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Penman and Thornthwaite Equations for Estimating Reference Evapotranspiration Under Semi-Arid Environment

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Abstract: The estimation of reference evapotranspiration (ETo) is required for effective development and management of agriculture water systems. In order to define the most accurate method to estimate ETo in semi-arid climatic environment of Faisalabad, Lahore and Peshawar. Penman ETo method and Thornthwaite ETo method are compared with standard Penman-Monteith (PM) ETo method. The statistical results show that the Penman ETo method overestimate ETo as compared to the PM ETo method in all the semi-arid climatic regions of Faisalabad, Lahore and Peshawar by 34.91%, 39.51% and 30.75%, respectively. The coefficient of determination (R^2) were 0.98, 0.98 and 0.99 at Faisalabad, Lahore and Peshawar weather stations, respectively. The root mean square error (RMSE) are 2.47 mm/day, 2.64 mm/day and 2.19 mm/day at Faisalabad, Lahore and Peshawar weather station, respectively. The mean bias error (MBE) of-2.41 mm/day,-2.58 mm/day and-2.13 mm/day are noted at Faisalabad, Lahore and Peshawar weather stations, respectively. The statistical results of Thornthwaite (Th) ETo method with PM ETo method indicate underestimation of ETo in winter season and overestimation of ETo in summer season by 13.81%, 22.43% and 14.54% at Faisalabad, Lahore and Peshawar stations, respectively. The coefficient of determination (R^2) of Thornthwait ETo method when compared with PM ETo method 0.92, 0.89 and 0.95 are noted at Faisalabad, Lahore and Peshawar weather stations, respectively. The root mean square error (RMSE) are 2.14 mm/day, 2.36 mm/day and 1.16 mm/day at Faisalabad, Lahore and Peshawar weather stations, respectively. The mean bias error (MBE) are-0.68 mm/day,-1.12 mm/day and 0.61 mm/day at Faisalabad, Lahore and Peshawar weather stations, respectively. Overall, Thornthwaite method gave better estimation of ETo than Penman ETo method at all the Weather stations.

Keywords: Penman, Thornthwaite, Penman-Monteith, Reference Evapotranspiration, Semi-arid

1. Introduction

Pakistan lies in arid to semi-arid region where average annual rainfall is 254 to 356 mm against a potential demand (of water for maximum crop production) of 1778 mm. This gap between the demands and supplies is met through applying irrigation. Moreover, the country is facing threat of rapidly increasing population with the annual growth rate of 2.05 percent. It has been observed that water availability for agriculture is expected to decline globally to 62 percent by

2020 as was available (72%) in 1995 and from 87% to 73% in developing countries [1]. Reference evapotranspiration (ETo) is one of the most significant factor to design and manage water reservoirs [2]' scheme of irrigation structures [3], effective irrigation management [4] and hydrological and meteorological investigations [5]. Types of crop and land use affect the evapotranspiration process [6]. The most accurate ETo method for the estimation of ETo is lysimeter [7-8]. Since lysimeters manufacturing is very expenses, experimental ETo methods are generally applied to estimate ETo. Numerous researchers have argued that Penmen–Monteith (PM) ETo method can be applied as a reference ETo method as compared to the other experimental ETo methods [9-12]. The Penman-Monteith (PM) ETo method requires large number of weather parameters i-e air temperature, humidity, solar radiation, wind speed etc. But, availability of these weather parameters is not accessible at all the weather stations of the world especially in developing country like Pakistan. Therefore, it appears reasonably to substitute it by other ETo methods which require small number of weather parameters [13]. The accuracy of a particular ETo method depends greatly on the climatic situations of the research area [14]. For humid subtropical weather climatic conditions Penman-Monteith (PM) ETo method is commonly suggested [15-16].

Many researchers including [17-20] revealed that temperature and radiation dependent ETo methods lean towards the highest and pan-coefficient dependent ETo methods give lowest ETo values. It is concluded that in dry and semi-dry climatic conditions solar radiation-dependent ETo methods give poor results [21]. However, application of regionally modified radiation-dependent ETo methods can give more accurate results than air temperature dependent ETo methods and even complex ETo methods [22-23]. As the accuracy of estimated values of ETo by different ETo methods is significant for water resources design and management, proper irrigation timing, control and agricultural efficiency; it has given rise to many researchers that were carried out in various regions of the globe to determine the most accurate ETo method which is appropriate for estimation of ETo in such regions [24]. A study is carried out to compare the various ETo methods including Turc [25], Blaney-Criddle [26], Hamon [27], Thornthwaite [28] and Priestley–Taylor [29] ETo methods against standard Penman-Monteith [30] ETo method for the estimation of ETo by applying weather parameters of 12 various weather stations. The results of the study indicated that the Turc and Penman-Monteith (PM) method showed the most accurate results [31]. Another research is conducted to evaluate the accuracy of 9 ETo methods against Penman-Monteith (PM) ETo method to estimate ETo. The conclusion of research showed that the Blaney-Criddle (BC) ETo indicated the most accurate ETo estimation and the Thornthwaite ETo method indicated the poor results of ETo estimation [32]. The main objective of this research is to compare the performance of Penman and Thornthwaite ETo methods against standard PM ETo method under semi-arid climatic conditions of Lahore, Faisalabad and Peshawar, Pakistan.

2. Materials and Methods

2.1. Geographical Area and Weather Data Set

The mean monthly weather data of three weather stations of semi-arid regions (Lahore, Faisalabad and Peshawar) is used to estimate reference evapotranspiration (ETo) by Penman and Thornthwaite ETo methods. The mean monthly weather data period, climate conditions and Global Positioning System (GPS) of weather stations used in the study are given in the table.

Table 1. *Global Positioning System and climate of weather stations of study regions.*

Station	Latitude	Longitude	Elevation (m)	Data Period	Climate
Lahore	31.33°N	74.20°E	214.0	2000-2009	hot semi-arid
Faisalabad	31.26°N	73.08°E	185.6	2001-2010	hot semi-arid
Peshawar	34.02°N	71.56°E	327.0	2000-2007	hot semi-arid

Methods for estimation of ETo

2.2. Penman-Monteith (PM) ETo Method

In this research paper, the Penman-Monteith (PM) ETo method [30] is recommended as the reference ETo method for estimation ETo. The accuracy of this ETo method has been proved by many researchers under various weather conditions [33-36]. The Penman-Monteith (PM) ETo method presented by [30] is given as:

$$\mathrm{ETo} = \frac{0.408\,(R_n - G) + 900\,\gamma\left(\frac{U_2}{T+273}\right) e_s - e_a}{\Delta + \gamma\,(1 + 0.34U_2)} \tag{1}$$

Where, ETo is reference crop evapotranspiration (mm/day); Δ is slope of the saturation vapor pressure function (kPa (°C)$^{-1}$); Rn is net solar radiations (MJ m^{-2} day^{-1}); G is earth heat flux thickness (MJ m^{-2} day^{-1}); T is average atmospheric temperature (°C); U_2 is the mean 24-hour air velocity at 2m elevation (ms^{-1}); (e_s-e_a) is the vapor pressure deficit (kPa); and γ is psychometric constant (kPa (°C)$^{-1}$) The estimation of all weather data essential for estimation of ETo followed the method of [30].

2.3. Thornthwaite Method

The Thornthwaite ETo method had been developed in 1948 by [28]. This ETo method is given as:

$$\mathrm{ETo} = \mathrm{ET}_{gr}\left(\frac{N}{12}\right)\left(\frac{d_m}{30}\right) \tag{2}$$

$$ET_{gr} = 16\ \left(\frac{10\,T_m}{I}\right)^{\alpha} \quad (3)$$

$$I = \sum_{i=1}^{12}\left(\frac{T_m}{5}\right)^{1.154} \quad (4)$$

Where, N is the maximum number of sunny hours in function of the month latitude; d_m is the number of day per month; ET_{gr} is the gross evapotranspiration; T_m is the mean temperature (°C); I is the monthly heat index.

$$\alpha = 0.49239 + 1792 \times 10^{-5}\, I - 771 \times 10^{-7}\, I^2 + 675 \times 10^{-9}\, I^3 \quad (5)$$

2.4. Penman Method

The Penman [37] ETo method is given as:

$$ETo = \frac{\frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma} 6.43\,((1+0.53\,u_2)(e_s - e_a))}{\lambda} \quad (6)$$

Where, ETo is the reference evapotranspiration (mm/day); Δ is slope of the saturation vapor pressure function (kPa $(°C)^{-1}$); Rn is net solar radiations (MJ m^{-2} day^{-1}); G is earth heat flux thickness (MJ m^{-2} day^{-1}); u_2 is the mean 24-hour air velocity at 2m elevation (ms^{-1}); (e_s-e_a) is the vapor pressure deficit (kPa); γ is psychometric constant (kPa $(°C)^{-1}$) and λ is the latent heat of vaporization in MJ kg^{-1} (λ = 2.45 MJ kg^{-1} at a temperature of 20°C).

2.5. Evaluation Criteria

In this study, the root mean square error (RMSE), percentage error of estimate (PE), mean bias error (MBE) and coefficient of determination (R2) are used for the evaluation of the ETo methods. The RMSE, PE, MBE and R^2 are defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (7)$$

$$\%PE = \left[\frac{\bar{P} - \bar{O}}{\bar{O}}\right] \times 100 \quad (8)$$

$$MBE = \frac{\sum_{i=1}^{n}(P_i - O_i)}{n} \quad (9)$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(P_i - \bar{P})(O_i - \bar{O})\right]^2}{\sum_{i=1}^{n}(P_i - \bar{P})^2 \sum_{i}^{n} O_i - \bar{O})^2} \quad (10)$$

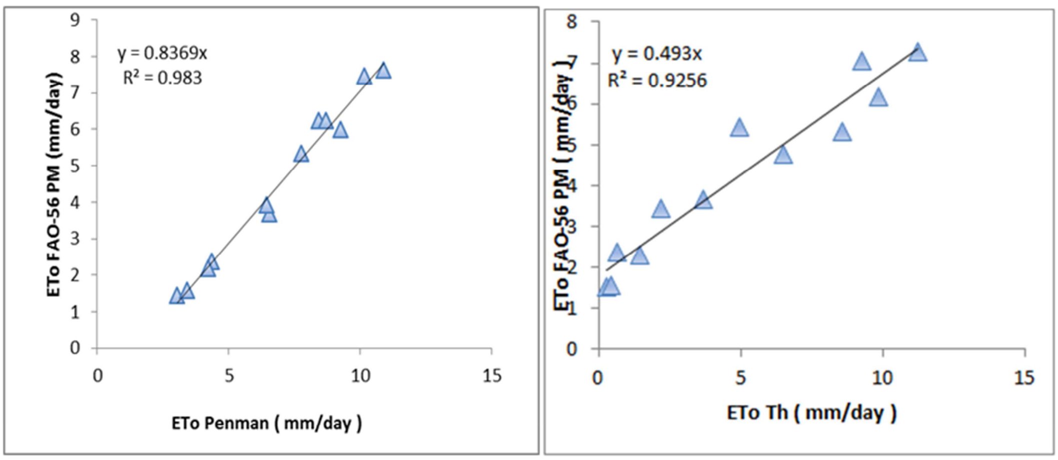
Where, Pi are the projected values and Oi are observed values. $\bar{P}$ is the mean of Pi and $\bar{O}$ is the mean of Oi, and n is the whole number of values.

3. Results and Discussion

The Penman ETo method and Thornthwaite ETo method that are temperature dependent ETo methods are compared with standard Penman-Monteith ETo method in different semi-arid climatic regions of Lahore, Faisalabad and Peshawar. According to the statistical analysis applied between Penman and PM ETo methods, the Penman ETo method indicated overestimation of ETo by 34.91% at Faisalabad weather station as concluded by [38] as shown in Figure 1 (a) and Table 2. The difference of variation between Penman and PM ETo methods has coefficient of determination (R^2) of 0.98 with root mean square error (RMSE) of 2.47 mm/day and mean bias error (MBE) of-2.41 mm/day at Faisalabad weather station. The statistical results between Thornthwaite ETo method and PM ETo method show that the Thornthwaite ETo method indicated underestimation in winter and overestimation in summer by 13.81% at Faisalabad station as concluded by [39-40], as shown in 1 (b) and table 2. The difference of variation between Thornthwaite ETo method and PM ETo method has coefficient of determination (R^2) of 0.92 with root mean square error (RMSE) of 2.14 mm/day and mean bias error (MBE) of-0.68 mm/day.

Table 2. *Statistical analysis of ETo calculated by Penman and Thornthwaite ETo methods compared with PM ETo method at Faisalabad station.*

Method	RMSE	R^2	MBE	% Error
Penman	2.47	0.98	-2.41	34.91
Thornthwaite	2.14	0.92	-0.68	13.81



(a) (b)

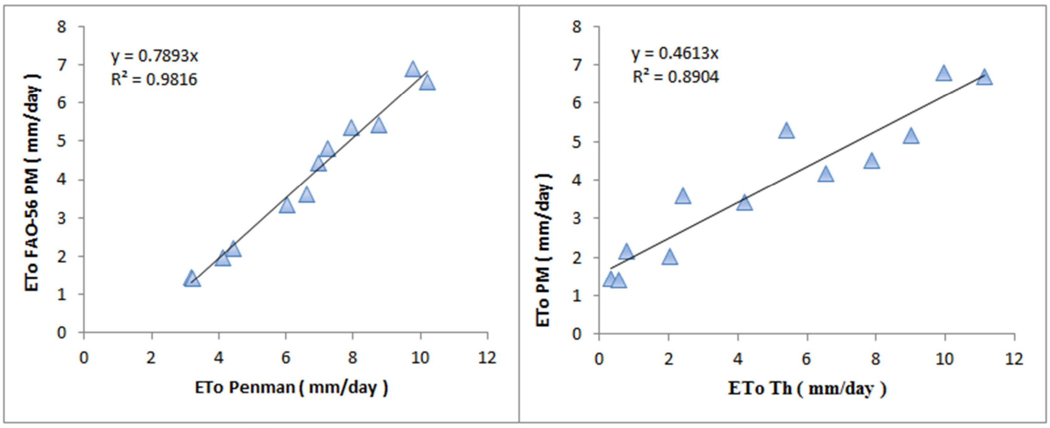
Figure 1. *Comparison of ETo by (a) Penman and (b) Thornthwaite ETo methods with PM ETo method at Faisalabad station.*

The monthly comparison of ETo estimated by Penman and PM ETo method at Lahore weather station indicate that the ETo estimated by Penman ETo method overestimated the PM ETo method by 39.51% as concluded by [41] as shown in the figure 2 (a) and table 3. The difference of variation between Penman ETo method and PM ETo method has coefficient of determination (R^2) of 0.98 with root mean square

RMSE of 2.64 mm/day and MBE of-2.58 mm/day at Lahore weather station as shown in table 3. The Thornthwaite ETo method indicate underestimation of ETo in first 3 and last months (January, February, March and December) and overestimated ETo in the remaining months of the year by 22.43% as concluded by [42] as shown in the Figure 2 (b) and in Table 3. The difference of variation between Penman ETo method and PM ETo method has R^2 of 0.89 with RMSE of 2.36 mm/day and MBE of-1.12 mm/day at Lahore weather station as shown in the Table 3.

Table 3. *Statistical analysis of ETo calculated by Penman and Thornthwaite ETo methods compared with PM ETo method at Lahore station.*

Method	RMSE	R^2	MBE	% Error
Penman	2.64	0.98	-2.58	39.51
Thornthwaite	2.36	0.89	-1.12	22.43



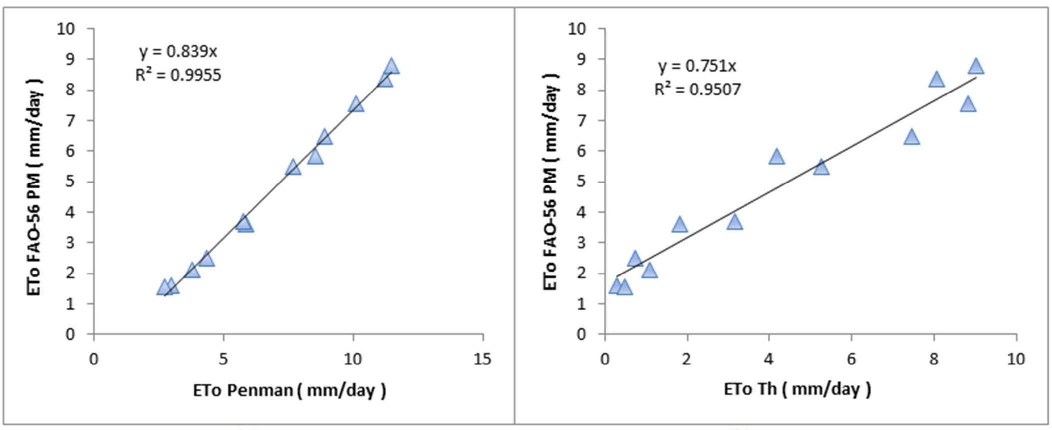
(a) **(b)**

Figure 2. *Comparison of ETo (a) Penman (b) Thornthwaite ETo methods with PM ETo method at Lahore station.*

The statistical analysis between Penman ETo method and PM ETo method at Peshawar weather station indicate that Penman ETo method show overestimation of ETo by 30.75% as compared to the PM ETo method as concluded by [43] as shown in figure 3 (a) and in Table 4. The difference of variation among Penman ETo method and PM ETo method has R^2 of 0.99 with RMSE of 2.19 mm/day and MBE of-2.13 mm/day. The mean monthly comparison between Thornthwaite ETo method and PM ETo method at Peshawar weather station indicate that Thornthwaite ETo method overestimated in 3 months of summer (June, July and August) and underestimated in the remaining months of the year by 14.54% as concluded by [44] shown in the Figure 3 (b) and table 4. The variation difference between Thornthwaite ETo method and PM ETo method has R^2 of 0.95 with RMSE of 1.16 mm/day and MBE of 0.61 mm/day.

Table 4. *Statistical analysis of ETo calculated by Penman and Thornthwaite ETo methods compared with PM ETo method at Peshawar station.*

Method	RMSE	R^2	MBE	% Error
Penman	2.19	0.99	-2.13	30.75
Thornthwaite	1.16	0.95	0.61	14.54



(a) (b)

Figure 3. *Comparison of ETo by (a) Penman (b) Thornthwaite ETo methods with PM ETo method at Peshawar station.*

4. Conclusion

This study compared the Penman and Thornthwaite ETo methods with PM ETo method to estimate ETo in different semi-arid climatic regions. The PM ETo method has been taken as reference ETo method as stated by many researchers including [45-46]. The statistical results show that the Penman ETo method overestimated PM ETo method for estimation of ETo at all the weather stations (Faisalabad, Lahore and Peshawar) of semi-arid climatic conditions. The Thornthwaite ETo method underestimated PM ETo method in winter season and overestimated PM ETo method in summer season in semi-arid climatic conditions of Faisalabad, Lahore and Peshawar weather stations. Overall, Thornthwaite ETo method gave better estimation of ETo than Penman ETo method at all the weather stations.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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