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Assessment of Evapotranspiration Estimation Methods in a Semi Arid Region

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ABSTRACT: Estimation of accurate reference crop evapotranspiration (ET_0) is necessary for a reliable irrigation management system. This paper deals with evaluation of seven reference crop evapotranspiration (ET_0) methods viz. 1982 Kimberly Penman (K-P 82), FAO-24 Penman (P-24), Penman 1963 (P-63), FAO 56 Hargreaves (F-H), Priestly-Taylor (P&T), Turc and FAO 24 Pan Evaporation (PE). These methods were compared with FAO-56 Penman-Monteith (F-PM) for their capabilities to predict ET_0. Daily weather data for the period of 1971 to 2002 were used for comparison on daily, weekly, and monthly basis.

The statistical results based on root mean squared error (RMSE) and average deviation ($\bar{D}$) indicated that for estimation of ET_0 in Marathwada region PE is the most reliable and accurate method. The sequence of performance from the most to the least accurate methods for the semi arid and sub-tropical region of Marathwada is PE, P-63, Turc, F-H, P&T, P-24, and KP-82.

Keywords: Reference Crop Evapotranspiration, Radiation Methods, Temperature Methods Combination Methods, Pan Evaporation.

INTRODUCTION

Marathwada region of Maharashtra (India) lies in semi-arid climate where rainfall received from the Southwest monsoon during the month of June to September is the major source of water. However, uneven and erratic nature of rainfall in the area necessitates efficient use of irrigation water considering the critical growth stages of crop so as to minimize the losses in crop yields. Process of evaporation and evapotranspiration are the major components of the hydrologic cycle which play a vital role in agricultural and hydro-meteorological studies as well as in the operation of reservoirs, design of irrigation and drainage systems and irrigation scheduling. For irrigation scheduling a better understanding of crop water demand at its critical growth stages is important using accurate reference crop evapotranspiration (ET_0) estimation method. The concept of ET_0 was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices (Allen *et al.,* 1998). The ET_0 and crop coefficient (K_c) further can be used for computing crop evapotranspiration (ET_c), which is one of the most decisive elements for efficient irrigation planning. Because of the variation in crop canopy and climatic conditions, ET_c varies with the crop type and its growth stages. It can be obtained by direct measurements of water loss from a soil using lysimeters and vegetation samples or can be estimated by the multiplication of ET_0 and K_c (Dorrenbos and Pruitt, 1977; Kang, 1986; Kerr *et al.,* 1993). ET_0 can be estimated by many methods (Jensen, 1974; Hill *et al.,* 1985; Kang *et al.,* 1994). These methods range from the complex energy balance equations (Allen *et al.,* 1989) to simpler equations that require limited meteorological data (Hargreaves and Samani, 1985). These methods use climatic parameters such as solar radiation, temperature, wind speed and relative humidity (Pruitt, 1966; Doorenbos and Pruitt, 1977; Burman *et al.,* 1980; Snyder, 1992; Smith *et al.,* 1996; etc.) to determine ET_0.

The FAO Penman-Monteith method (F-PM) was reported to give the best agreement with the observed data (Jensen *et al.,* 1990; Itenfisu *et al.,* 2000; Allen *et al.,* 1994 a, b, 1998, 2000; Smith *et al.,* 1996; Walter *et al.,* 2000, Gundekar *et al.,* 2008; etc.), and thus can

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be used as standardized equation for comparison of ET_0. Although Penman–Monteith method consistently gives more accurate ET_0 estimates than other ET_0 methods (Smith *et al.,* 1992), the climatic data necessary for this method are not always obtainable, especially in developing countries. Hence there is need to evaluate the other simpler ET_0 estimation methods for their accuracy in estimation and recommend them for use in the particular region. Even simpler Pan Evaporation (PE) method needs to be evaluated for its successful applicability. Therefore in this study, seven of the most commonly used ET_0 estimation methods are evaluated for their capability to estimate daily ET_0 and compared with the standard F-PM method.

MATERIALS AND METHODS

Study Area and Data

The study area Parbhani is situated in the Marathawada region of Maharashtra, India (longitude 76° 47′ E, latitude 19° 16′ N and altitude 409 m above msl). The local climate of Parbhani is semi-arid and sub-tropical with an average rainfall of 850 mm, which is received from the Southwest monsoon, mostly concentrated over the months of June to September. The annual average solar radiation is 5422.34 MJ/m^2. The total maximum and possible annual sunshine duration is about 4429 to 3212 h. The average annual air temperature is about 25.95°C, and the coldest and warmest monthly average temperatures are 4.6°C in December and 41.1°C in May, respectively. The average annual evaporation is around 2277 mm whereas the yearly average wind speed ranges from 0.25 to 5.1 ms^{-1}.

The climatic data required for the study was collected from the meteorological observatory located adjacent to the experimental field. The measured meteorological parameters include rainfall, temperature, humidity, actual sunshine hours, and pan evaporation along with wind speed measured at a height of 2.0 m.

Estimation of ET_0

Various empirical methods available for computation of reference crop evapotranspiration classifieds in four different categories are shown in Table 1.

Table 1: Methods for Estimation of ET_0

Sr. No	*Classification*	*Methods*	*Reference*
1.	Temperature	1. Thornthwaite	Thornthwaite (1948); Thornthwaite and Mather (1955)
		2. SCS Blaney-Criddle	USDA (1970)
		3. FAO-24 Blaney-Criddle	Doorenbos and Pruitt (1977); Allen and Pruitt (1986)
		4. Hargreaves	Hargreaves *et al.* (1985); Hargreaves and Samani (1985)
2.	Radiation	1. Turc	Turc (1961); Jensen (1966b)
		2. Jensen-Haise	Jensen and Haise (1963); Jensen *et al.* (1971)
		3. Priestly-Taylor	Priestly and Taylor (1972)
		4. FAO-24 Radiation*	Doorenbos and Pruitt (1977)
3.	Evaporation	1. Christiansen Pan	Christiansen (1968); Christiansen and Hargreaves (1969)
		2. FAO-24 Pan*	Doorenbos and Pruitt (1977)
		3. Pan Evaporation	–
4.	Combination	1. Penman VPD#1	Penman (1948, 1963)
		2. Businger-van Bavel	Businger (1956); Van Bavel (1966)
		3. Penman VPD #3 4. Penman-Monteith	Penman (1963) Monteith (1965); Allen (1986); Allen *et al.* (1989
		5. 1972 Kimberly-Penman	Wright and Jensen (1972)
		6. FAO-24 Penman (c = 1)	Doorenbos and Pruitt (1975, 1977)
		7. FAO-24 Corrected Penman*	Doorenbos and Pruitt (1977)
		8. FAO-PPP-17 Penman	Frere and Popov (1979)
		9. 1982 Kimberly-Penman	Wright (1982)

Table 2: Details of Different Evapotranspiration Methods Used

Methods	*Basic Equation*	*Basic Reference*	*Sub-Equations*	*Reference*
1982 Kimberly Penman	$ET_o = \frac{1}{\lambda}\frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{1}{\lambda}\frac{\gamma}{\Delta+\gamma} 6.43\ W_f^k\ (e_z^o - e_z)$	Wright JL (1982)	$\Delta, R_n, \gamma, W_f^{82KP}$	Kashyap and Panda (2001)
Penman 1963	$ET_o = \frac{1}{\lambda}\left[\frac{\Delta}{\Delta+\gamma}\right](R_n - G) + \frac{1}{\lambda}\left[\frac{\gamma}{\Delta+\gamma}\right](6.43)\ W_f^p\ (e_z^o - e_z)$	Penman H L (1963)	$\Delta, R_n, \gamma, W_f^{p3}, G$	Kashyap and Panda (2001)
FAO-24 Penman	$ET_o = C\left[\frac{\Delta'}{\Delta'+\gamma'}(R_n') + \frac{\gamma'}{\Delta'+\gamma'} f(u)\ (e_s' - e_a')\right]$	Doorenbos and Pruitt (1977)	$\gamma', f(u), \Delta', e_s', e_a', R_a, C$	Dorenbos an Pruitt (1977), Lowe (1977), Kreider (1979), Kotsopoulos and Babajimopoulos (1977), Nandagiri and Kovoor (2006)
FAO 56 Hargreaves	$ET_o = 0.0023 * R_a' * (\bar{T} + 17.8) * \sqrt{T_{max} - T_{min}}$	Allen *et al.* (1998)	R_a	Allen *et al.* (1998), Nandagiri and Kovoor (2006)
Turc	$ET_o = 0.31 * (\bar{T}/\bar{T}+15) * (R_s' + 2.09)$ $RH_{mean} > 50\%$ $ET_o = 0.31 * (\bar{T}/\bar{T}+15) * (R_s' + 2.09) * \left[1 + \frac{50 - \bar{RH}}{70}\right]$ $RH_{mean} < 50\%$	Shuttleworth (1992)	R_s	Allen *et al.* (1998), Nandagiri and Kovoor (2006)
Priestly-Taylor	$ET_o = \beta * (\Delta/\Delta+\gamma) * R_n'$	Shuttleworth (1992)	Δ, γ, R_n	Allen *et al.* (1998), Nandagiri and Kovoor (2006)
FAO 24 Pan Evaporation	$ET_o = K_p * E_{pan}$	Doorenbos and Pruitt (1977)	K_p	Doorenbos and Pruitt (1977), Nandagiri and Kovoor (2006)
FAO-56 Penman-Monteith	$ET_o = \frac{0.408\ \Delta\ (R_n - G) + \gamma\ \frac{900}{T+273}\ u_2\ (e_s - e_a)}{\Delta + \gamma\ (1 + 0.34\ u_2)}$	Allen *et al.* (1998)	$\Delta, \gamma, R_n, G, u_2, e_s, e_a$	Allen *et al.* (1998)

However for simplification, ET_0 calculated using seven most commonly used ET_0 estimation methods viz. K-P 82, P-24, P-63, F-H, P&T, Turc and PE are considered. The performance of each method was then compared with ET_0 estimates of F-PM for the period. For shortness, detailed computational equations of these seven methods are not included in the text and reader may refer to the respective publications in Table 2 for basic equations and sub-equations associated with each method. A computer program for average daily ET_0 computation was developed using daily climatic variables and site-specific data and validated using the numerical equations given in FAO-24 (Doorenbos and Pruitt, 1977) and FAO-56 (Allen *et al.*, 1998).

The daily ET_0 estimated by different methods were averaged to get the month-wise daily average ET_0. Comparison between F-PM method and each of the seven methods was justified using the statistical parameters like RMSE, $\bar{D}$, the coefficient of determination (R^2) and linear regression (forced through the origin). The best method is one with the smallest RMSE, smallest $\bar{D}$ and highest R^2. Statistical comparison was made individually for each method on daily basis. The RMSE and $\bar{D}$ are given by following equations,

$$RMSE = \left[\sum_{i=1}^{n} \frac{(P_i - M_i)^2}{n}\right]^{1/2} \quad \ldots (1)$$

$$\bar{D} = \frac{\sum_{i=1}^{n} |P_i - M_i|}{n} \quad \ldots (2)$$

where P_i is the estimated ET_0 values by eights methods ; M_i is the ET_0 value computed by F-PM method and n is the number of observations.

RESULTS AND DISCUSSION

Daily and Weekly ET_0 Estimates

Daily ET_0 estimated by different methods is compared with ET_0 estimates of F-PM method and shown in Figure 1. It is observed that K-P 82, P-24 and P-63 generally overestimated ET_0 for the whole range of values when compared with F-PM method (Figure 1). The P&T method underestimated ET_0 values for the

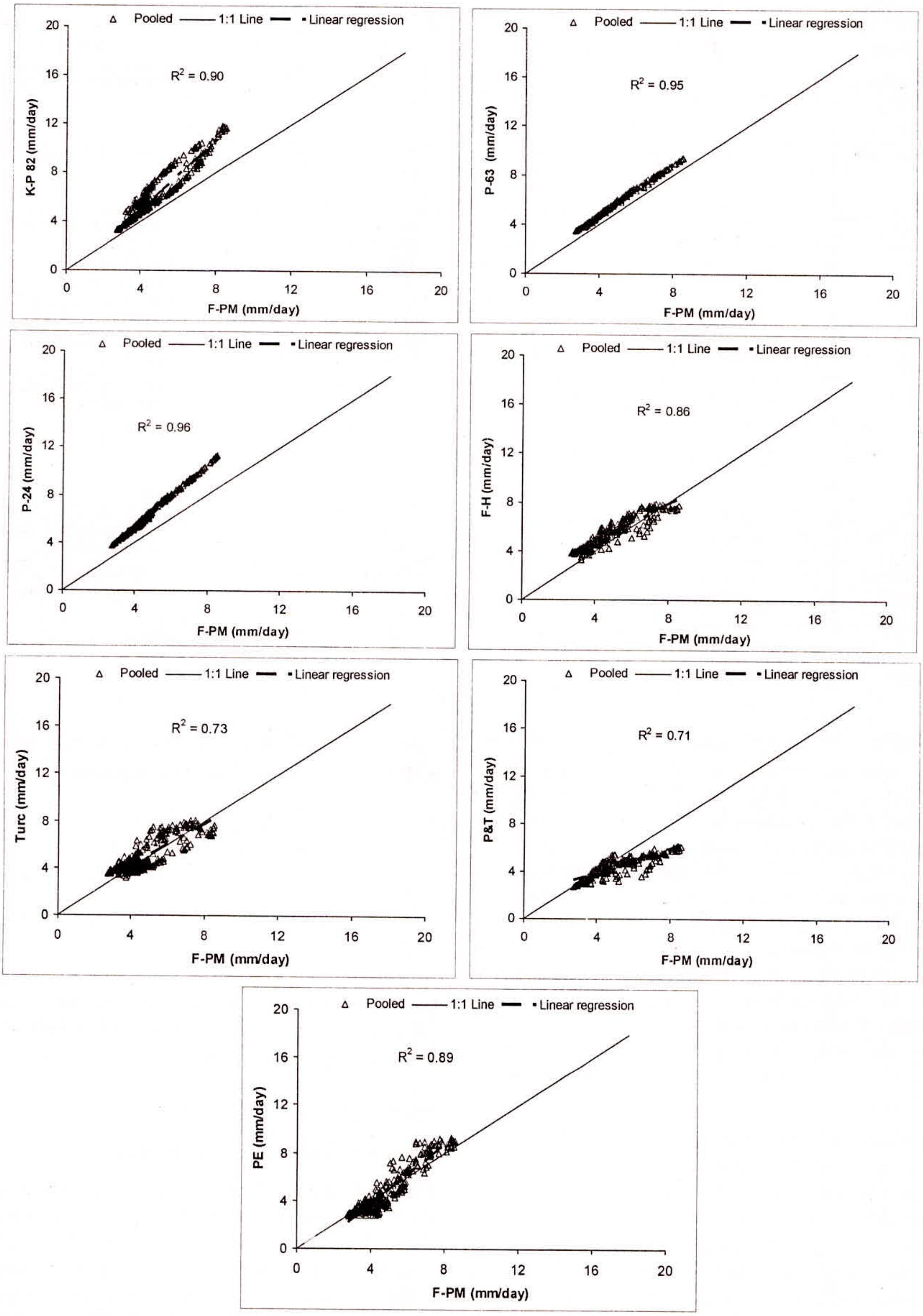

Fig. 1: Comparison of daily ET_0 estimates by different methods with F-PM method

range above ET_0 value of 5 mm. On the other hand ET_0 estimates of F-H, Turc and PE are well scattered around 1 : 1 line indicating their better performance.

Similarly daily ET_0 estimated by different methods were averaged to get the week-wise daily average ET_0 and shown in Figure 2. Visual interpretation of Figures 1 and 2 shows that the KP-82 method estimated higher ET_0 values whereas P&T method estimated lower values when compared with ET_0 estimated by F-PM method similarly.

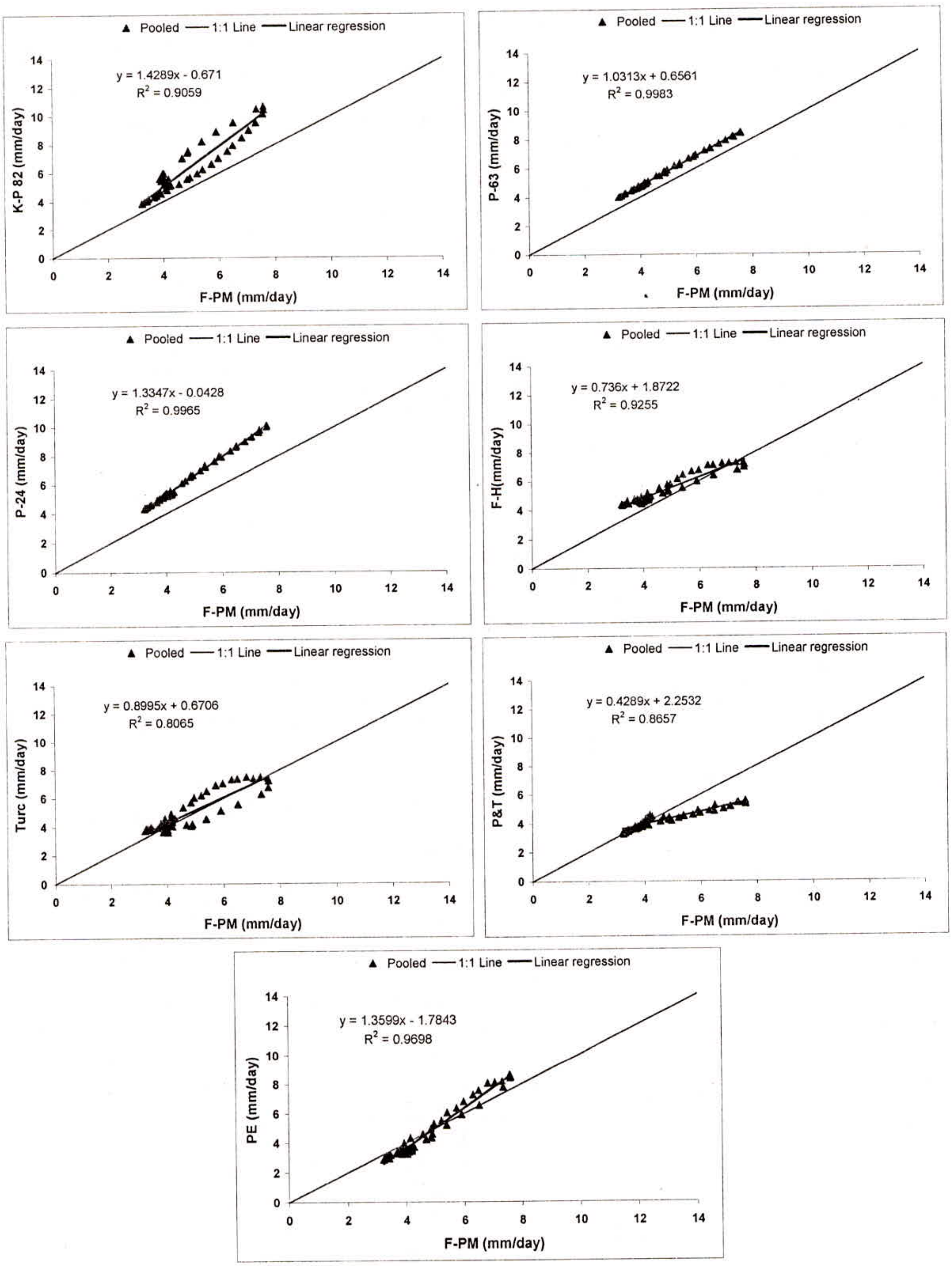

Fig. 2: Comparison of week-wise daily average ET_0 estimates by different methods with F-PM method

Comparative Performance of ET_0 Methods

Comparison of month-wise daily average ET_0 estimated by different methods is shown in Figure 3. All methods estimated lower ET_0 values in the month of December and higher values in May. Similar trend of ET_0 values was observed in almost all methods. The ET_0 estimates by PE method are closer to estimates of ET_0 by F-PM method (Figure 3), which is in conformity with the results of Rao and Rajput (1993). For more precise judgments the seven methods were compared with F-PM method on daily basis and the statistics related to performance (i.e. RMSE, $\bar{D}$, and R^2) of each method is given in Table 3. All the methods were ranked separately on the basis of RMSE, $\bar{D}$, and R^2. Since each statistical parameter highlights a different aspect of method performance, an "overall" rank number was also computed for each method computed from the average of all three statistical parameters (Nandagiri and Kovoor, 2006). Similarly the statistical parameters were also computed for comparison on weekly and monthly basis. The performance of each method was better for week-wise daily average and month-wise daily average ET_0 estimates as compared to daily estimates.

From these results (Table 3), it is evident that for a given ET_0 estimation method, considerable differences exists in rank numbers derived from the performance statistics and, therefore, overall rank may prove useful in selecting the best method. From Table 3, it is clear that the PE method yields the highest rank followed by P-63 and Turc method. On the other hand, ranking based on R^2, P-24 retained its first place, whereas P-63 method was ranked as second. From overall rank it can be concluded that PE method is the most reliable method for computation of ET_0 in semi-arid and sub-tropical region of Marathwada among the seven methods when compared with the F-PM method. Thus, the methods evaluated can be put in order from the most to the least accurate for the semi arid and sub-tropical region of Marathwada as PE, P-63, Turc, F-H, P&T, P-24, and KP-82.

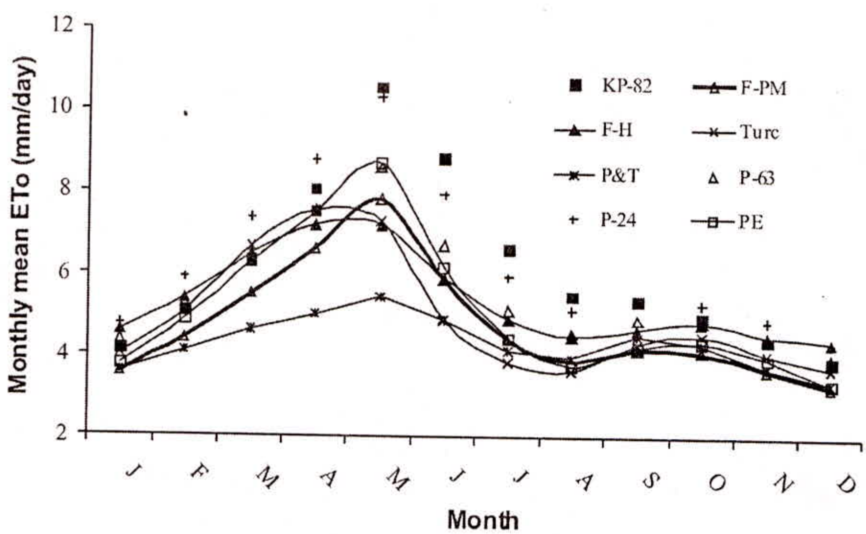

Fig. 3: Month-wise daily average ET_0 estimates by F-PM and other methods

Table 3: Daily Statistical Analyses between the F-PM Method and Other Methods of ET_0 for Period 1992 to 2003

Estimation Method	*Regression Equation*	R^2	*RMSE (mm d⁻¹)*	*Average Deviation (mm d⁻¹)*	*Overall Rank*
K-P 82	$y = 1.3859x - 0.4664$	0.90	1.61	1.38	6.00
P-63	$y = 1.0345x + 0.6407$	0.95	0.81	0.81	3.33
P-24	$y = 1.3104x + 0.0738$	0.96	1.62	1.56	5.67
H-S	$y = 0.7596x + 1.76$	0.86	0.82	0.76	4.67
Turc	$y = 0.8303x - 1.0018$	0.73	0.79	0.68	4.00
P&T	$y = 0.5054x + 1.8853$	0.71	0.97	0.64	5.00
PE	$y = 1.2534x - 1.2735$	0.89	0.77	0.61	2.33

Note: y = daily ET_0 (mm/day) by F-PM method and x = daily ET_0 (mm/day) by other respective methods.

CONCLUSIONS

The FAO-56 Pan Evaporation (PE) is the most reliable method for estimation of reference crop evapotranspiration in semi arid and sub-tropical region when compared with FAO-56 Penman Monteith method. The same can be efficiently used for estimation of ET_0 when the various climatic parameters are not available, which is usual condition in developing countries like India. Moreover the measurement of pan evaporation from the pan evaporimeter can be easily made if these pans are installed even at micro scale.

NOTATIONS

The following symbols are used in this paper:

C = adjustment factor used in FAO-24 Penman equation to incorporate difference between day night weather condition;
ET_0 = reference evapotranspiration;
e_a = actual vapour pressure (kPa);
$e_a^{'}$ = actual vapour pressure at mean temperature (mbar);
E_{pan} = pan evaporation (mm/day);
e_s = saturation vapour pressure;
$e_a - e_a$ = vapour pressure deficit of the air;
$e_s^{'}$ = saturation vapour pressure at mean temperature (mbar);
$e_z^0 - e_z$ = vapor pressure deficit at height z (kPa);
$f(u)$ = wind function used in FAO-24 Penman method;
G = soil heat flux density;
k_p = pan coefficient;
N = maximum possible duration of sunshine (h);
n = actual duration of sunshine (h);
p = ratio of actual daily day time hours to annual mean daily day time hour (%);
R^2 = coefficient of determination of linear fit;
R_a = extra terrestrial radiation at top of atmosphere [MJ/(m^2 day)];
$R_a^{'}$ = extra terrestrial radiation at top of atmosphere [mm/day];
R_n = net radiation at crop surface [MJ/(m^2 day)];
R_s = incoming solar radiation [MJ/(m^2 day)];
$R_s^{'}$ = incoming solar radiation (mm/day);
RH_{mean} = mean relative humidity (%);
$\overline{T}$ = mean air temperature at 2 m height (°C);
T_{max} = maximum air temperature (°C);
T_{min} = minimum air temperature (°C);
u_z = wind speed measured at any other height (m/s);
z = elevation of site above mean sea level;
β = Priestley-Taylor coefficient;
γ = psychrometric constant (kPa/°C);
γ' = psychrometric constant (mbar/°C)
Δ = slope of saturation vapour pressure-temperature curve at mean temperature (kPa/°C);
W_f^k = wind function for 1982 Kimberly Penman;
W_f^p = wind function for FAO-24 Penman.

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