Atmospheric evaporative demand and evaporation coefficient concepts

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Abstract

Four different conceptualisations of upper limit evaporation from vegetated surfaces and the concepts *crop* and *pan coefficient* are defined. It is shown that evaporation from a vegetated surface must be considered in terms of two components: soil evaporation and canopy transpiration. The crop coefficient also consists of two corresponding coefficients which must be separately determined. It is theoretically proved that pan and crop coefficients vary with change in climate. To regularise upper limit evaporation from natural vegetation, the concept *atmospheric evaporative demand,* AED, is defined. Methods of, precautions necessary and approximations used when determining AED are outlined.

Introduction

Atmospheric conditions create a 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 modelling 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 conceptualisation 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 the atmospheric driving forces is required. The relevant driving forces are radiation, wind and atmospheric temperature and humidity. This definition is the objective of the work reported here. The entity defined will be called *atmospheric evaporative demand.* Its determination for practical and modelling purposes will be described.

A new terminology

While streamlining the concepts involved, it was felt that something can be done to improve the terminology employed. Hence a new system will be developed. The 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 vaporisation, 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 or solid is transferred to the gaseous phase "at the interface between a wet 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 vaporisation 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 constant water temperature. The coefficient of latent heat of vaporisation is thus temperature dependent. It is not strictly applicable to the definition of evaporation adopted here. We will use the value $\lambda = 2{,}45\ \mathrm{MJ\ kg^{-1}}$ which corresponds to 20°C. This approximates values for temperatures between 0°C and 40°C to within 2%.

Monteith (1985) suggested that, when describing the water vapour exchange from natural surfaces, the multi-lettered *evapotranspiration*, be replaced simply by *total evaporation*. For convenience, *plant evaporation* will be defined as the evaporation of water which takes place, from vegetation, through stoma, from cell walls in sub-stomatal cavities and through cuticle.

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

$$E = E_v + E_s \qquad (1)$$

where:

E is the total evaporation rate from a natural surface;
E_v is the plant evaporation rate; and
E_s is the soil surface evaporation rate.

Thus subscripts "v" and "s" 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.

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Received 20 May 1988

Present day concepts

Total evaporation

Total evaporation, E, or the old "evapotranspiration", is described by Rosenberg *et al.* (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 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). This 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 in water or nutrients.

Maximal total evaporation

The concepts *reference* and *potential total evaporation*, however, do not apply to all cases found in nature. The natural dynamic changes in crop cover and soil surface water content throughout the growing season result in perplexities particularly relevant for irrigation managers. In an attempt to circumvent these problems, Bouchet and Robelin (1969) introduced the concept of 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), recognised 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 total evaporation, E_m, is here defined as the rate of evaporation from an incomplete actively growing vegetative cover under which the root zone soil water content corresponds to field capacity or greater and the soil surface is saturated.

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:

$$k_{pan} = E_o/E_{pan} \qquad (2)$$

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

The crop coefficient concept

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:

$$k_m = E_m/E_o \qquad (3a)$$

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 surfaces; Wright (1981) defined *basal crop coefficients*, k_{vm}, pertaining specifically to dry soil surface conditions. Thus:

$$k_{vm} = E_{vm}/E_o \qquad (3b)$$

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 convenience, 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 following symbol definition applies:

E_o = daily reference total evaporation (mm)
Q_o = extra-terrestrial daily total solar radiant density (where $1\ MJ\ m^{-2} \equiv 0{,}41$ mm)
u = daily windrun at 2 m 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)
Δ = slope of the saturation vapour pressure/mean daily temperature curve (P_aK^{-1}) = de_s/dT
γ = psychrometric constant (P_aK^{-1})
W = $\Delta/(\Delta + \gamma) = 0{,}58$; 0,71 and 0,77 at temperatures of 10°C, 20°C and 26°C respectively at 1 000 m above sea level
T = atmospheric temperature (°C)
e = atmospheric vapour pressure (P_a). Subscript "s" denotes saturated conditions.

The Penman equation is:

$$E = E_o = c[WR_n + (1 - W)\, f(u)\, (e_s(T) - e)] \qquad (4)$$

where:

$$R_n = 0{,}75[(0{,}25 + 0{,}50\ n/N)Q_o] - [\sigma T^4(0{,}34 - 0{,}44\sqrt{e})(0{,}1 + 0{,}9\ n/N)]$$

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

and

$$f(u) = 0{,}27(1 + u/100)$$

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 although Covey (1959) may have been the first to evaluate surface resistances for vegetation. The new equation operates best with hourly values of the weather variables. This modified form has become known as the Penman-Monteith equation.

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. (1) is negligibly small. Thus, for this case:

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

Given the coefficient of specific latent heat of vaporisation, λ (2,45 MJ kg^{-1} at 20°C); the slope of the saturated vapour pressure vs. temperature curve (at ambient temperature, T), Δ; soil heat flux density, G; the psychrometric constant, and density, ρ, and specific heat of air, C_p; the Penman-Monteith equation reduces to:

$$\lambda E = \lambda E_p = [\Delta(R_n - G) + \rho C_p(e_s(T) - e)\varnothing_a] / [\Delta + \gamma(1 + \varnothing_a/\varnothing_v)] \qquad (5)$$

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

$$\varnothing_a = f(u,h) \qquad (6)$$

According to Eq. (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, $\varnothing_v$, vegetation height, h, and the slope of the surface. The latter two influence $\varnothing_a$, atmospheric conductance to gaseous exchange. The vegetative surface conductance, $\varnothing_v$, seems (Russell, 1980 and Van Zyl and De Jager, 1987a) to maintain a constant value for wet soil. 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 a small extent, inherently dependent upon the nature and height of the vegetation. Failure to account for the latter two could cause problems.

Thus, it is not possible to characterise atmospheric evaporative demand completely, 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 conceptualisation of reference evaporation which applies to a standard vegetation type and its height.

The upper limit evaporation rate from a reference surface finds application in:

- climatological comparisons between regions; and
- providing a basis from which evaporation rates from natural surfaces may be estimated for surfaces with both full and incomplete cover.

It is therefore evident 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.

Open water surface

The use of a free water surface to provide estimates of the upper limit to 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 from 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 or evaporation from that surface.

The physical laws governing the evaporation process are contained in the surface energy budget described by Eq. (7) and (8). Now, apart from the 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 (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 the 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 modelling) 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 to approximate the maximum demand by the atmosphere for water from natural surfaces, however, led to the conceptualisation 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 the partially wet soil surface condition experienced during the many drying cycles which occur.

The crop and pan coefficient concepts

Crop and pan coefficients have 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 analysing the energy budgets of evaporating surfaces.

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

$$Q_n + \lambda E + G + C = 0 \tag{7}$$

where:

Q_n = net irradiance
E = evaporation rate
λ = coefficient of specific latent heat of vaporisation
G = soil heat flux density
C = sensible heat flux density to the atmosphere.

Eq. (7) may be written:

$$\lambda E = -Q_n - G - C \tag{8}$$

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

$$E_o = -Q_{no} - G_o - C_o \tag{9}$$

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

$$E = k_c E_o \tag{10}$$

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 determine accurately, and even more difficult to apply, the k_c of Eq. (10). Instead, two alternative types of crop coefficient have evolved: The basal crop coefficient of Wright (1981),

$$k_{vm} = E_{vm} / E_o \tag{11}$$

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

$$k_m = E_m / E_o \tag{12}$$

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

$$k_{pan} = E_{pan} / E_o \tag{13}$$

Climate dependence of k – values

It will be shown that all evaporation coefficients (k-values) are influenced by the prevailing climate. Let k represent any type of evaporation coefficient, i.e. any crop or pan coefficient. Substituting Eq. (8) and Eq. (9) in Eq. (10) for a specific site, then over a given period, k will be given by:

$$k = (-Q_n - G - C) / (-Q_{no} - G_o - C_o) \tag{14}$$

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

$$k' = (-Q_n' - G' - C') / (-Q_{no}' - G_o' - C_o') \tag{15}$$

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

$$k = k' \tag{16}$$

The only way that the assumption expressed by Eq. (16) could be true would be for the ratio on the right hand sides of Eq. (14) and Eq. (15) 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. (16), ever strictly to be valid. This is so because Eq. (7) 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 the 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 proved by 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 mean k_c values of 1,29 and 1,11 for 1978 and 1979 respectively for the identical site, wheat growth stage and cultivation practices. They explained this 16% difference as being due to the 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 they used. Measured daily deviations from the mean k_c can exceed 40% (Meyer *et al.* 1979). Van Zyl *et al.* (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 the 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} would 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 (De Jager *et al.*, 1981 and Wright, 1981). Burgers (1982) and Doorenbos and Kassam (1979) tried to solve the problem by approximating the average soil surface wetness.

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

This is achieved starting from Eq. (1), viz.:

$$E = E_v + E_s \tag{1}$$

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

$$E_v = k_v E_o \tag{17}$$

and

$$E_s = k_s E_o \tag{18}$$

where k_v and k_s are evaporation coefficients defined as the fractions of reference evaporation supplied by plant evaporation and soil evaporation respectively.

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

$$k_{vm} = E_{vm} / E_o \tag{19}$$

$$k_{sm} = E_{sm} / E_o \tag{20}$$

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:

$$k_v = k_{vm} F_l F_h \tag{21}$$

$$k_s = k_{sm} F_g (1 - F_l) \tag{22}$$

For these equations the following boundary conditions apply:

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

$$\text{and} \qquad 0 \leq k_s \leq k_{sm}$$

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

The physiological factor, F_h, reflects the limitation on plant evaporation due to plant water stress. It represents the ratio of actual to possible plant evaporation rate for the 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, $\varnothing_v$, to its maximum value, $\varnothing_{vo}$. F_l is a normalised factor reflecting the degree of foliage cover. It is a function of leaf area index, L. 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 (Monteith, 1981; Wright, 1981; De Jager *et al.*, 1981; Hanks and Hill, 1980).

Substituting Eq. (17) and Eq. (18) into Eq. (1) yields:

$$E = [k_v + k_s] E_o \tag{23}$$

When Eq. (23) is compared with Eq. (10) it follows that:

$$k_c = k_v + k_s \tag{24}$$

which, on substitution of Eq. (21) and (22), produces:

$$k_c = k_{vm} F_l F_h + k_{sm} F_g (1 - F_l) \tag{25}$$

When maximum total evaporation is under consideration:

$$F_h = F_g = 1$$

and thus Eq. (12) becomes:

$$E_m = [k_{vm} F_l + k_{sm}(1 - F_l)] E_o \tag{26}$$

For the basal evaporation case, $F_h = 1$ and $F_g = 0$, and Eq. (11) becomes

$$E_{vm} = k_{vm} F_l E_o \tag{27}$$

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

$$E = k_c E_o \qquad (10)$$

and either:

$$k_c = k_v + k_s \qquad (24)$$

or:

$$k_c = k_{vm} F_l F_h + k_{sm} F_g(1 - F_l) \qquad (25)$$

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 detemined empirically.

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 will soon be defined as atmospheric evaporative demand (AED). Then:

$$k_c = k_{vm} F_l + k_{sm} F_g(1 - F_l) \qquad (28)$$

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. (25) with $F_g = 1$ and $k_v = k_{vm}$ i.e. maximum total evaporation E_m (see Eq. (26)). Thus:

$$k_{vm} F_l \leq k_c \leq k_{vm} F_l + k_{sm}(1 - F_l) \qquad (29)$$

For 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 the variation in k_s as the soil surface dries. 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 (Doorenbos and Pruitt, 1979); or
k_v = f(leaf area index) – for k_{vm} assumed unity (Ritchie (1972) and De Jager *et al.* (1987)); and
k_s = f(time since latest wetting event) – (Hanks and Hill, 1980 and De Jager *et al.*, 1981) (for both k_{sm} was assumed unity), or Wright (1981), Monteith (1981); or
k_s = f(water deficit below field capacity in the top soil layer) – for k_{sm} assumed unity (De Jager *et al.*, 1987).

It is emphasised 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 at least four conceptualisations of the upper limit to the evaporation rate from natural surfaces are in use at present, 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 conceptualisation 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 conceptualisation of this upper limit.

The term atmospheric evaporative demand has been used in numerous scientific articles. Yet, nowhere 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. (5) that atmospheric evaporative demand is primarily the resultant of atmospheric driving forces acting upon a natural surface. The major emphasis in its 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 proposed here 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 150 mm of soil equals its current value.

Mathematically this definition entails replacing E with AED in Eq. (10) and using Eq. (28) to evaluate k_c.

It is important to note that this definition:

(i) acknowledges the dominant influence of the atmospheric conditions; but
(ii) also basically accounts for crop type, crop growth stage and soil surface water content.

The major differences between this definition of AED and the present day definitions E_o, E_p, E_m and E_{vm} are the 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 the 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 epitomised by E_o, E_m, E_p and E_{vm}. Its main advantage lies in its precise quantification of the 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, regularise 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 modelling 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, two 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 *et al.*, 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.
- Estimation, or calculation, of the special case of AED called E_o and multiplication thereof by an appropriate crop coefficient. Thus:

$$AED = k_c E_o \quad (30)$$

The latter method will now be discussed.

Estimating E_o

De Jager (1984) suggested that the Penman-Monteith equation (Eq. 5) provides the best method of determining both E_p, potential evaporation and E_o, reference evaporation. Crop surface conductance (usually an estimate) is, however, included in this equation. Allen and Asce (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} was assumed and in some cases crop height was varied according to age. Allen and Asce (1986) also obtained accurate daily estimates of reference total evaporation, E_o, using Eq. (5). They found that values of $\varnothing_v$ varying between 0,013 m s^{-1} and 0,03 m s^{-1} provided the most accurate results. In both USA and South Africa, weather station observations also produced reliable estimates of E_o.

Van Zyl and De Jager (1987b) demonstrated the accuracy of using the Pichê evaporimeter to estimate the aerodynamic component in the combination equation Eq. (5). Hourly and daily estimates of E_p from wheat accurate to 0,07 mm h^{-1} and 0,7 mm d^{-1} respectively were obtained. Hence this method could also be successfully employed to determine E_o.

It warrants emphasising that both these methods are absolutely fundamental and not subject to the errors due to empirical approximations found in the Penman method.

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 climatic differences. The Penman estimate was multiplied by the factor 'c' which adjusts it for the ratio of day to night-time wind, relative humidity, solar radiation and wind speed. Application of the Penman equation in different climates without these corrections is dangerous. Pruitt and Doorenbos (1977) showed that interactions between the 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 wind speed 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°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°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 the altered mean energy balance under the different climates.

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) 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. When work at present being undertaken in the Department of Agrometeorology UOFS has been completed, it should be possible to reach some conclusion as to whether, and how, to utilise pan evaporation. At this stage the Pichê evaporimeter method seems as simple and convenient to apply and its accuracy has been proved (Van Zyl and De Jager, 1987b).

Determining the crop coefficients

The use of crop coefficients to estimate AED is based upon the assumption that evaporation coefficients are independent of climatic conditions. This is an incorrect assumption. Determining crop coefficients in different climate conditions will change values of terms in either, or both, numerator and denominator of Eq. 14 (Eq. 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 on only the rarest occasions.

From Eq. (10) and Eq. (28) atmospheric evaporative demand may be calculated using

$$AED = k_c E_o \quad (30)$$

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. (28) 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:

$$F_g = EXP[0,03(V_m - V)] \quad (31)$$
$$F_l = 0,186\,LAI,\ 0 \leqslant F_l \leqslant 1 \quad (32)$$

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. (30), Eq. (31) and Eq. (32) 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, minimise errors.

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

- 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;
- where possible, the coefficients should be experimentally determined for the climates in which they are to be applied; and
- 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 minimise errors incurred when applying crop coefficient theory. This is particularly true of the response of the ratio E_p / E_0 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 with present definitions which apply only to special cases of upper limit evaporation. It accords atmospheric influences their rightful emphasis and minimises the errors inherent in the evaporation coefficient concept.

It was shown that it is incorrect to utilise 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 on how to apply these new concepts correctly and what precautions are necessary when determining evaporation coefficients were given.

Indications of avenues of interesting future research were outlined.

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