



Optimizing radiation and temperature models to estimate reference plant evapotranspiration

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ABSTRACT

To estimate potential evapotranspiration, many relationships based on the climatic conditions of different regions have been proposed by researchers, which need to be evaluated and calibrated before applying them to specific locations. Each of these relationships has different functions depending on the climatic conditions. This study aimed to optimize temperature and radiation models for estimating ET_0 at the Jolfa synoptic station. The Penman-Monteith model served as a benchmark for evaluating these models. Calibration was performed using linear and power equations. The t-test results indicated that there was no significant difference between the ET_0 values obtained from the Hargreaves, Linacre, and Jensen-Haise methods compared to the standard FAO56-Penman-Monteith method. Among the methods used, the Thornthwaite method had the highest coefficient of determination, with values above 0.891 across all months. The Hargreaves and Linacre methods showed the strongest correlation with the Penman-Monteith method after Thornthwaite, with determination coefficients of 0.883 and 0.874, respectively. Consequently, using the Thornthwaite, Hargreaves, and Linacre methods, after applying calibration coefficients, is recommended for estimating ET_0 in the study area.

Highlights

- Thornthwaite model best post-calibration ($R^2=0.89$) for ET_0 estimation.
- Hargreaves & Linacre models show low error, high correlation with FAO56-PM.
- Jensen-Haise outperforms other radiation-based models (RMSE=60.65 mm/month).
- Temperature-based models excel over radiation-based models in accuracy.
- Calibration improves ET_0 estimates for arid regions like Jolfa, Iran.



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1. Introduction

Evapotranspiration is one of the most fundamental data for many studies, such as determining the amount of water required by crops, irrigation planning, construction and operation of irrigation and drainage systems, dams, determining the amount of precipitation infiltration into groundwater, and drought monitoring (Pandey et al., 2016). Optimal water management in meeting the water needs of crops is one of the ways to reduce the water crisis in agriculture due to the low efficiency of its use and the excessive use of available water resources. In this context,

evapotranspiration is actually a determining index in the growth process that is considered equivalent to the water required by crops (Ghamarnia and Soltani, 2019). The most accurate method for determining evapotranspiration is to use a lysimeter, which is not economically viable. Aerodynamic methods, energy balances, and numerous empirical models have been developed by researchers to estimate potential evapotranspiration, each of which considers one or more factors based on the climate and weather of the region under study. The appropriate selection of the evapotranspiration model is essential to ensure accurate estimation of crop water requirements. Therefore, before using these models, they must be evaluated using statistical methods and the necessary

modifications must be made to optimize them for the desired location.

More than 50 methods have been proposed by different researchers to estimate reference evapotranspiration, and the results obtained from each of them differ from each other in different climatic conditions (Grismer et al., 2002). In 1991, the International Commission on Irrigation and Drainage (ICID) and the Food and Agriculture Organization (FAO) proposed the FAO–Penman–Monteith method as a standard method for estimating ET_0 (potential evapotranspiration) and for evaluating the performance of other methods (Allen et al., 1998). This method requires a large amount of meteorological data to estimate ET_0 . It provides a good estimate of reference evapotranspiration with a high level of confidence over a wide range of regions and climates. Several empirical models for estimating ET_0 were evaluated by Anyadike (1987) in four climatic regions of West Africa. The results showed that the estimates obtained by the Penman method had higher positive correlation coefficients than the Thornthwaite method and that the Linacre method had a lower error compared to the Thornthwaite method. Xu and Singh (2002) evaluated five empirical equations for estimating ET_0 based on the Penman-Monteith method at the Changins Station in Switzerland. The results showed that the Priestley-Taylor and Makkink methods (radiation-based), Hargreaves and Blaney-Criddle (temperature-based), and Rohwer (mass transfer) were the most appropriate methods for the station, respectively. The results of the study by Babamiri and Dinpazhoh (2014) after calibrating the methods for estimating reference plant evapotranspiration based on three general methods of air temperature, solar radiation and mass transfer, indicated that among the methods based on air temperature, the Hargreaves method with a coefficient of determination (R^2) of 0.96, among the methods based on radiation, the Doorenbos-Pruitt method with a R^2 of 0.982, and among the methods based on mass transfer, after calibration, the Meyer method with a R^2 of 0.895 are the best methods for the studied region. For the warm and cold months of the year, Salarian et al. (2014) conducted a study to determine the best method for estimating ET_0 in Isfahan, using the FAO-radiation, FAO-Blaney-Criddle, Makkink, Hargreaves-Samani, Priestley-Taylor, and Turc methods. Comparison of the outputs from the models with the data from the FAO-Penman Monteith method showed that the Blaney-Criddle, radiation, Hargreaves, Turc, and Priestley-Taylor equations are suitable alternatives to the FAO-Penman Monteith relationship, respectively. Atard et al. (2015) conducted a study to evaluate the empirical methods of estimating ET_0 in two groups based on temperature and radiation with data from the F.P.M method. They concluded that on a daily scale, the Turc method had the closest estimate to the standard method, on a monthly scale, in April. In the second half of the year, the Turc method, in the summer, the Blaney-Criddle method, and in May and June, the Hargreaves-Samani method had the least error and the best estimate.

Amatya et al. (2016) conducted a study in the humid and coastal regions of the eastern United States to determine the most accurate method for estimating ET_0 based on the standard Penman-Monteith method. The results of their

research showed that the Turc method is the best method for estimating ET_0 for that region. Antonopoulos and Antonopoul (2018) estimated ET_0 at a station located in northern Greece with 13 empirical methods and a model based on artificial neural networks (ANN). They evaluated them based on the results obtained from the Penman-Monteith model, as the standard method. They stated that the Penman, Priestley-Taylor, Makkink, de Bruin-Kijman, and modified Penman methods had the best correlation with the Penman-Monteith method, while mass transfer models and the Jensen-Haise, Copais, and Valiantzas methods had the lowest correlation. Bodian et al. (2024) in their study to evaluate the methods for estimating reference evapotranspiration in the Senegal, Gambia, and Casamance river basins concluded that after calibration, the Trabert, Hargreaves, Hargreaves-Samani, Trajkovic, and Oudin methods are the most reliable and appropriate methods for estimating reference evapotranspiration in the aforementioned basins.

Many studies have been conducted in different regions of the world on the evaluation and calibration of ET_0 estimation models, but in relation to Jolfa city, which is considered one of the centers of agricultural production in Iran, the calibration of ET_0 estimation models has not been carried out. The aim of the present study was to evaluate the performance and calibrate radiation-based models as well as temperature-based models to estimate ET_0 of Jolfa synoptic station based on the FAO 56-Penman-Monteith standard method.

2. Materials and Methods

2.1 Study area

The study area is Jolfa County, Iran. This county is located in the northwest of East Azerbaijan Province. Iran between $45^{\circ}17'$ and $46^{\circ}31'$ East longitude and between $38^{\circ}39'$ and $39^{\circ}2'$ North latitude as a narrow strip on the northern border of the province and extends to the Aras River and the Republics of Azerbaijan, Nakhchivan and Armenia from the north. The area of this county is 31.1670 km^2 , with the eastern boundary of Kalybar County and the southern neighbors of Ahar and Marand counties. The climate of this county is dry according to the De Martonne method, cold dry according to the Amberg method and semi-arid according to the Karimi method. The average annual temperature of this city is changing and fluctuating in different places. So that the average annual temperature on the banks of the Aras River reaches 15°C and in the highlands it reaches 5°C . In terms of rainfall, Jolfa is also considered one of the rainiest areas of East Azerbaijan, the average annual rainfall in this city is estimated to be about 280 mm. The mountainous conditions and geographical latitude of this city are considered to be the factors of cold in most of this region. The location of the study site is presented in Fig. 1.

The meteorological variables used in this study included monthly average temperature, monthly maximum temperature, monthly minimum temperature, monthly maximum relative humidity, monthly average relative humidity, monthly minimum relative humidity, air pressure, wind speed at a height of 2 m, extraterrestrial radiation, percentage of sunshine hours for the statistical years 1990-2021 of the Jolfa synoptic station. The relevant statistics were

obtained from the Meteorological Department of East Azerbaijan Province, Iran. These variables were used in estimating monthly ET_0 with radiation-based models and temperature-based models, as well as their calibration.

2.2 Models used to estimate potential evapotranspiration

In this study, two groups of radiation-based and temperature-based models were used due to their history of application

and acceptance of their performance in studies conducted by various researchers. The radiation-based models used included Doorenbos and Pruitt (1977), Turc (1961), Stephens (1965), Makkink (1957), Olivier (1961), and Jensen-Haise (1963). Thornthwaite (1948), Linacre (1977), Blaney and Criddle (1950), and Hargreaves (1989) were also temperature-based models that were used in this study. Table 1 summarizes the relationships of all the models used.

Fig. 1 Location of the study site in East Azarbaijan province, Iran

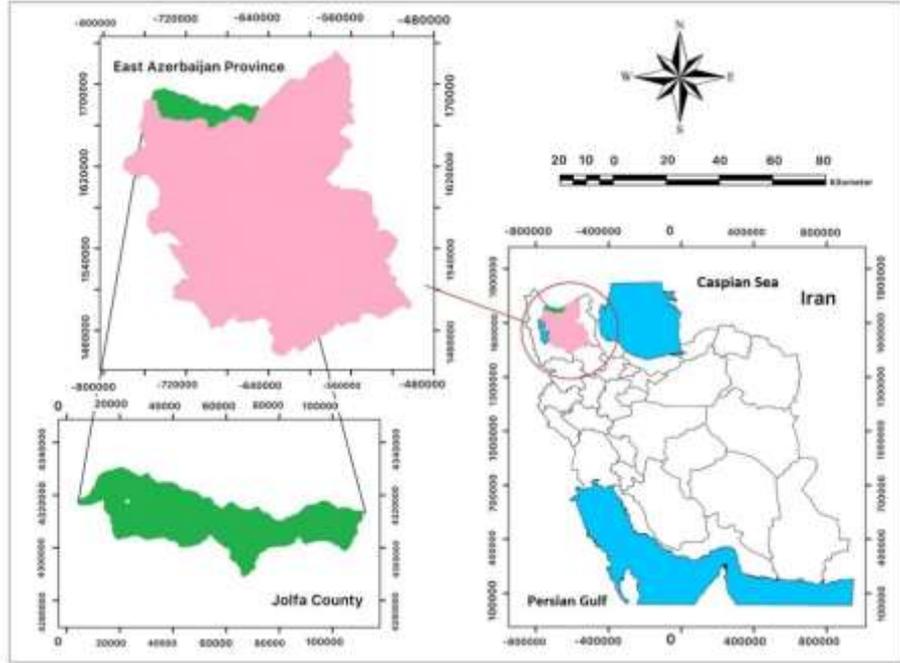


Table 1 The equations of the models used to estimate potential evapotranspiration

Proposer	Equation
Hargreaves (1989)	$ET_0 = 0.0023R_a (TC + 17.8)TR^{0.50}$
Linacre (1977)	$ET_0 = \frac{\left[\frac{700T_M}{100 - L} + 15(T_A - T_D) \right]}{80 - T_A}$
Blaney Criddle (1950)	$ET_0 = [a + b[P(0.46T_{MEAN} + 8.13)]] \left(1 + 0.1 \left(\frac{EL}{1000} \right) \right)$
Thornthwaite (1948)	$ET_0 = 1.6 \left[\frac{10T_{MEAN}}{I} \right]^a, I = \sum_1^{12} i = \sum_1^{12} \left(\frac{T_{MEAN_i}}{5} \right)^{1.514}$
Jensen and Haise (1963)	$ET_0 = \left((38 - 2 \frac{EL}{305}) + 7.3 \frac{50}{e_2 - e_1} \right)^{-1} (T_a - -2.5 - 0.14(e_2 - e_1) - \frac{EL}{550}) R_s$
Olivier (1961)	$ET_0 = (T_a - \frac{\gamma \cdot T_a + \Delta \cdot T_d}{\Delta + \gamma}) \cdot W \Phi$
Doorenbos and Pruitt (1977)	$ET_0 = 1.066 - 0.00128RH_{MEAN} + 0.045U_d - 0.0002RH_{MEAN} \cdot U_d - 0.0000315(RH_{MEAN})^2 - 0.001103(U_d)^2 \left(\frac{\Delta}{\Delta + \gamma} \times R_s \right)$
Turc (1961)	$ET_0 = .013 \frac{T}{T+15} (R_S + 50)$ $ET_0 = .013 \frac{T}{T+15} (R_S + 50) \left(1 + \frac{50 - RH}{70} \right)$ $RH > 50\%$ $RH < 50\%$
Stephens (1965)	$ET_0 = (0.014T - 0.37) \frac{R_s}{1500}$
Makkink (1957)	$ET_0 = 0.61 \frac{\Delta}{\Delta + (1.6134 \frac{1013 - 0.1055EL}{2500.78 - 2.3601T})} \times \frac{R_s}{58.5} - 0.12$

2.2.1 FAO 56-Penman-Monteith baseline model

The Penman-Monteith equation estimates potential evapotranspiration from meteorological data as an alternative to direct evapotranspiration measurements (lysimeters). This equation, which was developed by FAO for modeling potential evapotranspiration, is widely used. In 1990, a group of experts from the Food and Agriculture Organization (FAO), the International Irrigation and Drainage Association, and the World Meteorological Organization proposed the combined Penman-Monteith method as a new standard method for calculating reference evapotranspiration. In 1998, FAO Technical Journal No. 56 was published on the topic of evapotranspiration estimation based on the modified Penman-Monteith method. In this method, the reference plant is a hypothetical grass cover with a constant surface resistance of 70 m.s^{-1} , a height of 0.12 m, and a reflectance coefficient of 0.23, whose evaporation is very similar to that of a large green grass surface with uniform height, active growth, and sufficient water availability. This relationship is independent of plant type, plant growth, and agro-environmental management activities and is only affected by climatic data and is presented as Eq. 1 (Allen et al. 1998).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

Where, ET_0 is potential evapotranspiration (mm.d^{-1}), R_n is net radiation entering the plant surface ($\text{MJ.m}^{-2}.\text{d}^{-1}$), G is soil heat flux ($\text{MJ.m}^{-2}.\text{d}^{-1}$), T is daily average temperature ($^{\circ}\text{C}$), U_2 is wind speed at 2 m height (m.s^{-1}), e_a is actual vapor pressure (kPa), e_s is saturated vapor pressure (kPa), Δ is the slope of the vapor pressure curve ($\text{kPa.}^{\circ}\text{C}^{-1}$) and γ is the psychrometric constant coefficient ($\text{kPa.}^{\circ}\text{C}^{-1}$).

2.3 Calibration and performance evaluation of models

By estimating ET_0 from two groups of radiation-based and temperature-based models, as well as potential evapotranspiration values obtained from the FAO 56-Penman-Monteith standard method, using statistical techniques and analyses, including linear and nonlinear regressions, to make the correction coefficients in them as accurate as possible, the correlation coefficients were calculated movingly. Linear and power equations were used to obtain the calibration coefficients. The linear equation used is in the form of Eq. 2.

$$ET_{0a} = a.ET_{0c} + b \quad (2)$$

In this relation, ET_{0a} is the potential evapotranspiration after calibration, ET_{0c} is the potential evapotranspiration calculated using the mentioned models, a and b are the correction coefficients. The power equation used to correct and regionalize the ET_0 estimation models is in the form of Eq. 3.

$$ET_{0a} = p.ET_{0c}^q \quad (3)$$

In this relation, p and q are correction coefficients. To evaluate the performance of the models, t-test, root mean

square error, coefficient of determination, mean absolute error, and mean error deviation were used according to Eqs. 4 to 7 (Rudolf et al., 2010).

$$RMSE = \left(\sum_{i=1}^n (ET_{0c_i} - ET_{0s_i})^2 / n \right)^{1/2} \quad (4)$$

$$R^2 = \left(\sum_{i=1}^n (ET_{0s_i} - \overline{ET_{0s}})^2 - \sum_{i=1}^n (ET_{0c_i} - ET_{0s_i})^2 \right) \times \left(\sum_{i=1}^n (ET_{0s_i} - \overline{ET_{0s}})^2 \right) \quad (5)$$

$$MBE = \left(\sum_{i=1}^n (ET_{0c_i} - ET_{0s_i}) / n \right) \quad (6)$$

$$MAE = \left(\sum_{i=1}^n |ET_{0c_i} - ET_{0s_i}| / n \right) \quad (7)$$

where, RMSE is the root mean square error, MAE and MBE are the mean absolute error and mean deviation of error, respectively, and R^2 is the coefficient of determination.

$\overline{ETP_s}$ is the average of the values obtained from the standard method, ET_{0s} and ET_{0c} are the values obtained from the standard and computational methods of ET_0 , respectively.

3. Results and Discussion

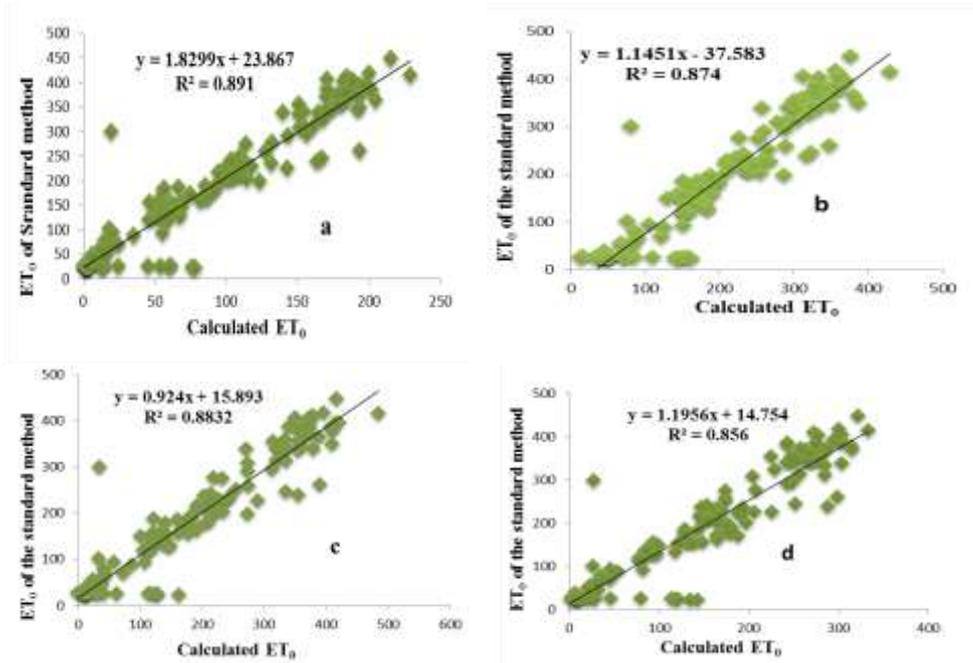
Using the climatic factors of the Jolfa synoptic station, monthly potential evapotranspiration was calculated with radiation-based models, including Turc, Olivier, Doorenbos-Pruitt, Makkink, Jensen-Haise, Stephens and temperature-based models including Linacre, Thornthwaite, Blaney-Criddle, and Hargreaves using the Visual Basic programming language.

3.1 Analysis of Temperature-Based Models

Fig. 2 shows graphs comparing the potential evapotranspiration values calculated with temperature-based models with the values obtained from the FAO 56-Penman-Monteith standard method.

The graphs in Fig. 2 are related to the Linacre, Blaney-Criddle, Stephens, and Thornthwaite methods. As can be seen from the above graphs, the highest coefficient of determination and correlation coefficient are related to the Thornthwaite method with values of 0.891 and 0.944, respectively. The lowest coefficient of determination among the temperature methods, with a small difference, is related to the Blaney-Criddle method. In general, it can be said that the coefficient of determination in temperature methods is above 0.85, and the equivalent correlation coefficient will be above 0.92. This indicates the high correlation and agreement of temperature methods in calculating potential evapotranspiration with the values obtained from the FAO 56-Penman-Monteith standard method. In the graphs in Fig. 2, the form of the presented calibration relations is linear; the reason for this was the high coefficient of determination in them compared to power relations.

Fig. 2 Comparison of ET_0 calculated from models based on temperature and the standard Penman-Monteith method ($mm.month^{-1}$): a) Thornthwaite, b) Linacre, c) Hargreaves, and d) Blaney-Cridde



3.2 Analysis of Radiation-Based Models

In the graphs in Fig. 3, the potential evapotranspiration values calculated by radiation-based methods including Turc, Olivier, Doorenbos-Pruitt, Makkink, Jensen-Haise, and Stephens are compared with the values obtained from the standard FAO56-Penman-Monteith method.

Olivier, Doorenbos-Pruitt, Makkink, Jensen-Haise, and Stephens are compared with the values obtained from the standard FAO56-Penman-Monteith method.

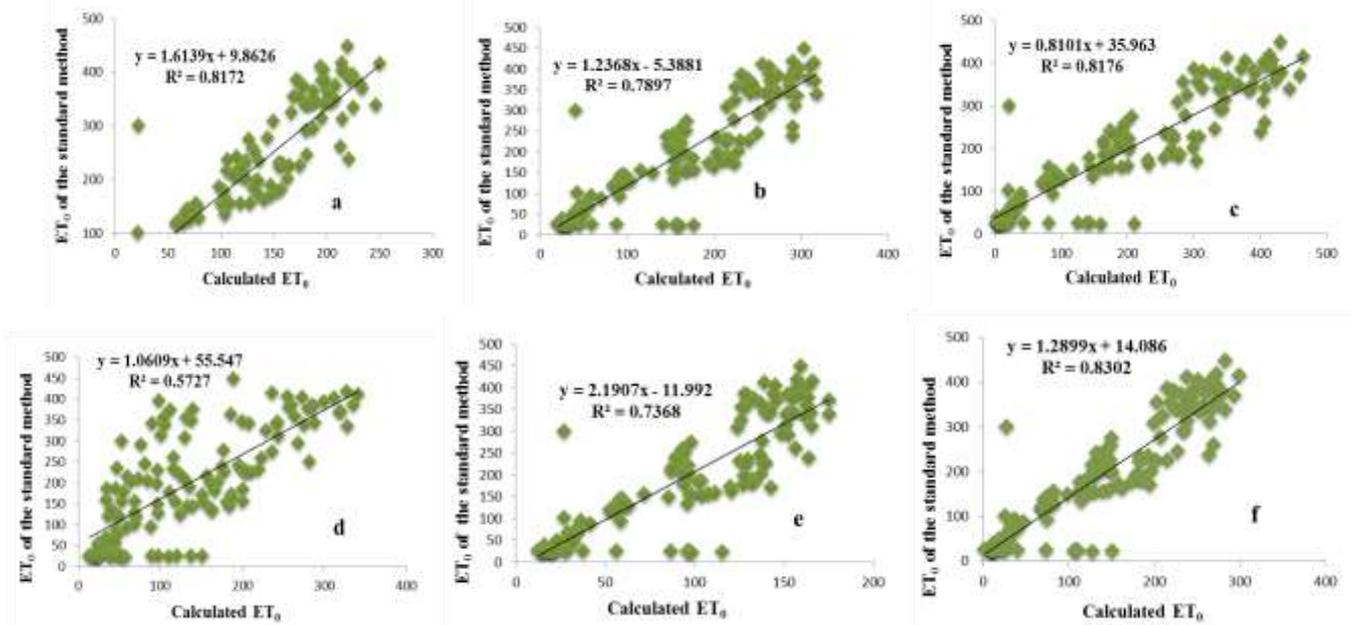


Fig. 3 Comparison of ET_0 calculated from models based on radiation and the standard Penman-Monteith method ($mm.month^{-1}$): a) Turc, b) Doorenbos-Pruitt, c) Jensen-Haise, d) Olivier, e) Makkink, and f) Stephens

According to the graphs in Fig. 3, the highest coefficient of determination was related to the Stephens method with a value equal to 0.83. The coefficients of determination for the Jensen-Haise, Turc, Doorenbos-Pruitt, Makkink, and Olivier methods were estimated to be 0.817, 0.817, 0.789, 0.736, and 0.576, respectively. Among the radiation methods, the coefficient of determination for the Oliver method has the lowest value by a large margin. As can be seen in the graphs in Fig. 3, the form of the correction relations is similar to the temperature-based methods, because the coefficients of determination in linear relations are higher than in power

relations, and the correction coefficients are presented in the form of linear equations. The potential evapotranspiration values calculated by temperature-based and radiation-based methods were analyzed with the values obtained from the FAO56-Penman-Monteith standard method using statistical techniques and analyses, and the correlation coefficients as well as the calibration coefficients were obtained. The results showed that the use of linear equations was superior compared to power equations.

3.3 Calibration results of radiation and temperature models

presented in a moving form for the Thornthwaite method, considering the better agreement of this method compared to other methods.

In [Table 2](#), the values of the correlation coefficients and the coefficients related to the linear correction equation are

Table 2 Calibration coefficients b, a, and correlation coefficients R_l of the Thornthwaite model using the linear equation

$$ET_0_a = a.ET_{0_c} + b$$

Month	April	May	June	July	August	September	October	November	December
a									
April	2.16	1.73	1.92	1.92	1.91	1.91	1.91	1.82	1.83
May		5.04	2.29	2.11	2.08	2.01	1.96	1.83	1.83
June			1.9	1.75	1.67	1.81	1.89	1.79	1.82
July				1.09	1.27	1.8	1.89	1.79	1.82
August					1.23	1.81	1.9	1.77	1.81
September						0.7	1.88	1.65	1.74
October							0.91	1.22	1.59
November								3.8	3.2
December									0.53
b									
April	8.64	22.47	9.29	10.24	11.23	12.88	12.35	24.96	23.87
May		-294.52	-43.34	-21.6	-17.1	-5.09	3.85	23.85	23.02
June			14.14	40.7	55	29.67	16.15	31.37	27.41
July				171.23	131.79	31.19	16.18	31.47	27.45
August					135.41	28.1	14.79	32.09	27.61
September						149.26	14.8	37.82	29.57
October							67.29	50.56	32.3
November								8.45	17.8
December									25.91
R_l									
April	0.32	0.54	0.86	0.91	0.92	0.91	0.93	0.93	0.94
May		0.81	0.88	0.91	0.9	0.9	0.93	0.93	0.95
June			0.61	0.74	0.69	0.87	0.94	0.94	0.96
July				0.41	0.5	0.89	0.95	0.95	0.96
August					0.46	0.9	0.95	0.93	0.95
September						0.25	0.9	0.83	0.89
October							0.25	0.45	0.66
November								0.27	0.48
December									0.26

In [Table 2](#) the parameters R_l and a , and b are the correlation coefficient and the correction coefficients of the corresponding linear equation, respectively. The correlation coefficients obtained when using the linear equation were higher than when using the power equation to correct the Thornthwaite method. [Table 2](#) shows correlation coefficients up to 0.96.

3.3.1 Guidance on using the calibration table

When using [Table 2](#) to extract the correlation coefficient and correction coefficients of the models, the permissible range is specified for the month or months in which the correction coefficients are to be applied, and based on the highest correlation coefficient in that range, the corresponding correction coefficients a , b are extracted from the upper rows of the relevant table. If the correlation coefficient and correction coefficients of June are considered in the Thornthwaite method, the permissible range for selecting the correlation coefficient in June is specified in [Table 2](#), and the highest correlation coefficient in the range, which is 0.96, is selected as the optimal correlation coefficient. In this case, the corresponding coefficients a , b (1.82 and 27.41) will be selected for the optimal correction coefficients. The

advantage of this table is that the most optimal and highest correlation coefficient and, subsequently, the optimal correction coefficients for the desired month or months can be selected within the permissible ranges.

3.4 Comparison of results before and after calibration

3.4.1 Radiation-based models

[Fig. 4](#) presents graphs comparing the calculated monthly average ET_0 values before and after applying the calibration coefficients of the Jensen-Haise, Stephens, Makkink, Olivier, Doorenbos-Pruitt, and Turc radiation methods with the values obtained from the standard FAO56-Penman-Monteith method.

The results presented in the graphs of [Fig. 4](#) indicate that in radiation-based methods, the best agreement of the calculated ET_0 before and after calibration with the standard FAO 56-Penman-Monteith method is related to the Jensen-Haise method. After that, the agreement of the Stephens method after calibration appears better than other methods. In all graphs, the agreement of the calculated ET_0 with the standard FAO 56-Penman-Monteith method after calibration has improved.

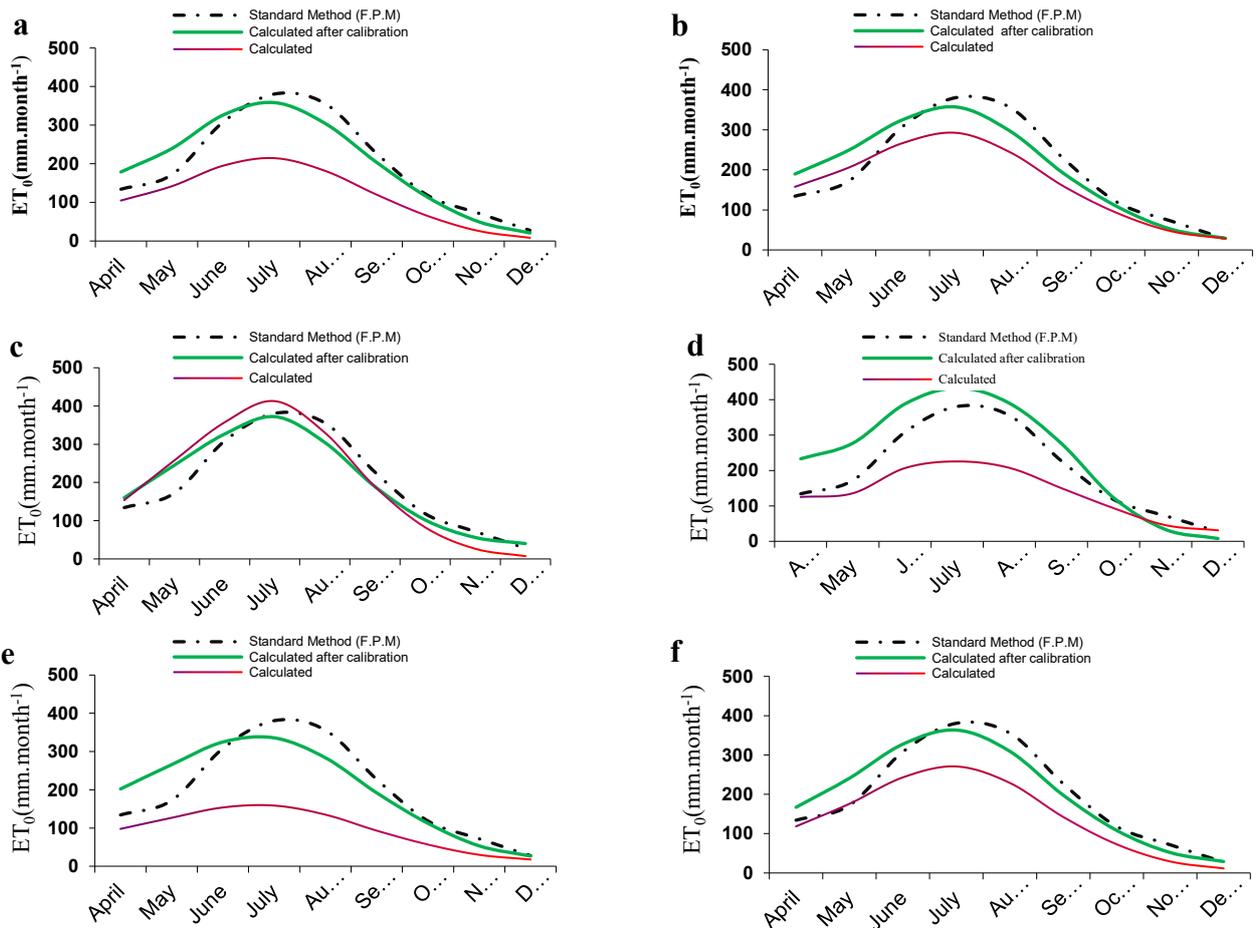


Fig. 4 Comparison of ET_0 resulting from the standard Penman-Monteith method and models based on radiation before and after calibration ($mm.month^{-1}$): a) Turc, b) Doorenbos-Pruitt, c) Jensen-Haise, d) Olivier, e) Makkink, and f) Stephens

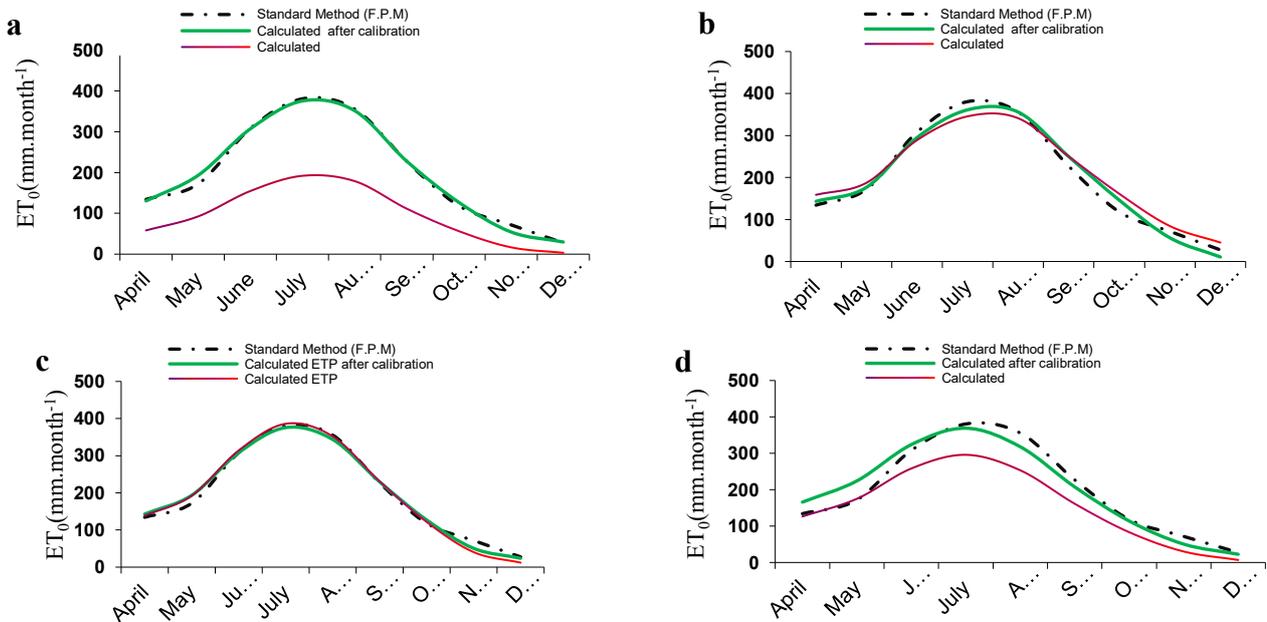


Fig. 5 Comparison of ET_0 resulting from the standard Penman-Monteith method and temperature-based models before and after calibration ($mm.month^{-1}$): a) Thornthwaite, b) Linacre, c) Hargreaves, and d) Blaney-Criddle

3.4.2 Temperature-based models

The graphs in [Fig. 5](#) also compare the monthly average ET_0 values calculated before and after calibration of temperature-

based methods, including Thornthwaite, Linacre, Hargreaves, and Blaney-Criddle, with the values obtained from the standard FAO56-Penman-Monteith method.

As is clear from the graphs in Fig. 5, the best agreement of the calculated ET₀ from the temperature-based models, compared to the values obtained from the base model, is related to the Hargreaves and Linacre methods. The outputs from the radiation-based and temperature-based methods, with the potential evapotranspiration values obtained from the FAO 56-Penman-Monteith standard method, were analyzed and evaluated using the t-test and the indices of the root mean square error, the coefficient of determination, the mean error deviation, and the mean absolute error. The

results of this analysis are presented in Table 3. In the graph related to the Thornthwaite method, the calculated ET₀ values have a large difference with the values obtained from the FAO 56-Penman-Monteith standard method, which is also evident in Table 3, where the RMSE of this method had the highest value among the temperature-based methods. However, after calibration, its agreement with the standard FAO 56-Penman-Monteith method has improved greatly, so that its coefficient of determination is higher than all methods.

Table 3 The results of statistical analyses of ET₀ estimation models used in research

Method	MBE (mm/month)	MAE	RMSE (mm/month)	Mean Difference	R ²	Variance	t Critical two-tail	t Stat
Radiation based methods								
Doorenbos-Pruitt	33.84	53.18	70.79	33.84	0.78	8404	1.96	2.50
Makkink	102.54	109.15	135.52	103.13	0.73	2499	1.96	8.72
Turc	81.98	88.39	107.64	82.23	0.81	5107	1.96	6.51
Jensen-Haise	-2.37	45.93	60.65	2.22	0.82	20287	1.96	-0.14*
Stephens	55.75	64.76	80.81	55.75	0.83	8123	1.96	4.14
Olivier	63.81	78.24	104.92	64.21	0.57	8284	1.96	-4.71
Average	55.93	73.28	93.39	56.90	0.75	8784		
Temperature based methods								
Blaney-Criddle	44.98	55.15	68.54	45.12	0.85	13959	1.96	3.23
Hargreaves	0.78	28.88	44.55	0.78	0.88	16842	1.96	0.05*
Linacre	-7.51	35.55	48.16	7.52	0.87	10852	1.96	-0.53*
Thornthwaite	103.44	106.36	124.58	105.65	0.89	4332	1.96	8.37
Average	35.42	56.49	71.46	39.77	0.87	11496		

*At the 5% level, the null hypothesis (H₀: μ₁=μ₂) is confirmed

According to the results of Table 3 the closest and least erroneous outputs to the results of the FAO 56-Penman-Monteith standard method among the radiation methods are the Jensen-Haise method with RMSE, MAE, MBE values of 60.65, 45.93, and -2.37 mm/month, respectively. The Jensen-Haise method is the only method among the radiation methods in which the null hypothesis (H₀: μ₁=μ₂) was confirmed in the t-test at the 5% level. The coefficient of determination of the Jensen-Haise method, after the Stephens method, which had the highest value among the radiation methods with a value of 0.83, was equal to 0.82, which indicates the consistency of this method with the FAO 56-Penman-Monteith standard method. Among the radiation methods, the Makkink method had the highest error, but with a coefficient of determination of 0.73, it has a relatively good consistency with the data of the standard method. The Doorenbos-Pruitt and Stephens methods had less error than other radiation methods after the Jensen-Haise method. The results of the t-test for temperature-based methods showed that the first hypothesis (H₁: μ₁≠μ₂) was rejected in the Hargreaves and Linacre methods, and the null hypothesis (H₀: μ₁=μ₂) was confirmed. According to Table 3, the Hargreaves and Linacre methods were the least error-prone methods among the temperature-based methods. The accuracy of the Hargreaves method has also been confirmed by various researchers, including Gentilucci et al. (2021) in Italy. Although the capability of the Thornthwaite method was not confirmed in the t-test, this method had the highest coefficient of determination among the temperature-based methods and also the radiation-based methods. This indicates a high agreement of this method with the FAO56-Penman-

Monteith standard method. Hafeez et al. (2020) confirmed the acceptability and accuracy of the Thornthwaite method in a study they conducted on the evaluation of reference evapotranspiration estimation methods in the semi-arid climates of *Faisalabad, Lahore, and Peshawar*.

4. Conclusion

This study evaluated and calibrated various reference evapotranspiration (ET₀) estimation models at the Jolfa synoptic station. Given the critical importance of accurate ET₀ estimation for water resource management and irrigation planning, the following key findings were obtained:

1. The Hargreaves and Linacre models showed the lowest errors (RMSE = 44.55 and 48.16 mm/month) and highest correlations (R² > 0.87) versus FAO56-PM. Their simplicity and low data needs make them suitable for data-scarce regions.
2. Despite an initial high error (RMSE = 124.58), the Thornthwaite model achieved the best R² (0.89) post-calibration, demonstrating strong potential when adjusted.
3. Among radiation-based models, Jensen-Haise performed best (RMSE = 60.65 mm/month) with null hypothesis confirmation in the t-test.
4. Temperature-based models outperformed radiation-based ones, with significantly lower average error (71.46 vs. 93.39 mm/month).

This analysis was limited by its monthly temporal resolution and single-site assessment framework, which may affect the generalizability of the results across time scales and

geographic locations. It is suggested that future research prioritize higher-resolution temporal analyses while expanding the spatial coverage of model validation. Integrating emerging computational techniques with traditional physical models offers a promising avenue for increasing forecast robustness. Particular emphasis should be placed on developing adaptive modeling frameworks that are capable of adapting to climate change, and parallel efforts should focus on improving data availability and quality assurance protocols across monitoring networks.

Statements and Declarations

Data availability

Data can be sent by the correspondng author via email (ahad.molavi@iau.ac.ir) upon request.

Conflicts of interest

The author of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

A. Molavi: Writing, preparing the main draft, methodology, conceptualization, performing software and statistical analysis, analyzing and reviewing the results, editing and revising the article, and preparing the final version.

AI Use Declaration

This study did not incorporate artificial intelligence techniques; instead, all analyses and optimizations were conducted using conventional and widely accepted analytical methods. AI-based tools were used to correct language and improve grammar.

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