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A COMPARISON OF THE PRIESTLEY-TAYLOR AND PENMAN METHODS FOR ESTIMATING REFERENCE CROP EVAPOTRANSPIRATION IN TROPICAL COUNTRIES

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ABSTRACT

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An equation for Potential Evaporation (PE) proposed by Priestley and Taylor in 1972 has fewer data requirements than the well established Penman Potential Transpiration (Et) equation. From their definitions, PE and Et values should both provide acceptable estimates of Reference Crop Evapotranspiration (ETo), as defined by Doorenbos and Pruitt. Analysis of mean monthly climatic data from 30 tropical stations, widely spread within the latitude zone 25° N to 25° S, showed that PE and Et estimates agreed closely when monthly rainfall exceeded monthly Et. The minimum data requirements for the Priestley-Taylor equation are daily net radiation and mean air temperature. The Penman equation additionally requires daily data for humidity and run of wind. As reliable field net radiometers become more widely available, the Priestley-Taylor PE equation offers a satisfactory alternative to the Penman Et equation for estimating ETo in humid tropical climates.

INTRODUCTION

In the General Conclusion of his 1948 paper, Penman referred to two aspects of evaporation, "that of the physicist and mathematician seeking facts to fit a formula" and "that of the 'practical' man — water engineer or meteorologist — seeking a formula to fit the facts". Although his own approach to evaporation was welcomed by physicists for its sound scientific reasoning (Monteith, 1965; Thom and Oliver, 1977), it was rejected by 'practical' men for many years on the grounds that the equations were too complex and that the data required were not available for many sites.

For irrigation engineers and agronomists in tropical countries the problems of complexity have been largely overcome by the preparation of tables for field computation of Penman estimates by McCulloch (1965) and Doorenbos and Pruitt (1977), and by the widespread use of electronic calculators and micro-computers in recent years.

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As to availability of data, the basic requirements for calculating Penman estimates are daily readings of: (a) maximum and minimum temperatures; (b) morning values of wet and dry bulb temperatures; (c) wind run over 24 h; (d) hours of bright sunshine.

Although increasing numbers of tropical stations are equipped to this level, they are by no means densely distributed, and it is therefore worth evaluating evaporation equations developed since Penman's original work which are soundly based in physics, but whose data requirements are less than those listed above.

One such equation for estimating evaporation from well watered areas has been proposed by Priestley and Taylor (1972). Their basic data requirement was net radiation, which may be derived, for a vegetated surface: (a) from a net radiometer mounted above the surface; (b) from energy balance calculations, as in the Penman equation, using mean air temperature, humidity and solar radiation data; (c) on a regional scale, from remote sensing data.

In their paper, Priestley and Taylor were particularly interested in regional evaporation estimates based on satellite data, but they also urged that it was essential to "encourage every meteorologist to accept net radiation into his daily thinking as one of the basic synoptic variables". It has been suggested (Shuttleworth, 1979) that the performance of the Priestley-Taylor evaporation formula should be studied under tropical conditions. The aim of this paper is to assess, from a practical user's standpoint, whether or not the Priestley-Taylor method offers advantages over the Penman method for estimating reference crop evapotranspiration in tropical countries.

THEORY

Defining crop evaporation

A major problem in defining crop evaporation is the number of terms used. Evaporation from a freely transpiring short green crop — a basic concept in calculating crop evaporation — has been variously described as *consumptive use*, *potential evaporation*, *potential evapotranspiration*, *potential transpiration* and *reference crop evapotranspiration*. To add confusion, each term may specifically relate to one equation, or may be used by different authors, each using the same term with different definitions.

The term *reference crop evapotranspiration*, ETo (Doorenbos and Pruitt, 1977) has the advantage of indicating the general concept of evaporation from a well watered short green crop. It is defined as "rate of evapotranspiration from an extended surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water". Although these conditions may not be fully satisfied at all times at a real tropical meteorological station, the usefulness of reference crop evapotranspiration is that it allows the general concept to be separated from any particular method of computation.

Before comparing evaporation estimates derived using the methods of Penman and Priestley-Taylor, it is necessary to define the forms of evaporation which their authors expected their equations to predict. In his original paper, Penman (1948) used Et for evaporation from turf (ie. a well established stand of short green grass), adequately supplied with water. He later (1963) defined Et as *potential transpiration*, which was "expected to be a measure of the transpiration rate from an extensive short green cover completely shading the ground and adequately supplied with water". In both cases Et was derived indirectly from calculated values of open water evaporation (Eo), using the equation:

$$\mathrm{Et} = f\,\mathrm{Eo} \tag{1}$$

where f was an empirical factor.

As an alternative approach, Penman (1961) proposed that Et could be calculated directly, using a reflection coefficient (albedo) appropriate to vegetation rather than open water. Et in this case was "expected to be applicable to actively growing vegetation, completely shading the ground, and sufficiently extensive for edge effects to be negligible" (Penman et al., 1967). Priestley and Taylor (1972) were concerned with evaporation on a regional scale. Their term *potential evaporation*, PE, was defined as "evaporation from a horizontally uniform surface", and their equation was proposed for use over "substantial land areas".

From these definitions, Et and PE might not seen strictly comparable — one relating to a specified vegetation cover, and the other giving generalised evaporation over large area. If the equations are used with data from the same meteorological station, however, values of Et and PE both come close to the concept expressed by Eto, assuming the station and its immediate surroundings have a well watered vegetation cover and that it is not an "oasis" in an otherwise arid area. Firstly, Et and ETo have closely similar definitions. Secondly, as net radiation for PE is derived — either directly or indirectly — from station instrument readings, PE must relate more closely to local rather than regional climate.

General forms of the Et and PE equations

Penman's equation for direct estimation of potential transpiration, Et, may be expressed, in terms of depth of water evaporated, as:

$$\mathrm{Et} = \underbrace{\frac{\Delta}{\Delta+\gamma}\, Q^*}_{\text{energy term}} + \underbrace{\frac{\gamma}{\Delta+\gamma}\, \mathrm{Ea}}_{\text{aerodynamic term}} \tag{2}$$

where Δ = rate of change of saturated vapour pressure with temperature; γ = psychrometric constant; Q^* = net radiation; Ea = a term indicating the drying power of advected air crossing the site.

The equation for potential evaporation (PE) proposed by Priestley and Taylor, using similar notation, is:

$$\mathrm{PE} = \alpha \frac{\Delta}{\Delta+\gamma} (Q^* - G) \tag{3}$$

where G = soil heat flux; α = "Priestley-Taylor coefficient".

Accepting that values of net soil heat flux can be neglected over periods greater than 24 h, equation (3) becomes:

$$\mathrm{PE} = \alpha \frac{\Delta}{\Delta+\gamma} Q^* \tag{4}$$

Although we later discuss differences between values of Et and PE derived from the same climatic data, it is worth noting the special case where values of the two estimates are equal. Assuming $\alpha = \alpha^*$ for this special case, and rearranging equations (2) and (4):

$$\alpha^* = \frac{\dfrac{\Delta}{\Delta+\gamma} Q^* + \dfrac{\gamma}{\Delta+\gamma} \mathrm{Ea}}{\dfrac{\Delta}{\Delta+\gamma} Q^*} \tag{5}$$

$$= 1 + \frac{\dfrac{\gamma}{\Delta+\gamma} \mathrm{Ea}}{\dfrac{\Delta}{\Delta+\gamma} Q^*} \tag{6}$$

The second term on the right hand side of equation (6) is the ratio of the aerodynamic to energy terms of the Et equation. Using the general value of $\alpha = 1.26$ (as proposed by Priestley and Taylor) for α^*, the Et aerodynamic term is 26% of the energy term when Et = PE.

Specific forms of equations used

The equation used for Et is basically one proposed by Penman in 1963. Apart from changes in units, the only modification is the use of a relationship between sunshine hours and solar radiation proposed by Doorenbos and Pruitt for tropical latitudes. This replaces Penman's original relationship, which was more suited to British conditions. The terms used for Q^* and Ea in equation (2) were:

$$Q^* = R_a (1 - \mathrm{alb})(0.25 + 0.5\, n/N) - \sigma T_a^4 (0.56 - 0.08\sqrt{e_d})(0.1 + 0.9\, n/N) \tag{7}$$

and

$$E_a = 0.26 (1 + U_2/160)(e_a - e_d) \tag{8}$$

where R_a = theoretical maximum solar radiation at the top of the earth's atmosphere (mm/day); alb = reflection coefficient (albedo), taken as 0.25 for short green cover; n = mean daily hours of bright sunshine; N = possible hours of bright sunshine; σ = Stefan's constant (mm day^{-1} K^{-4}); T_a = mean air temperature (K); e_d = mean actual vapour pressure (mb); U_2 = mean daily wind speed at 2 m height (km/day); e_a = saturated vapour pressure (mb).

PE values were calculated from equations (4) and (7).

ANALYSIS

To compare the performance of the Et and PE equations over a wide range of tropical climates, data were principally selected from tables of mean monthly values in volumes of the World Survey of Climatology covering Africa (Griffiths, 1971). Central and Southern America (Schwerdtfeger, 1976), and Northern and Eastern Asia (Arakawa, 1969). Two stages of selection were used. Firstly, all stations were listed which lay within specified latitude and altitude limits, and for which suitable data to calculate equations (7) and (8) were available. Secondly, to provide a balanced range of climates, patterns of wet and dry months were used, depending on whether mean rainfall exceeded mean monthly Et or Et/2.

At the initial stage, stations were selected according to the following criteria:

(1) latitude less than 25° N or S;

(2) altitude less than 500 m;

(3) mean monthly climatic data available for: (a) maximum and minimum temperatures; (b) humidity, as wet bulb depression, vapour pressure deficit or relative humidity; (c) wind run, as daily or monthly total; (d) hours of bright sunshine, as daily or monthly total.

The altitude limit was applied to exclude the effect of altitude on the Penman equation values (McCulloch, 1965). This first selection produced 44 stations from the three volumes of the World Survey, to which were added data obtained separately from Bhopal in Central India, the World Survey volume for Southern and Western Asia not having been published at that time.

Apart from the criteria above, the listing of a station in the first stage selection was only dependent on it having been selected by the authors of the World Survey to illustrate the climate of a particular area. To provide a balanced range of climates for comparing Et and PE values, individual months for each station were grouped as follows: (a) "wet" months — mean monthly rainfall greater than mean monthly Penman Et; (b) "intermediate" months — rainfall less than Et, but greater than Et/2; (c) "dry" months — rainfall less that Et/2.

After applying this classification, the 45 stations were listed in order of number firstly of wet months, then of intermediate months (ie. a station with 4 wet, 5 intermediate and 3 dry months was listed above one with

TABLE I

Climatic stations used in the analysis — listed in order of decreasing "wetness" (see text)

	Annual rainfall (mm)	Annual Penman Et (mm)	Number of "wet" months	Number of "intermediate" months	Number of "dry" months
Eala, Zaire 0°03′N, 18°18′E	1749	1364	10	2	0
Maripasoula, French Guiana 3°38′N, 54°02′W	2368	1476	9	2	1
Libreville, Gabon 0°27′N, 9°25′E	2592	1355	9	0	3
Georgetown, Guyana 6°48′N, 58°08′W	2420	1739	8	4	0
Guangzhou, China [a] 23°00′N, 113°13′E	1720	1243	8	2	2
Kinshasa, Zaire 4°19′S, 15°17′E	1378	1363	8	0	4
Malabo, Bioko, Equatorial [b] Guinea 3°46′N, 8°46′E	1898	1095	7	3	2
Porto Nacional, Brazil 10°31′S, 48°43′W	1813	1463	7	0	5
Bouaké, Ivory Coast 7°42′N, 5°00′W	1210	1472	6	2	4
Vitoria, Brazil 20°19′S, 40°21′W	1410	1431	5	6	1
Fort-de-France, Martinique 14°35′N, 61°12′W	1840	1919	5	4	3
Abidjan, Ivory Coast 5°15′N, 3°56′W	2144	1589	5	3	4
San Fernando de Apure, Venezuela 7°53′N, 67°26′W	1491	1776	5	1	6
Nanning, China 22°48′N, 108°18′E	1322	1252	4	7	1
Kalémié, Zaire [c] 5°53′S, 29°11′E	1064	1383	4	3	5
Moundou, Chad 8°37′N, 16°04′E	1228	1810	4	2	6
Asunción, Paraguay 25°16′S, 57°38′W	1392	1770	3	8	1
Corumbá, Brazil 19°00′S, 57°39′W	1121	1488	3	6	3
Juba, Sudan 4°52′N, 31°36′E	982	1742	3	4	5
Malakal, Sudan 9°31′N, 31°39′E	783	2095	3	2	7
Bhopal, India 23°17′N, 77°21′E	1205	1746	3	1	8
Caetité, Brazil 14°03′S, 42°37′W	807	1410	2	3	7

TABLE I (continued)

	Annual rainfall (mm)	Annual Penman Et (mm)	Number of "wet" months	Number of "intermediate" months	Number of "dry" months
Ouagadougou, Upper Volta 12° 22′N, 1° 31′W	897	2005	2	2	8
Rio de Janeiro, Brazil 22° 54′S, 43° 10′W	1093	1388	1	10	1
Tete, Mozambique 16° 11′S, 33° 35′E	604	1877	1	2	9
Abéché, Chad 13° 51′N, 20° 51′E	505	2387	1	1	10
Maracaibo, Venezuela 10° 41′N, 71° 39′W	533	1879	0	3	9
Luanda, Angola 8° 49′S, 13° 13′E	367	1679	9	2	10
Mogadiscio, Somalia 2° 02′N, 45° 21′E	399	2014	0	1	11
Wadi Halfa, Sudan 21° 50′N, 31° 18′E	3	2647	0	0	12
			126	86	148

[a] Formerly Canton.
[b] Formerly Santa Isabel, Fernando Poo.
[c] Formerly Albertville.

4 wet, 4 intermediate and 4 dry months). For the second stage of selection, stations were chosen from this list so that no pattern of wet/intermediate/dry months was duplicated. This gave a final list of 30 stations (Table I), providing 360 individual station months: 126 wet, 86 intermediate and 148 dry. For each of the three groupings all pairs of Et and PE values were plotted, and linear regressions calculated, as shown in Figs. 1, 2 and 3.

DISCUSSION

PE and Et as estimates of ETo

As individual site conditions have been merged by the broad climatological approach used, two basic assumptions were made:

(1) Data sources were "typical" tropical meteorological stations, with grassed site enclosures surrounded by short vegetation.

(2) During wet months, when mean rainfall exceeded mean Et, ground conditions to satisfy the definition of ETo applied.

Applying these assumptions, Fig. 1 shows that PE and Et gave similar values in wet months, indicating that either would give a satisfactory estim-

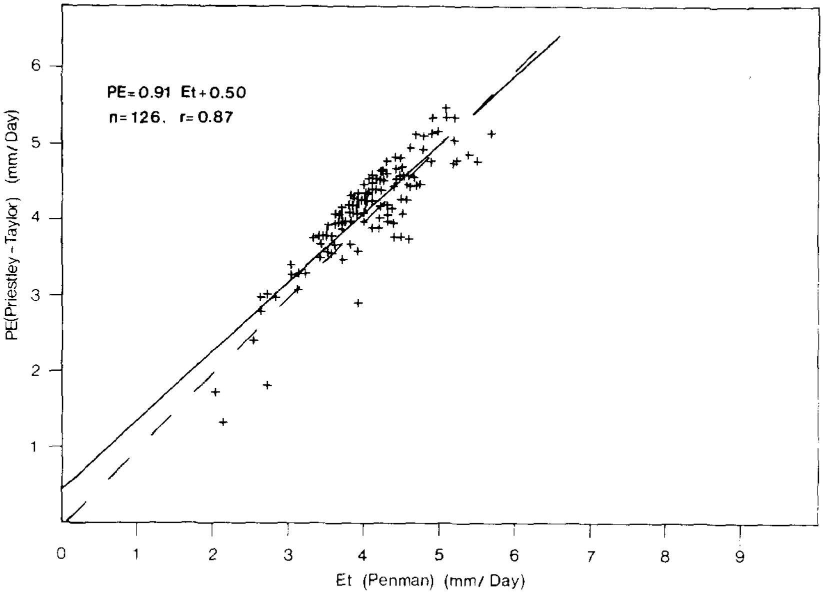

Fig. 1. Linear regression of Priestley-Taylor PE against Penman Et for "wet" months. (monthly mean rainfall > monthly mean Penman Et).

ate of ETo under those conditions. It could not be assumed, however, that ground conditions to satisfy ETo applied *exclusively* in wet months, so the intermediate grouping was used to check agreement under slightly drier conditions. Fig. 2 shows that agreement between PE and Et values was still

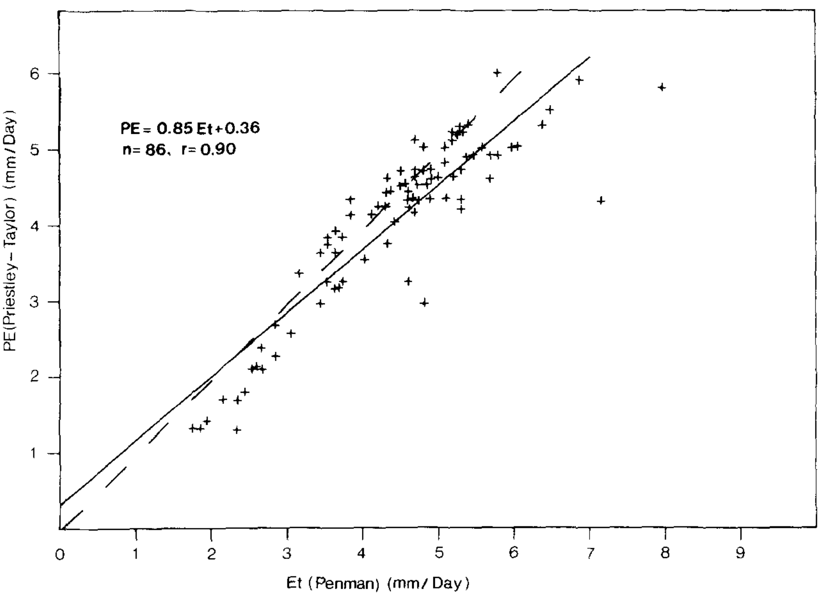

Fig. 2. Linear regression of PE against Et for "intermediate" months (monthly mean Et > rainfall > Et/2).

fairly close for intermediate months. The similarity found between PE and Et over the two groupings of months indicates strongly that both estimates would give satisfactory values for ETo under humid tropical conditions.

These results further indicate that the "general" value of 1.26 for α, proposed by Priestley and Taylor, is acceptable for humid tropical, as well as temperate climates. Derivation of α values using measured evaporation rates from specific well-watered vegetated sites in tropical latitutes has not yet been carried out to our knowledge. Priestley and Taylor themselves (1972) used lysimeter data for grass in Victoria, Australia and snap beans in Wisconsin, U.S.A. Data supporting a value of α close to 1.26 have come from irrigated ryegrass in Ontario, Canada (Davies and Allen, 1973), irrigated potatoes in Wisconsin (Jury and Tanner, 1975) and from a 6 m diameter grassed weighing lysimeter near Toronto, Canada (Mukammal and Neumann, 1977). The present study only provides generalised PE values. It remains for tropical site experiments to be carried out before detailed queries raised over the short term variation of α (Shuttleworth and Calder, 1979), and the physical soundness of any "general" value such as 1.26 (Monteith, 1981) can be answered for tropical vegetation and climates.

Breakdown of Et/PE relationships in drier conditions

Fig. 3 shows that Et and PE do not generally agree when mean monthly rainfall is below Et/2. Useful information on the Et/PE relationship was found by comparing values of the Et aerodynamic/energy term ratio for wet

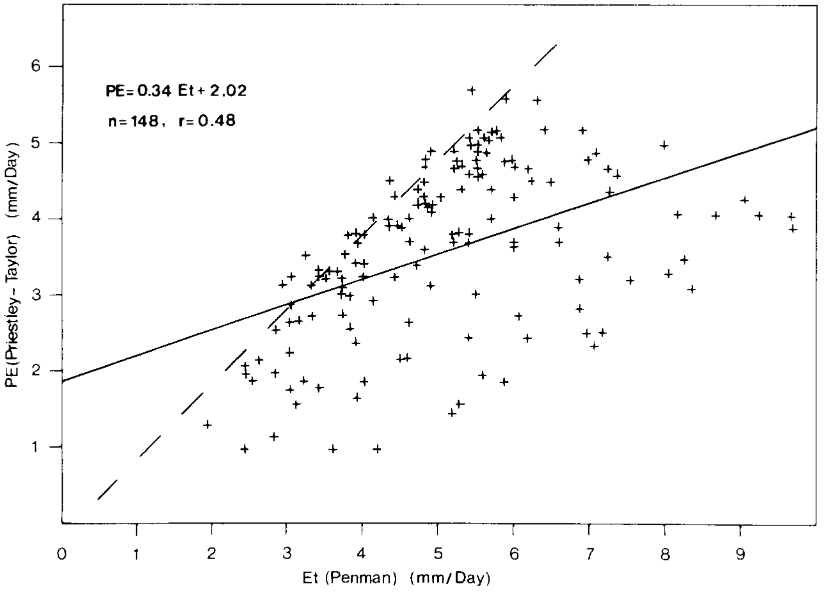

Fig. 3. Linear regression of PE against Et for "dry" months (monthly mean rainfall < Et/2).

and dry months with the set value of 0.26 fixed in the PE estimate (see equation 6). This may be summarised by using data for the two extreme stations in Table I, Eala in Zaire and Wadi Halfa in Sudan, for which mean monthly values of rainfall, Et and PE appear in Fig. 4. In Table II, 2 months are compared for which values of the Et energy term were identical at 3.2 mm/day.

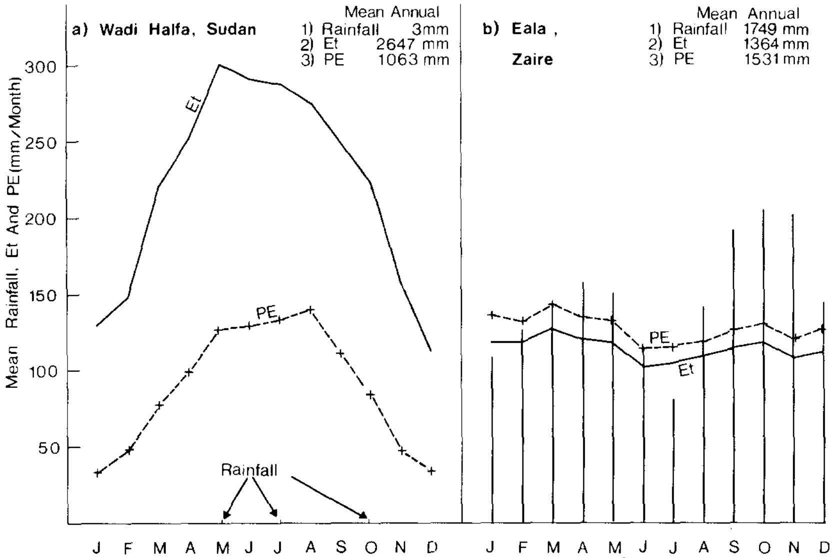

Fig. 4. Mean monthly rainfall, Et and PE for two stations at climatic extremes: (a) Wadi Halfa, Sudan; (b) Eala, Zaire.

TABLE II

PE and Et values for extreme wet and dry months with the same energy term value (units: mm/day)

	Station	
	Eala	Wadi Halfa
	Month	
	December	May
Aerodynamic term of Et	0.4	6.5
Energy term of Et	3.2	3.2
Aerodynamic term/ Energy term	0.13	2.03
0.26 × Energy term	0.83	0.83
Et	3.6	9.7
PE	4.0	4.0
Et/PE	0.90	2.43

The aerodynamic term value of 0.4 mm/day for Eala in December was amongst the lowest found in the study. However, at 13% of the energy term it was sufficiently close to the fixed PE value of 26% for Et and PE to only differ by 10% in these extreme humid conditions. At Wadi Halfa in May, very low humidity forced the aerodynamic term up to 203% of the energy term whilst PE was constrained to 126% of the same value. Although such climates will not produce natural ground conditions to satisfy ETo, they indicate that the close Et/PE relationship found for humid tropical climates will breakdown when low humidities force up the aerodynamic term — an effect also produced by high wind speeds.

Instrument requirements

It was implied earlier that the PE equation would be especially useful if it gave as good an estimate of ETo as Et, but with lower input data needs. If PE estimates are calculated using net radiation derived from standard climatological instruments (Equation 7), the saving in data needs over the Penman estimate will be that no wind run measurements are required. This advantage is reduced, however, due to the close link in many countries between the extension of networks of meteorological stations and the expansion of civil aviation. Under these conditions the presence of an anemometer at an airfield meteorological station is far more likely than the presence of a sunshine recorder, or solarimeter. Stations specifically established for agricultural climatology tend to have both sunshine recorders and anemometers.

Direct measurement of net radiation would reduce data needs. For PE estimates, mean daily air temperature would be needed to set Δ, the slope of the s.v.p./temperature curve, but Et would require, in addition, humidity and wind run data. Net radiometers are now available which are robust and reliable enough for routine field operations (eg. Model DRN 301 of Didcot Instrument Company), but, to satisfy the definitions of Et, PE and ETo, the correct ground cover beneath the instrument must be maintained. The area of ground which significantly affects the downward-looking sensor of the net radiometer is quite small. With the instrument mounted at 2 m, the effective downward field-of view may be only a matter of a few square metres. Providing this small area is under short, well-watered grass — within a larger expanse of the same cover — PE (or Et) values based on net radiometer data should provide good estimates of reference crop evapotranspiration.

CONCLUSIONS

From their definitions, Penman Et and Priestley-Taylor PE evaporation estimates should both simulate Reference Crop Evapotranspiration (ETo), providing data come from a grassed meteorological station under humid climatic conditions.

For months when mean rainfall exceeded mean Et, values of Et and PE agreed closely. Data came from 126 months spread between 26 stations widely distributed geographically between latitudes 25° N or S.

Good agreement between Et and PE was maintained for a further 86 station-months, for which mean rainfall lay between Et and Et/2. The overall agreement between Et and PE indicates that either could be used to estimate ETo in humid tropical climates.

Agreement between Et and PE breaks down when low humidities or high wind speeds force the ratio of the Et aerodynamic to energy terms greatly above 0.26.

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REFERENCES

Arakawa, H. (Editor), 1969. Climates of Northern and Eastern Asia. Vol. 8, World Survey of Climatology, Elsevier, Amsterdam, 248 pp.

Davies, J.A. and Allen, C.D., 1973. Equilibrium, potential and actual evaporation from cropped surfaces in southern Ontario. J. Appl. Meteorol., 12: 649—657.

Doorenbos, J. and Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper 24, FAO, Rome (Second Edition), 114 pp.

Griffiths, J.F. (Editor), 1971. Climates of Africa. Vol. 10, World Survey of Climatology, Elsevier, Amsterdam, 604 pp.

Jury, W.A. and Tanner, C.B., 1975. Advection modification of the Priestley and Taylor evapotranspiration formula. Agron. J., 67: 840—842.

McCulloch, J.S.G., 1965. Tables for the rapid computation of the Penman estimate of evaporation. East Afr. Agric. For. J., 30: 286—295.

Monteith, J.L., 1965. Evaporation and environment. Symp. Soc. Exp. Biol., 19: 205—234.

Monteith, J.L., 1981. Evaporation and surface temperature. Q. J. R. Meteorol. Soc., 107: 1—27.

Mukammal, E.I. and Neumann, H.H., 1977. Application of the Priestley-Taylor evaporation model to assess the influence of soil moisture on the evaporation from a large weighing lysimeter and a Class A pan. Boundary-Layer Meteorol., 12: 243—256.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. London Ser. A., 193: 120—145.

Penman, H.L., 1961. Weather, plant and soil factors in hydrology. Weather, 16: 207—219.

Penman, H.L., 1963. Vegetation and Hydrology. Tech. Commun. 53, Commonwealth Bureau of Soils, Harpenden, 42 pp.

Penman, H.L., Angus, D.E. and Van Bavel, C.H.M., 1967. Microclimatic factors affecting evaporation and transpiration. In: R.M. Hagen, et al. (Editors), Irrigation of Agricultural Lands. American Society of Agronomy, Madison, WI, pp. 483—505.

Priestley, C.H.B. and Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev., 106: 81—92.
Schwerdtfeger, W., 1976. Climates of Central and Southern America. Vol. 12, World Survey of Climatology, Elsevier, Amsterdam, 532 pp.
Shuttleworth, W.J., 1979. Evaporation. Report No. 56, Institute of Hydrology, Wallingford, 61 pp.
Shuttleworth, W.J. and Calder, I.R., 1979. Has the Priestley-Taylor equation any relevance to forest evaporation? J. Appl. Meteorol., 18: 639—646.
Thom, A.S. and Oliver, H.R., 1977. On Penman's equation for estimating regional evaporation. Q. J. R. Meteorol. Soc., 103: 345—348.