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The Accuracy of Evapotranspiration Estimated with the FAO Modified Penman Equation

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Summary. The FAO modified Penman equation has gained acceptance as a standard method of estimating reference crop evapotranspiration. Although theoretically sound the Penman equation becomes increasingly empirical when parameters or variables have to be estimated. When evapotranspiration estimates are being used for practical purposes the uncertainties introduced by these empirical factors and relationships should not be neglected. Evapotranspiration estimates for north-east Sri Lanka are used to illustrate the importance of the empiricisms in the FAO modified Penman equation. It is shown that the different empirical relationships used to estimate net radiation and the wind function in the FAO modified Penman equation and in the Penman (1963) equation produce a 23% difference in the estimate of annual reference crop evapotranspiration.

Introduction

The FAO Irrigation and Drainage Paper No. 24: Crop Water Requirements written by Doorenbos and Pruitt in 1975 and revised in 1977 provided comprehensive guidelines for estimating evaporation which were readily understandable by people with little knowledge of evaporation physics. It is therefore not surprising that their recommendations for estimating evaporation have gained acceptance by agronomists and engineers all over the world. For the calculation of crop water requirements they recommend their "Modified Penman" equation for estimating reference crop evapotranspiration (ET) which they defined 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". The actual evapotranspiration from a crop (ET_c) is obtained by multiplying ET by an appropriate experimentally-determined crop factor (k):

$$ET_c = ET \times k \tag{1}$$

There is no longer much dispute over the relative superiority of the Penman method of estimating evapotranspiration in most practical situations. However, discussion persists on the precise form the Penman equation should take and arguments for modifications to the equation and reasons for a 'standard' Penman equation have been reported frequently (Doorenbos and Pruitt 1975, 1977; Thom and Oliver 1977; Frère and Popov 1979; Stigter 1979, 1980, 1983; Cuenca and Nicholson 1982; Weiss 1983). Nevertheless, it is apparent that the most widely used method of estimating evapotranspiration is the 'Modified Penman' equation and crop factors proposed by Doorenbos and Pruitt (1975, 1977). It is also apparent that many engineers and agronomists use the method without enough attention to the uncertainties that can arise from the inherent empiricisms in the equation. For although the Penman equation has a sound theoretical basis, it does become quite empirical when used with crop factors and daily or longer-period mean meteorological data as opposed to hourly meteorological data (Pruitt and Doorenbos 1977). The physical reality of the equation is reduced such that the reliability of the evapotranspiration estimates for a particular region will depend to a great extent on how appropriate the empiricisms are to this region.

In this paper evapotranspiration calculations for north-east Sri Lanka are used to illustrate the relative importance of these empirical relationships to the final evapotranspiration estimates. Estimates of reference crop evapotranspiration calculated by the 'Modified Penman' equation and the 'Penman (1963)' equation are combined with locally determined crop factors to give estimates of actual evapotranspiration from paddy rice. These estimates are compared with independent estimates of actual evapotranspiration which were made by combining measurements of leaf and panicle resistances with meteorological data in the Penman-Monteith equation (Batchelor and Roberts 1983).

Methods and Materials

Data

The data used in this study were recorded at a meteorological site on the Kaudulla Irrigation Scheme in north-east Sri Lanka (8°12′N; 80°54′E; 50 m M.S.L.). These data, which are summarised in Table 1, were collected as part of the Kaudulla Water Management Study (Holmes et al. 1980). Additional data were recorded during the period May 1979 to February 1981 to enable calculation of the 'Modified Penman' adjustment factor. The climate of the region is dominated by two monsoons, the southwest monsoon from May to September and the northeast monsoon from December to February. Most of the annual rainfall is associated with the northeast monsoon.

Basic Equations

The 'Modified Penman' equation was rearranged so that the terms could be compared with those of the 'Penman (1963)' equation. For estimates of evapotranspiration, the equations may be written as the sum of three terms: the net shortwave radiation term, the longwave back radiation term and the aerodynamic term. The first two terms provide a measure of the effect of radiant energy from the sun and sky and the third term provides a measure of the effect of the ventilation, turbulence and dryness of the air above the evaporating surface.

The 'Penman (1963)' Equation is:

$$\mathrm{ET}_s = \frac{\Delta}{\Delta+\gamma}\mathrm{Rs}\,(1-\alpha) - \frac{\Delta}{\Delta+\gamma}\mathrm{Rb}_s + \frac{\gamma}{\Delta+\gamma}\mathrm{fu}_s\,(ea-ed) \tag{2}$$

The 'Modified Penman' Equation is:

$$ET_m = c\left[\frac{\Delta}{\Delta+\gamma} Rs\,(1-\alpha) - \frac{\Delta}{\Delta+\gamma} Rb_m + \frac{\gamma}{\Delta+\gamma} fu_m\,(ea - ed)\right] \tag{3}$$

where ET is the reference crop evapotranspiration, Rs is the solar radiation, Rb is the back radiation, fu is the wind function, *ea* is saturated vapour pressure (svp) at the mean air temperature, *ed* is the actual vapour pressure, α is the albedo, Δ is the slope of the svp curve at mean air temperature, γ is the psychrometric constant and c is an adjustment factor. Subscripts s and m refer to the 'Penman (1963)' and the 'Modified' versions of the Penman equation.

The factors involving Δ and γ are weighting factors related to the efficiency of conversion of radiant and advected energy into energy of vaporization of water. The albedo takes into account the amount of shortwave solar radiation reflected by the Earth's surface. In this study a value of 0.25 was used; this is a typical value for short green vegetation (Monteith 1973).

The solar radiation was estimated from hours of sunshine by the Angstrom equation (Prescott 1940) with coefficients, appropriate to north-east Sri Lanka, given by Doorenbos and Pruitt (1977):

$$Rs = Ra\,(0.25 + 0.50\,n/N) \tag{4}$$

where Rs is the solar radiation, Ra is the radiation at the top of the atmosphere, n is the observed number of hours of sunshine and N is the day length.

Table 1. Monthly mean climatic data for Kaudulla Headworks meteorological site

Month and year	Temperature (°C)						Wind speed (km/h)		shine
	Max	Min	am Dry	am Wet	pm Dry	pm Wet	Day	Night	(h/day)
Mar 1979	33.1	21.6	26.9	24.5	30.2	24.5	5.3	1.8	9.8
Apr	35.6	23.4	29.2	25.7	31.5	25.9	5.8	3.7	9.9
May	34.4	24.3	29.3	25.2	31.3	25.6	14.8	11.2	8.9
June	35.2	25.7	29.8	24.7	31.5	24.7	22.3	16.0	9.3
Jul	34.3	25.1	29.2	24.1	30.4	23.7	23.2	17.2	8.8
Aug	34.6	24.7	28.9	23.7	31.0	23.6	22.0	14.7	9.5
Sep	32.4	23.6	28.0	24.4	28.0	24.1	14.0	9.1	7.3
Oct	31.8	23.2	27.8	24.9	27.1	24.4	6.7	3.9	7.5
Nov	29.8	22.8	26.3	24.6	26.1	24.5	3.1	1.2	5.0
Dec	29.1	21.9	25.8	24.2	26.1	24.2	2.9	0.5	5.5
Jan 1980	29.6	19.8	25.0	22.8	26.7	22.6	6.0	0.6	8.1
Feb	31.7	19.4	25.8	23.0	28.4	22.9	7.0	1.3	10.0
Mar	34.5	21.8	27.4	24.4	30.6	24.0	7.0	1.8	10.1
Apr	33.9	23.8	29.0	25.9	29.5	25.5	6.2	2.7	7.9
May	34.4	25.6	29.7	26.0	31.3	26.6	12.1	9.1	9.5
June	33.1	25.7	28.9	24.9	30.1	25.1	20.6	16.6	8.4
Jul	33.5	22.0	28.5	24.2	30.1	24.3	22.7	18.4	8.5
Aug	33.6	24.4	28.5	24.0	30.3	24.0	20.6	16.9	8.9
Sep	34.6	25.1	29.1	24.0	30.4	24.0	18.2	13.2	9.1
Oct	31.8	23.9	27.6	24.5	28.0	24.1	10.2	5.5	7.5
Nov	30.3	22.6	26.6	24.7	26.5	24.5	2.2	0.3	5.9
Dec	29.4	22.1	25.7	23.9	26.5	23.8	3.9	0.9	7.1
Jan 1981	29.3	19.8	24.5	22.7	26.6	23.0	4.8	0.8	8.8
Feb	30.3	20.2	24.8	22.9	27.7	23.2	5.8	1.1	8.7

The 'Penman 1963' estimates the net longwave or back radiation by an equation proposed by Brunt (1934):

$$Rb_s = \sigma Ta^4 (0.56 - 0.08 \sqrt{ed}) (0.1 + 0.9 n/N) \quad (5)$$

The 'Modified Penman' uses the equation proposed by Goss and Brooks (1956):

$$Rb_m = \sigma Ta^4 (0.34 - 0.044 \sqrt{ed}) (0.1 + 0.9 n/N) \quad (6)$$

where Rb is the back radiation, σ is Stefan's constant and Ta is the mean absolute air temperature.

The wind function used in the 'Penman (1963)' was:

$$fu_s = 0.26 (1 + U2/160) \quad (7)$$

and in the 'Modified Penman':

$$fu_m = 0.27 (1 + U2/100) \quad (8)$$

where fu is the wind function and $U2$ is the average wind speed in units of km/day at a height of 2 m.

Adjustment Factor

The 'Modified Penman' includes an adjustment factor to account for differences in day and night-time weather conditions between the climate for which the ET estimate is required and the climates in which the data used to calibrate the wind function were recorded. The 'Modified Penman' wind function was determined for climatic conditions of moderate winds, maximum relative humidity (RH_{max}) of about 70% and a ratio of day-time to night-time wind speed of between 3 : 2 and 2 : 1. To enable the adjustment factor (*c*) to be determined additional afternoon wind speed measurements were taken at the Kaudulla met. site. The wind speed ratio was taken as the ratio of the mean wind speed between 08.30 h and 17.30 h and the mean wind speed between 17.30 h and 08.30 h. The maximum relative humidity was estimated from the actual vapour pressure and the svp at the minimum temperature. In this study the adjustment factor was calculated on a daily basis using a computer program to carry out necessary interpolations.

ET Calculations

Although both data and the results are presented as monthly means, the calculations were carried out using the daily measurements.

Results

Adjustment Factor

The monthly mean adjustment factors are plotted in Fig. 1 along with the monthly rainfall totals. The factors are less than 1.00 for three or four months a year at the end of the dry season when the day to night-time wind speed ratios are less than two, the day wind runs are high, RH_{max} remains above 79% and there is high solar radiation. The largest factors of up to 1.20 coincide with the end of the wet season when the day to night-time wind speed ratios are large, the day wind speeds are less than 2 m/s, RH_{max} is approaching 100% and there is high solar radiation.

Incoming Radiation Term

The contribution of the incoming radiation terms to the ET estimates are presented in Table 2. The same formula (4) is used in both the 'Penman (1963)' and 'Modified Penman' equations for calculating the incoming radiation term. As one would expect for a site at a latitute of 8 °N with high monthly mean values of hours of bright sunshine this is consistently large. The lowest rates of 3.7 mm/day occur in 1979 during the wet season months of November and December; during the dry seasons from April to September the rates exceed 5 mm/day.

Back Radiation Term

The contribution of the back radiation terms to the ET estimates are presented in Table 2. The back radiation terms of both the 'Penman (1963)' and 'Modified Penman' equations do not exceed 2 mm/day. This is mainly due to the dependence of the back radiation formulae (5, 6) on the actual vapour pressure of the air, which remains high in north-east Sri Lanka even during the dry season. In more arid areas of the tropics the back radiation term commonly exceeds 3 mm/day during the dry seasons. Even in the months of November and December when the aerodynamic terms and incoming radiation terms are at their smallest, the difference in the back radiation terms produces a difference in the ET estimates of less than 8%.

Aerodynamic Term

The large seasonal variation in the aerodynamic terms (Table 2) is caused by the dependence of the wind functions on the mean daily wind speeds, which are high during the dry season and low during the wet seasons. The 'Modified Penman' monthly mean aerodynamic terms are 15–50% larger than those of the 'Penman (1963)' with the largest differences occurring in the middle of the dry season.

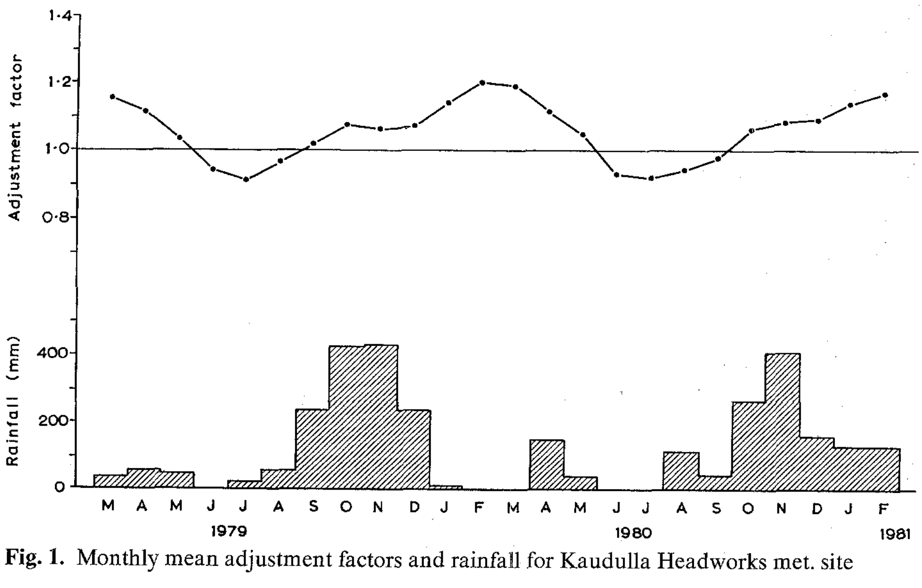

Fig. 1. Monthly mean adjustment factors and rainfall for Kaudulla Headworks met. site

Table 2. Monthly mean evaporation estimates for Kaudulla Headworks met. site

Month and Year	Incoming Radiation Term (mm/day)	Back Radiation Term (mm/day)		Aerodynamic Term (mm/day)		Evapotranspiration (mm/day)		
	$\frac{\Delta}{\Delta+\gamma}$ Rs $(1-\alpha)$	$\frac{\Delta}{\Delta+\gamma}$ Rb_s	$\frac{\Delta}{\Delta+\gamma}$ Rb_m	$\frac{\gamma}{\Delta+\gamma}$ $fu_s(ea-ed)$	$\frac{\gamma}{\Delta+\gamma}$ $fu_m(ea-ed)$	ET_s	ET_m	ET_m/c
Mar 1979	6.0	1.4	1.1	0.8	1.0	5.4	6.7	5.8
Apr	6.2	1.3	1.1	1.1	1.4	6.0	7.3	6.6
May	5.7	1.3	1.0	1.9	2.7	6.3	7.6	7.4
Jun	5.8	1.5	1.1	3.4	5.1	7.7	9.1	9.7
Jul	5.6	1.5	1.1	3.6	5.4	7.7	9.0	9.9
Aug	6.0	1.7	1.3	3.5	5.2	7.8	9.5	9.9
Sep	5.1	1.1	0.9	1.7	2.4	5.6	6.7	6.6
Oct	5.0	1.1	0.9	0.9	1.3	4.8	5.8	5.4
Nov	3.7	0.7	0.6	0.4	0.5	3.4	3.8	3.6
Dec	3.7	0.8	0.6	0.3	0.4	3.2	3.7	3.5
Jan 1980	4.6	1.3	1.0	0.5	0.7	3.9	4.9	4.3
Feb	5.7	1.6	1.2	0.8	0.9	4.8	6.5	5.4
Mar	6.2	1.6	1.2	1.0	1.3	5.6	7.5	6.3
Apr	5.4	1.0	0.8	0.9	1.1	5.2	6.3	5.7
May	6.0	1.2	1.0	1.7	2.4	6.4	7.7	7.3
Jun	5.4	1.2	1.0	2.6	3.9	6.8	7.8	8.4
Jul	5.3	1.3	1.0	2.6	3.9	6.6	7.5	8.2
Aug	5.7	1.5	1.1	3.1	4.7	7.3	8.7	9.3
Sep	5.9	1.6	1.2	3.1	4.6	7.4	9.1	9.3
Oct	5.0	1.1	0.9	1.3	1:7	5.1	6.2	5.8
Nov	4.1	0.8	0.7	0.4	0.4	3.6	4.1	3.8
Dec	4.3	1.1	0.8	0.4	0.5	3.6	4.3	3.9
Jan 1981	4.8	1.4	1.0	0.5	0.6	3.9	5.0	4.4
Feb	5.2	1.4	1.0	0.6	0.7	4.4	5.7	4.9

Table 3. Comparison between the back radiation term humidity corrections of the 'Penman (1963)' and 'Modified Penman' equations

ed (mb)	'Penman (1963)' Correction $(0.56-0.08\sqrt{ed})$	'Modified Penman' Correction $(0.34-0.044\sqrt{ed})$	Mod/Pen (1963) %
5	0.38	0.24	63
10	0.31	0.24	65
15	0.25	0.17	68
20	0.20	0.14	70
25	0.16	0.12	75
30	0.12	0.10	83
35	0.09	0.08	89

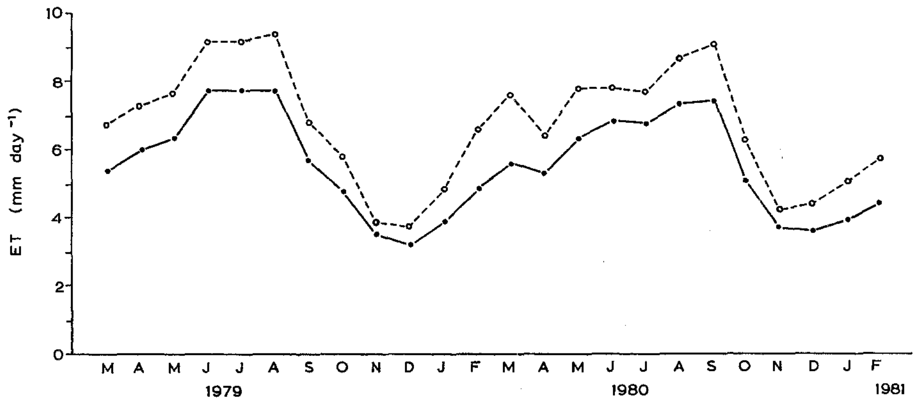

Fig. 2. Monthly mean estimates of ET for the "Modified Penman" (○) and the "Penman (1963)" (●) equations

ET Estimates

The 'Modified Penman' monthly mean estimates are 10–35% larger than those given by the 'Penman (1963)' equation (Table 2). The extreme differences are limited by the adjustment factors being less than unity during the dry season. Conversely, a significant difference is maintained during the wet season as the adjustment factor is greater than unity. This effect can be seen by comparing the columns ET_m and ET_m/c with ET_s, in Table 2. ET_m/c is the 'Modified Penman' ET estimate, divided by the adjustment factor.

The annual ET estimates for the Kaudulla site were 1,896 mm using the 'Penman (1963)' equation and 2,333 mm using the 'Modified Penman' equation, a difference of 23%.

Discussion

Back Radiation Term

The differences between the back radiation estimates are a result of the different empirical coefficients in the humidity correction term. These lead to large differences in the back radiation estimates at low vapour pressures (Table 3). The 'Penman (1963)' coefficients are taken from Brunt (1934) whereas the 'Modified Penman' coefficients are taken from Goss and Brooks (1956). The humidity correction used by Monteith and Szeicz (1962) was $(0.47-0.065\sqrt{ed})$, Wright and Jensen (1972) used $(0.325-0.44\sqrt{ed})$, Fitzpatrick and Stern (1965) used $(0.35-0.42\sqrt{ed})$ and Budyko (1956) used $(0.39-0.5\sqrt{ed})$. Thus the 'Modified Penman' formula is in closer agreement with these other authors than the 'Penman (1963)' formula.

Aerodynamic Term

In the dry season at Kaudulla the difference between the wind functions (7, 8) causes the aerodynamic term of the 'Modified Penman' to be up to 1.8 mm/day greater than that of the 'Penman (1963)' equation. In a drier climate with similar wind speeds but larger vapour pressure deficits the differences would have been greater. Table 4 provides a comparison of the two wind functions over a range of daily wind speeds.

Adjustment Factor

In a generalised description of evaporation Monteith (1965) suggested that the rate of evaporation is controlled by two resistances: the surface resistance to diffusion of water vapour from some saturated region below or within the canopy to the surface itself and the aerodynamic resistance to diffusion of water vapour away from the surface into the atmosphere. In deriving (2) Penman made the assumptions that vegetation which is not short of water has a zero, or at least negligible, surface resistance. This cannot be true unless the surface is wet, as is the case during or soon after rainfall (Thom and Oliver 1977). Since it has been shown that the unmodified Penman equation has been very successful in estimating ET particularly as regards annual totals (Penman 1949, 1952, 1956, 1963; Van Bavel and Wilson 1952; Gerber and Decker 1961; Wang and Wang 1962; Stanhill 1961; Edwards and Rodda 1970), it has been inferred that the omission of a surface resistance term is compensated by an unrealistically small wind function (Thom and Oliver 1977). The Thom and Oliver version of the Penman equation includes a surface resistance term and, like the 'Modified Penman' equation, a larger more realistic wind function. Doorenbos and Pruitt state that the adjustment factor in the 'Modified Pen-

Table 4. Comparison between the wind functions of the 'Penman (1963)' and 'Modified Penman' equations

$U2$ (km/day)	'Penman (1963)' fu_s $0.26(1+U2/160)$	'Modified Penman' fu_m $0.27(1+U2/100)$	Mod/Pen (1963) %
50	0.34	0.41	121
100	0.42	0.54	129
200	0.59	0.81	137
400	0.91	1.35	148
800	1.56	2.43	156

man' is to account for differences in day and night-time weather conditions between the climate for which the ET estimate is required and the climates in which the data used to calibrate the wind function were recorded. However if the 'Modified Penman' is to provide good estimates of ET the adjustment factor must implicitly take account of surface resistance. This is a far from ideal situation since the wind function correction and the surface resistance should be treated separately and explicitly. In climates which do not require a wind function correction the adjustment factor will be unity and the large wind function will not be compensated by a surface resistance correction. In the regions where a correction to the wind function is necessary then it would be more logical if it were only applied to the aerodynamic term; equation (3) would then be written as:

$$\mathrm{ET}_m = \frac{\Delta}{\Delta+\gamma}\,\mathrm{Rs}\,(1-\alpha) - \frac{\Delta}{\Delta+\gamma}\,\mathrm{Rb}_m + c\,\frac{\Delta}{\Delta+\gamma}\,\mathrm{fu}_m\,(ea-ed) \qquad (9)$$

ET Calculations

The most difficult problem that arises in applying the 'Modified Penman' instead of the 'Penman 1963' is the requirement of additional climatological data. Calculation of the adjustment factors necessitates measurements of day and night-time wind speed; these are seldom taken at standard meteorological stations. This puts the agronomist or engineer in the position where he has either to neglect the adjustment factor altogether, or to partition daily wind speeds into day and night-time wind speeds by informed guesswork or to extrapolate values from the closest station with available data. In using the last option difficulties arise in some countries through data only being available for airports near large cities.

ET_c Calculations

The most important crop in north-east Sri Lanka is paddy rice. The reference crop evapotranspiration estimates were combined with the crop factors determined by Joshua (1977) (Table 5) to give estimates of paddy rice evapotranspiration. The dry season estimate for a 3½ month rice variety calculated with the 'Modified Penman' ET estimate was 871 mm, 19% larger than the 'Penman (1963)' estimate of 733 mm. In the 1981 dry season Batchelor and Roberts (1983) estimated evapotran-

Table 5. Paddy rice crop factors and length of growth stages for Sri Lanka (Joshua 1977)

Growth cycle		Initial	Growth stages		
			Crop development	Mid-season	Late-season
3½ months	days	20	30	30	25
	k	1.00	1.15	1.20	0.90
4½ months	days	30	40	45	20
	k	1.00	1.15	1.20	0.90

spiration from a 3½ month rice variety by combining measured canopy resistances and meteorological data in the Penman-Monteith equation (Monteith 1965). Their estimate fell half way between the 'Modified Penman' and 'Penman (1963)' estimates.

For the wet season (4½ month rice variety) the 'Modified Penman' estimate was 21% greater than the 'Penman (1963)' estimate, at 708 mm and 585 mm respectively. Although it is difficult to say which estimate is closest to being correct for well irrigated rice, these figures do give a measure of the uncertainty which may be attributed to the empirical relationships and factors in the Penman equation. This uncertainty can be minimised by wherever possible using measurements and not estimates of parameters or variables. Crop factors which have been derived locally will compensate to some extent for inadequacies in empirical relationships, as long as the crop factors are being combined with reference crop evapotranspiration estimates calculated using the same method as for the original crop factor determination.

Conclusions

Doorenbos and Pruitt (1975, 1977) have provided guidelines for estimating evapotranspiration which are comprehensive and generally available to engineers and agronomists. When using the FAO 'Modified Penman' equation consideration must be given to the uncertainties in the evapotranspiration estimates. For north-east Sri Lanka the difference between the annual estimates of reference crop evapotranspiration of the FAO 'Modified Penman' equation and the 'Penman (1963)' equation was found to be 23%. This difference is attributable to different empirical relationships employed by the two forms of the Penman equation and not to the basic physics of the combination equation. The uncertainties in the evapotranspiration estimates may be minimised by using measurements, and not estimates, of variables and parameters and where possible crop factors which have been derived locally.

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