An Update for the Definition of Reference Evapotranspiration

Richard G Allen
University of Idaho

Alain Perrier
Sorbonne Université

An Update for the Definition of Reference Evapotranspiration*

R.G. Allen[1], M. Smith[2], A. Perrier[3], and L.S. Pereira[4]

Abstract : Grass reference evapotranspiration (ET_o) is redefined as the evapotranspiration (ET) from a clipped grass surface having 0.12 m height and bulk surface resistance equal to 70 s m^{-1}. The FAO Penman-Monteith equation with standardized roughness and bulk surface resistance parameters is recommended as the equation used to represent the new ET_o definition. This change in definition and selection of a specific calculation method to represent the definition is intended to help eliminate problems in measuring a living reference ET_o and to provide consistent ET_o values in all regions of the globe. Use of the FAO Penman-Monteith equation overcomes problems of overestimation by the FAO Penman equation. Common problems in measuring ET_o are discussed. The calculated hypothetical reference ET_o can be used to calibrate empirical ET_o equations and as a basis for determining crop coefficients where ET_o is not measured simultaneously with crop ET.

Résumé : L'évapotranspiration de référence (ET_o) est redéfinie comme l'évapotranspiration (ET) d'une surface étendue de gazon avec hauteur de 0,12 m et résistance du couvert de 70 s m^{-1}. L'équation FAO Penman-Monteith, ayant des paramètres de rugosité et de résistance de surface normalisés, est recommandée comme équation qui représente la nouvelle définition de l'ET_o. Le changement de la définition et la sélection d'une méthode de calcul appropriée à la nouvelle définition prétend contribuer à éliminer les problèmes liés à la mesure de l'ET_o sur une culture de référence vivante, et permettre l'obtention des valeurs de ET_o consistantes dans toutes les régions du globe.

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* **Actualisation de la Définition de l'Evapotranspiration de Référence**

1. Member, ICID Working Group on Crops and Water Use and Assoc. Professor of Biological and Irrigation Engineering, Utah State Univ., Logan, UT 84322-4105.

2. Senior Officer, Land and Water Development Division, UN-FAO, Rome, Italy.

3. Member, ICID Working Group on Crops and Water Use and Professor of Bioclimatology, Institut National Agronomique de Paris-Grignon, France.

4. Chairman, ICID Working Group on Crops and Water Use and Professor of Agricultural Engineering, Technical Univeristy of Lisbon, Tapada da Ajuda, 1399 Lisboa Cedex, Portugal.

All authors are members of the FAO Expert Consultation on FAO Methodologies for Crop Water Requirements.

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D'autre part, l'utilisation de l'équation FAO Penman-Monteith permet de dépasser les problèmes de surestimation propres à l'équation Penman. Les problèmes plus fréquents de la mesure de l'ET_o sont aussi discutés. L'utilisation de la nouvelle méthode de calcul de l'ET_o est indiquée pour la calibration des équations empiriques de ET_o et, aussi, pour la détermination des coefficients culturaux quand ET_o n'est pas mesurée simultanément avec l'évapotranspiration culturale.

1. Introduction

The United Nations Food and Agriculture Organization (FAO) adopted the concept of reference evapotranspiration (ET_o) in the FAO Guidelines for Crop Water Requirements by Doorenbos and Pruitt (1975, 1977). This approach to calculating crop evapotranspiration is widely accepted by engineers, agronomists and managers in field practice, design and research. The concept of reference ET_o relates ET_o to a living reference crop of grass, and is represented in FAO-24 by climatic formulas which were calibrated against lysimeter data from several locations (Pruitt and Doorenbos, 1977).

Researchers have attempted to improve the estimation of ET_o for different locations and data availability through experimental and theoretical studies. Unfortunately, many have shown weaknesses in the FAO-24 methodologies for worldwide application. First, relating calculated ET_o to a reference crop has proved to be difficult: the definition of a grass variety and its morphological characteristics has not been standardized for different climatic conditions. Furthermore, grass management varies from one location to another and with time in the same location. Others have proposed alfalfa as a reference crop, but have experienced similar varietal and management problems (Wright and Jensen, 1972; Wright, 1988; Allen et al., 1989; Jensen et al., 1990). Thus, it is evident that a "living" reference crop is difficult to reproduce over a range of locations. In addition, there have been problems with lysimeter and micrometeorological measurements which have affected ET_o measurements (Aboukhaled et al., 1982; Allen et al., 1991).

Second, the Penman combination equation adapted by FAO-24, termed the FAO Penman, despite being the most comprehensive climatic formula then proposed, was soon found to frequently overestimate ET_o. Research indicated weaknesses in the calculation of the wind function, the vapour pressure deficit (VPD), the net long wave radiation, and the use of the correction coefficient, c. These problems have stemmed essentially from the procedures used to compute parameters within the equation and partly from the reliability and processing of data.

Third, other equations proposed in FAO-24, namely the FAO-Radiation, FAO-Blaney-Criddle and FAO-Pan evaporation equations, have shown variable adherence to a reference ET_o. However, in general, these equations do not deviate from the grass reference ET_o as widely as does the FAO Penman.

Results from numerous studies led FAO, in collaboration with the International Commission on Irrigation and Drainage (ICID), to revise adopted methodologies to improve the estimation of crop water requirements. Consequently, during an expert consultation held in Rome, 28 to 31 May, 1990, a decision was made to change the concept of reference evapotranspiration and to revise calculation procedures. A hypothetical reference canopy, which is described by an appropriate Penman-Monteith equation (Smith et al., 1991), has been substituted for a living reference crop. Based on existing studies, all calculations, including the parameters related to the radiation and aerodynamic components, have been revised and are included in the annexes of the companion paper by Allen et al. (1994). These revisions apply also to other climatic formulas which should be calibrated against the new reference represented by the Penman-Monteith equation.

The intent of this paper, and that of FAO and ICID, is to encourage the use of the redefined standard ET_o reference and associated updated ET_o calculation procedures, together with detailed justification for the proposed changes. This will hopefully facilitate improved estimation of ET_o and provide for feed-back from scientists. We expect that new FAO Guidelines will be published at a later time when other methodologies for calculating crop water requirements will also be updated.

2. Theoretical Considerations

Evaporation of water requires relatively large amounts of energy, either in the form of sensible heat or radiant energy. Therefore the evapotranspiration (ET) process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available. Because of this limitation, it is possible to predict the rate of ET given a net balance of energy fluxes.

The primary energy components which supply or diminish energy at a vegetation surface are net radiation from the atmosphere (R_n), sensible heat from the equilibrium boundary layer (H), and sensible heat from the soil (G). Other fluxes or sinks are present, such as energy requirements for photosynthesis, but these are quite small relative to R_n, H, and G. The sum of R_n, H and G equals the flux density of energy converted into latent heat energy (λET) during the ET process. Therefore the energy balance can be written in terms of these four components as

$$\lambda ET = R_n - H - G \tag{1}$$

where λET is the latent heat flux density, positive upward from the surface; R_n is the net radiation flux density, positive downward toward the surface; H is the sensible heat flux density, positive upward from the surface; and G is the soil heat flux density, positive downward from the surface. All terms are expressed in units of energy per horizontal area per unit of time. λ is the latent heat required to vaporize one unit of water and is expressed as energy units per unit of mass.

The terms on the right side of the energy balance can be computed from measured or estimated climatic and vegetation factors. The climatic factors include short wave and long wave radiant fluxes from and into the atmosphere (R_n), effects of horizontal air movement (wind speed) and air and surface temperatures on H, and soil heat fluxes (G). Vegetation factors include the resistance to diffusion of vapour from within plant leaves and stems and the resistance to diffusion of vapour from near the vegetation surface upward into the atmosphere.

For general predicting purposes, the complex turbulent structures within and above vegetation canopies and the effects of partitioning of net radiation and energy within the canopies can be described in terms of simple resistances. Generally this is accomplished using the linear "big leaf" model of Monteith (1965; 1985) where two resistances, canopy and aerodynamic, operate in series between leaf interiors and some reference height above the vegetation. Canopy, or bulk surface, resistance (r_s) can be computed from the resistance of vapour flow through individual stomata openings (r_l) and total leaf area of the vegetation. Aerodynamic resistance (r_a) describes the resistance to the random, turbulent transfer of vapour from the vegetation upward to the reference (weather measurement) height and the corresponding vertical transfer of sensible heat away from or toward the vegetation. The r_a term includes the effects of diffusive resistance through thin molecular layers along leaf surfaces, momentum transfer through pressure forces within the plant canopy, and turbulent transfer among canopy leaves and above the canopy.

Other factors which may affect the general application of the energy balance equation (equation 1) for predicting evapotranspiration fluxes include the effect of buoyant stability of the equilibrium boundary layer above the surface on the mean value of r_a and the diurnal variation in r_l (and r_s) due to variation in R_n, air temperature (T), relative humidity and the availability of soil moisture. Usually, when making predictions of ET for planning and operating studies for irrigation and drainage systems, the effects of buoyant stability or instability on r_a and diurnal variations in r_s can be ignored. This is especially true for calculations made on daily, weekly, or monthly time-steps for a reference crop which is well-watered.

The energy balance equation can be arranged in terms of parameters R_n and G and parameters within the H and λET components. When this arrangement is made using assumptions for extrapolating temperature and vapour pressure from the weather measurement height to the evaporating surface (plant leaves), the combination equation of Penman (1948) results.

If one assumes that eddy diffusion transfer factors for latent heat and sensible heat are the same and that differences between transfer factors for momentum and those for heat can be quantified through a simple ratio then the Penman-Monteith form of the combination equation (Monteith, 1965) results:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho C_p(e_a - e_d)/r_a}{\Delta + \gamma\,(1 + r_s/r_a)} \qquad (2)$$

where e_a - e_d represents the vapour pressure deficit of air at the reference (weather measurement) height, ρ represents mean air density, c_p represents specific heat of air at a constant pressure, Δ represents the slope of the saturation vapour pressure-temperature relationship, γ is the psychrometric constant, and r_s and r_a are the bulk surface and aerodynamic resistances. Parameter units for all terms in equation (2) are defined in Annexes I and II of Allen et al. (1994). Procedures for calculating the mean daily values for r_a and r_s are given in equations (4) and (5) in section 4.3 and in the equations presented in Annex II of Allen et al. (1994).

The Penman-Monteith equation as formulated in equation (2) includes all parameters which govern, in a major way, energy exchange and corresponding latent heat flux (evapotranspiration) from uniform expanses of vegetation. Most of the parameters in equation (2) are measured or can be readily calculated from weather measurements on a daily basis for a wide array of weather station locations. Therefore, equation (2) is generally capable of responding to changes in weather and climate in a manner similar to an agricultural crop, so that it is reasonable to use equation (2) to represent reference evapotranspiration conditions.

3. Need for a Concept of Reference Evapotranspiration, ET_o

Grass reference ET_o was defined in FAO-24 as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water." (Doorenbos and Pruitt, 1977). This same definition was used by the American Society of Civil Engineers (ASCE) in ASCE Manual 70 (Jensen et al., 1990) for a clipped grass reference. It is generally accepted that the grass reference crop is a "cool-season", C-3 type of grass with roughness, density, leaf area and bulk surface resistance characteristics similar to perennial ryegrass (*Lolium perenne* L.) or alta fescue (*Festuca arundinacea Schreb.* 'Alta').

The concept of reference ET was introduced by various irrigation engineers and scientists (Wright and Jensen, 1972; Jensen, 1974, Doorenbos and Pruitt,

1977) to avoid ambiguities that existed in the definition of potential ET (Perrier, 1978). Reference ET_o refers to ET from vegetation over which weather measurements are made and provides for a consistent set of crop coefficients to be used to determine ET for other crops. Relating ET_o to a specific crop has an advantage of providing a mental image of the evapotranspiration process and in representing the biological and physical processes involved in the energy balance at a cropped surface. In addition, by adopting a reference ET_o, it has become easier to select consistent crop coefficients and to make reliable crop ET estimates in new areas. The use of the crop coefficient-ET_o approach has been enormously successful in obviating the need to calibrate a separate ET equation for each crop and stage of growth (Perrier, 1978; Wright, 1982; Jensen et al., 1990). It has also provided a working model which can be used until more sophisticated methods become available for direct estimation of actual crop ET. Therefore, it is important at the time of this writing to retain the use of reference ET_o and to promote its use in making routine estimates of crop ET.

3.1 Problems in selecting a reference crop

Many of the American studies to define a reference ET have promoted the use of alfalfa (lucerne) as a living reference crop due to its roughness characteristics and leaf area which are more like those of many other agricultural crops at full cover as compared to clipped grass (Wright and Jensen, 1972; Jensen 1974; Wright 1982; Jensen et al., 1990). This similarity in exchange coefficients r_a and r_s (see equation (2)), generally results in less variation in the ratio of crop ET to ET_o (crop coefficient) with variation in climate and location (Doorenbos and Pruitt, 1977; Jensen et al., 1990). Alfalfa also has an extensive root system that makes it less sensitive to decreasing soil water as compared to grass.

Table 1 lists the general ratios of alfalfa to grass reference ET for several locations and climates as computed by the Penman-Monteith equation, where roughness length, z_{om}, and bulk surface (stomatal) resistance were varied according to reference type (Allen et al., 1989). Calculations were made using one weather data set for each location. The ratios in Table 1 averaged 1.32 ($ET_{alfalfa}/ET_{grass}$) over the 11 locations and were lower in humid climates.

The alfalfa to grass ratios in Table 1 demonstrate that the larger roughness of the alfalfa crop and lower bulk surface resistance result in higher ET relative to clipped grass, but in varying degree, according to climate. It is important to note that the ratios listed in Table 1 are probably 5 to 10% greater than the ratios of alfalfa to grass ET which would be realized in real settings (Allen et al., 1989). This is due to the fact that in reality, the vapour pressure deficit and air temperature above vegetation are affected by radiation, heat and vapor exchange at the surface (Tanner and Fuchs, 1968; Itier and Perrier, 1976a,b; Brutsaert, 1982; McNaughton and Jarvis, 1984; Perrier and Tuzet, 1991). Therefore, under similar radiation and wind conditions, vapour pressure deficit and temperature would be expected to be lower over alfalfa than over grass due to greater latent heat flux density and lower sensible heat flux density from the alfalfa surface as compared to grass. Therefore, the ratio of $ET_{alfalfa}$ to ET_{grass} would be expected to be lower than that those listed in Table 1. Wright (1985, personal communication) measured ratios of $ET_{alfalfa}/ET_{grass}$ which averaged 1.26 for 0.3-0.6 m alfalfa and for 0.08-0.15 m clipped fescue grass on precision weighing lysimeter systems at Kimberly, Idaho. The 1.26 ratio measured by Wright is about 9% lower than the season average ratio of 1.37 listed in Table 1 for Kimberly which was computed using the Penman-Monteith equation and using the same weather data set for both reference crop types. This supports the suggestion that the ratios in Table 1 may be overestimated by 5 to 10%. Regardless of the absolute accuracy of the ratios in Table 1, the variation among ratios supports the fact that crop coefficients, when computed as the ratio of crop ET to grass reference ET_o, will vary to some degree with climate for crops which are substantially rougher than the grass reference or which have substantially lower bulk surface resistances.

Table 1. Ratios of $ET_{alfalfa}$ to ET_{grass} (K_r) for eleven lysimeter sites based on the Penman-Monteith equation where alfalfa and grass heights were assumed to be 0.5 and 0.12 m and r_s values were assumed to be 45 and 70 s m^{-1} for alfalfa and grass (from Allen et al., 1989). Latitudes and elevations are included to show diversity among locations

Location	Lat., deg.	Elev., m	K_r Peak month	K_r Average
Arid Locations				
Aspendale, Australia	-38	3	1.34	1.37
Brawley, California	34	-30	1.34	1.34
Davis, California	39	16	1.31	1.38
Kimberly, Idaho	42	1195	1.32	1.37
Scottsbluff, Nebraska	42	1280	1.37	1.34
South Park, Colorado	39	2774	1.24	1.30
Humid Locations				
Copenhagen, Denmark	56	28	1.28	1.35
Coshocton, Ohio	40	360	1.22	1.29
Lompoc, California	35	26	1.17	1.25
Seabrook, New Jersey	39	37	1.35	1.39
Yangambi, Zaire	0	487	1.13	1.12

Difficulties with an Alfalfa reference. Some varieties of alfalfa exhibit different amounts of erectness of stems and leaves and stomatal control. These variations may create differences in actual ET among alfalfa varieties as large as 10% (Wright, 1988). In addition, alfalfa can be difficult to grow in some tropical climates and in regions having severely cold winter temperatures. It may therefore be difficult to define a specific cultivar of alfalfa which will grow effectively worldwide in order to provide local validation of alfalfa ET_o methods. Alfalfa crops must be harvested periodically so that breaks in measurement records occur. Therefore, ET_o equations such as equation (2) are needed to fill in missing periods if continuous records of ET_o measurements are required.

Difficulties with a grass reference. Grass variety and morphology can significantly affect the rate of ET_o during peak periods of consumptive use. Large differences may exist between warm-season (C-4) and cool-season (C-3) grass types, with cool-season grasses having a lower degree of stomatal control with corresponding higher rates of ET (Beard, 1985). It may be difficult to grow cool-season grasses in some arid, tropical climates, but other warm-season species can be well adapted. ET from grass is also affected by periodic clipping. Discussions and comparisons of differences in ET_o between grass types can be found in articles by Marsh et al. (1980), Biran et al. (1981), Frank (1981), Wehner and Watschke (1981), Hargreaves (1983), Beard (1985), Snyder et al. (1987) and Jensen et al. (1990).

Selection of grass as the reference Crop. Although alfalfa has roughness and leaf areas which are advantageous relative to grass, present limitations hinder its adoption as the standard international ET reference. Engineers and scientists generally agree that a clipped, cool season grass provides a better year-round representation of reference ET than does alfalfa because its characteristics are better defined and fixed (Smith et al., 1991). Grass is also widely adaptable and available for validation. Therefore, grass should be used at the present time to define reference ET_o.

3.2 Problems in maintenance and measurement of reference ET_o

The accepted working definition of a living reference grass crop provides for a height ranging between 0.08 to 0.15 m (Doorenbos and Pruitt, 1977). This range provides for manageable periods between clippings. However, according to the general, approximate leaf area index[5] (LAI) relationship by Allen et al. (1989) and Jensen et al. (1990) for clipped grass ($LAI = 24\ h_c$ where h_c = mean height in m), the LAI can easily range from 1.9 to 3.6 over the accepted 0.08 to 0.15 m height range. This is equivalent to 45 % of the LAI for a 0.12 m crop. The equivalent variation in bulk surface (stomatal) resistance when r_s is computed following Allen et al. (1989) as $r_s = 100/(0.5\ LAI)$, s m^{-1}, is 105 to 55 s m^{-1}. This range is equivalent to 70% of the value of r_s for a 0.12 m grass crop. Therefore

5 Leaf area index is defined as the planal area of leaves per unit area of ground surface. Only one side of a leaf is considered. Units are m^2 m^{-2}.

he average r_s and associated aerodynamic resistances may vary appreciably with time between clippings and locations, depending on the structural characteristics and regrowth rates of the grass variety and management schedules (Biran, et al., 1981; Stringer et al., 1981; Frank, 1981; Beard, 1985; Choisnel et al., 1992). Tanner and Pelton (1960) also discussed the effect of vegetation height on evapotranspiration rate and other important issues involving the combination equation.

The definition of ET_o includes the requirement of an actively growing crop completely shading the ground and not short of water. Validation, therefore, requires a densely planted and maintained stand with adequate levels of soil moisture and drainage. These requirements demand rigorous management.

One-dimensional aspects. Above all, the definition and concept of ET_o must be one dimensional with respect to evaporation and energy exchange processes. This means that all fluxes within the energy balance (radiation, sensible heat, soil heat, and latent heat) must be uniformly vertical along the horizontal surface so that the reference surface completely represents the one-dimensional ET processes of large plantings.

The requirement that the measurement of ET_o be one-dimensional is often violated in lysimeter studies, where the crop in the lysimeter or measurement area is taller or shorter than that outside or extends beyond the horizontal dimensions of the lysimeter. Failure to maintain proper environmental and management requirements, poor instrumentation, or improper data reduction and interpretation are likely causes for differences in results presented by many authors rather than actual differences in physical relationships and processes (Jensen et al., 1990; Allen et al., 1991).

It is generally difficult to maintain environmental conditions at lysimeter sites such that the measurements represent one-dimensional ET processes. Various problems and effects of the maintenance of the necessary environmental, site and equipment conditions have been discussed by Perrier et al. (1974), Pruitt and Lourènce (1985), Meyer and Mateos (1990), Howell et al. (1991), Grebet and Cuenca (1991), Allen et al. (1991), Pruitt (1991), Walter et al. (1991) and Neale et al. (1991). Lysimeters and other micrometeorological methods for measuring or estimating ET_o are expensive and are generally labor intensive.

Lysimeter measurements. Many errors in using lysimeters stem from the difficulties in determining the actual evaporating and transpiring area of lysimeter vegetation when converting changes in depths or volumes of water losses into equivalent depths of ET. The evaporating and transpiring area is usually larger than the area of the inside of the lysimeter tank because leaves or stems from the lysimeter crop extend outward to a greater degree than the outer vegetation extends inward. If the rim is not fully covered with vegetation, sensible heat and radiation can be transferred from the rim into the lysimeter vegetation, thereby increasing ET. The surface error (%) for circular tanks can be approximated by twice the ratio of the diameter of the vegetation surface to the inner diameter of the tank. This yields 10% error for a 0.10 m ring in a tank of 1 m radius where vegetation extends 0.05 m beyond the inside of the ring. Errors in ET measurements due to errors in determining the evaporation area can range as high as 20 to 50 % (Allen et al., 1991; Pruitt, 1991). A 20% error is quite common.

The immediate area surrounding a lysimeter must have vegetation of identical height, type, vigor, and water management as the lysimeter vegetation. If it is not, then the above errors will prevail, in addition to micro-scale transfer of sensible heat from areas of lesser ET immediately outside the lysimeter. Extreme care must be taken around lysimeters to minimize foot traffic, trampling of vegetation and compacting soil (Wright, 1991). Perrier et al. (1974) found local physical and biological heterogeneity to cause 2 to 3% variation for a 5 m^2 grass cover and 10% when the same lysimeter was planted to corn. These errors would increase as the lysimeter area decreases.

Heights of vegetation inside lysimeters must be the same as outside. Van Bavel et al. (1963), Pruitt and Lourence (1985), Meyer and Mateos (1990), Pruitt (1991), and Allen et al. (1991) have each demonstrated the effects of having lysimeter vegetation at different heights relative to the outside vegetation. When lysimeter vegetation is taller than that outside, the lysimeter vegetation operates like a clothesline where horizontal bombardment of wind increases turbulent transfer of advected heat to and evaporation from the vegetation. Radiation capture is also increased. ET measurements can increase by as much as 30 to 40 %.

Grebet and Cuenca (1991) reported increased ET from a lysimeter in Argentina of 30% during the first year of operation due to increased height of vegetation inside the lysimeter caused by low soil density. Meyer and Mateos (1990) reported a 30 % reduction in ET for soybean when lysimeter vegetation was 0.1 m shorter than the surrounding crop. This was caused by shielding of radiation and wind by the surrounding crop and reduced turbulent transfer within the lysimeter vegetation.

Generally, inconsistency of ET_o calculations relative to lysimeter measurements at locations within a similar climate and region should signal some type(s) of problems in lysimeter measurements, management, or instrumentation. For example, in ET_o and lysimeter comparisons by Tarantino (1991), ratios of ET_o to lysimeter measurements (ET_{lys}) for seven different reference estimating methods proportionately and consistently increased when transferred between two grassed weighing lysimeter locations located approximately 100 km apart. The same trends in ratios for different types of ET equations indicate that lysimeter conditions somehow deviated from standard reference conditions at one or at both locations. However, this problem was not discussed in Tarantino's paper. This is an example of some of the difficulties in advocating and using a living ET_o.

Boundary layer measurements. ET measurement systems which utilize characteristics of the conservative sub-boundary layer (equilibrium layer) above an evaporating surface can also be beset with operational problems. These types of systems, which include eddy correlation and Bowen ratio systems, require long fetch in the upwind direction to ensure that the vapour and heat fluxes measured are characteristic of the surface in question and are not affected by energy balances of different surfaces upwind (Blad and Rosenberg 1974). Often ratios of 50:1 to 200:1 are suggested for fetch length to height of equipment above the vegetation surface to reduce problems with flux divergence (Itier and Perrier, 1976a, b).

In addition to problems in obtaining and maintaining sufficient fetch, boundary layer measurement equipment components are delicate and require special maintenance. These requirements often limit eddy correlation and Bowen ratio systems to research studies. Some eddy correlation systems have problems with wetness of sonic anemometer transducers during early morning hours and after precipitation (Gash et al., 1989). Sometimes it is difficult to predict evapotranspiration during periods when the Bowen ratio is close to -1 (Pruitt and Swann, 1986).

Seguin et al. (1982) suggested that measurement errors of Bowen ratio systems were approximately 10 % when all environmental and instrument conditions were perfect. They estimated that errors increase to 15 to 20 percent for daily ET totals when operating Bowen ratio systems over periods of 1 month or more. Perrier et al. (1976) found only 60% of Bowen ratio estimates of daily ET to lie within 20 % of actual ET measurements, and 90% within 40% of actual. Total ET during the measurement period, computed by summing daily Bowen ratio estimates, was within 10% of the actual ET, indicating that most errors were random and had both positive and negative signs. Recent improvements in instrumentation and adherence to fetch requirements can reduce errors to perhaps 5%. However, calibration and maintenance requirements of instrumentation are demanding.

This review indicates that problems in maintenance and measurement of reference ET, both with lysimeters and with boundary layer methods, do not favor a standardized living reference crop.

3.3 Problems in using the FAO-Penman method

Background. The FAO-24 "Corrected" Penman method was first presented by Doorenbos and Pruitt (1975) and Pruitt and Doorenbos (1977) for computing grass ET_o. Nine locations having grass ET_o measurements from weighing lysimeters were used in developing the wind function for the FAO-Penman equation and in developing the correction factor (Pruitt and Doorenbos, 1977). These locations were Brawley, California, U.S.A.; Copenhagen, Denmark; Coshocton, Ohio, U.S.A.; Davis, California, U.S.A.; Montfavet, France; Port au Prince, Haiti; Tal Amara, Lebanon; Wageningen, The Netherlands; and Yangambi, Zaire. The Brawley data were alfalfa measurements adjusted to represent grass ET_o. Unfortunately, data from some of these sites may have adversely biased the FAO-Penman calibration due to the over measurements of ET_o or humidity or under measurements of wind (Pruitt and Swann, 1986, Pruitt, 1990, personal communication). These biases may have resulted in the generally high estimations experienced in subsequent studies with the FAO-Penman method.

The FAO-Penman method includes a correction factor which requires additional weather measurements and factors relative to the standard Penman equation, making its application somewhat laborious. In the FAO-Penman method (Doorenbos and Pruitt, 1977), ET_o is computed as:

$$ET_o = \frac{\Delta R_n + 0.27\gamma\,(a_w + b_w U_2)(VPD)}{\Delta + \gamma} \qquad (3)$$

where Δ is the slope of the saturation vapour pressure curve, mb °C^{-1}; R_n is net radiation, mm d^{-1} ; γ = pyschrometric constant, mb °C^{-1}; a_w and b_w are constant wind function coefficients (1.0 and 0.864); U_2 is wind speed at 2 m height, m s^{-1}; and VPD is mean daily vapour pressure deficit, mb, computed as $e°(T_{mean}) - e°(T_{dew})$, where $e°(T)$ represents the saturation vapour pressure function and T_{mean} and T_{dew} are daily mean air temperature and daily mean dewpoint. ET_o in Equation (3) has units of mm d^{-1}.

Parameters required to compute the "c" factor are daytime (700 to 1900 hr) wind speed (U_d), daily solar radiation (R_s), maximum daily relative humidity (RH_{max}), and the average ratio of daytime to nighttime wind speed (U_d/U_n). A regression relationship for predicting the values for c tabled and graphed in FAO-24 was presented by Allen and Pruitt (1991). This expression predicts the value of c better than the equation proposed by Frevert et al. (1983) for typical values of RH_{max} (60 to 90%).

Overestimation by the FAO-Penman. The FAO-Penman method has been found to overestimate grass ET_o under a wide variety of conditions. This tendency was suggested by Pruitt and Swann (1986) and Pruitt (1990, personal communication) based on comparisons with lysimeter measurements of ET_o at Davis, California, U.S.A. and micrometeorological measurements of ET_o in N.S.W., Australia. Pruitt and Swann (1986) introduced a downward adjustment for the FAO-Penman equation based on calculations made with the "CIMIS" hourly Penman wind function at automated weather stations in agricultural locations in California. The same relationship agreed well with Bowen ratio measurements over grass taken in New South Wales. The form of the adjustment by Pruitt and Swann (1986) is $ET_o = 0.94\ CPEN - 0.01181\ CPEN^2$, where ET_o is the correct ET_o and CPEN is the FAO-"Corrected" Penman estimate. For an average peak period ET_o rate of 8 mm d^{-1}, this adjustment reduces the FAO-Penman estimate by about 21%.

An indication of the potential for overestimation by the FAO-Penman method at Davis, CA is shown in Figure 1a, where 24-hour (daily) calculations of ET_o by the FAO-Penman method are compared with daily measurements of ET_o by a precision lysimeter for a five year period, including winter months. Data are from Pruitt (1986, personal communication). The height of clipped rye grass on the lysimeter averaged 0.12 m and ranged from approximately 0.08 to 0.15 m. The average overestimation by the FAO-Penman equation during the five year period shown was about 34%.

A tendency toward overestimation by the FAO-Penman equation was also indicated in analyses by Allen et al (1989) as reported in ASCE Manual 70 (Jensen et al., 1990). ET_o by the FAO-"Corrected" Penman method overestimated lysimeter ET_o by 30 to 35% during both peak months and seasonally at Davis, California and by an average of 12% seasonally and 8% during peak months at five U.S. and one Australian lysimeter locations which were classified in the study as arid or semiarid climates. The FAO-"Corrected" Penman method overestimated ET_o at five humid or semihumid locations by an average of 35% both seasonally and during peak months.

Batchelor (1984) found the FAO-Penman estimated about 20% higher than the 1963 version of the Penman equation (Penman, 1963) and about 10% higher than Penman-Monteith estimates for ET from rice in Sri Lanka. Weiss (1982) found the FAO-24 Penman estimated 9% higher than lysimeter measured alfalfa ET at Mead, Nebraska. Allen et al. (1989) found the FAO-Penman overestimated alfalfa ET at Scottsbluff, Nebraska by 13% after adjustment with a K_r of 1.25.

Castrignanò et al. (1985) found the FAO-Penman overestimated lysimeter measurements of ET from clipped grass by 18% over a 12 month period in southern Italy, and by 14% during the April-September period. Tarantino (1991) found the FAO-Penman overestimated lysimeter measurements of grass ET by 13 to 45% in central Italy.

It appears that, based on the tendency to overestimate ET_o and the additional complexity of the c factor, a different approach to estimating ET_o with the combination equation is warranted.

3.4 Comparisons among different equations

A large number of wind functions and calibrations for the Penman equation have been developed. Cuenca and Nicholson (1982) described eight different empirical wind functions for the Penman equation and six methods for computing the saturation VPD. Stewart (1983) discussed relationships between the principal forms of the combination equation and described five major forms of the Penman equation, four of which were single- or multi-layer resistance formulations. Jensen et al. (1990) evaluated nine variations of the combination equation which included deviations in the wind function and in the method for computing VPD.

The analysis in the ASCE Manual 70 (Jensen et al, 1990) includes an evaluation of 20 equations, nine of which are combination equations. Eleven locations having weighing lysimeter measurements of grass or alfalfa ET_o were used in the analysis of monthly ET_o estimates. These 11 locations were selected on the basis of data integrity. Criteria for selection were site fetch conditions, lysimeter management, soil moisture adequacy for reference conditions, weather data instrumentation and equipment maintenance (Allen et al., 1989 and Jensen et al., 1990). Location selection was also based on whether trends in lysimeter measurements were reproducible by the common Penman equation forms. This criterion was used to screen both lysimeter and associated weather measurements.

A summary of results from the ASCE analyses is reported in Table 2. All Penman estimates summarized in Table 2 were calculated using net radiation estimates as recommended by Wright (1982) with Angstrom and Brunt coefficients (see Annex I) selected to match the regional climate (Jensen et al., 1990).

Three of the lysimeter locations in the ASCE study were planted to alfalfa. Only data for periods having full cover alfalfa (heights greater than 0.3 m) were included in the analyses. All reference ET_o equations, whether developed for alfalfa or grass prediction, were applied to both grass and alfalfa lysimeter measurements. This required adjusting ET estimates to the appropriate location reference type using the "reference ratio", K_r defined earlier in section 3.1. A fixed value for K_r equal to 1.15 was used. However, based on Table 1, a value of K_r of 1.20 to 1.25 may have been a more appropriate range for the site conditions used. The Penman-Monteith method was directly applied to both alfalfa and grass reference conditions by using resistance algorithms specific to each reference type so that a K_r was not required.

The Penman-Monteith and the 1982 Kimberly Penman (Wright, 1982) methods were the two best at the 11 locations evaluated in terms of mean accuracy of estimation and standard deviation of estimates about lysimeter measurements.

Table 2. Summary of results from the ASCE Manual 70 analyses of reference ET equations (after Jensen et al., 1990)

Method	All months			Peak month			
	(1) ET_{eq}/ET_{lys}	(2) R	(3) ASEE	ET_{eq}/ET_{lys}	R	ASEE	(4) WSEE
Penman-Monteith (Allen et al., 1989 r_s and r_a equations)	101	0.99	0.36	97	0.99	0.47	0.40
1982 Kimberly Penman (Wright, 1982)	107	0.96	0.49	107	0.96	0.73	0.59
FAO-PPP-17 Penman (Frére and Popov, 1979)	111	0.97	0.56	105	0.97	0.72	0.66
Penman (1963)	106	0.97	0.57	99	0.96	0.81	0.67
Penman (1963) using VPD = 0.5 $(e_s(T_{max})+e_s(T_{min}))-e_d$	113	0.97	0.57	105	0.96	0.77	0.68
1972 Kimberly Penman (Wright and Jensen, 1972)	112	0.96	0.67	102	0.97	0.70	0.72
FAO-Radiation	114	0.97	0.59	110	0.96	0.78	0.73
FAO-Blaney-Criddle	108	0.96	0.64	106	0.94	0.97	0.76
FAO Penman (c = 1)	121	0.96	0.65	111	0.96	0.76	0.82
Jensen-Haise (1963)	85	0.95	0.71	83	0.92	1.06	0.95
Hargreaves et al. (1985)	108	0.93	0.88	101	0.87	1.39	1.05
Businger-van Bavel (Businger, 1956)	121	0.92	0.90	110	0.91	1.16	1.08
FAO-Penman	127	0.96	0.65	122	0.93	1.00	1.10
FAO-Pan	100	0.92	0.88	95	0.82	1.57	1.11
SCS Blaney-Criddle	101	0.87	1.15	103	0.89	1.26	1.20
Christiansen (1968) pan	92	0.91	0.94	88	0.78	1.73	1.21
Pan evaporation	118	0.92	0.87	113	0.83	1.56	1.35
Turc (1961)	90	0.89	1.07	85	0.84	1.49	1.46
Priestley-Taylor (1972)	85	0.90	1.02	86	0.78	1.72	1.48
Thornthwaite (1948)	79	0.78	1.47	79	0.79	1.70	1.84

1 ET_{eq}/ET_{lys} is the ratio of the ETequation/ETlysimeter in % after adjustment of alfalfa measurements or alfalfa reference equations by dividing alfalfa ET by Kr = 1.15

2 R is the correlation coefficient for regression through the origin.

3 ASEE is the standard error of estimate computed for regression of the lysimeter measurement vs. the equation estimate through the origin.

4 WSEE is the weighted SEE which is a standard error of estimate computed by Jensen et al. (1990) using standard errors of estimate for all months and for the peak month (70 and 30 % weightings). WSEE was additionally weighted for both linear regression (67%) and regression through the origin (33%).

The FAO-PPP-17 Penman (Frére and Popov, 1979) and the 1963 Penman equation (Penman, 1963), which were applied as grass ET_o methods, were the next best performing combination ET_o methods in terms of SEE. The FAO-Radiation method was the best of the non-combination equation methods. The FAO-Penman method was poorly ranked due to its chronic overestimation.

The Penman-Monteith method was applied with roughness length (z_{om}), leaf area index (LAI) and bulk surface resistance (r_s) estimates which were based on mean crop height (h_c). This gave the Penman-Monteith method a distinct advantage over the other Penman equations in comparisons with lysimeter observations in that noted changes in h_c for some of the lysimeter locations were able to be incorporated into the Penman-Monteith estimates. No adjustments were made for the other methods as h_c changed.

Average standard errors of estimate (SEE) by the Penman-Monteith and 1982 Kimberly Penman equations were 0.36 and 0.49 mm d^{-1} during growing seasons and 0.47 and 0.73 mm d^{-1} during peak ET months at all locations (Table 2). Average SEE's by the FAO-PPP-17 Penman and 1963 Penman were 0.56 and 0.57 mm d^{-1} during growing seasons and 0.72 and 0.81 mm d^{-1} during peak months, respectively. The lowest SEE for a non-combination method was 0.59 and 0.78 mm d^{-1} for seasonal and peak month for the FAO-Radiation method. The SEE represents the amount of absolute error or difference between equation estimates and/or measurements which would be exceeded only 32% of the time.

The average SEE for the Penman-Monteith estimates was 0.36 mm d^{-1} for monthly time-steps across 11 locations, and increased to 0.77 mm d^{-1} for daily time steps at three locations (Jensen et al., 1990). These values of SEE include any errors or systematic biases introduced with lysimeter measurements. Allen and Fisher (1990, 1991) reported a SEE for the Penman-Monteith equation of 0.78 mm d^{-1} when applied to clipped grass and forage grass lysimeter measurements during a growing season at Logan, Utah in 1988. This value agrees with the ASCE analysis. The SEE computed between the two paired electronic weighing lysimeters in the Allen and Fisher study was 0.33 mm d^{-1} indicating that approximately one-third of the SEE ascribed to the Penman-Monteith estimate resulted from errors in lysimeter measurements. This proportion would be higher if systematic biases existed in the lysimeter measurements due to design or management procedures.

A study comparing nine ET_o equations using lysimeter data from six locations in Europe was performed by Choisnel et al. (1992). These authors adopted an approach different from that in the ASCE study and did not test the FAO equations. However, results of the comparison support using the Penman-Monteith equation for ET_o estimates.

4. A New Definition for a Reference Crop

4.1 Use of an ET_o equation to represent a hypothetical reference crop

The primary purpose for developing ET_o equations is to approximate a reference ET by which a crop coefficient is multiplied in order to obtain an estimate of crop evapotranspiration. In many instances, the ET_o equation has represented a "hypothetical" living grass reference in order to provide for a complete record of ET_o during the development of crop coefficients and during calibration or analysis of other ET equations.

Wright and Jensen (1972) and Wright (1982) used a calibrated form of the Penman equation ("Kimberly" Penman) to represent a hypothetical alfalfa ET_o during the determination of crop coefficients. This was necessary because alfalfa was not always grown during all years of their crop studies. In addition, the ET_o estimate provided estimations during periods following alfalfa cuttings. The 1972 Kimberly Penman (Wright and Jensen, 1972) was used in Chapter 6 of Jensen (1974) and the 1982 Kimberly Penman (Wright, 1982) was used in Chapter 6 of Jensen et al. (1990) to represent "lysimeter ET" during an analysis and comparison of example ET equations. All equations analyzed compared the average July data from these chapters to the hypothetical Kimberly Penman "lysimeter".

George et al. (1985) and Pruitt and Swann (1986) used the hourly "CIMIS" Penman wind function derived at Davis, California and Penman equation to represent a hypothetical grass ET_o when calibrating and comparing other methods in California and in New South Wales, Australia. The decision to use the hypothetical reference was based on the excellent and consistent agreement between CIMIS equation estimates and lysimeter measurements at Davis.

Feddes (1987) used a hypothetical reference crop represented by the Penman equation to convert Penman-based crop coefficients to Makkink equation-based crop coefficients. This was done by multiplying Penman-based crop coefficients by the ratio $ET_{Penman}/ET_{Makkink}$. This manipulation demonstrated another advantage of using a hypothetical, equation-based ET_o, in that crop coefficients based on an equation-based definition can be readily converted into a new set of coefficients based on a different definition of ET_o or on new ways of calculating ET_o.

4.2 The Penman-Monteith method as the definition of grass reference evapotranspiration

Many recent studies have advocated using the Penman-Monteith formulation for estimating ET. Sharma (1985) and Hatfield and Fuchs (1990) considered the Penman-Monteith equation to be the most acceptable form of the combination equation for computing crop and reference evapotranspiration. Watts and Hancock (1985) advocated using the Penman-Monteith to directly estimate ET for crops in Australia. French studies (Perrier, 1978; Gosse et al., 1977; Perrier et al., 1980; Perrier, 1982; Katerji and Perrier, 1983) have used the Penman-Monteith equation and advocated its use throughout France for direct computation of crop evapotranspiration. These studies recommended using environmentally induced "critical" aerodynamic and surface resistance coefficients specific to each crop. The HAPEX-MOBILHY study of regional evapotranspiration in southwest France during 1986 (Gash et al., 1989) obtained aerodynamic roughness and bulk surface resistances for use in the Penman-Monteith equation.

The MORECS system (Thompson et al., 1981) used the Penman-Monteith equation to estimate ET from various types of vegetation throughout the British Isles. General algorithms for predicting aerodynamic roughness and surface resistance parameters were developed for both perennial and annual crops based on crop and vegetation growth characteristics.

Allen (1986), Allen et al. (1989), and Jensen et al. (1990) supported the use of the Penman-Monteith equation to represent both alfalfa and grass ET_o. Differences between the two reference types were described using simple roughness-length:crop-height ratios and simple algorithms for predicting the leaf area index. The Penman-Monteith method was ranked high among all methods evaluated in the Jensen et al. (1990) study, both as a grass and as an alfalfa reference. Allen and Fisher (1991) used the Penman-Monteith equation with a simple LAI-height algorithm for grass to predict 30-minute ET from 0.2 m clipped grass under advective conditions without the need to vary r_s with time of day or modify r_a for stability effects.

The different wind functions and calibrations of the Penman equation have caused confusion for users, primarily to scientists and practitioners in non-engineering or non-agronomic professions. FAO and ICID recognize the need to standardize on one ET_o method in order to represent and define a hypothetical grass reference crop by which to calibrate or validate other ET_o methods. Based on results of the studies reported here, the FAO Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements (Pereira and Smith, 1989; Smith et al., 1991) recommended the Penman-Monteith method as the primary ET_o method for defining grass ET_o and for determining crop coefficients. The Penman-Monteith method was selected because it closely approximates grass ET_o at the locations evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters.

4.3 Standardized crop characteristics in the Penman-Monteith definition for grass ET_o

The Penman-Monteith method, as applied to grass ET_o, was presented in Equation (2). Aerodynamic resistance r_a for use in the Penman-Monteith equation can be computed assuming neutral stability conditions as

$$r_a = \frac{\ln \frac{z_m - d}{z_{om}} \ln \frac{z_h - d}{z_{oh}}}{k^2 U_z} \qquad (4)$$

where z_m is the height of wind measurements, z_h is the height of air temperature and humidity measurements, z_{om} is roughness length governing momentum transfer, z_{oh} is roughness length governing transfer of heat and vapour scalars, k is the von Karman constant (0.41), U_z is wind speed at the z_m height, and d is the zero plane displacement height. r_a has units of s m^{-1} when U_z has units of m s^{-1}. z_{om} can be generalized as 0.123 h_c, where h_c is mean grass height and z_{oh} is estimated as 0.1 z_{om} (Chamberlain ,1966; Brutsaert, 1982) (see Annex 2 of Allen et al. 1994). Parameter d can be estimated as 0.67 h_c. Units of z_m, z_h, d, z_{om}, z_{oh} and h_c terms must be the same.

Bulk surface resistance. Bulk surface resistance for grass can be estimated as:

$$r_s = \frac{100}{0.5\ LAI} \qquad (5)$$

where LAI is estimated for clipped grass as LAI = 24 h_c where h_c is in m (Allen et al., 1989; Jensen et al., 1990) The 100 s m^{-1} in the numerator of the r_s equation represents an average leaf resistance for 24-hour time steps and the 0.5 LAI in the denominator indicates that generally only the upper half of a dense grass cover may be active in the evapotranspiration and energy exchange process. It is known that surface resistances are not independent of climate (Monteith, 1965; Jarvis, 1976; Perrier, 1982; Stewart, 1988, 1989; Choisnel et al., 1992). Nevertheless, the adoption of a constant r_s aims at formulating a normalized ET_o definition which can be adopted worldwide. Errors in ET_o estimates caused by using a constant r_s (or r_l) are expected to be in the range of errors in lysimeter and weather measurements.

Allen et al. (1989) and Jensen et al. (1990) found a constant value of r_s to yield good results with the Penman-Monteith equation for the eleven lysimeter locations listed in Table 1. However, Choisnel et al. (1992) have suggested, based on an analysis of grass lysimeter data from European countries, that r_s may vary with location. The variation suggested by Choisnel et al. (1992) was necessary to account for the apparent increase in r_s noted when going from northern Europe to southern Europe. The change in r_s was based on residual calculations from lysimeter measurements. From descriptions given in Choisnel et al. (1992), some of the apparent changes in r_s with location could have been caused by the differences in grass varieties, grass height, lysimeter management, soil moisture regimes and fetch noted in the study, rather than caused by an actual feedback mechanism based on VPD.

Recent studies on ET from a native grassland in Kansas, U.S.A. indicate that stomatal resistance is influenced to some extent by radiation intensity and vapor pressure deficit (Stewart and Gay, 1989; Kim and Verma, 1991; Stewart and Verma, 1992). Relationships proposed in these references predict decreases in r_s with increasing R_s and increases in r_s with increasing VPD. Kelliher et al. (1993) have correctly pointed out that r_s - VPD interactions should be expressed using VPD calculated at the leaf surface in order to eliminate biases caused by variation in r_a. However, most current relationships, including those presented by Stewart and Gay (1989), Kim and Verma (1991) and Stewart and Verma (1992) and Itier (1994), are based on VPD calculated at the equipment reference height. A relationship representing average results from the Stewart-Verma studies can be expressed as $r_s = 67\ f(R_s)\ f(VPD)$, where $f(R_s) = (230/R_s + 0.77)$ for R_s in W m^{-2} and where $f(VPD) = (1\text{-}0.17\ VPD)^{-1}$ for VPD in kPa. These relationships are valid for $R_s > 0$ and LAI ~ 2.9. Under many conditions, the $f(R_s)$ and f(VPD) functions in the Stewart-Verma equation partially counteract one another, since both R_s and VPD increase during morning hours toward midday. The result is a relatively constant r_s during daylight hours as compared to calculations made using only R_s or only VPD. This is demonstrated in the following example and in Figure 3.

Itier et al. (1994) (referenced by Itier (1994)) have proposed estimating r_s from VPD only. The suggested relationship is $r_s = 10 + 40$ VPD for r_s in s m^{-1} and VPD in kPa. The effect of employing the Stewart-Verma functions and the Itier function on calculations of grass ET are evaluated in the following section.

Comparisons showing effects of using a constant and variable r_s. The Itier (1994) r_s relationship was tested using the daily Davis lysimeter data set described previously, where ET_o calculations made using Equation (2) with constant r_s (70 s m^{-1}) are plotted in Figure 1b against lysimeter measurements of ET_o, and ET_o calculations made using Equation (2) with r_s calculated as 10 + 40 VPD s m^{-1} are plotted in Figure 1c against lysimeter measurements of ET_o. Calculations by the 1963 form of the Penman equation (Penman, 1963) are included in Figure 1d for comparative purposes. Calculations using the Stewart-Verma r_s function at Davis are not shown in Figure 1 since only 24-hour data

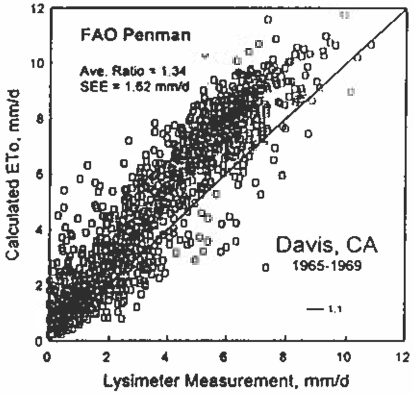

Figure 1a

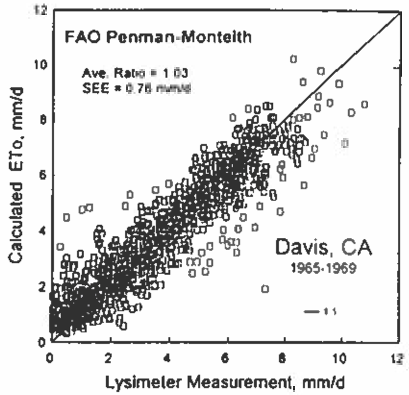

Figure 1b

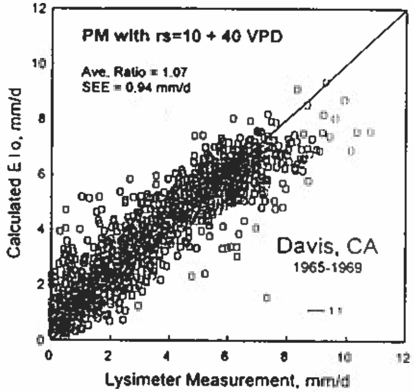

Figure 1c

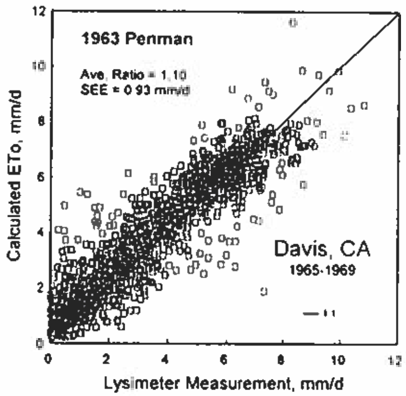

Figure 1d

Figure 1. Daily calculations of ET_o vs. lysimeter measurements at Davis, CA, U.S.A. during 1965-1969 for (a) The FAO (24) Penman method; (b) the Penman-Monteith method (Equation (6)) with $r_s = 100/(0.5\ LAI) = 70\ s\ m^{-1}$ for 0.12 m grass; (c) the Penman-Monteith method (Equation (2)) with $r_s = 10 + 40\ VPD$; and (d) the 1963 Penman form.

were used. Therefore, the mean 24-hour R_s values did not reflect actual r_s - R_s interactions occurring within each day and resulted in overprediction of r_s and underprediction of ET_o. This indicates that coefficients in the $f(R_s)$ and f(VPD) functions will require modification for application to 24-hour periods.

There was significant scatter between ET_o calculations and lysimeter measurements within the Davis data set due in part to day to day variation in height of lysimeter vegetation between mowings (see Section 3.2), random instrument measurement errors and estimation of R_n. This type of variation is typical. What one should notice from Figures 1b and 1c is that the estimates by Equation (2) with r_s = 70 s m^{-1} provided estimates of ET_o which were nearer lysimeter measurements as compared to using the relationship suggested by Itier (1994) during both low and moderate ET_o periods when VPD's were low and during days with high ET_o when VPD was large. Estimates by Equation (2) with r_s = 10 + 40 VPD overpredicted ET_o during low and moderate ET_o periods due to an underestimation of r_s and underpredicted ET_o during high ET_o periods due to an overestimation of r_s. The SEE between ET_o estimates and lysimeter measurements increased by 24% when the Itier relationship was used. The ET_o calculations which were made using a constant r_s (Figure 1b) are observed to be more linear relative to lysimeter measurements as compared to those made using a variable r_s (Figure 1c).

Calculations of ET for hourly periods are plotted against lysimeter measurements of ET from 0.24 m clipped fescue grass over a 3 day period in 1990 at Logan, Utah, U.S.A.. Details of the site, data set, and calculations are given in Allen et al. (1994). In this application, ET calculated using a constant r_s computed from Equation (5), using r_s computed following Itier (1994), and using r_s computed following Stewart-Verma are compared against lysimeter measurements. Because the grass in the Logan lysimeter was taller than the 0.12 m grass reference definition (see section 4.4) and had an LAI of about 5, calculations for r_s by Stewart-Verma and Itier were adjusted by multiplying by a ratio of 2.9/5, where 2.9 represents an LAI for the 0.12 m grass reference definition. However, this adjustment may not be valid, since Stewart and Verma (1992) have found that r_s for a native grassland in Kansas was not sensitive to variations in total LAI between 1 and 3. Calculations for r_s in all ET calculations shown in Figure 2 were corrected for boundary layer stability using Richardson numbers based on surface-air temperature differences (Allen et al., 1994).

Results from all three r_s calculations were similar over the 3 day period shown in Figure 2, especially during periods of low ET. The Stewart-Verma relationship predicted slightly higher ET estimates during some high ET periods and the Itier (1994) relationship underestimated ET during high ET periods. The overall ratios of predicted ET to measured ET shown in Figure 2 were 0.94, 0.90, and 0.97 for the Penman-Monteith equation using the constant, Itier, and Stewart-

Verma r_s calculations, respectively. Values for SEE were 0.05, 0.06 and 0.05 mm h^{-1} for the three methods.

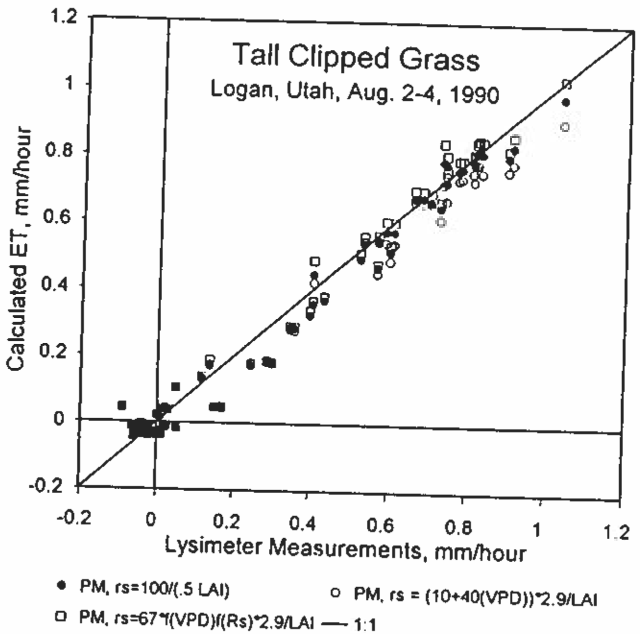

Figure 2. Hourly calculations of ET vs. lysimeter measurements for 0.24 m tall clipped fescue grass at Logan, UT, U.S.A. during a three day period in August, 1990 for estimates using Equation (2) with r_s = 100/(0.5 LAI) and with r_s = 10 + 40 VPD

Figure 3 demonstrates how the r_s calculations by the three methods varied during the day of August 2, 1990 relative to r_s values which were back-calculated by rearranging Equation (2). Back-calculated values for r_s during the midday period varied from 10 to 60 s m^{-1} and averaged about 25 s m^{-1}. The relatively large variability in values for back-calculated r_s from one hour to the next is a result of the accumulation of measurement errors (lysimeter and weather data) into the residual r_s calculations and is not a real phenomenon. The constant r_s = 36 s m^{-1} was calculated using Equation (5). Values for r_s from the Stewart-Verma relationship (r_s = 67 f(R_s) f(VPD)), adjusted for LAI, ranged from about 20 to 25 s m^{-1} during the midday period and were relatively constant. Values for r_s predicted using Itier (1994) ranged from 30 to about 70 s m^{-1} during the midday period and averaged about 60 s m^{-1}. Calculated aerodynamic resistance r_a are also shown in Figure 3 to indicate relative magnitudes of values and to demonstrate the effect of corrections for atmospheric stability (using the Richardson number, Ri) which were relatively large during the late morning hours when grass leaf temperatures exceeded air temperature.

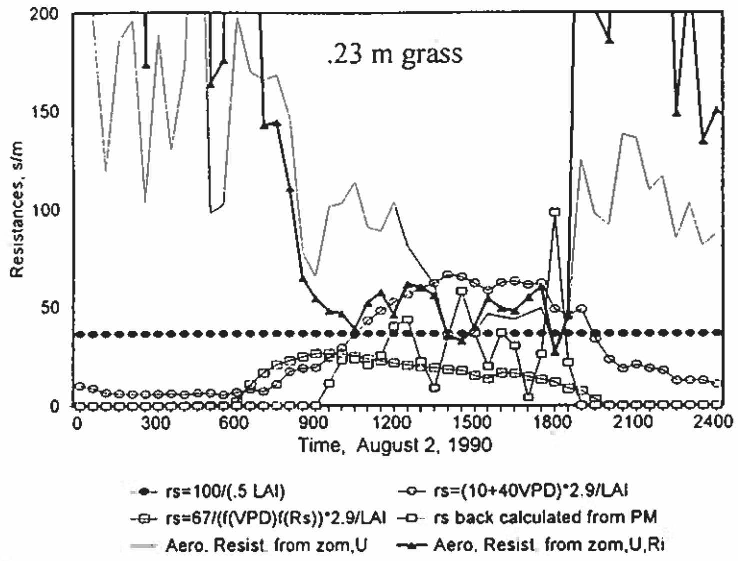

Figure 3. Calculations for 30-minute values of r_s at Logan, UT on August 2, 1990 using Equation (5), Itier (1994) and Stewart-Verma relationships. Also shown are values for r_s obtained as back-calculations on Equation (2) and calculations of r_a from wind data with and without the use of the Richardson stability number (Ri)

The three procedures for calculating hourly r_s which are shown in Figure 3 produced markedly different estimates of r_s for the Logan data. However, relative differences in calculated ET among the three methods were not nearly as large, as shown in Figure 2 where all three methods, especially Equation (5) and the Stewart-Verma function, produced acceptable estimates of ET. This was due to the relatively large values of r_a for the clipped grass (averaging about 50 s m^{-1} during midday periods having strong wind) as compared to smaller values for r_a which would have occurred over taller, rougher vegetation. Therefore, the ratio of r_s/r_a in Equation (2) for the grass crop did not vary substantially with changing r_s. The result was relatively low sensitivity of Equation (2) to the value of r_s when applied to grass under conditions of adequate soil moisture. This was also observed by Kim and Verma (1991) for the native grassland in Kansas and by Kelliher et al. (1993) for general applications.

The comparisons presented here and in the adjoining paper by Allen et al. (1994) indicate that using a constant value for r_s appears to be valid for predicting ET from clipped grass during hourly, daily and monthly time periods. If r_s were to be varied with weather parameters, then it appears that all relevant climatic variables need to be included since these variables can in many situations counteract one another. In the case of the grass reference, the r_s function should include both R_s and VPD and perhaps leaf or air temperature, but should not include VPD alone. However, varying r_s with climate is not recommended for ET_o calculations unless calculations of r_a can additionally be corrected for boundary layer instability, as both calculations provide about the same, minor degree of improvement to ET_o estimates. Because most routinely measured weather data lack the multilevel air temperature and wind measurements or surface temperature measurements required to correct r_a for boundary layer stability or instability, the constant value of r_s is recommended for calculating ET_o.

Clearly, the selection of constant height and bulk surface resistance parameters is a compromise and may not represent reality in all climatic regimes. However, this selection provides consistent ET_o values in all regions and climates and among research locations. The Penman-Monteith equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. By using the Penman-Monteith definition of ET_o, one may calculate crop coefficients at research sites where ET_o is not measured simultaneously with measured ET from nonreference crops. In addition, various crops may exhibit variations in r_s with climate which are different from those exhibited by grass. In the $K_c\,ET_o$ approach, the variations in r_s and r_a relative to the reference crop are accounted for within the crop coefficient, which serves as an aggregation of the physical and physiological differences between crops. The aggregation of various differences and development of crop coefficients should be simplified by using the constant r_s in the ET_o definition.

4.4 A definition and equation for the FAO Penman-Monteith grass reference

Defining grass reference evapotranspiration (ET_o) as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water, the estimation of the ET_o can be based on the Penman-Monteith approach. When combined with r_s = 70 s m^{-1} and with the calculation for aerodynamic resistance for a fixed 0.12 m grass height using guidelines in Section 4.3, the Penman-Monteith equation for 24-hour periods becomes (Allen et al., 1989; Smith et al., 1991; and Annex II of Allen et al., 1994) :

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} U_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34\,U_2)} \qquad (6)$$

where ET_o is the grass reference ET, mm d^{-1}, R_n and G have units of MJ m^{-2} d^{-1}, T is the mean daily air temperature, °C, γ and Δ have units of kPa °C^{-1}, U_2 has units of m s^{-1} and $e_a - e_d$ has units of kPa. Equations and complete definitions for the components in Equation (6) are given in Annexes 1 and 2 of Allen et al. (1994).

The definition of ET_o given by Equation (6) has been recommended by the FAO Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements (Smith et al., 1991). The form of equation (6) is not very different from other empirical Penman expressions with the exception of the addition of T in the numerator and U_2 in both the numerator and denominator. Application requires the same parameters as other forms of the combination equation. A form of Equation (6) for calculating hourly ET_o is presented in Allen et al. (1994). The FAO Penman-Monteith equation as formulated here should not require local calibration or use of a localized wind function if wind speed is measured at a height of 2 m or is adjusted to this height.

No weather-based evapotranspiration equation can be expected to predict ET perfectly under every climatic situation due to simplifications in formulation and errors in data measurement. It is probable that precision instruments under excellent environmental and biological management conditions will show the FAO Penman-Monteith equation (equation (6)) to deviate at times from true measurements of grass ET_o. However, it is our opinion and that of the Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements that the hypothetical reference definition of the FAO Penman-Monteith equation should be used as the definition for grass ET_o when deriving crop coefficients. This recommendation is based on the important need to standardize the ET_o concept and its use.

4.5 Using the FAO Penman-Monteith equation as a reference definition by which to calibrate other ET_o equations

Many locations have only air temperature and precipitation records. Simplified or empirical temperature-based methods are needed to estimate ET_o for these regions (Hargreaves et al., 1985). Because simplified methods lack some of the major weather parameters which affect the value of ET_o, local or regional calibration may be necessary. The FAO Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements (Smith et al., 1991) recommended that empirical methods be calibrated or validated for new regions using the standard FAO Penman-Monteith definition for ET_o. These calibrations should be done at the closest location(s) having sufficient and valid weather measurements to apply the FAO-Penman-Monteith equation. The weather measurements need to be taken at a properly watered agricultural setting, otherwise adjustment to air temperature, humidity and wind measurements may be necessary.

For regional calibration, simple calibration factors can be computed on a monthly basis as :

$$b = \frac{ET_o}{ET_{equation}} \quad \text{or} \quad b = \frac{ET_o - a}{ET_{equation}} \tag{7}$$

where ET_o is grass reference ET as defined by the FAO Penman-Monteith equation and $ET_{equation}$ is ET predicted by the equation being calibrated. Coefficients b and a are calibration factors which may vary with month. Grass ET_o is then calculated at locations with limited data as :

$$ET_o = b\, ET_{equation} \quad \text{or} \quad ET_o = a + b\, ET_{equation} \tag{8}$$

The concept of using one equation to calibrate or validate a second, more empirical equation has been widely used. Gunston and Batchelor (1983) used the FAO-Penman to calibrate coefficients for a Priestley-Taylor equation for application in tropical regions. They were careful to use only weather data from months during which precipitation was greater than ET_o to insure that the stations were surrounded by green, evaporating vegetation for the calibration and that weather measurements were synchronized with the reference ET energy exchange (see section 5.4). Gunston and Batchelor found a significant deviation of the Priestley-Taylor calibration from the Penman equation estimate when months with precipitation less than ET_o were utilized.

Allen and Brockway (1983) used the 1972 Kimberly Penman equation to develop adjustment factors for the FAO-Blaney-Criddle equation at five locations having data for applying the Penman method. The adjustment factors and FAO-Blaney-Criddle equation were then applied to 100 air temperature stations in Idaho, U.S.A. They used the reference adjustment factors to correct for under and over estimation by the FAO-Blaney-Criddle equation at different times of the year and to convert the equation to an alfalfa reference. Allen (1992) used the FAO-Penman-Monteith equation (6) to develop generalized calibration factors for the 1985 Hargreaves temperature difference equation.

All methods contained in FAO-24 other than the FAO-Penman equation (FAO Blaney-Criddle, FAO Radiation, FAO Pan) have the same importance as before. When sufficient data to solve the FAO Penman-Monteith equation are not available, then these FAO-24 methods or other methods such as the Priestley-Taylor (Priestley and Taylor, 1972) or Hargreaves et al. (1985) can be used. However, we definitely recommend that all methods be calibrated against the FAO Penman-Monteith equation. Calibrations should adhere to weather station environmental requirements discussed in section 5.3.

5. Conclusions and Recommendations

5.1 Conclusions

1. The 1977 FAO Penman equation has a tendency to overestimate grass reference ET_o by 15 to 20% in a wide range of locations.

2. The FAO Penman-Monteith equation with standardized roughness and bulk surface resistance parameters can and should be used to represent a hypothetical grass reference surface (ET_o) to help eliminate problems in measuring a living reference ET_o and problems of overestimation by the FAO Penman equation.

3. The recommendation to use the FAO Penman-Monteith equation with standardized roughness and bulk surface resistance parameters to represent a hypothetical grass reference ET_o is a step forward in computing crop evapotranspiration and is not an end in itself. Scientific research will continue to improve methods for estimating both reference and other crop evapotranspiration which will be recommended and adopted as they become available.

5.2 Recommendations

1. The standardized FAO Penman-Monteith reference estimate should be used in determining crop coefficients during field studies. Researchers should direct their time, resources and energy to determine new crop coefficients based on the Penman-Monteith reference estimate rather than grow and maintain a living grass reference. We believe that the hypothetical reference definition is sufficiently close to the real condition, as far as canopy and energy balance exchanges and processes are concerned, that basing developed crop coefficients on the hypothetical definition will result in satisfactory, consistent and transferrable crop coefficients.

2. The simple methods used first by Monteith (1965) to establish a model which considers the crop as a big leaf at the $d + z_{om}$ level and later by Chamberlain (1966), Brutsaert (1982) and Jensen et al. (1990) to obtain an average value for z_{oh} equal to 0.1 z_{om} do not correspond fully to the theory of exchange between the crop and the air (Tanner and Fuchs, 1968; McNaughton and Jarvis, 1984; Perrier and Tuzet, 1991). Therefore, it is of particular importance that boundary layer studies be continued on this subject in order to improve the accuracy of estimated exchange coefficients (or aerodynamic resistances).

3. Some scientists should continue to use lysimeters and micrometeorological

instruments under excellent environmental and management conditions at a few select locations to bring refinement to the definition of grass ET_o (aerodynamic, radiation, and bulk surface characteristics, etc.) in order to develop a better representation of the hypothetical reference crop. These studies should emphasize equipment integrity, uniformity of the measurement surface and fetch, and duplication of instruments and measurements.

4. The calculation procedures for hypothetical grass ET_o as represented by the FAO Penman-Monteith equation should be used globally when possible to compute localized adjustment coefficients for simple, empirical equations, including the FAO radiation, Blaney-Criddle and pan evaporation equations. These adjusted equations can then be used at locations having limited sets of weather data to estimate reference ET_o for purposes of computing crop evapotranspiration.

5. Future efforts should be directed toward updating crop coefficients and developing improved measurement and calculation practices for determining crop and reference ET.

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