International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

Reliability in the Estimation of ET_0 Using Minimum Climatological Data

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ABSTRACT: Numerous studies have already shown that the Penman-Monteith equation is the most reliable method of evapotranspiration estimation when necessary weather and vegetation data are available, these inputs are difficult and expensive to obtain for many locations in developing countries like India. In such circumstances, radiation based methods or temperature based methods may constitute often the only alternative for the evaluation of ET_0. Therefore, reliability of temperature based approaches (Hargreaves-Samani and Thornthwaite) and radiation based approaches (Priestley-Taylor and Turc) in the estimation of ET_0 is tested in the present study. These methods alongwith Penman-Monteith method are used to estimate monthly potential evapotranspiration (ET_0) at Pantnagar (Uttarakhand), India. The measured values of potential evapotranspiration are selected as the standard of comparison for evaluating these methods. Regression performed between observed and estimated values of ET_0 suggested that mean monthly correction factors instead of single local correction factor need to be introduced for improving the performance of these methods. Mean monthly correction factors are then developed and incorporated. The results indicate that ET_0 estimates using corrected Hargreaves and Turc methods are well correlated with measured ET_0 with coefficient of determination (R^2) greater than 0.96. If radiation, humidity and wind-speed data are not available, either the Hargreaves or Turc method with mean monthly correction factors for the study region can be utilized for reliable estimation of ET_0.

INTRODUCTION

Reliable estimates of Evapotranspiration (*ET*), the major components of the hydrologic cycle, are important for planning, design and operation of irrigation systems. Most of the hydrologic, water-management, and crop-growth models also require an accurate estimate of potential evapotranspiration (ET_0) for its reliable application (Parmele 1972; Skaggs 1982). A common procedure for estimating *ET* 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*.

ET_0 is defined by Allen *et al.* (1998) 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."

A large number of methods for calculation of ET_0 from weather data have been developed and tested for varying geographic and climatological conditions. The Food and Agriculture Organization of the United Nations (FAO) has proposed the Penman-Monteith (FAO-56 PM) method as the standard method for estimating reference evapotranspiration (ET_0), and for evaluating other methods. Although numerous studies have already shown that the Penman-Monteith equation is the most reliable method when necessary weather and vegetation data are known, these inputs are difficult and expensive to obtain for many locations. In such circumstances, radiation based methods or temperature based methods may constitute often the only alternative for the evaluation of ET_0.

According to Samani (2000), temperature and solar radiation explain at least 80% of ET_0 and temperature data are available for most of the stations. Thornthwaite method with correction factors is still widely used for estimating ET_0 (Smajstrla *et al*., 1984). However, there are only a limited number of studies that have tested the reliability of temperature and radiation based methods for Terai region of Uttarakhand.

The basic goal of this paper is to examine whether it is possible to attain the reliable estimation of ET_0 by temperature and radiation based approaches. This goal has been achieved by evaluating the reliability of two

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temperature based approaches (Hargreaves-Samani and Thornthwaite) and two radiation based approaches (Priestley-Taylor, and Turc) as compared to the Penman–Monteith method. The measured ET_0 was taken as a standard for comparison in this study. The mean monthly and annual total ET_0 values estimated by the five methods were compared with the measured ET_0. The objective for such comparisons is to examine the relationships and to determine the method that best predicted ET_0 as compared to the Penman–Monteith method.

STUDY AREA

Daily weather data from meteorological observatory of Crop Research Centre, G.B. Pant University of Agriculture and Technology, Pantnagar (India) have been used for estimating and analyzing the ET_0 calculation methods. The site is located in the Terai belt at the foothills of Shivalik range of the Himalayas. Its geographical location is 29.5°N latitude and 79.3°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 20°C to 40°C. The minimum temperature varies between 5°C to 25°C. 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.

METHODOLOGY

On the basis of available data, the methods selected for estimation of ET_0 are categorized into (i) temperature based methods; (ii) radiation based methods and (iii) combination methods and are briefly described here:

Temperature Based Methods

Hargreaves and Samani Method

The Hargreaves method (Hargreaves and Samani, 1985; Hargreaves and Allen, 2003) 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,

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

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

Thornthwaite Method

Thornthwaite (1948) correlated mean monthly temperature with ET_0 as determined by east-central United States water balance studies. The Thornthwaite equation is,

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

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

Radiation Based Methods

Turc Method

Turc (1961) developed an equation for potential ET for 10 days periods under general climatic conditions of Western Europe. He proposed the following equations for two humidity conditions,

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

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

When $RH_{\text{mean}} \leq 50\%$,

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

Where, T_{mean} is mean air temperature (°C), RH_{mean} is mean 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,

$$R_s' = R_s / 0.041869 \quad \ldots (5)$$

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

$$\lambda = 2.501 - 0.002361 T_{\text{mean}} \quad \ldots (6)$$

Priestly-Taylor Method

Priestly and Taylor (1972) proposed an equation for surface area generally wet, which is a condition, required for potential evaporation. The equation can be expressed as,

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

Where, Δ is slope of saturation vapor pressure-temperature curve (kPa/°C), it can be calculated if T_{mean} values are known using Tetens (1930) expression as,

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

Where, e^0_{mean} is saturation vapor pressure at mean temperature (kPa), γ is Psychometric constant (kPa/°C), 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).

Combination Method

Penman-Monteith

The International Commission for Irrigation and Drainage and Food and Agriculture Organisation of the United Nations has proposed the Penman–Monteith method as the standard method for estimating reference evapotranspiration,

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

Where, ET_0 is reference evapotranspiration (mm/day), U_2 is average 24 hour wind speed at 2 m height (m/s), and $e_a - e_d$ is vapor pressure deficit (kPa).

The FAO-56 Penman–Monteith (FAO-56 PM) method requires maximum and minimum air temperature, maximum and minimum relative air humidity (or the actual vapor pressure), wind speed at 2 m height, and solar radiation (or sunshine hours).

Where radiation data are lacking, or not reliable, the difference between the maximum and minimum temperature can be used for the estimation of solar radiation (Hargreaves and Samani, 1985; Allen, 1998),

$$R_S = K (T_{max} - T_{min})^{0.5} R_a \quad \ldots (10)$$

Where, K is the adjustment coefficient,

The data requirement of these methods is summarized in Table 1.

Data

Daily meteorological data of maximum and minimum temperature, relative humidity, wind velocity at 2 m height, sunshine hours and pan evaporation were available for a period from January, 1991 to December, 2000. The average monthly values of weather data over the period from 1991 to 2000 are given in Table 2.

A program in Microsoft Visual Basic (VB 6.0) language was developed to calculate ET_0 from five methods mentioned above. Daily weather data for the period from January, 1991 to December, 1998 were averaged on monthly basis and the monthly weather data were used to estimate the mean monthly ET_0 (mm/day).

Table 1: Data Requirements of Estimation Methods

Data \ *Methods*	*Penman-Monteith*	*Priestly-Taylor*	*Turc*	*Thornthwaite*	*Hargreaves*
Max. and min temperature	R^1	R^1	R^1	R^1	R^1
Average temperature	R^2	R^2	R^2	R^2	R^2
Max. and min. RH	R^1	R^1	R^1	–	–
Average relative humidity	R^2	R^2	R^2	–	–
Avg. wind speed	R^1	R^1	–	–	–
Sunshine hours	R^1	R^1	R"	–	–
Solar radiation	R"	R"	R"	–	–
Net radiation	R"	R"	R"	–	–
Other data	Latitude Elevation Julian day	Latitude Elevation Julian day	Latitude Elevation Julian day	Latitude Julian day	Latitude Julian day

Note: (i) symbol R^1 indicates that data is essential, (ii) symbol R^2 indicates that data can be derived from R^1 and used in calculations, (iii) Data having symbol R" indicates that any one of these data is required.

Table 2: Average Monthly and Annual Weather Data

Month	Temperature		Relative Humidity		Wind velocity (km/h)	Sunshine hours h	Pan Evaporation mm/day
	min (°C)	max (°C)	min (%)	max (%)			
Jan.	06.23	19.50	56.76	93.04	3.77	5.63	01.70
Feb.	08.25	23.00	48.37	90.89	4.15	7.24	02.77
Mar.	11.63	27.95	38.71	86.87	5.29	8.20	04.78
Apr.	16.69	34.97	25.24	69.13	5.97	9.50	08.43
May	22.19	37.66	31.37	62.39	7.69	9.60	10.97
Jun.	25.03	36.26	48.69	74.06	7.93	8.03	09.21
Jul.	25.42	32.90	68.86	88.87	5.85	5.93	05.81
Aug.	24.99	31.77	73.89	92.16	4.83	5.20	04.54
Sep.	23.29	31.73	67.61	91.96	3.20	6.88	04.12
Oct.	17.39	30.92	49.55	86.89	2.30	8.63	03.51
Nov.	11.20	27.33	44.50	89.42	2.04	8.30	02.87
Dec.	07.02	22.77	48.66	93.02	2.15	6.85	01.93
Average	16.61	29.73	50.18	84.89	4.60	7.50	05.05

Regressions have been performed to examine the relationships of the monthly ET_0 estimates from the five methods with the measured ET_0. The regression equations computed is of the form,

$$Y = mX + C \quad \dots (11)$$

Where, Y represents observed monthly ET_0; X is the monthly ET_0 estimated from each of the five methods; and m and C are slope and intercept, respectively.

Coefficient of determination (R^2), the slope of the regression, root Mean Square Error (RMSE) and Absolute Average Deviation (AAD) were used as the main parameters for evaluating the reliability of methods in predicting 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, C value closest to zero, m value closest to 1.0, the smallest RMSE, and the highest R^2 (Parmele and McGuinness, 1974).

RESULTS

The mean monthly ET_0 values estimated by each of the five methods for the period of record used are given in Table 3 and are also shown in Figure 1. All the methods, in general, underestimate mean monthly ET_0 for the summer months (April to June) and overestimate for the winter months (October to February) except Thornthwaite method which underestimated for both the seasons.

The extent of the overestimation of total annual ET_0 by all the methods ranges from 6.33% (Priestly-Taylor) to 24.26% (Hargreaves). Priestly-Taylor method is in closest agreement with the measured ET_0. The radiation methods are generally closer in estimating the total annual ET_0.

Percentage Relative Error (PRE) in the estimation of ET_0 by each method with respect to measured ET_0

Table 3: Observed and Estimated Mean Monthly ET_0 (mm/day) and Total Annual ET_0 (mm)

Month	Measured	Penman-Monteith	Hargreaves	Thornthwaite	Turc	Priestly-Taylor
Jan.	1.19	1.52	2.15	0.5	1.84	1.41
Feb.	1.94	2.09	2.73	0.94	2.54	1.89
Mar.	3.35	3.3	4.03	1.97	3.48	2.92
Apr.	5.9	5.25	5.89	4.56	5.02	4.26
May	7.68	6.59	6.79	7.36	5.74	5.41
Jun.	6.45	6.02	6.32	8.08	5.06	5.75
Jul.	4.07	4.54	5.1	6.93	4.34	5.26
Aug.	3.18	3.95	4.51	6.08	3.99	4.78
Sep.	2.88	4	4.47	5.19	4.2	4.8
Oct.	2.46	3.63	4.43	3.3	4.03	4.12
Nov.	2.01	2.55	3.55	1.62	3.1	2.76
Dec.	1.35	1.71	2.78	0.74	2.21	1.76
Annual	1273.44	1354.71	1582.32	1417.88	1365.63	1354.05

and ranks of each method on the basis of PRE are given in Table 4. The ranks for different months were then averaged to calculate the final points of each method based on which final ranks were given. The table shows that Penman-Monteith method is, in general, the best in predicting mean monthly ET_0 followed by Turc, Priestley-Taylor, Hargreaves and Thornthwaite methods.

Results obtained from the regression of mean monthly ET_0 estimated by each of the five methods against mean monthly measured ET_0 are presented in Table 5. Based on these results, the Penman-Monteith regression model ranked first with the lowest root mean square error (0.790), lowest absolute average deviation (0.648) and the second highest coefficient of determination (0.892) for monthly ET_0 predictions. On the basis of coefficient of determination, Hargreaves regression model is best (R^2 = 0.893). Thornthwaite model is the best as per slope (closest to unity) and intercept (nearest to zero) of regression line.

Since, different parameters showed different trends, the analysis has been further extended by giving ranks to all the methods according to: (i) slope of regression equation closest to unity; (ii) intercept of regression equation closest to zero; (iii) highest coefficient of determination; (iv) lowest root mean square error and (v) lowest absolute average deviation. The overall ranking showed that Penman-Monteith regression equation is the best followed by Hargreaves, Thornthwaite, Turc and Priestley-Taylor.

None of the method having coefficient of determination (R^2) greater or equal to 0.80 has slope of regression line equal to unity therefore it will not be possible to improve the estimation accuracy of any method using single correction factor for all months in the year. Hence mean monthly correction factors instead of single local correction factor were needed to be introduced. Mean monthly correction factors for all the five methods have been computed as the ratio of the observed monthly total ET_0 to the predicted monthly total for each method averaged over the record period and are given in Table 6.

The monthly correction factors are then used to improve the accuracy of these methods. The monthly ET_0 values for years 1999 and 2000 are computed using these enhanced equations. These values are then tested by comparing with observed data of the same period. The results of corrected mean monthly ET_0 estimates are shown in Figure 2.

Table 4: Performance of Estimation Methods Based on Percentage Relative Error

Month	Penman-Monteith		Hargreaves		Thornthwaite		Turc		Priestly-Taylor	
	PRE	Rank	PRE	Rank	PRE	Rank	PRE	Rank	PRE	Rank
Jan.	27.46	2	80.86	5	–58.07	4	54.16	3	18.56	1
Feb.	7.53	2	40.79	4	–51.68	5	30.89	3	–2.32	1
Mar.	–1.26	1	20.44	4	–41.26	5	4	2	–12.67	3
Apr.	–11	2	–0.19	1	–22.74	4	–14.95	3	–27.84	5
May	–14.14	3	–11.6	2	–4.2	1	–25.25	4	–29.55	5
Jun.	–6.56	2	–2.03	1	25.38	5	–21.56	4	–10.75	3
Jul.	11.53	2	25.41	3	70.52	5	6.64	1	29.41	4
Aug.	24.25	1	41.92	3	91.13	5	25.44	2	50.25	4
Sep.	38.85	1	55.19	3	80.14	5	45.51	2	66.6	4
Oct.	47.44	2	80.04	5	34.19	1	63.74	3	67.6	4
Nov.	27	2	76.28	5	–19.62	1	54.05	4	37.15	3
Dec.	27.15	1	106.16	5	–44.96	3	63.8	4	30.79	2
Final rank		1.8		3.4		3.7		2.9		3.3

PRE: percentage relative error in the estimation

Table 5: Summary Statistics of Regression

	Regression Equation	R^2	RMSE	AAD
Penman-Monteith	Y = 0.7401 X + 1.1452	0.892	0.790	0.648
Hargreaves-Samani	Y = 0.678 X + 1.9822	0.893	1.179	1.041
Thornthwaite	Y = 1.0351 X + 0.2771	0.633	1.681	1.393
Turc	Y = 0.5127 X + 1.9799	0.806	1.163	1.002
Priestly-Taylor	Y = 0.5418 X + 1.8449	0.563	1.387	1.113

Table 6: Mean Monthly Correction Factors

Month	*Penman-Monteith*	*Hargreaves*	*Thornthwaite*	*Turc*	*Priestiy-Taylor*
January	0.76	0.53	2.37	0.63	0.82
February	0.89	0.70	2.01	0.75	0.99
March	0.95	0.80	1.64	0.93	1.08
April	1.09	1.04	1.37	1.17	1.37
May	1.13	1.14	1.16	1.33	1.48
June	1.04	1.05	0.89	1.31	1.17
July	0.85	0.78	0.60	0.91	0.75
August	0.80	0.72	0.55	0.80	0.67
September	0.69	0.63	0.57	0.67	0.58
October	0.66	0.54	0.76	0.60	0.58
November	0.75	0.54	1.21	0.63	0.69
December	0.77	0.48	1.78	0.60	0.73

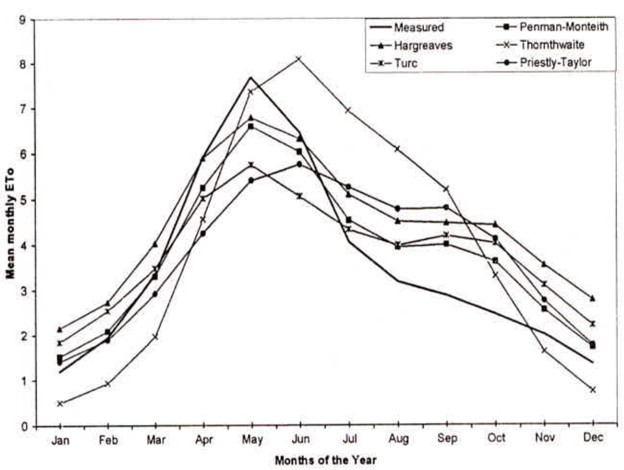

Fig. 1: Measured and estimated mean monthly ET_0

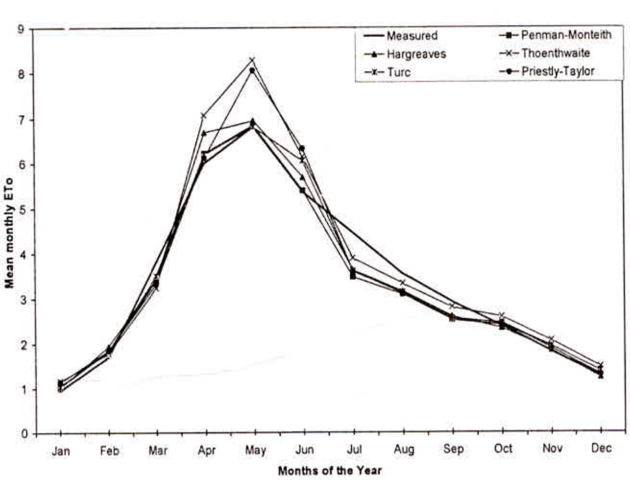

Fig. 2: Measured and estimated mean monthly ET_0 using correction factors

Coefficient of determination, absolute average deviation and root mean square error in the estimation are given in Table 7. All the methods used here exhibit good R^2 (>0.9), low RMSE and AAD, Penman-Monteith is in the closest agreement with measured ET_0 values having highest R^2 (0.966), lowest RMSE (0.363) and lowest AAD (0.246) followed by Turc, Hargreaves-Samani, Priestley-Taylor and Thornthwaite methods respectively.

Table 7: Performance Statistics of Estimation Methods

	R^2	*AAD*	*RMSE*
Penman-Monteith	0.966	0.246	0.363
Hargreaves-Samani	0.964	0.290	0.381
Thornthwaite	0.949	0.475	0.628
Turc	0.961	0.276	0.374
Priestly-Taylor	0.939	0.409	0.563

After applying correction factors, performance of Penman-Monteith method has been found to be the best. The results of performance statistics presented in Table 7 indicates that values of R^2, AAD and RMSE for Hargreaves and Turc methods are very close to those of Penman-Monteith method. The same inference is drawn from Figure 2.

These results indicate that Hargreaves and Turc methods with monthly correction factors can be reliably used in the estimation of ET_0 where Penman-Monteith method can not be used due to unavailability of sufficient data.

CONCLUSIONS

In general, all the methods in their original form, underestimate mean monthly ET_0 for the summer months (April to June) and overestimate for the winter months (October to February) except Thornthwaite method which underestimate for both the seasons. On the basis of percentage relative error, Penman-Monteith method is, in general, the best in predicting mean monthly ET_0 followed by Turc, Priestley-Taylor, Hargreaves and Thornthwaite methods, however, Priestley-Taylor method yield the best average estimate of total annual ET_0.

On the basis of regression statistics, it is found that none of the ET_0 estimation method has slope of regression line equal to unity with coefficient of determination (R^2) greater than 0.85, this emphasize the need of generation of separate correction factors for different periods of year. Hence mean monthly correction factors instead of mean annual correction factor are applied to ET_0 estimation methods.

The ET_0 estimates using corrected Hargreaves and Turc methods are well correlated with measured ET_0 with coefficient of determination (R^2) greater than 0.96. If radiation, humidity, and wind-speed data are not available, either the Hargreaves or Turc method with correction factors for the study region can be utilized for reliable estimation of ET_0. Further, this procedure may be followed for other regions by developing monthly local correction factors.

ACKNOWLEDGEMENTS

The authors [(1)] gratefully acknowledge the Council of Scientific and Industrial Research, New Delhi for providing financial support and the Joint Director, Crop Research Centre, G.B. Pant University of Agriculture and Technology, Pantnagar for providing relevant data.

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