COMPARATIVE EVALUATION OF DIFFERENT POTENTIAL EVAPOTRANSPIRATION ESTIMATION APPROACHES

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Abstract

Accurate estimation of potential evapotranspiration is necessary step in water resources management. Recently, the FAO-56 version of Penman-Monteith equation has been established as a standard for calculating reference evapotranspiration (ET_0). Still there are different approaches (requiring less data) which estimate ET_0 closely to Penman-Monteith method for different climatological conditions. Performance Evaluation of all the approaches on the same basis is prerequisite for selecting an alternative approach in accordance with available data. Therefore, two most popular temperature-based approaches (Hargreaves and Thornthwaite) and two radiation based approaches (Priestley-Taylor and Turc) were used to estimate monthly potential evapotranspiration (ET_0) at Pantnagar (Uttarakhand), India. Further, the performance of all these methods were evaluated by regression and error analysis between standard ET_0 derived using FAO-56 Penman-Monteith method and ET_0 values estimated using all the four methods, on monthly and seasonal basis. On monthly basis Turc method performed best with lowest RMSE (0.562), ARE (0.137), AAD (0.448) and high coefficient of determination (0.792). On seasonal basis, the Priestley-Taylor methodwas found to be the best for Rabiseasonwith lowest error values and minimum seasonal over/under ET_0 predication rate with respect to standard ET_0.Turc method holds second rank in Rabi season. However in Kharif season Truc method performed better than any other method with lowest error terms and lowest seasonal over/under predication rate. In summer season all the methods performed poorly compared to other two seasons but Hargreaves method performed better than other methods. Though the performance and accuracy of FAO-56 Penman-Monteith method can never be debated in theoretical or practical applications yet the comparative evaluation performed in this paper can be used as guideline for selection of alternative or less data dependent methods in case of non-availability of data.

Keywords:*Potential Evapotranspiration, FAO-56 Penman-Monteith method, Hargreaves method, Turc method, Priestley-Taylor method.*

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1. INTRODUCTION

Evapotranspiration (ET) is one of the major components of the hydrologic cycle. Around 64 % of landbased average annual precipitation returns back to atmosphere due to process of evaporation [8,31,22]. Evapotranspiration not only plays major role in global water balance but also significantly influence the global energy balance. Hence, quantification of evapotranspiration is necessary for water resources management, irrigation scheduling and environmental assessment [14]. A general procedure for estimating actual evapotranspiration (ET_a) is to first estimate potential evapotranspiration (ET_0). Further, crop coefficients, which depend on the crop characteristics and local conditions, are used to convert ET_0 to the ET_a. Allen *et al.*[1] defined ET_0 as "the rate of evapotranspiration from a hypothetical crop with an assumed crop height (0.12 m) and a fixed canopy resistance (70 s/m) and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water." There are numerous methods available in literature for estimation of potential evapotranspiration (ET_0), these methods are generally classified as temperature-based,radiation-based, pan evaporation-based or combination type methods based on type of data required [26,37,38,21].

The comparative evaluation of these methods is done by several researchers [5,19,2,35,39,13,26,37,38]in varying climatic conditions worldwide. In Indian context earlier studies suggested FAO-24 [7] method as most accurate one [29,18]. However, attempts were also made by researchers to find out less data demanding and simpler methods for few locations in India [20]. Mohan [20] has recommended the FAO-24 radiation method in per-humid climates, the Hargreaves and Samani[11] temperature-based method in humid climates, and the FAO-24 Blaney–Criddle temperature-based method in subhumid and semiarid climates of Tamil Nadu, India.

Owing to its superiority tested worldwide the "physically based" combination approach of FAO-56 version of Penman–Monteith (FAO-PM) equation [1] has been established/accepted as a standard for calculating reference evapotranspiration [14,36,12,13,9,17,4,3]. Superior accuracy of FAO-56 Penman–Monteith methods is also verified in Indian conditions by Kashyap and Panda [15] over FAO-24 Penman method. Application of FAO-PM methods will certainly improve the irrigation water-use efficiencies, water balance and water distribution at project and state levels, [13,34,21]. However, use of FAO-PM method is constrained by non-availability of detailed meteorological data (especially the radiation, wind velocity and relative humidity) even in developed countries [9] and at majority of locations in developing country [22]. The better performance of temperature and radiation based approach with observed radiation data over FAO-56 PM methods with estimated radiation data is evident [22]. Therefore by the time dense network of advance meteorological observatories (automatic weather stations) is established in the country, simpler and less data demanding evapotranspiration estimation techniques will be widely preferred by researchers and water resources professionals. Hence, there is an urgent need to re-evaluate the performances of simpler ET_0 estimation methods with reference to the FAO-56 PM method under different climatic conditions most commonly encountered in India [21].

So, the basic goal of this paper is to evaluate the comparative performance of most popular Temperature-based approaches; Hargreaves method [11] and Thornthwaite method [32], Radiation based approaches; Priestley-Taylor method [25], and Turc method [33] with standard ET_0 derived using FAO-56 Penman–Monteith method [1], on monthly and seasonal basis.

2. STUDY AREA

Monthly weather data from meteorological observatory of G. B. Pant University of Agriculture and Technology, Pantnagar have been used for estimating and analyzing the ET_0 using different methods. The site is located in the Terai belt at the foothills of Shivalik range of the Himalayas. Its geographical location is 29.50º N latitude and 79.30º E longitude. Pantnagar has an altitude of 243.8 m above mean sea level. It has humid, sub-tropic climate. The summer is too dry and hot, the winter is too cold and the rainy season has a heavy rainfall. The hygrometer shows upto 90% relative humidity during winter and upto 55% during summer at 7.00 AM. The monthly mean of maximum temperature lies in the range of 20ºC to 40ºC. The minimum temperature varies between 5ºC to 25ºC. May is the hottest and January is the coolest month. The monsoon season experiences about 90% of the average annual rainfall of about 148.3 cm.

3. METHODOLOGY

3.1 Data and Methods

Monthly meteorological data of maximum and minimum temperature, relative humidity, wind velocity at 2 m height and sunshine hours were available from meteorological observatory in the campus of G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India for the time period from January, 1991 to December, 2000. The monthly weather data was used to estimate the monthly ET_0 (mm/day). The average monthly values of weather data over this period are given in Table 1.

Table 1: Average monthly and annual weather data

	Temperature		Relative Humidity		Wind velocity	Sunshine hours
	min	max	min	max		
Month	(ºC)	(ºC)	(%)	(%)	(km/h)	h
Jan	06.23	19.50	56.76	93.04	3.77	5.63
Feb	08.25	23.00	48.37	90.89	4.15	7.24
Mar	11.63	27.95	38.71	86.87	5.29	8.20
Apr	16.69	34.97	25.24	69.13	5.97	9.50
May	22.19	37.66	31.37	62.39	7.69	9.60
Jun	25.03	36.26	48.69	74.06	7.93	8.03
Jul	25.42	32.90	68.86	88.87	5.85	5.93
Aug	24.99	31.77	73.89	92.16	4.83	5.20
Sep	23.29	31.73	67.61	91.96	3.20	6.88
Oct	17.39	30.92	49.55	86.89	2.30	8.63
Nov	11.20	27.33	44.50	89.42	2.04	8.30
Dec	07.02	22.77	48.66	93.02	2.15	6.85
Average	16.61	29.73	50.18	84.89	4.60	7.50

On the basis of available data, the methods selected for estimation of ET_0 were categorized into (i) Temperature based methods:- Hargreaves method (HS) and Thornthwaite method (TH), (ii) Radiation based methods:- Priestley-Taylor method (PT), and Turc method (TC). As per the recommendations FAO expert consultation Panel [28] the ET_0 estimated using FAO-56 Penman-Monteith method should be taken as standard ET_0 for comparative evaluation of other ET estimation methods so, FAO-56 Penman–Monteith method [1] was used to estimating ET_0 as standard for comparison of results of other four methods listed above. The potential evapotranspiration (ET_0) estimated using FAO-56 Penman–Monteith (FAO-PM) method will be termed as standard ET_0 hereafter. All the five methods used to estimate ET_0 in this paper are briefly described here:

3.1.1 Temperature Based Methods

1) Hargreaves Method:-The Hargreaves method [11, 10] enables reference crop evapotranspiration (ET_0) estimation in areas where meteorological information is scarce. This is an empirical estimation method that uses the average daily air temperature, T (°C), in combination with the extraterrestrial radiation, R_a (MJ/m^2/day)as an indicator of the incoming global radiation. The Hargreaves equation is expressed as:

$$ET_0 = 0.0023 R_a \left(\frac{T_{\max} + T_{\min}}{2} + 17.8 \right) \sqrt{T_{\max} - T_{\min}} \qquad (1)$$

Where, T_{max} and $T_{min}$are average maximum and minimum temperatures.

2) ThornthwaiteMethod:-Thornthwaite [32] correlated mean monthly temperature with ET as determined by east-central United States water balance studies. The Thornthwaite equation is:

$$ET_{0k} = \frac{16N_k}{360}\left(\frac{10T_k}{\sum_{k=1}^{12}(0.2T_k)^{1.514}}\right)^{0.016\sum_{k=1}^{12}(0.2T_k)^{1.514}+0.5} \qquad (2)$$

Where, $ET_{0\,k}$is potential evapotranspiration in the kth month (mm); N_k is the maximum possible duration of sunshine in the kthmonth (hours); $T_k$is the mean air temperature in the kthmonth (°C) and $k = 1, 2, \ldots, 12$.

3.1.2 Radiation Based Methods

1) TurcMethod:-Turc[33] developed an equation for potential ET under general climatic conditions of Western Europe. He proposed the following equations for two humidity conditions:

When $RH_{mean} > 50\%$,

$$ET_0 = 0.013\frac{T_{mean}}{(T_{mean}+15)}\left(R_s^{'}+50\right)\frac{1}{\lambda} \qquad (3)$$

When $RH_{mean} \le 50\%$,

$$ET_0 = 0.013\frac{T_{mean}}{(T_{mean}+15)}\left(R_s^{'}+50\right)\frac{1}{\lambda}\left(1+\frac{(50-RH_{mean})}{70}\right) \qquad (4)$$

Where, $T_{mean}$is mean air temperature (ºC), RH_{mean}ismean relative humidity (%), $R^{'}_s$is solar radiation (cal/cm^2/day). If R_s (MJ/m^2/day) is known, it can be calculated as

$$R^{'}_s = R_s/0.041869 \qquad (5)$$

λ is the latent heat of vaporization (MJ/kg). it can be estimated using mean air temperature as

$$\lambda = 2.501 - 0.002361T_{mean} \qquad (6)$$

2) Priestly-Taylor Method:-Priestly and Taylor [25] proposed an equation for surface area generally wet, which is a condition, required for potential evaporation. The equation can be expressed as:

$$E_p = \alpha\frac{1}{\lambda}\frac{\Delta}{(\Delta+\gamma)}(R_n - G) \qquad (7)$$

Where, Δ is slope of saturation vapor pressure-temperature curve (kPa/ºC), it can be calculated if T_{mean}values are known using Teten's expression as:

$$\Delta = \frac{4098e^0_{mean}}{(T_{mean}+237.3)} \qquad (8)$$

Where, e^0_{mean} is saturation vapor pressure at mean temperature (kPa), γ is Psychometric constant (kPa/ºC), R_n is Net Radiation (MJ/m^2/day), α is short wave reflectance or albedo and its value is taken as 0.23, and G is heat flux density to the ground (MJ/m^2/day).

3.1.3 Combination Method

1) FAO Penman-MonteithMethod:-The International Commission for Irrigation and Drainage and Food and Agriculture Organisation of the United Nations has proposed the FAO Penman–Monteith method [1] as the standard method for estimating reference evapotranspiration. FAO modified Penman–Monteith method popularly known and FAO-56 PM method is expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_{mean}+273}U_2(e_s - e_a)}{\Delta+\gamma(1+0.34U_2)} \qquad (9)$$

Where, ET_0 is reference evapotranspiration (mm/day), U_2 is average 24 hour wind speed at 2 m height (m/s), and $e_s\!-\!e_a$is saturation vapour pressure deficit (kPa), R_n is net radiation at the crop surface (MJ/m^2/day), G is soil heat flux (MJ/m^2/day), Δ is slope of vapour pressure curve (kPa/ºC), γ is psychrometric constant, $e_s$is saturation vapour pressure (kPa), $e_a$is actual vapour pressure (kPa).

The FAO-56 Penman–Monteith (FAO-56 PM) method requires observations of maximum and minimum air temperature, maximum and minimum relative air humidity (or the actual vapour pressure), wind speed at 2 m height, and solar radiation for accurately estimating ET_0. Where radiation data are lacking, or not reliable, the solar radiation (R_n) can be estimated using bright sunshine hours records as suggested by Allen *et al*[1]

$$R_n = R_{ns} - R_{nl} \qquad (10)$$

Where, $R_{ns}$is net shortwave radiation (MJ/m^2/day) and R_{nl} is net longwave radiation (MJ/m^2/day)

$$R_{ns} = (1-\alpha)R_s \qquad (11)$$

Where, $R_s$is incoming solar or shortwave radiation (MJ/m^2/day) and α albedo or canopy reflectance coefficient (α = 0.23, for hypothetical grass reference surface).

$$R_S = \left(a_s + b_s \frac{n}{N} \right) R_a \quad (12)$$

Where, $R_a$is extraterrestrial radiation (MJ/m^2/day), n is actual duration of sunshine (hours), N is maximum possible duration of sunshine, a_s is regression constant expressing the fraction of extraterrestrial radiation that will reach the earth surface on overcast/cloudy days (n=0) and a_s+b_s is fraction of extraterrestrial radiation that reaches earth surface on clear sky days (n=N)

$$R_a = \frac{1440}{\pi} G_s\, d_r \left[\omega_s \sin(\phi)\sin(\delta) + \sin(\omega_s)\cos(\phi)\cos(\delta)\right] \quad (13)$$

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} J\right) \quad (14)$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (15)$$

$$\omega_s = \arccos\left[-\tan(\phi)\tan(\delta)\right] \quad (16)$$

Where, G_s is solar constant (0.0820 MJ/m^2/day), $d_r$inverse relative Earth-Sun distance, ω_s is sunset hour angle (rad), δ is solar declination angle (rad) and Φ is latitude of station (rad), J is the number of the day in calendar year.

$$R_{nl} = \sigma\left[\frac{T^4_{\max,K} - T^4_{\min,K}}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \quad (17)$$

Where, σ is Stefan-Boltzman constant (4.903 $\times 10^{-9}$ MJ/K^4/m^2/day), $T_{max,K}$&$T_{min,K}$ are absolute maximum and minimum temperature values (^{0}K), ratio R_s/R_{so} is relative shortwave radiation (limited to ≤ 1.0) and R_{so} is clear sky radiation (MJ/m^2/day) estimated as;

$$R_{so} = \left(a_s + b_s\right)R_a$$

The data requirement of all these methods are summarized in Table 2.

A program in Microsoft Visual Basic (VB 6.0) language was developed to calculate ET$_0$ from five methods mentioned above. The height of the reference crop was chosen as 12 cm with a fixed canopy resistance of 70 sec/m, and albedo as 0.23 to resemble ET from an extensive surface of actively growing green grass of uniform height, completely shading the ground and not short of water. Values of monthly ET$_0$ (mm/day) were estimated using this program. Monthly values were then used to calculate seasonal (Rabi, Kharif and Summer) ET$_0$ values.

Table 2: Data requirements of estimation methods

Methods **Data**	FAO-PM	PT	TC	TH	HS
Max. and min temperature	✓	✓	✓	✓^{2}	✓
Average temperature	✓^{2}	✓^{2}	✓^{2}	✓	✓^{2}
Max. and min. RH	✓	✓	✓	-	-
Average relative humidity	✓^{2}	✓^{2}	✓^{2}	-	-
Avg. wind speed	✓	✓	-	-	-
Sunshine hours	✓	✓	✓*	-	-
Solar radiation	✓*	✓*	✓*	-	-
Net radiation	✓*	✓*	✓*	-	-
Other data	Latitude Elevation Julian day	Latitude Elevation Julian day	Latitude Elevation Julian day	Latitude Julian day	Latitude Julian day

Note: *i) sign ✓ indicates that the data is essential, ii) Data having superscript ^{2} indicates that the data can be derived from primary data (i.e. ✓), iii) Data having superscript * indicates that the any one of these data is required.*

3.2 Evaluation Criteria

The regressions analysis was done to examine the performance of four methods compared with the standard ET$_0$ on monthly and seasonal basis. The regression equations computed is of the form:

$$Y = mX + C \quad (18)$$

Where, Y represents estimated monthly ET$_0$ (mm/day); Xis standard ET$_0$ from each of the four methods (mm/day); and mand C are slope and intercept, respectively. Care was taken to force the regressions lines to have intercept zero for all the cases [22].

Further, statistical error analysis was carried out with the parameters; root mean square error (RMSE), absolute average deviation (AAD) and absolute relative error (ARE) [9,22].

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - x_i\right)}{n}} \quad (19)$$

$$AAD = \frac{\sum_{i=1}^{n} ABS\left(y_i - x_i\right)}{n} \quad (20)$$

$$ARE = \frac{ABS\left(y_i - x_i\right)}{x_i} \quad (21)$$

Where, $y_i$is estimated and x_i is standard ET$_0$.
The RMSE parameter has been used to indicate the

goodness-of-fit of ET_0 estimates. The best method is the one with the lowest absolute average deviation, mvalue closest to 1.0, the smallest RMSE, and the highest R^2 [23,24]. The difference in ET_0 rates with respect to standard ET_0 was also estimated and termed as over/under prediction rate of particular methods on both monthly and average seasonal time scale. The comparative evaluation of methods was performed on monthly and seasonal time scale using regression analysis (R^2, m) and error analysis (RMSE, AAD, ARE, over/under predication rate).

4. RESULTS

The monthly ET_0 values estimated by each of the five methods for the period of record used in present study are shown in Fig. 1 and their mean values are given in Table 3. Results obtained from the regression of ET_0 estimated by each of the four methods against standard ET_0 (derived using FAO-PM method) on monthly basis and seasonal basis are presented in Table 4 and Table 5 respectively.

Table 3: Standard and estimated mean monthly ET_0 (mm/day) and total annual ET_0 (mm).

Month	Standard	HS	TH	TC	PT
Jan	1.518	2.15	0.5	1.84	1.41
Feb	2.085	2.73	0.94	2.54	1.89
Mar	3.304	4.03	1.97	3.48	2.92
Apr	5.250	5.89	4.56	5.02	4.26
May	6.592	6.79	7.36	5.74	5.41
Jun	6.024	6.32	8.08	5.06	5.75
Jul	4.535	5.1	6.93	4.34	5.26
Aug	3.951	4.51	6.08	3.99	4.78
Sep	4.003	4.47	5.19	4.2	4.8
Oct	3.627	4.43	3.3	4.03	4.12
Nov	2.554	3.55	1.62	3.1	2.76
Dec	1.714	2.78	0.74	2.21	1.76
Annual	1375.78	1582.32	1417.88	1365.63	1354.05

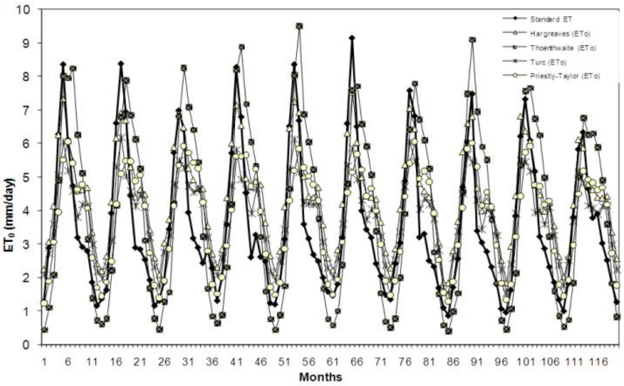

Fig. 1 Estimated and standard monthly ET_0.

4.1 Monthly Basis

The comparative evaluation of error and regression analysis results indicates that the TC method performed best with the lowest RMSE (0.562), lowest AAD (0.448), second lowest AAR (0.137) and the high coefficient of determination ($R^2 = 0.792$)for monthly ET_0 predictions. HS method was found to be closely following the TC method owing to low RMSE (0.704) highest coefficient of determination ($R^2 = 0.792$) values as shown in Table 4. Though the R^2 values of HS are higher than TC method, since coefficient of determination (R^2) in linear regression is only an indicator of how well the regression line fits with original data and do not consider the actual closeness/error of each estimated record with respect to actual/standard record [6], more weightage is given to the results of error analysis in present study.It is evident from Table 4 that PT method also closely follows HS method with reference to error analysis results however, the second rank has been given to HS method owing to it's minimal data requirement compared to the extensive data requirement of PT method (almost equivalent to FAO PM method).

4.2 Seasonal Basis

The regression analysis between monthly ET_0 estimates of each of the method and standard ET_0 was done for three seasons (Rabi: November to March; Summer: April to June and Kharif: July to October) to evaluate performance of each of the technique. The definition of time frame of each season is based on standard agricultural practice followed in the region. The trend of predicting/estimating ET_0 by each technique is derived by comparing the ET_0 estimates with standard ET_0 values and numerated in the form of slope of trend line and coefficient of determination (R^2) in Table 5.

Table 4:Summary statistics of regression and error (mm/day) analysis between standard and estimated ET_0

	Regression equation	R^2	RMSE	AAD	ARE
Hargreaves-Samani(HS)	Y = 1.1224 * X	0.889	0.704	0.632	0.223
Thornthwaite (TH)	Y = 1.1173 * X	0.752	1.424	1.260	0.387
Turc (TC)	Y = 0.9607 * X	0.792	0.562	0.448	0.137
Priestly-Taylor (PT)	Y = 0.9722 * X	0.771	0.724	0.550	0.133

Table 5: Regression analysis between monthly values of standard and estimated ET_0 for three seasons

Season	**HS**		**TH**		**TC**		**PT**	
	m	**R^2**	**m**	**R^2**	**m**	**R^2**	**m**	**R^2**
Rabi	1.322	0.857	0.538	0.769	1.156	0.775	0.956	0.796
Kharif	1.135	0.652	1.335	0.560	1.024	0.658	1.173	0.915
Summer	1.068	0.128	1.124	0.467	0.876	-0.11	0.855	0.046

It is not possible to evaluate the overall performance of any method based on single parameter (i.e. coefficient of determination) because judging the accuracy of these methods is not simple task. Even experimentally observed data have limitations due to the difficulties of simulating the ideal conditions as defined for ET_0. Therefore, as suggested by Kumar *et al.*[16] the physical and dynamical nature of these methods, which will be reflected by closeness of estimates with standard ET_0 values has to be taken as a basis for evaluating the relative merits of each of the technique. Hence the results of error analysis as shown in Table 6 were also considered for comparative evaluation of these methods.

Table 6: Error (mm/day) analysis between values of standard and estimated ET_0 for three seasons

Season	**HS**			**TH**		
	RMSE	AAD	ARE	RMSE	AAD	ARE
Rabi	0.796	0.768	0.369	1.106	1.077	0.512
Kharif	0.608	0.563	0.153	1.708	1.492	0.373
Summer	0.688	0.522	0.097	1.420	1.205	0.203
Season	**TC**			**PT**		
	RMSE	AAD	ARE	RMSE	AAD	ARE
Rabi	0.469	0.434	0.212	0.287	0.204	0.084
Kharif	0.277	0.226	0.061	0.721	0.683	0.172
Summer	0.904	0.797	0.128	1.105	0.895	0.145

On the basis of errors in estimating ET_0 in Rabi season, the PT method performed better over all other methods with lowest RMSE values (0.287) as shown in Table 6. Though the R^2 value of HS was highest (0.857) in Rabi season however, the difference in R^2 values between PT and HS is practically insignificant.

The seasonal over/under predication rate of ET_0 (mm/day) shown in Table 7 indicates that PT predicts ET_0 most closely to FAO-PM method. So in Rabi season PT holds the rank of best method among all four method for estimating potential evapotranspiration (ET_0). However, the data requirement of PT method is similar to FAO-PM method hence the accuracy obtained by this method do not have any practical significance in data non-availability scenario. On the other hand, less data demanding TC methods holds second rank in Rabi season based on error analysis (RMSE = 0.469) and seasonal over/under predication rates (+0.397). In Kharif season TC method performs better than all other methods with lowest RMSE (0.277) lowest AAD (0.226) and lowest seasonal over/under ET_0 estimation rate (0.108). Though R^2 value of PT in Kharif is highest as shown in Table 5, but the deviations in ET_0 estimated using PT from standard ET_0 (FAO-PM) values are more compared to deviations between standard ET_0 and estimates of TC method as evident form AAD values of TC and PT in Kharif season (0.226 and 0.683 respectively) shown in Table 6. This indicates that TC estimates ET_0 values more close to standard ET_0 values and hence TC is the best method in Kharif season for estimating ET_0 compared with reference to FAO-PM method results (standard ET_0).

In case of summer season the R^2 value of all the methods are low hence no inference can be drawn from these values but the analysis of errors and over/under prediction rates in this season indicates that HS method performers well compared to all other methods with average 0.375 mm/day over predication of ET_0 and lowest RMSE (0.688). It is observed that the rate of over predication and values of RMSE in summer season are high in case of all the methods. This may be due to extreme hot and dry climate of the Pantnagar station in summer months. However the performance of HS method in Summer season is appreciable as compared to all other (radiation and combination based) methods as it utilizes very small amount of meteorological data and provide fairly accurate results of $ET_{0.}$

Table 7: Over/under estimates of ET_0 (mm/day) for different seasons.

Season	Month	**HS**		**TH**	
		Over	**Under**	**Over**	**Under**
Rabi	Nov	0.991	-	-	0.937
	Dec	1.065	-	-	0.972
	Jan	0.636	-	-	1.019
	Feb	0.645	-	-	1.148
	Mar	0.726	-	-	1.338
	Seasonal	**+ 0.813**		**- 1.083**	
Summer	Apr	0.638	-	-	0.692
	May	0.195	-	0.764	-
	Jun	0.292	-	2.059	-
	Seasonal	**+ 0.375**		**+ 0.710**	
Kharif	Jul	0.564	-	2.398	-
	Aug	0.562	-	2.127	-
	Sep	0.471	-	1.190	-
	Oct	0.802	-	-	0.326
	Average	**+ 0.600-**		**+1.347**	
Season	**Month**	**TC**		**PT**	
		Over	**Under**	**Over**	**Under**
Rabi	Nov	0.544	-	0.204	-
	Dec	0.494	-	0.049	-
	Jan	0.318	-	-	0.106
	Feb	0.453	-	-	0.191
	Mar	0.176	-	-	0.382
	Seasonal	**+ 0.397**		**- 0.085**	
Summer	Apr	-	0.233	-	0.993
	May	-	0.853	-	1.183
	Jun	-	0.967	-	0.270
	Seasonal	**-0.684**		**-0.815**	
Kharif	Jul	-	0.199	0.727	-
	Aug	0.038	-	0.827	-
	Sep	0.192	-	0.800	-
	Oct	0.401	-	0.496	-
	Average	**+0.108**		**+0.713**	

Note *: the +ve sign in the seasonal over/under estimation row indicates the over estimation rate in mm/day and the –*

ve sing indicates the under estimation rate in mm/day

The performance and accuracy of FAO-PM method can never be debated in theoretical or practical applications, yet the comparative evaluation performed in this paper can be used as guideline for selection of alternative or less data dependent methods in case of non-availability of data. To facilitate the researchers, water managers or decision makers in selecting the best suitable method in case of less data availability (less parameters), the comparative evaluation of four most popular methods is summarized in Table 8. The decision maker can refer to this table with respect to data available in hand and/or accuracy required for particular ET estimation task.

Table 8: Applicability viz-a-viz expected error in ET_0 estimation of all four methods

	ET Estimation Methods			
	HS	**TH**	**TC**	**PT**
Data Available	***Applicability of method***			
T	✓	✓	×	×
T+RH	✓*	✓*	✓	×
T+RH+Rad/SS	✓*	✓*	✓*	✓
T+RH+Rad/SS+W	✓*	✓*	✓*	✓*
Time Period	***Expected error in ET_0 estimation (RMSE) [mm/day]***			
Monthly Basis	0.704	1.424	0.562	0.724
Rabi Season	0.794	1.106	0.469	0.287
Kharif Season	0.608	1.708	0.277	0.721
Summer Season	0.688	1.420	0.904	1.105
Time Period	***Over/Under estimation rates [mm/day]***			
Monthly Basis	+0.195 to +1.065	-1.338 to +2.398	-0.967 to +0.544	-1.183 to +0.827
Rabi Season	+0.813	-1.083	+0.397	-0.085
Kharif Season	+0.600	+1.347	+0.108	+0.713
Summer Season	+0.375	+0.710	-0.684	-0.815

***Note** : 1) In data available section T = Temperature data, RH = Relative Humidity data, Rad= Radiation data, SS= Sunshine Hours data, W= Average Wind Velocity data*
*2) ✓ = method can be applied using this data, *= some of the available parameters will not be used in this method, × = method cannot be applied due to insufficient data.*
3) The +ve sign in the over/under estimation rows indicates the over estimation rate in mm/day and the –ve sing indicates the under estimation rate in mm/day

5. SUMMARY AND CONCLUSIONS

Five methods (FAO-56 Penman-Monteith, Priestley-Taylor, Turc, Hargreaves and Thornthwaite) have been applied to estimate reference evapotranspiration using weather data of meteorological observatory at GBPUA&T, Pantnagar. As per the recommendations of FAO expert consultation Panel [28] the ET_0 estimated using FAO-56 Penman-Monteith method was taken as standard ET_0 for comparative evaluation of other four methods.

The regression and error analysis of these methods on monthly time scale shows that TC method performance as best among all the methods on monthly basis with lowest error (RMSE=0.562, AAD=0.448 & ARE=0.137) and high coefficient of determination (R^2 = 0.794). The total annual ET_0 values estimated using TC method are closest to standard annual ET_0 values. While HS method was found to be second to TC method on monthly time scale with low RMSE (0.704) highest coefficient of determination (R^2 = 0.889).

On seasonal scale it was observed that the coefficient of determination (R^2) do not give the actual representation of accuracy of method with respect to closeness of ET_0 estimate with standard ET_0. Hence performance evaluation of each of the method was done using error and under/over predication rate as criteria. In Rabi season PT method performed better than all other methods with minimum RMSE (0.287) and minimum over/under predication rate with reference to standard ET_0 (-0.085). Total seasonal ET_0 in Rabi season estimated using PT is almost equal to Standard ET_0. On the other hand less data requiring TC method holds second rank with approximately 0.5 mm/day root mean square error. Hence the analysis indicates that, in case of non-availability wind and radiation data TC method can be applied using temperature, humidity and sunshine hours data to derive fairly accurate results of ET_0.

In Kharif season TC method performs best among all other methods with lowest errors (RMSE =0.277, ARE=0.172), lowest deviation in standard and estimated ET_0 (AAD =0.226) and lowest seasonal over/under ET_0 estimation rate (0.108). In summer season all the methods performed poorly compared to other two seasons, but HS performed well among all other methods with lowest errors (RMSE=0.688, ARE=0.097), lowest deviation from standard ET_0 values (AAD=0.522). It was observed that the seasonal rate of over/under predication of all other methods was high in summer season, however the seasonal over/under predication rate of HS method is minimum in summer not only in compression to other method but also in compression to it's own rate in other seasons. This may be because of basic physical and dynamical nature of this method.

The comparative performance evaluation of these four ET estimation techniques done in present paper is site specific and the results may vary site to site, but this form of study will help decision maker to select the best possible ET estimation technique with respect to data/cost constraints or accuracy constrains. Similarly kind of studies on larger scale for each agro-climate zone will enable compilation of standard document for selection of best possible ET estimation of technique in accordance with data/fund availability.

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