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COMPARING SEVEN DIFFERENT REFERENCE EVAPOTRANSPIRATION EQUATIONS WITH PENMAN-MONTEITH FOR ANTALYA, TURKEY

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ABSTRACT

Evapotranspiration (ET) is one of the most difficult processes in nature. The most accurate and reliable method to determine ET is lysimeter, which is difficult, expensive and time-consuming. On the other hand, ET can be estimated using reference crop evapotranspiration (ET_o) and crop coefficient (k_c). easily Many ET_o equations using meteorological data have been developed. The most widely accepted equation for ET_o is FAO-56 Penman-Monteith (FAO-56 PM) equation. However, FAO-56 PM equation needs numerous meteorological data and is hard to measure for farmers. For this reason, equations which need less meteorological data have been gaining importance. Characteristic Mediterranean climate prevails in coastal areas of Antalya, Turkey. In the present study, long term data (1985 to 2015) obtained from meteorological stations was used to compute ET_o in Antalya. Seven different ET_o equations (Penman, FAO 24 Penman, Hargreaves, Turc, Priestley-Taylor, FAO 24 Pan, Christiansen Pan) were compared with FAO-56 PM. It was shown that the Turc equation gives results close to FAO-56 PM equation.

KEYWORDS:
ET_o, Penman-Monteith, Humid conditions, Turkey, Turc

INTRODUCTION

Determining the amount of evapotranspiration for optimal irrigation programming is important because of declining water resources. But determining of ET is one of the most difficult processes in nature. The most accurate and reliable method to determine ET is lysimeter, which is difficult, expensive and time-consuming. On the other hand, ET can be estimated with meteorological data and crop coefficient easily. ET quantification frequently must be preceded by the determination of reference evapotranspiration (ET_o) [1, 2].

Although FAO-56 PM is considered as a standard and most accurate model under various climatic conditions to estimate ET_o [3, 4, 5, 6, 7, 8, 9, 10] many models have been developed in accordance with various climate and geographical conditions. The major limitation to FAO-56 PM model is that it requires many meteorological inputs, thereby limiting its utility in data-sparse areas. It is expensive to equip meteorology stations to measure these data essentially in developing countries. Therefore, it is recommended to apply simpler models because they need parameters that are readily available from station observing meteorological data [11]. For this reason, many researchers had investigated the performance of ET_o models that need less climate parameters.

Penman [12], FAO-24 Penman [13], Hargreaves [14], Turc [15], Priestley-Taylor [16], FAO-24 Pan [13], Christiansen Pan [17, 18] models require less climate parameters than the FAO-56 PM [4] model. However, the accuracy of these models relative to the FAO-56 PM varies with climate, region and altitude.

Djaman et al. [10] evaluated sixteen reference evapotranspiration methods under Sahelian conditions in the Senegal River Valley. They revealed that the Hargreaves equations systematically overestimated ET_o with the highest percentage error of estimate (PE) while Turc equations systematically underestimated ET_o. Sheikh and Mohammadi [19] tested different estimation methods of ET_o in semi-arid regions. Their results showed that the Hargreaves-Samani equation gave the smallest difference compared to the FAO-56 PM.

Tabari et al. [2] compared 31 ET_o models against FAO-56 PM under humid conditions. The results indicated that all of the pan evaporation-based methods had a tendency to underestimate FAO-56 PM ET_o. In contrast with the pan evaporation-based, the temperature-based and radiation-based equations overestimated against FAO-56 PM.

According to Bogawski and Bednorz [20], the best estimations were obtained using the radiation-based models, followed by pan coefficient-based and temperature-based models at the border between two humid climates in Poland. In addition, the authors indicated that the pan evaporation methods were not applicable in Poland and that the Class A Pan was not routinely used for ET_o calculation. Also, the Hargreaves methods produced the least accurate

monthly ET_o estimates.

Fernandes et al. [21] compared six different equations against FAO-56 PM. The results showed that the Hargreaves, Priestley-Taylor and Makkink methods presented the highest agreements with respect to the FAO-56 PM equation. These methods achieved better performances due to the approach of improving the representation of the effects of the radiative process, since they use solar radiation. Xystrakis and Matzarakis [8] evaluated thirteen different ET_o equations and compared with FAO-56 PM in order to determine the equation that gives closest results to FAO-56 PM in Mediterranean region. The radiation-based equations generally performed better than those that included only temperature-related input variables.

Several researchers [6, 11, 22, 23, 24, 25, 26] indicated that the Turc model performs well in humid climate. Similarly, Tukimat et al. [26] found that radiation based methods (Turc, Priestley-Taylor) gave better performance compared to temperature-based methods (Hargreaves) in estimation of ET_o in the humid area. They also said that Turc method needs less number of parameters to estimate ET_o compared to Priestley-Taylor method and therefore, much easier to use.

Tabari [11] evaluated four models (Makkink, Turc, Priestley–Taylor and Hargreaves) commonly used to estimate monthly ET_o values for different climates and altitude. The author concluded that Hargreaves and Turc model presented the best estimates for warm humid climate. Lu et al. [25] reported that the radiation based equations (Priestley-Taylor and Turc) showed best performance for the southeast side of the United States. Trajkovic and Kolakovic [6] tested five commonly used models to estimate ET_o under humid condition which were compared to corresponding values estimated using the standardized FAO-56 PM equation. They indicated that the Turc equation was the most suitable model for estimating ET_o at humid locations. Fontenot [24] evaluated seven commonly used ET_o equations (FAO-24 Radiation, Blaney-Criddle, Hargreaves and Samani, Priestley-Taylor, Makkink and Turc) against ET_o values computed by the FAO-56 PM model in humid area. The results of this study indicated that the Turc model was the most accurate model in estimating daily and monthly ET_o.

The aim of this study was to assess the performance of seven ET_o equations models against FAO-56 PM model which was accepted as a standard method. By using FAO-56 PM model as reference for these models, multiple regression equations were developed in Antalya conditions.

MATERIALS AND METHODS

Study Area and Climate Dataset. In the present study, long term data (1985 to 2015) obtained from meteorological stations was used to compute ET_o in Antalya (Fig 1). All climatic data were obtained from the Turkish State Meteorological Service.

Climatic data used in ET_o calculation was collected daily during the period between January of 1985 and December of 2015. The long term average data used is given in Table 1.

Antalya is under the influence of the Mediterranean climate with hot summers and rainy winters. Since this site lies within the coastal plane, the solar radiation values are very high in summer and rather low in the winter periods. The solar radiation is under the influence of humidity due to excessive evaporation in this region.



FIGURE 1
Location of Antalya on map of Turkey.

TABLE 1
Monthly means of the main climatic variables at Antalya station from 1985 to 2015.

Station no: 17302		Latitude: 36.8851				Longitude: 30.6828						Altitude: 47.0	
Month		1	2	3	4	5	6	7	8	9	10	11	12
T_{max}	(°C)	15.06	15.55	18.06	21.24	26.15	31.63	34.52	34.46	31.26	27.19	21.02	16.35
T_{min}	(°C)	5.54	5.86	7.70	10.86	15.24	19.83	23.05	22.92	19.28	15.47	10.22	7.23
RH	(%)	63.35	61.05	64.60	68.00	66.10	58.70	58.22	60.64	60.27	60.55	63.32	66.39
u_2	(m s^{-1})	2.35	2.59	2.32	2.01	1.76	2.01	1.85	1.76	1.90	1.85	1.97	2.13
Rs	(MJ $m^{-2}day^{-1}$)	8.71	12.05	16.25	19.76	23.16	25.95	25.25	22.78	19.49	14.23	9.70	7.38
N	(hours)	5.56	6.11	7.02	8.00	9.87	11.78	11.91	11.25	9.67	8.02	6.41	5.09
E_{pan}	(mm)	1.64	1.97	2.60	3.14	4.22	6.03	6.45	5.92	4.77	3.24	1.95	1.40

T_{max} is maximum air temperature; T_{min} is minimum air temperature; RH is relative humidity; u_2 is wind speed at 2 meter; R_s is solar radiation; n is sunshine hours and E_{pan} is pan evaporation.

Reference Evapotranspiration Estimation Methods. FAO-56 Penman-Monteith. The FAO Penman-Monteith [4] method for calculating ET_o is given in Eq. 1:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean}+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\, u_2)} \quad (1)$$

where ET_o is the reference crop evapotranspiration (mm day^{-1}); R_n is the net radiation (MJ m^{-2} day^{-1}); G is the soil heat flux (MJ m^{-2} day^{-1}); γ is the psychometric constant (kPa $^oC^{-1}$); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); and Δ is the slope of the saturation vapor pressure temperature curve (kPa $^oC^{-1}$); T_{mean} is the average daily air temperature (^oC) and u_2 is the mean daily wind speed at 2 m (m s^{-1}).

Combination-Based ET_o equations. Penman 1963. Penman's formula [12] combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface based on standard climatic records of sunshine, temperature, humidity and wind speed [27].

The Penman equation (Eq. 2) is expressed as:

$$ET_o = \left[\frac{\Delta}{\Delta+\gamma} R_n + \frac{\gamma}{\Delta+\gamma} E_a\right] 0.8 \quad (2)$$

where ET_o is reference evapotranspiration (mm day^{-1}); Δ is the slope of saturation vapour pressure temperature curve (kPa $^oC^{-1}$); γ is the psychometric constant (kPa $^oC^{-1}$); R_n is the net radiation (mm day^{-1}); E_a is aerodynamic term (mm day^{-1}). The aerodynamic term is given in equation (Eq. 3):

$$E_a = 0.35(1 + 0.22u_2)(e_s - e_a)7.4 \quad (3)$$

where u_2 is wind speed measured at 2 m (m s^{-1}); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa).

FAO 24 Penman. The FAO-24 Penman equation [13] is expressed as Eq. 4:

$$ET_o = \left[0.408\frac{\Delta}{\Delta+\gamma}(R_n - G) + 2.7\frac{\gamma}{\Delta+\gamma}(1 + 0.864u_2)(e_s - e_a)\right] \quad (4)$$

Where ET_o is reference evapotranspiration (mm day^{-1}); R_n is the net radiation (MJ m^{-2} day^{-1}); G is the soil heat flux (MJ m^{-2} day^{-1}); γ is the psychometric constant (kPa $^oC^{-1}$); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); and Δ is the slope of the saturation vapor pressure temperature curve (kPa $^oC^{-1}$); and u_2 is the mean daily wind speed at 2 m (m s^{-1}).

Temperature-based ET_o equations. Hargreaves. The Hargreaves model is not truly temperature-based method because it contains a radiation term. Since measurement is not needed for extraterrestrial radiation, this method may be classified as a temperature-based method [28]. The Hargreaves model [14] is expressed as Eq. 5.

$$ET_o = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a \quad (5)$$

where ET_o is reference evapotranspiration (mm day^{-1}); T_{mean} the daily mean air temperature (^oC); T_{max} the daily maximum air temperature (^oC); T_{min} the daily minimum air temperature (^oC) and R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}).

Radiation-Based ET_o Equations. Turc. The Turc model [15] developed in the Netherlands is given below by Eq. 6-7.

For RH ≥ 50%
$$ET_o = 0.013\frac{T_{mean}}{T_{mean}+15}\frac{23.88xR_s + 50}{\lambda} \quad (6)$$

For RH < 50%
$$ET_o = \left(1 + \frac{50 - RH}{70}\right) 0.013\frac{T_{mean}}{T_{mean}+15}\frac{23.88xR_s + 50}{\lambda} \quad (7)$$

where ET_o is reference crop evapotranspiration (mm day^{-1}); T_{mean} is the mean monthly air temperature (^oC), R_s is solar radiation (MJ m^{-2} day^{-1}), and λ is the latent heat of vaporization (MJ kg^{-1}). If the mean daily relative humidity (RH mean) was greater than or equal to 50%, then equation 6 is used. If the mean daily relative humidity was less than 50%, then equation 7 is used.

Priestley-Taylor. The Priestley-Taylor equation [16] which is a simplification of the Penman equation, is expressed as Eq. 8;

$$ET_o = 1.26\frac{\Delta(R_n - G)}{\Delta + \gamma} \quad (8)$$

where ET_o is the reference crop evapotranspiration (mm day^{-1}); R_n is the net radiation (MJ m^{-2} day^{-1}); G is the soil heat flux (MJ m^{-2} day^{-1}); γ is the psychometric constant (kPa $^oC^{-1}$) and Δ is the slope of the saturation vapor pressure temperature curve (kPa $^oC^{-1}$).

Pan Evaporation-Based Estimation. For the most of countries, Class 'A' pan is used at monitoring stations to measure evaporation from free surface water.

FAO 24 Pan. E_{pan} can be used to estimate ET_o when the k_{pan} coefficient is applied as expressed by Eq. 9.

$$ET_o = k_{pan} x E_{pan} \quad (9)$$

k_{pan} values were determined from the FAO-24 table prepared by Doorenbos and Pruitt [13].

Christiansen Pan. The following equation (Eq. 10) was developed by Christiansen and Hargreaves [18] to estimate ET_o using Class 'A' pan and various climate parameters.

$$ET_o = 0.755 E_{pan} C_{T2} C_{w2} C_{H2} C_{S2} \quad (10)$$

where E_{pan} is class A pan evaporation (cm d^{-1}), C_{T2}, C_{W2}, C_{H2} and C_{S2} are estimated by following set of equations:

$$C_{T2} = 0.862 + 0.719\left(\frac{T_{mean}}{20}\right) - 0.041\left(\frac{T_{mean}}{20}\right)^2 \quad (11)$$

$$C_{W2} = 1.189 - 0.240\left(\frac{u}{6.7}\right) + 0.051\left(\frac{u}{6.7}\right)^2 \quad (12)$$

$$C_{H2} = 0.499 + 0.620\left(\frac{RH_{mean}}{60}\right) - 0.119\left(\frac{RH_{mean}}{60}\right)^2 \quad (13)$$

$$C_{S2} = 0.904 - 0.0080\left(\frac{\frac{n}{N}}{0.80}\right) + 0.088\left(\frac{\frac{n}{N}}{0.80}\right)^2 \quad (14)$$

where T_{mean} is the mean air temperature (°C); u is wind speed (km/hr), RH_{mean} is the mean relative humidity (%,) n is the actual sunshine hours (h) and N is maximum possible sunshine hours.

Statistical Analysis. The FAO-56 PM model was assumed as the equation giving the most accurate ET_o value. Other seven methods were compared and evaluated to determine the ET_o equation that provides the best fit with the FAO-56 PM model on daily time step. For this purpose, some performance criteria were used including coefficient of determination (R^2), root mean square error (RMSE), relative error (RE), mean bias error (MBE), The Willmott index [29] of agreement. These criteria are defined as in Eq. 15, 16, 17, 18 and 19.

$$R^2 = \frac{\left[\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})\right]^2}{\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}(Y_i - \overline{Y})^2} \quad (15)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{n}} \quad (16)$$

$$RE = \frac{RMSE}{\overline{Y}_i} \quad (17)$$

$$MBE = \frac{\sum_{i=1}^{n}(X_i - Y_i)}{n} \quad (18)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=n}^{n}\left((X_i - \overline{Y}_i) + (Y_i - \overline{Y}_i)\right)^2} \quad (19)$$

Where n is number of observations, X_i is estimated ET_o by other equations, Y_i is estimated ET_o by FAO-56 PM and $\overline{Y}_i$ is mean value of ET_o by FAO-56 PM. The most accurate result is obtained when RMSE, RE and MBE were equal to 0 and d and R^2 equal 1.

RESULTS AND DISCUSSION

Seven methods were compared and evaluated against the reference evapotranspiration data calculated using the FAO-56 PM model. These results are given in table 2.

Combination-Based ET_o equations. The results of the statistical analysis of the combination-based methods versus the FAO-56 PM model are given in Table 2. According to the MBE values and figure 2-3, all of the combination-based methods overestimated in comparison with FAO-56 PM model. Although the combination methods had high R^2 values, these methods gave the worst results in all other statistical cases.

Similarly, some researchers [30, 31] reported that Penman's method estimated the ET_o values higher in humid region. However, it had been determined that ET_o value is less predicted by Penman method in arid regions. According to Lopez-Urrea et al. [1] and Jensen et al. [3] the Penman method underestimated the lysimetric measurement in arid region. Also, they declared that FAO-24 Penman estimated higher ET_o value.

Temperature-based ET_o equations. According to Table 2 and Figure 4, our study showed that Hargreaves method did not give good result (R^2= 0.758, RMSE= 0.811mm day^{-1}, RE= 0.247 and d= 0.931).

The result obtained by the Hargreaves method is similar to previous studies of different researchers [6, 21, 30, 31, 32, 33]. As a result of many studies Hargreaves equation is not recommended for humid areas because Hargreaves equation was developed in the dry climate region of California [11, 25, 33, 34]. According to Temesgen et al. [35] higher wind speed

TABLE 2
Statistical performance of the seven different ET_o models versus the FAO-56 PM model for estimating daily ET_o during study period (1985-2015)

	R^2	RMSE (mm day^{-1})	RE	MBE (mm day^{-1})	d
Penman	0,997	0,689	0,210	-0,647	0,959
FAO-24 Penman	0,995	1,212	0,370	-1,167	0,889
Hargreaves	0,758	0,811	0,247	-0,131	0,931
Turc	0,973	0,267	0,081	-0,059	0,993
Priestley-Taylor	0,965	0,494	0,151	0,165	0,979
FAO-24 Pan	0,945	0,486	0,148	0,319	0,974
Christiansen Pan	0,931	0,674	0,206	0,535	0,952

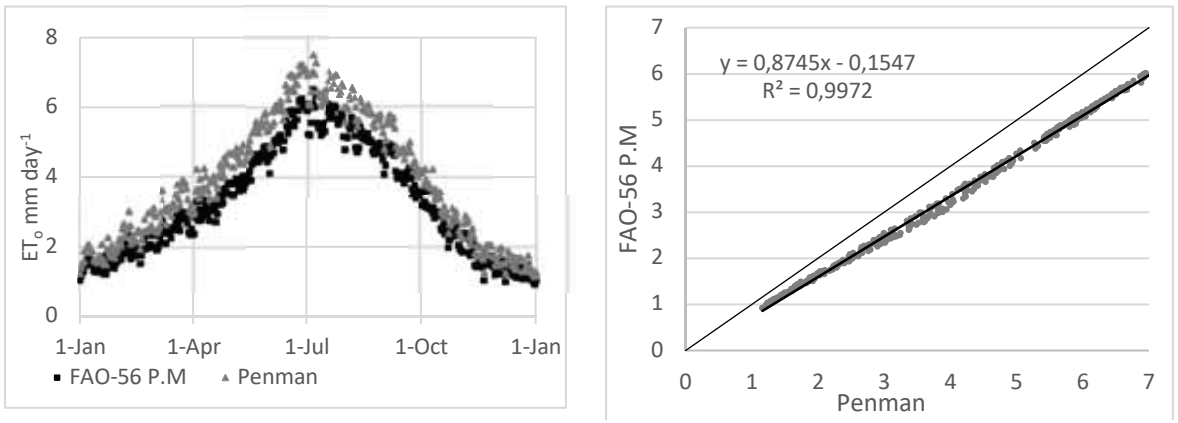


FIGURE 2
Daily ET_o comparison between the Penman and the FAO-56 PM equation

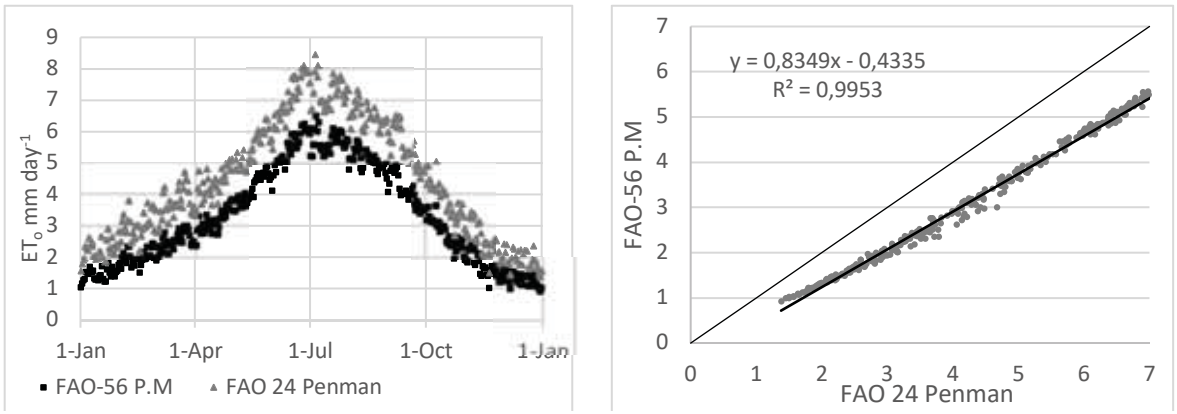


FIGURE 3
Daily ET_o comparison between the FAO-24 Penman and the FAO-56 PM equation

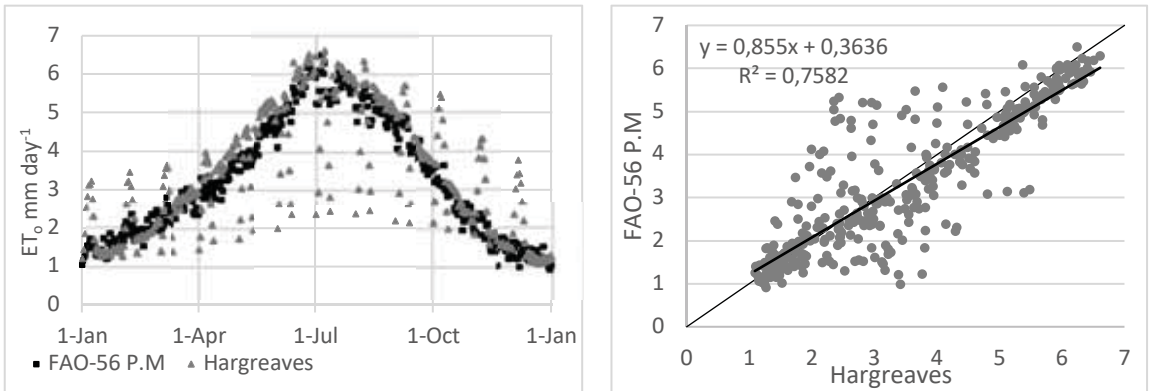


FIGURE 4
Daily ET_o comparison between the Hargreaves and the FAO-56 PM equation

combined with lower humidity resulted in lower values of Hargreaves ET_o compared to FAO-56 PM ET_o. Also, lower wind speed combined with higher humidity resulted in higher values of Hargreaves ET_o compared to FAO-56 PM ET_o. This is probably due to the lack of explicit wind speed and humidity terms in the Hargreaves et al. [14] equation.

Radiation-Based ET_o Equations. According to the results obtained, radiation-based ET models made the closest estimates to FAO-56 PM (Figure 5-6) for our region. In particular, the Turc model (R^2=0.973, RMSE=0.267, RE=0.081, RE=-0.059, d=0.993) achieved the best result compared to all other methods (Table 2). Also Turc method needs less number of parameters to estimate ET compared to Priestley-Taylor method and therefore, much easier to use [26].

Trajkovic and Kolakovic [6] indicated that the Turc equation is most suitable for estimating reference evapotranspiration at humid locations when weather data are insufficient to apply the FAO-56 PM equation. Similarly, Lu et al. [25] stated that radiation based methods that were developed for warm, humid climate conditions (Priestley-Taylor and Turc methods) perform well for the southeastern United States. Kashyap and Panda [30] and Tukimat et al. [26] also declared that the Turc model gave the closest results to the FAO-56 PM model.

Similar to Trajkovic and Kolakovic [6] Priestley-Taylor method gave reasonable results in our study (R^2= 0.965, RMSE= 0.494, RE=0.151, MBE=0.165, d=0.979). Fernandes et al. [21] achieved the good performances by Priestley-Taylor method with high coefficients of determination (over 0.9) and indices of agreement close to 1.

Pan Evaporation-Based Estimation. The results showed that Pan Evaporation-Based models underestimated in comparison with FAO-56 PM (Table 2 and Figure 7-8). In this study, the FAO-24 model gave more significant results than the Christiansen model.

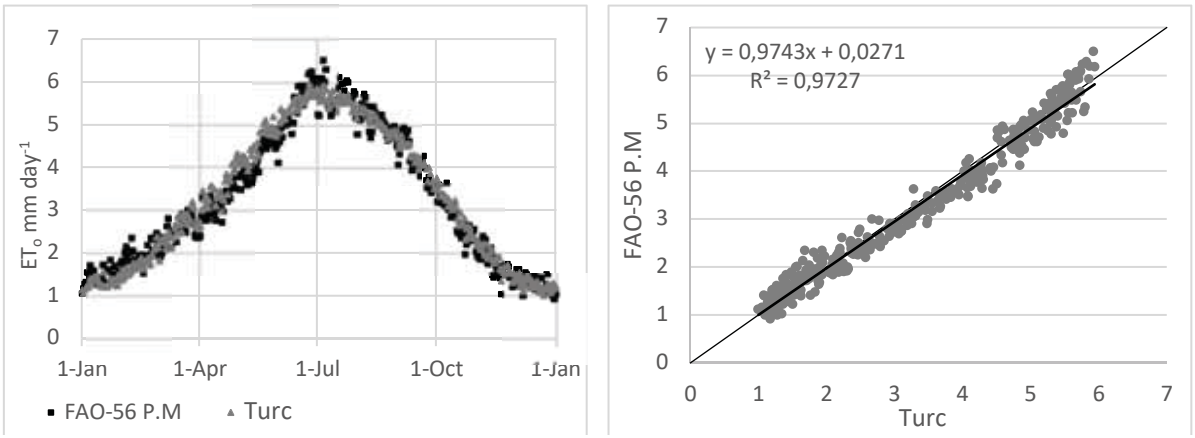


FIGURE 5
Daily ET_o comparison between the Turc and the FAO-56 PM equation

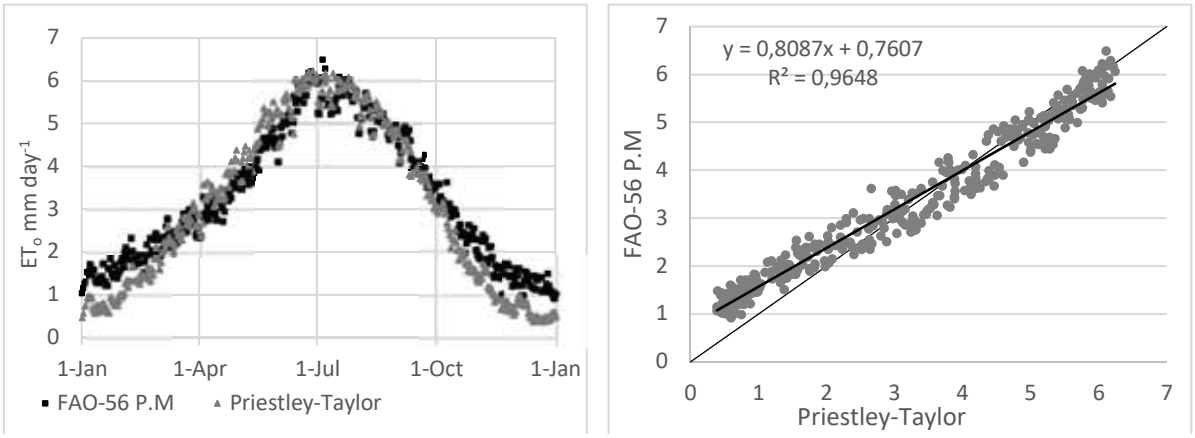


FIGURE 6
Daily ET_o comparison between the Priestley-Taylor and the FAO-56 PM equation

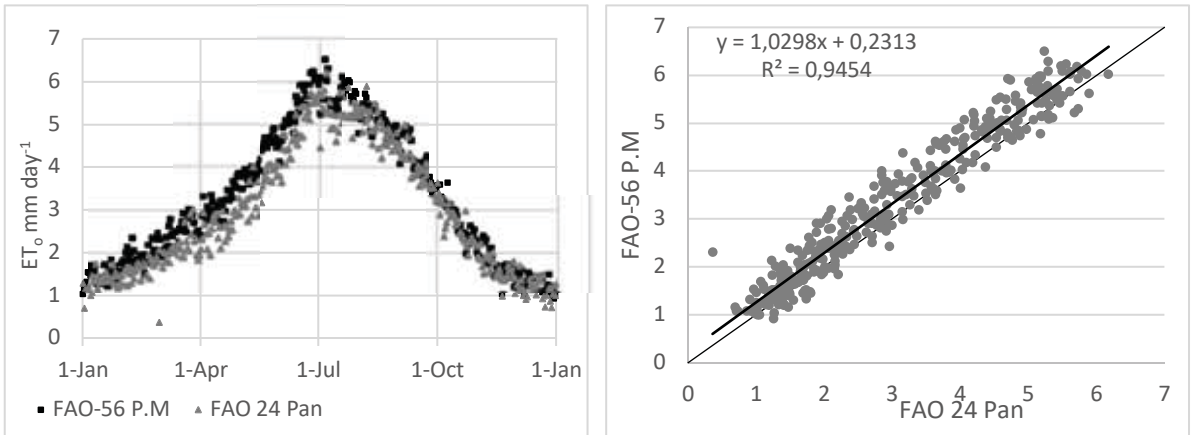


FIGURE 7
Daily ET_o comparison between the FAO-24 Pan and the FAO-56 PM equation

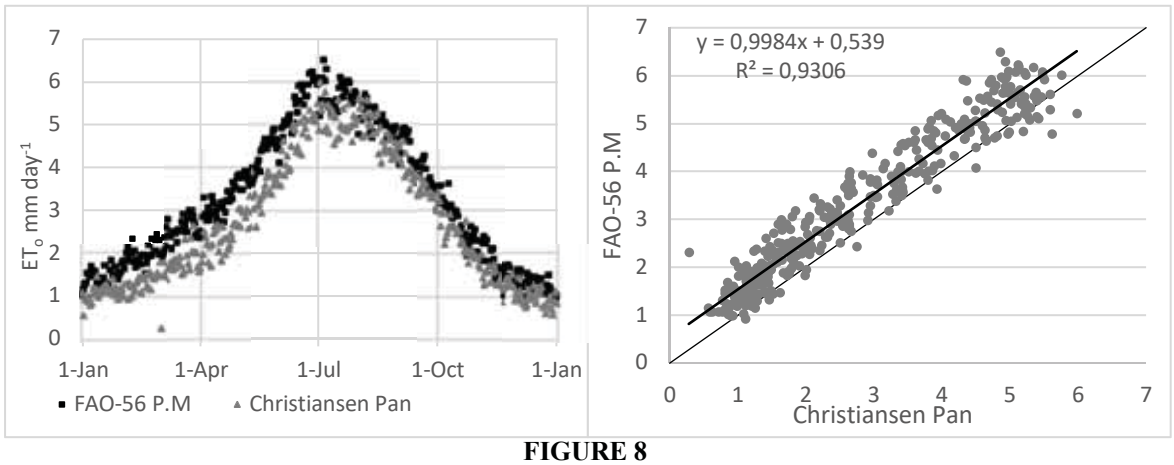


FIGURE 8
Daily ET_o comparison between the Christiansen Pan and the FAO-56 PM equation

Figure 7 and Table 2 compares the daily ET_o values computed by FAO-24 Pan model and the obtained values by FAO-56 PM. As shown, the FAO-24 Pan model presented the good results at our region. But Christiansen Pan model did not present good results in comparison with other models.

According to Irmak and Haman [36] Christiansen model significantly and consistently underestimated E_{pan} throughout the year. The results obtained from this study are similar to previous studies in this regard.

CONCLUSIONS

Although the FAO-56 PM model is considered the standard model, it requires a large number of climatic parameters. For this reason, seven simple commonly used ET_o equations evaluated against FAO-56 PM as the standard equation of estimating reference evapotranspiration.

FAO-24 Penman model gave the worst result in comparison with other models. Because of high evaporative demand periods Hargreaves model did not give good results. Similar to previous studies, it is not recommended to use the Hargreaves equation for this region. The FAO-24 Pan model gave better results comparison with Christiansen model when the Pan Evaporation-Based models were examined.

In this study, the best results were obtained with radiation-based equations. Turc model was the best estimating ET_o model. Also Priestley-Taylor model gave good result. Because it needs less number of parameters to estimate ET_o and much easier to use it is recommended to use Turc model against Priestley-Taylor.

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