q(h)	–	Diffuse radiation (W/m^2)
Sv(h)	–	Direct vertical radiation (W/m^2)
St(h)	–	Total radiation (W/m^2)

Introduction

Estimates of wheat crop water use are indispensable to planning and scheduling of irrigation. The demand for soil water by vegetation is determined mainly by values of weather elements which constitute the atmospheric evaporation demand. The latter is often called the maximum total evaporation (Em). Em is defined as the rate of water use by transpiration from a crop, in its current stage of development, plus evaporation from the soil surface when the water content in the soil does not limit either water transfer process.

Common methods for approximating Em involve use of one or other evaporimeter. For example, the American Class A-pan provides a measure of the evaporation rate, Ep, from a circular water surface area of 1,13 m^2. The water depth is 250 mm. An approximation of Em for a given crop is obtained using the equation

$$Em = kp\ Ep \quad (1)$$

where:
kp is the appropriate coefficient for converting pan evaporation to maximum total evaporation. It is a function of crop growth stage and management practice.

Currently accepted kp values for use with the American Class A-pan have been collected and published by Green (1985). Problems exist with the use of such coefficients, however, as it has been found that kp values vary markedly from day to day and from one climatic zone to another and from season to season (Thom *et al.*, 1981 and Howell *et al.*, 1983).

Despite the fact that daily errors tend to compensate for one another over an irrigation cycle of a week or longer, the variations mentioned can and do lead to inefficient use of irrigation water (over or under-irrigation) with significant financial implications.

Errors in kp values arise from failure to account for interactions between evaporimeter design and exposure, crop architecture, atmospheric stability and the non-linear heat exchange relationships between ambient air and evaporimeter.

The lack of universality in ke values (i.e. ratios of Em to evaporation from evaporimeters in general), referenced to artificial, is due to the marked difference between the character and architecture of a growing crop and of the evaporimeters. Doorenbos and Pruitt (1983) are of the opinion that a more stable coefficient would result if k values are referenced to a surface more closely resembling a growing crop. For this purpose a short grass cover probably offers the best possibilities. Bearing in mind the various ratio's (k values) relevant to this study, it is best, at this stage, to clearly define them. Thus together with Eq. (1):

$$Er = kr\ Ee \quad (2)$$

and

$$Em = ke\ Ee \quad (3)$$

Em, Er, Ep and Ee are measurable quantities.

If the abovementioned shortcomings can be overcome, the use of evaporimeters could provide a simple, practical solution to a complex problem and may be expected to increase in the future. Because of this, there appears to be an urgent need for firstly, a set of, preferably simple, equations yielding appropriate factors which will remove the most significant variance inherent in the use of k values and evaporimeters for estimating atmospheric evaporative demand, and secondly, for an improved evaporimeter design which will reduce and perhaps even eliminate as many potential errors as possible.

The largest portion of the discrepancies introduced when using evaporimeters such as Class A evaporation pans to estimate Em probably result from the insensitivity of the evaporation pan to solar radiation as compared to the extreme sensitivity of crop evaporation to this weather element. It is to be expected therefore that correction factors for evaporation pans will be strongly dependent upon incoming solar radiation, or in particular, net radiation. Unfortunately only a sparse network of radiation stations is distributed throughout the irrigation areas of southern Africa. A substantial network of sunshine duration recorders does, however, exist. Hence the possible use of sunshine duration data instead of radiant flux density for correcting k values should also receive attention.

This study therefore, reviews the following topics relating to the use of evaporimeters for estimating maximum total evaporation:

- estimation for Er;
- review of evaporimeters, their physical characteristics and mechanisms of evaporation; and
- possible ways of utilising sunshine duration data in this type of study.

Estimation of Er using weather variables

Er is defined as the amount of water transpired in unit time from unit area of a reference crop.
The latter is defined as:
A short, green grass cover of uniform height which covers an area that has at least a 50 m radius. The grass must be supplied with sufficient water to prevent physiological plant water stress. The rate of transpiration of such a surface is determined entirely by prevailing weather conditions.

It is stipulated that a large grassed surface must surround the measuring point to ensure an equilibrium boundary layer. Monteith (1973) indicates 100 to 200 times the vegetation height to be an adequate fetch. The height of the grass being 0,05 m yields the fetch of 50 m on all sides here suggested.

In the event of measuring Er directly, the grass could be established in a container having a surface area of 5 m^2 and which is 0,5 m deep. Adequate provision for free water to drain out of the container is an absolute necessity since waterlogging influences transpiration. While the soil in the root zone should be close to field capacity the grassed surface itself should not be wet.

Er may be estimated using the Penman-Monteith formula (Thom, 1975). This in its simplest form is:

$$Er = 3\,600\,[sH + Cp\delta e\,\varnothing a]/\lambda[(s + \gamma^*)] \quad (4)$$

Where 3 600 ensured the coherency of units,

$$H = Qn - G \quad (5)$$

$$\gamma^* = \gamma\,(1 + \varnothing_a/\varnothing_s) \quad (6)$$

$$\varnothing_a = 1/ra \quad (7)$$

and

$$ra = \{\ln(z-d)/zo\}^2/k^2u(z) \quad (8)$$

In Eq. 8 zo and d are 0,001 and 0,007 m respectively (Monteith, 1973). It is assumed that $\varnothing_s$ equals 0,03 m/s (Russell, 1980).

These equations apply strictly to conditions of approximate atmospheric neutral stability. For stable and unstable conditions, Eq. 8 should be multiplied by a stability function, Φm. For stable conditions Lumley and Panofsky (1964), Munn (1966) and Webb (1979) developed the relationship:

$$\Phi m = (1 - 5\,Ri)^{-1,0} \text{ for } Ri > 0 \quad (9)$$

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

$$\Phi m = (1 - 16\,Ri)^{-0,25} \text{ for } Ri < 0 \quad (10)$$

Evaporimeters

Water surfaces

Evaporation rates from water held in suitable containers (pans) are frequently used for estimating Em. At first glance accurate measurements are convenient and easy from such equipment. Unfortunately both the energy and the aerodynamic component 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 Em. 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 (Doorenbos and Pruitt, 1983) 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 of the order of 5 to 8% compared to the 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 the radiation which is not reflected.
- Heat storage within the water in the pan can be appreciable. This induces additional evaporation during the day and particularly the night. Most crops naturally have little water loss by transpiration at night time due to stomatal closure.
- The existence of a markedly different turbulent temperature and humidity regime in the air immediatly above the surfaces (Thom *et al.*, 1981).
- Lateral heat transfer through the sides of the pan, may be considerable for pans (Thom *et al.*, 1981) but is not significant 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 (0,1 mm in diameter by 50 mm mesh), while reducing evaporation by approximately 10%, have to be employed in practice to prevent water consumption by animals. Turbidity of the water could also affect evaporation by 5% or more.

Pans installed within an area of poor grass cover, dry bare soil or, even more undesirably, concrete or asphalt apron, experienced air temperatures at pan level, up to 5°C higher and relative humidities 20 to 30% lower than suitably exposed pans (Doorenbos and Pruitt, 1983). It is thus apparent that observations from pans so exposed would require marked corrections before applying relevant factors. Reductions of up to 20% might be frequent. Doorenbos and Pruitt (1983) suggest that for areas with moderate levels of wind, temperature and relative humidity, reductions of the order of 5 to 10% are necessary, while small reductions in k values are required in humid, cool conditions. Where pans are placed in a small enclosure but 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 to 10% increases are required for calm, humid conditions.

Doorenbos and Pruitt (1983) also reported that k values obtained at specific wind speeds, but at various relative humidities, remained unchanged for the Colorado sunken pan sited in a short green cropped area. At the same site, k values however, varied between 14 to 22% in the case of the A-pan. On the other hand, the variation in k values for the Colorado sunken pan for a specific relative humidity was about twice that of the A-pan for a change in wind speed from 1,5 m/s to approximately 5 m/s.

Aerodynamic type empirical equations, viz.

$$E = F(u)(Cs - Cz) \quad (11)$$

have been used extensively for estimating bulk evaporation from natural water bodies. In spite of an obvious urgent requirement, no single universally accepted equation has emerged. Sill and Asce (1983) found approximately 100 different equations in the literature. They examined the 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 forms of the Dalton type equations, viz.

$$E = CD\,u(z)(1 + 0,73\,CR^2)(Cs - Cz) \text{ for } CR < 1,37 \quad (12)$$

and

$$E = CD\,u(z)(1 + Cr)(Cs - Cz) \text{ for } CR > 1,37 \quad (13)$$

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

$$Ep = s(aQn - S) / (s + c^*\gamma) + (b\gamma fvp(u)\delta e)/(s + c^*\gamma) \quad (14)$$

where:

$$a = Qnc/Qn, \quad (15)$$
$$b = c^*\,xd^* \quad (16)$$
$$x = fvc(uc)/(fvp(u), \text{ and} \quad (17)$$
$$d^* = (\delta e)c/\delta e. \quad (18)$$

The parameter a, is obtained by comparison of simultaneous measurements of net radiation above the A-pan (Qnc) and the vegetation (Qn).

The parameter c* was estimated as follows: The effectivity of sensible heat exchange from the sides of the pan was assumed to be the same as that from the open water surface. Since 50% of the base area of the pan rests upon wooden slabs, it was 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 of the water surface. Setting sensible heat exchange per unit surface area from the water surface = 1, it follows that exchange at the walls is 0,85 and at the base of the pan 0,25 giving c* = 1 + 0,85 + 0,25 = 2,1.

The value of $d^* = 1$ 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, δe and $(\delta e)c$ were obtained at heights of 0,4 and 2 m respectively.

For pan evaporation, the wind functions, fvc(uc) were obtained from appropriate Nusselt and Sherwood numbers with reference dimension or 1,21 m (the pan diameter) (Monteith, 1973). Thus for forced convection, with wind speed measured at a height of 2 m:

$$fvc = 0{,}26\ uc^{0,8} \quad (19)$$

and for free convection:

$$fvc = 0{,}105(Ts - Tc)^{0,33} \quad (20)$$

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

$$fvp(u) = 0{,}26(1 + 0{,}54\ u) \quad (21)$$

Study of the behaviour of the parameters a, b and c* will enable the climatological differences in regression comparisons between Em and Ep to be evaluated.

Piché evaporimeter

Much work has been done with the Piché atmometer (Stanhill, 1962; Heine, 1981; Kyaw Tha PawU and Massamba Gueye, 1983; Jacobs and Linclean Arriens-Bekker, 1983; Stigter and Uiso, 1981), approximately a century after its invention by Jelinek and Hann (1883). On account of its peculiar shape and exposure, it is difficult to relate Piché evaporation rate to evaporation rates from natural surfaces. Usually, the instrument is placed in a shelter and is not exposed to solar radiation. Hence, evaporation is primarily in response to the atmospheric humidity deficit, and to a lesser extent, wind velocity. It might be expected that this instrument would provide readings analogous to a simple leaf exposed in the shade, rather than to an open water surface 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 the daily evaporation from an exposed Piché atmograph. This approach yielded a 1:1 relationship for modelled leaf evaporation to observed Piché evaporation and accounted for 70 to 90% of the variance observed. Hourly values were simulated in the experiments.

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 first model is given by:

$$Ep1 = \{\frac{s}{s+\gamma}\}\{\frac{qd}{\rho w\lambda}\} + \{\frac{1}{s+\gamma}\}\{\frac{hw}{\rho w\lambda}\}\{\delta e\} \quad (22)$$

The second model is given by:

$$Ep2 = 0{,}12 \times 10^{-3} D\{\frac{u(z)^{1/2}}{\nu d}\}\{\frac{e_s}{T_s} - \frac{e_a}{T_a}\} \quad (23)$$

The first model simulates the entire energy balance. It produced a slope of 1,09 and intercept of 0,59 mm and correlation of coefficient of $r = 0{,}98$ for the regression. Seven hourly values of Ep1 were compared to actual measurements. This meant an overestimation of approximately 30%. The second model simulated only the aerodynamic component. Comparisons with actual measurements resulted in regression coefficients of $a = 1{,}23$; $c = -0{,}127$ 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 the omission of the energy component. The model of Stigter and Uiso (1981) had been developed for an evaporimeter within a screen while Jacobs *et al.* (1983) 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 a Piché atmometer (Eps) installed at a height of 2 m, in double-louvered thermometer screens with the aerodynamic term of Penman's formula (Ea), viz.

$$Ea = 0{,}35(\delta e)(0{,}5 + u/100)A \text{ (mm/d)} \quad (24)$$

The line of best fit was:

$$Ea = 0{,}1469\ Eps + 0{,}1118 \quad \text{(mm/d)} \quad (25)$$

The mean standard error of estimate was approximately 0,146 (mm/d) (15% of Ea) and the regression accounts 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, (Epen) (1956). From the graphical comparison presented (no regression analyses were carried out), he derived the following relationship:

$$Epen = 0{,}81\ Epse + 0{,}7 \quad \text{(mm/d)} \quad (26)$$

Carborundum evaporimeter

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

Portable capillary evaporimeter

Williams *et al.* (1984) developed and tested a portable evaporimeter constructed from precision bore glass capillary tubing joined to a round plate covered by a water saturated filter paper. The water lost by evaporation from the paper surface is replaced by water through capillary rise in the tube. Comparisons between the quantity of water lost from the evaporimeter, Ec, and the Class A-pan evaporation measurement, Ep, yielded the following relationship:

$$Ep = -0{,}297 + 0{,}678\ Ec \quad \text{(mm/h)} \quad (27)$$

The correlation coefficient found was 0,80 with a probability of less than 10% that the 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 data

The aerodynamic component of the Penman formula (Stanhill, 1962) alone cannot be used to estimate maximum total evaporation from a vegetative surface. Reliable estimates of Em are possible if the energy component is added to the aerodynamic component. Hence accurate estimates of the energy component are necessary. Such estimates are possible from either actual measurements of the first term $(s/(s + \gamma))$ $\{Qn - G\}$ or estimated values of St.

It was thus deemed necessary to review possible empirical relationships for estimating St.

Such methods involve the direct and diffuse components of St. 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:

$$Iv(h) = Io/rv \sin(h) \qquad (28)$$

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

$$Sv(h) = a(h)Iv(h) \qquad (29)$$

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

$$a(h) = \mathrm{Exp} - \{0{,}089(p.m/1013)^{0,75} + 0{,}174(w.m/20)^{0,6} + 0{,}083(dp.m)\}^{0,9} \qquad (30)$$

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 td (surface dewpoint temperature). He obtained a correlation coefficient of r = 0,97 and the regression equation:

$$w = 10(\ln 0{,}0845 - td - 0{,}236) \qquad (31)$$

An empirical relationship for Sv(h) for southern Africa was developed by Archer (1964), viz:

$$Sv(h) = 1127 \sin h \; 0{,}888^{\mathrm{cosec}\, h} \qquad (32)$$

The same author related diffuse radiation to solar elevation obtaining:

$$q(h) = 94{,}23(\sin(h))^{0,5} \qquad (33)$$

Total radiation on a cloudless day is simply given by:

$$St(h) = Sv(h) + q(h) \qquad (34)$$

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 min 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, Iv(h) for each 20 min period was calculated at the top of the atmosphere. The total incoming radiation was estimated taking into account Eq. 30, 31 and 33. 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

This review suggests that the most suitable evaporating surface to which crop evaporation can be directly referenced to, appears to be a short grass cover. Reasons for this include its consistent, homogeneous vegetative character and the similarity between the energy balance of its surface and that found in field crops. Although the soil characteristics and soil climate will not be identical to those of the field crops, they certainly reflect field conditions more closely than a water body. During the early crop growth stages incomplete cover prevails. Hence at this time, a factor compensating for leaf cover is required for determining actual evaporation. This aspect is most important when scheduling irrigation, as accurate scheduling leads to water saving.

Unreliability and poor repeatability in using various evaporimeters to estimate Em stems from inadequate compensation for the difference in energy balances existing between evaporimeters and natural surfaces. Appropriate corrections to the different coefficients can only be obtained by careful accounting of these energy balances. It is of the utmost importance to understand the complex mechanisms governing both transpiration and evaporation. The surface temperature of the evaporimeter and heat conduction away from its surface into the body of the evaporimeter appear to be extremely significant. At this stage it seems that the greatest advances in this technology would result from concurrent hourly measurements, from a grass lysimeter for measuring Er, and Em observations in cropped lysimeters. Alternatively then, Er observations could be replaced by suitable evaporimeter measurements. The results should be interpreted in terms of the available theoretical models in order to establish how best to use evaporation data to estimate Em.

The literature offers little direction as to which instrument would be the most reliable evaporimeter for measurements of evaporation in southern Africa, or elsewhere. The American 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.

The Piché evaporimeter has been shown to be most accurate when used for determining the aerodynamic component in the Penman-type equation. The correct exposure for the Piché evaporimeter, inside or outside a screen, is still uncertain. When, however, it is employed as a measure of the aerodynamic component, it should be exposed directly in the atmosphere, but shielded from long and short direct radiation. In this manner, the contribution of diffuse radiation intercepted by the sensing surface during most of the day is small in comparison to the wind and water vapour deficit effects.

The portable capillary evaporimeter offers possibilities but has not been compared to actual measurements of Er or Em. Its use is limited by the length of the capillary tube utilised.

Finally, it appears that k values used with the A-pan will require complex correction factors to provide estimates of Er or Em. A suitably exposed Piché evaporimeter for estimating the aerodynamic component and accurate estimates of hourly sunshine duration probably offers the most convenient and accurate method of determining Em or Er. The main advantages of such an approach are low capital outlay, ease of installation, convenience and simplicity of operation, minimal time consumption, and low running costs.

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