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A Test of Two Empirical Evapo-transpiration Formulae for Semi-Arid Regions

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Abstract Potential evapo-transpiration (PET) data are required for a number of climatic analyses. As measured PET values are seldom available, particularly in historical climate data sets, it is necessary to estimate PET from available climatic data, which are often limited to rainfall and temperature in ordinary, rural meteorological observatories. Simple, empirical PET estimation procedures, even though generally location or region specific, are often the only alternative. In this study we compared open pan evaporation and estimates of daily PET from two empirical formulae viz., Linacre and Campbell (a modified Priestly-Taylor formula), with PET estimates by the Penman formula, usually considered the most accurate PET formula, for five diverse arid and semi-arid locations in India. Estimates of PET from the Linacre equation were (1) generally more linearly correlated with Penman estimates of PET, and (2) the standard deviations of the difference between Linacre and Penman estimates were lower, relative to similar comparison between either open pan evaporation or Campbell PET estimates and Penman PET. Estimates of PET by the Linacre formula were consistently higher than the Penman equation estimates, but with an appropriate calibration factor, derived from a few years of complete weather data, the Linacre formula can be used to estimate PET for semi-arid locations where input data for the Penman equation are not available.

Key words Potential evapo-transpiration, Empirical evaporation formulae, Open pan evaporation

To estimate potential crop production or the occurrence of drought stress, the available moisture supply (rainfall plus stored soil moisture) must be compared with water requirement or potential evapotranspiration of the crop over the cropping season. Potential evapotranspiration (PET) is defined as the amount of water that will be lost from a surface completely covered with short vegetation if sufficient water was available at all the times for use by the vegetation (Thornthwaite & Mather, 1955). Since actual measured PET data are not readily available in most arid and semi-arid regions, especially in historical climate data sets, it becomes necessary to use formulae which can estimate PET from available climatic data. There are two kinds of such formulae, physical and empirical. The detailed physical formulae such as that of Penman (1948) need at least four climatic elements, i.e., net radiation, saturation vapour pressure, wind speed and temperature. These are not all commonly available at many weather monitoring locations, and in older, historical climatic data sets. In practice, the only available data for most locations in the arid and semi-arid regions are maximum and minimum temperatures and rainfall, often readily available only as weekly means. Many simplified, empirical formulae for estimating PET which require fewer climatic elements than Penmans formula have been published (Linacre 1977, Fitzpatrick 1963, Swan & Volum 1986, Hargreaves & Samani 1985, Cahoon *et al.* 1991). The major limitation to the use of these empirical formulae is that their application is limited to the climates, seasons or environments similar to those used to derive them.

With only a relatively few meteorological stations in semi-arid India recording the full requisite elements to compute PET by the Penman equation, analysis of drought occurrence or water budgeting will require the use of an empirical formula for PET estimation. The choice of such a formula, however, must be based on its ability to accurately estimate

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local PET. In this paper, we compare PET estimated by two simple empirical formulae, *viz.* the Penman formula, using daily weather data from five selected semi-arid locations in India for which long term input data for Penman PET are available. The long term climatic data sets for these locations also included US Weather Bureau Class A Open Pan evaporation data. Although open pan evaporation is a direct measurement, rather than an estimate, the relationship between open pan evaporation and PET varies with pan installation, surroundings, and micro and macro meteorological conditions, and therefore also requires local calibration. Pan data were included in the study, to compare the relationships (and the resulting calibration problems) of the two empirical formulae with the Penman formula to the relationship of open pan evaporation with Penman-estimated PET.

Materials and Methods

Computational methods

The rate of potential evapotranspiration from well watered vegetation was estimated using the Penman (PET_P) fromula (FAO 1983) as :

$PET_P = [Ea/\Delta]/[1 + T/\Delta]$, in mm day^{-1}, where :

Δ = aerodynamic component slope of the curve of the saturation vapour presssure against temperature,

T = psychrometric constant,

Ea = aerodynamic component, and

Rn = net radiation in evaporation units (mm).

Linacre (1977) estimated the of PET_l from well watered vegetation as

$PET_l = [500Tm/100 - A) + 15(t - t_d)]/(80 - T)$ in mm day^{-1}, where :

Tm = T + 0.006h (where h = elevation in meters).

T = daily mean temperature

A = latitude in degrees, and

td = dew point temperature.

Further Linacre (1977) estimated $T\text{-}T_d$ using the following equation :

$t\text{-}td = 0.0023h + 0.37T + 0.35 R_{ann} - 10.9$, where:

h = elevation in metres

R = mean daily range in temperature, and

R_{ann} = mean annual range of monthly mean temperature

Campbell (1977) computed potential evapotranspiration using a modified Priestley-Taylor equation (Priestley & Taylor 1972) as follows :

$PET_C = [0.0014(T + 3)] * R_n$ in mm day^{-1}, where:

R_n = net solar radiation in mm, estimated from sunshine hours and latitude (FAO 1983), and

T = daily mean temperature.

Long-term (1950-1980) daily weather data were obtained from the India Meteorological Department, for Akola, Jodhpur and Agra, from ICRISAT (1972-1989) for Patancheru, and from the Andhra Pradesh Agricultural University for Anantapur (Table 1). The locations represent a broad range of semi-arid environments in India, in terms of latitude, rainy season length and aridity. The data were not complete to calculate PET by Penman equation for all the years. For locations other than Patancheru, where measured solar radiation data were not available, solar radiation was estimated from sunshine hours and global radiation as described in FAO (1983). Regression of the FAO estimates of solar radiation on actual measured radiation for Patancheru indicated a very good fit of etimated to actual data with the FAO formula (r = 0.99 and b = 0.97).

Comparisons among estimates

Evaporation estimates for each location from the two empirical formulae, plus the open pan-

Table 1 *Latitute, longitude, elevation and long term mean annual rainfall of the five test locations.*

Location	Latitute (°N)	Longitude (°E)	Elevation (m)	Rainfall* (mm)
Anantapur	14.66	77.62	348	590
Patancheru	17.45	78.49	545	764**
Akola	20.70	77.00	282	840
Jodhpur	26.30	73.02	224	383
Agra	27.17	78.00	169	824

* Source : Virmani *et al.* 1982.

** Mean of 15 years.

Table 2 *Means and ranges of yearly correlation coefficients of PET estimated by different formulae and with measured USWB Class A pan evaporation.*

ET method	Anantapur (10 years)			Patancheru (17 years)			Akola (16 years)			Jodhpur (11 years)			Agra (12 years)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Linacre	0.82	0.75	0.88	0.91	0.83	0.95	0.89	0.67	0.94	0.82	0.79	0.88	0.89	0.67	0.94
Campbell	0.69	0.54	0.79	0.81	0.77	0.85	0.79	0.43	0.89	0.76	0.70	0.81	0.79	0.59	0.88
Pan	0.81*	0.69*	0.94*	0.93	0.82	0.96	0.88	0.59	0.96	0.92	0.88	0.95	0.84	0.62	0.94

* 7 year data only Correlations are based on daily data

evaporation values, were compared with estimates from the Penman equation using correlation analysis. Individual daily estimates from the different formulae for each location were compared to Penman PET on a yearly (Table 2) and a monthly (Table 3) basis to determine overall agreement and seasonal trends in agreement, if any. The departures of mean (across years) weekly estimates (weekly means of individual daily values) of PETl, PETc and pan evaporation from PETp (Fig.1) were computed for all 52 weeks of the year. The standard deviations of the departures for weekly mean PET estimated from different equations and pan-evaporation were calculated to assess the magnitude of the variation of the departure values over the year (Table 4).

For each location the mean weekly estimates of $\mathrm{PET_l}$, $\mathrm{PET_c}$ and pan evaporation were regressed against estimates from $\mathrm{PET_p}$ to test the deviation of intercept from zero and the slope from 1.0 (Table 5). PET estimates from the Linacre and Campbell formulae and pan evaporation were then adjusted using the regression parameters for five years chosen at random as calibration factors for each location: The estimated PET from the calibrated empirical formulae were then compared to Penman-deviations of the calibrated formulae from Penman PET, to assess the improvements in the accuracy of estimation with a local calibration factor.

Results and Discussion

Comparisons among estimates

Weekly mean values (for 10-17 years) of daily PET calculated by the three methods (Penman, Linacre and Campbell) for the five stations are illustrated in Fig.1. At all the five locations the Linacre formula overestimated Penman PET, but the magnitude of the difference varied with location. The differences in the two were less at Anantapur and Patancheru than at Jodhpur, Agra and Akola which had higher absolute PET values. $\mathrm{PET_l}$ estimates were generally parallel to Penman estimates, however. The Campbell formula also overestimated PET but the differences were greater in the dry periods (weeks 1 to 22 and 40 to 52) than in rainy periods (weeks 23 to 39, Fig.1). Pan evaporation rates showed a similar trend as the Campbell estimates, but with a greater tendency to overestimate Penman in the dry season, when advective energy inputs were the greatest (Fig.1).

Overestimation of PET by the Linacre formula has been reported for similar arid and semi arid climates in Africa (Linacre 1977, Anyadike 1987) and Australia (Linacre 1977). For locations in more humid regions of Africa, however Anyadike (1987) found satisfactory agreement between Linacre and Penman estimates of PET. Cahoon et al. (1991) found that the Linacre formula underestimated Penman PET in humid regions of southern United States of America (annual rainfall 1100 mm). Thus the Linacre formula is apparently sensitive to extremes of vapour pressure and will require calibration in arid regions.

Despite the tendency of the empirical formulae to overestimate PET as calculated by Penman, there were strong correlations between daily PET estimated by the Linacre and Penman formulae (Table 2). With the exception of Jodhpur, mean correlation coefficients for daily $\mathrm{PET_l}$ and for pan evaporation were very similar across loca-

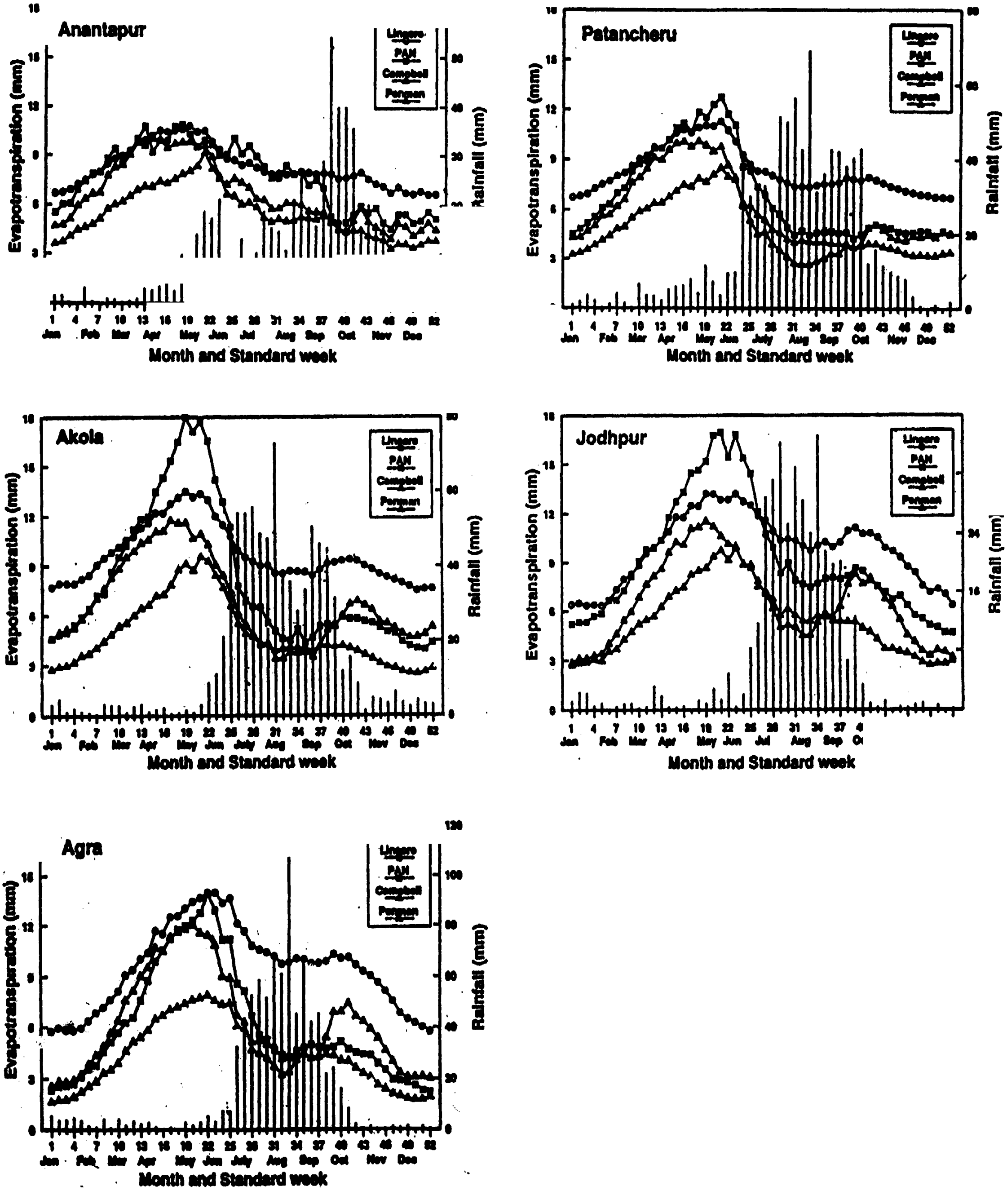

Fig 1 Weekly mean estimates of daily PET by different formulae, weekly mean daily USWB class A pan evaporation and total weekly rainfall (bars) for Anantapur Patancheru, Akola, Jodhpur, and Agra.

Table 3 *Monthly mean correlation coefficients between daily PET estimates by different formulae, and measured USWB class A pan evaporation (Pan) for the number of years indicated in Table 2, for each month for the five locations. Correlations are based on daily data.*

Month	Anantapur			Patancheru			Akola			Jodhpur			Agra		
	ET_l	ET_c	Pan	ET_l	ET_c	Pan	ET_l	ET_c	pan	ET_l	ET_c	pan	ET_l	ET_c	pan
Jan.	0.39	0.06	0.59	0.55	0.35	0.65	0.51	0.45	0.69	–0.05	–0.04	0.67	0.38	0.41	0.72
Feb.	0.50	0.35	0.64	0.60	0.55	0.83	0.47	0.56	0.65	0.43	0.39	0.69	0.63	0.71	0.67
Mar.	0.54	0.22	0.24	0.57	0.59	0.82	0.44	0.43	0.71	0.37	0.36	0.73	0.72	0.75	0.79
Apr.	0.47	0.05	0.19	0.66	0.61	0.77	0.60	0.55	0.75	0.42	0.33	0.81	0.54	0.51	0.65
May	0.53	0.36	0.22	0.74	0.66	0.84	0.53	0.54	0.70	0.41	0.39	0.81	0.59	0.49	0.71
Jun.	0.47	0.32	0.32	0.85	0.81	0.89	0.84	0.76	0.87	0.55	0.57	0.85	0.83	0.64	0.54
Jul.	0.41	0.41	0.60	0.78	0.74	0.82	0.75	0.69	0.74	0.74	0.66	0.91	0.84	0.65	0.81
Aug.	0.26	0.19	0.41	0.71	0.68	0.78	0.73	0.75	0.69	0.72	0.67	0.87	0.76	0.64	0.77
Sep.	0.36	0.20	0.31	0.68	0.67	0.75	0.67	0.68	0.68	0.56	0.51	0.79	0.74	0.63	0.70
Oct.	0.43	0.25	0.22	0.73	0.73	0.79	0.65	0.44	0.59	0.45	0.40	0.67	0.76	0.69	0.59
Nov.	0.47	0.35	0.37	0.55	0.42	0.69	0.61	0.35	0.62	0.31	0.14	0.76	0.62	0.63	0.60
Dec.	0.40	0.20	0.54	0.51	0.31	0.71	0.37	0.39	0.60	0.10	0.04	0.61	0.30	0.31	0.54

tions. Both PET_l and pan were consistently more closely related to PET_p than was PET_c (Table 2).

The comparison of the correlation coefficients of the various PET estimations with PET_p on a monthly basis was more revealing of differences among them. With the exception of Anantapur (where the monthly mean PET estimates were poorly correlated to PET_p for all months), there was a clear trend of much better agreement of the two empirical forumulae and Penman in the rainy season (June- September) than in the dry season (Table 3). In many of the locations, the two empirical formulae were as good as pan evaporation in predicting PET_p in the rainy season, but definitely poorer in the dry season. Monteith (1991) reported a similar difference in PET estimates by the Priestly-Taylor and Penman-Monteith formulae between the rainy and dry seasons in semi-arid Niamey, Niger. The Linacre equation is known to be less accurate in the absence of rainfall and at low mean temperatures, as the estimation of dew point temperature from annual and diurnal temperature ranges in less accurate in the absence of rainfall (mm) and/ or at low mean temperatures (Linacre 1977).

For the rainy months only, the Linacre and Campbell formulae provided equally good estmates of PET at Patancheru and Akola, while the Linacre estimates were marginally better at Agra and Jodhpur, based on the strength of their correlation coefficients to the Penman estimates of PET (Table 3). Linacre estimates were as good as pan evaporation at Patancheru and Jodhpur, but somewhat poorer at the other two locations, based on the same criterion.

The means and standard deviations of the differences between weekly means of daily PET estimates of the empirical formulae and of pan evaporation and the weekly mean Penman estimates were calcuated to evaluate the magnitude and consistency of the errors in the empirical estimates (Table 4). The mean differences were in the order of PET_l, pan evaporation and PET_c. The standard deviations of the departures (which measures the range in weekly mean differences) were, however, much lower for the Linacre than for either Campbell or even for pan evaporation. Thus the Linacre formula, although it overstaimates PET_p, does so in very systematic fashion. Although the mean departures of estimates from Campbell formula from those of Penman were lower at all locations than the departures of the estimates from Linacre equation, the standard deviations were very high, indicating that calibration of the Campbell formula would be less effective than calibration of the Linacre formula.

Calibration of empirical estimates

Table 4 *Means and standard deviations (SD) of departures of weekly means of daily PET estimates by the Linacre and Campbell formulae, and mean weekly measured USWB Class A pan evaporation, from weekly means of daily PET estimates by the Penman formula, for the five locations.*

Location	Linacre		Campbell		Pan	
	Mean	SD	Mean	SD	Mean	SD
Anantapur	2.60	±0.654	0.75	±1.180	1.98	±0.765
Patancheru	3.36	±0.367	0.76	±1.251	1.90	±1.149
Akola	4.79	±0.436	1.90	±1.379	3.19	±2.336
Jodhpur	4.39	±0.844	1.11	±1.262	3.70	±1.550
Agra	5.28	±0.800	1.81	±1.582	1.72	±1.577

We determined calibration coefficients for both empirical formulae and for pan evaporation by linear regression of weekly means of daily PET estimates by these three methods on weekly means of daily PET estimates by the Penman formula for the five sites (Table 5). In this method of calibration, weekly mean PET estimates are calibrated by multiplying by the regression coefficient (b value) and adjusting the product by the intercept (a value). Although the PET$_l$ estimates had significant negative intercepts for all locations, the regression coefficients were not different from 1.0 for all but one location. In contrast, intercepts for both PET$_c$ and pan evaporation data were not significantly different from zero in most cases. but the regression coefficients were significanlty lower than 1.0 (Table 5). Cahoon *et al.* (1991) also reported significant negative intercepts for Linacre PET estimates calibrated against pan evaporation of Penman PET estimates. Thus the Linacre formula, although systematically overstimating PET (significant intercepts), did not have a systematic bias in its estimates (regression coefficients not different from 1.0). Therefore simple additive correction factors could be used for Linacre estimates. For both the Campbell formula and pan evaporation, a more complex correction based on both the a and b values from the regression would be required.

Appropriate calibration factors for each PET estimation procedure for each location were calculated from the respective regression coefficients for data for five years chosen at random, and used to adjust the mean weekly estimates for the remaining years. The adjusted PET values were compared to PET$_p$ estimates for the same years on the basis of mean weekly difference and its standard deviation. The calibration significantly reduced the differences between the Penman and the other PET estimates. The adjusted PET$_l$ estimates had the smallest mean departure and standard deviation of departure of the three estimates. For example, for the year 1990 at Patancheru, the departure for the adjusted Linacre estimate was 0.004±0.39 mm d^{-1}, for the adjusted pan evaportion the departure was 0.12±0.41 mm d^{-1}, and for the adjusted Campbell PET it was 1.42±0.76 mm d^{-1}

Conclusions

Empiricial formulae requiring limited meteorological observations for computing PET are essential for crop water balance applications and for climatic studies in many areas where only rudimentary weather data are avaiable. The results from the present study indicate that the Linacre forumula based on air temperatures and site parameters (latitude and altitude) oversetimated PET for semi-arid Indian locations, but it can be easily calibrated, if a few years of complete climate data are available for locations of interest. The Linacre formula appeared to be superior to the Campbell formula as its deviation from Penman PET is systematic where that of the Campbell formula is not. The other advantage of the Linacre formula over the Campbell formula is that the former is based on temperatures and the latter in addition to temperaturers requires an estimate of solar radiation in addition. In view of the very limited availability of the necessary meteorological data to compute PET by physical equations, the Linacre formula seems to offer a particularly useful tool for variety of agroclimatic studies based on soil

Table 5 *Regression intercepts (a in mm) and regression coefficient (b in mm^{-1}), and correlation coefficient (r) between weekly means of daily PEt estimates by the Penman formula and weekly means of daily PET estimates by the Linacre and Campbell formulae and weekly mean USWB Class A pan evaporation (PAN).*

Location	Linacre			Campbell			Pan		
	a	b	r	a	b	r	a	b	r
Anantapur	−3.66	1.13	0.91	1.64	0.63	0.80	−0.03	0.75	0.93
Patancheru	−4.41	1.13	0.98	1.61	0.59	0.87	0.95	0.59	0.98
Akola	−6.07	1.13	0.98	0.42	0.66	0.85	1.18	0.46	0.97
Jodhpur	−3.68	0.93	0.92	0.72	0.72	0.87	0.12	0.58	0.97
Agra	−2.85	0.76	0.96	0.83	0.57	0.87	0.98	0.56	0.96

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