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Calibration and evaluation of six popular evapotranspiration formula based on the Penman-Monteith model for continental climate in Turkey

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ABSTRACT

Due to the difficulties in measuring and collecting meteorological data, it may be necessary to use methods that allow for the estimation of reference evapotranspiration values by using the few available data. For this reason, it is useful to calibrate empirical formulas locally, which enables obtaining accurate and reliable estimates with a small number of data. The effects of other parameters excluded from the employed data are included in the formula as regional coefficients. In this study, six empirical evapotranspiration formulas among temperature-based and solar radiation-based methods, including Thornthwaite (1948), Makkink (1957), Turc (1961), Jensen and haise (1963), Priestley and Taylor (1972), and Hargreaves and samani (1985) are calibrated, for continental climates of Central Anatolia's. To this end, meteorological data of three synoptic stations located in the west of Turkey in Kutahya province are employed from 2007 through 2019. Moreover, the data of the fourth station are applied for evaluating the accuracy of the estimated results. The main reason for employing these six formulas are behind in the fact that they are globally used, easy-to-use, and need few types of data. Meanwhile, Penman-Monteith 56 equation is applied to calibrate the empirical equations. In total, three methods are followed to estimate the local calibration coefficients. Finally, the evaluation of the results is performed by using the coefficient of determination, percentage error of estimate, mean absolute error, and root-mean-square error. According to the evaluation criteria, among calibrated formulas, Jensen and haise's (1963) formula was obtained to be the best for estimating ET_o.

1. Introduction

Accurate and reliable prediction of the evapotranspiration (ET) phenomenon is crucial for various engineering branches such as hydrology, irrigation, agriculture, and water resources. ET is a function of the supply of heat energy, air movement, and vapour pressure gradient (Allen et al., 1998). Gong et al. (2006) provided the following definition for Reference Evapotranspiration (ET_o): "the potential evapotranspiration of a hypothetical surface of green grass of uniform height, actively growing and adequately watered". Nowadays, with the increase in population and the decrease in freshwater resources, high water efficiency has become necessary. This issue becomes even more significant in arid and semi-arid regions where the amount of freshwater is restricted. As climate change generally exacerbates drought in these regions, water resources have become more valuable and vulnerable. Moreover, since 2019, the world has faced a worldwide epidemic called covid-19. In response, most countries around the world have implemented lockdowns. This event plus some local conflicts and wars significantly affected the world chain of food supply. In this new era, minimum self-sufficiency in food for countries is inevitable. It is clear to all that there is a direct relationship between agricultural products and freshwater. Therefore, to increase the amount of efficiency in using the available freshwater, accurate prediction of ET_o is crucial. There are two methods for estimating ET_o values: the direct measurement method and the predicting method. As a direct measurement device, Lysimeter can employ to obtain the values of ET_o. Nevertheless, in comparison to the predicting methods, using this device is time-consuming, expensive, and tiresome. On the other hand, "the use of weather data to indirectly estimate evapotranspiration offers an easy and very reliable alternative" (Wang et al., 2009). For this purpose, the United Nations Food and Agriculture Organization (FAO) recommends employing the Penman-Monteith 56 method (PMFAO56) as a sole method to calculate the value of ET_o (Allen et al., 1998). Unfortunately, the PMFAO56 method requires various types of meteorological data like humidity,

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wind speed, sunshine duration, solar radiation, and air temperature. Most of the time, some or most of this data is not available for a particular location. Such limitations result in calibrating equations that require fewer data types (Irmak et al., 2003; Tabari and Hosseinzadeh Talaee 2011). The inclusions of missing types of meteorological data and other regional effects into the equations are possible by calibrating the empirical formulas for the region. The evapotranspiration phenomenon is dependent on both the geographical and meteorological characteristics of the region. Therefore, the calibration coefficients for empirical formulas should be determined specifically for the region. As highlighted earlier, it is assumed that the PMFAO56 equation by employing various types of meteorological data, could estimate the most accurate results in this field. Consequently, many researchers have calibrated ET_o equations based on the PMFAO56 (e.g., Alexandris et al., 2008; Tabari and Hosseinzadeh Talaee 2011, Moeletsi et al., 2013; Djaman et al., 2016; Farias et al., 2020; Rodrigues and Braga 2021). In addition, many studies calibrate empirical evapotranspiration equations using lysimeters. (Lo'pez-Urrea et al., 2006; Razzaghi and Sepaskhah 2010; Djaman et al., 2016; among many). Examination of these studies shows that calibrations mainly were done for the empirical formulas that require less kind of data and are frequently used. In the present study, for local calibration of empirical formulas, six widely applied, easy-to-use, and needed fewer meteorological data formulas, including Thornthwaite (TwF), Makkink (MF), Turc (TF), Jensen and Haise (JHF), Priestley and Taylor (PTF), and Hargreaves and Samani (HSF) have been selected. The last but not least point is that the PMFAO56 equation is picked for evaluation of the performance of the empirical formulas.

Many scholars have calibrated or evaluated the empirical formulas in this field. Trajkovic and Kolakovic (2009) assessed five empirical formulas (i.e., HSF, TwF, TF, PTF, and JHF) for the humid area. They announced that TF is the most appropriate equation for predicting ET_o. Bautista et al. (2009) calibrated HSF and TwF for a semi-arid and sub-humid tropical climate in Mexico. They proposed several constants for time periods of a year. Tabari and Hosseinzadeh Talaee (2011) calibrated HSF and PTF's for Iran's arid and cold climates. For cold and dry climates, they proposed new coefficients as 0.0031 and 0.0028 for the HSF, and 1.82 and 2.14 for the PTF, respectively. Xu et al. (2012) adjusted the HSF for a moist territory in the east of China. They recommended the 0.00138 value as an adjusted coefficient for the case study location. Berti et al. (2014) suggested a constant value of 0.0020 for the HSF in northeastern Italy. Valipour and Eslamian (2014) determined the ET_o with eleven temperature-based empirical formulas for Iran. They declared that modified HSF determined the ET_o better than the other models for most provinces. Mehdizadeh et al. (2016) improved HSF and PTF's for the east and west Azerbaijan provinces in the northwest of Iran. They announced the improved coefficients for HSF and PTF as 0.0026 and 1.68, respectively. Issaka et al. (2017) calibrated and validated five empirical formulas over Doha in Qatar. They announced that among the employed empirical equations, TF obtained the best estimation. Cobaner et al. (2017) calibrated HSF for the whole of Turkey by using meteorology recorded data of 275 stations. Also, they considered the effect of wind speed in their calibrations. Finally, they proposed constant coefficients for seven regions in Turkey, regardless of the months of the year. Gafurov et al. (2018) assessed and calibrated the HSF to predict ET_o values for irrigated areas of the Kashkadarya region of Uzbekistan in the Amudarya river basin. Trajkovic et al. (2019) modified the TwF for estimating ET_o for a specific location in Europe. They announced that the result of the original TwF was not acceptable and generally underestimated PM values. Farzanpour et al. (2019) used meteorological data over a 12-year period for ten stations in east Azerbaijan province in Iran to investigate the accuracy of twenty empirical ET_o formulas. They declared that the outcomes of temperature-based and radiation-based formulas were similar to each other and the mass transfer-based formulas estimated the worst results. Farias et al. (2020) modified several empirical formulas for the north region of Brazil. They stated that TF and FAO 24 Blaney-Criddle did not need calibration and presented the best results for all statistical criteria. Moreover, the PTF, MF, and FAO 24 Radiation methods produced the best outcomes after calibration, and the methods of Camargo and HSF obtained the worst outcomes. Şarlak and Bağçaci (2020) evaluated the performance of the original six empirical equations for the Konya closed basin in Turkey. They reported that TF was best among the six original employed empirical equations. Niranjan and Nandagiri (2021) assessed the impacts of site-specific calibration of model parameters for HSF. For this purpose, they selected Karnataka State in India as the study area. They reported that the local calibration of the empirical equations is inevitable. Aydın (2021) compared the performance of two original empirical ET_o formulas (i.e., HSF and TF) for the southeast Anatolian region of Turkey. He stated that in the absence of reliable climatic data, the HSF could be used as an alternative to the PMFAO56. Sharafi and Mohammadi Ghaleni (2021) modified 32 empirical formulas, including solar radiation–based, temperature-based, and mass transfer-based formulas to estimate ET_o values for different climates in Iran. They revealed that each climatic region has its own superior empirical formula and, with the complexity of climatic variables, the accuracy of empirical formulas varies. Hadria et al. (2021) compared the performance of five empirical temperature-based formulas for estimating ET_o for Morocco. They stated that there was an important correlation between PMFAO56 and solar radiation, mean and maximum air temperatures. Also, they stated that Dorji's formula estimated the most accurate results for that region.

The main goals of this research are (i) to predict the ET_o value employing several empirical equations, (ii) to calibrate the empirical formulas, and (iii) to compare and analyze the outcomes of the calibrated formulas for the research field. Based on our best knowledge, the effort to calibrate empirical equations of ET_o in Turkey has been carried out merely for HSF. Other researchers preferred to compare results of uncalibrated formulas only. One of the uniqueness of this paper is that six globally used temperature-based (i.e., TwF, HSF) and solar radiation-based (i.e., MF, TF, JHF, PTF) evapotranspiration methods are assessed, and calibrated against the PMFAO56 equation. Consequently, new monthly-based calibrated coefficients are introduced for the case study. Furthermore, three different methods have been examined to extract the coefficients. In addition, second-order polynomial relationships between empirical coefficients and months are investigated. Kutahya province in Turkey was selected as a sample of continental climates of Central Anatolia.

1.1. Description of study area

As highlighted earlier, the province of Kutahya (Turkish: Kütahya) was chosen as the study location. Kutahya province is a part of Central Anatolia's continental climate with snowy, cold winters and dry, hot summers. The territory generally receives a low amount of precipitation throughout the year. This province has large, gently sloping areas with agricultural lands, culminating on high mountain ridges in the north and west. The chief soil type of this region is grey-brown and podzolic grey-brown forest soils. Some of the significant agricultural products of this province are wheat, barley, corn, legumes, sugar beet, tomatoes, eggplants, and peppers. In this study for calibration, daily recorded meteorological data of three stations between 2007 and 2019 in western Turkey, including Dumlupinar, Gediz, and Simav, are used. Additionally, daily recorded meteorological data of the abovementioned three stations for the year 2020 and data of Çavdarhisar station for four years (i.e., 2016–2019) have been employed for evaluation of the calibrated results. Meteorological data, including relative humidity (%), wind speed (m/s), the actual duration of sunshine (hour), and minimum, mean, and maximum air temperatures (^{o}C), have gained from the Turkish State Meteorological Service. In this study, meteorological data exceeding 15500 days were used. The monthly mean values of the main climatic variables at Kutahya province during 2007–2020, are given in Table 1. As everyone knows, complete data availability is a significant

Table 1
Monthly mean values of the meteorological data at Kutahya province from 2007 to 2020.

Month	T_{min} (°C)	T_{max} (°C)	T_{mean} (°C)	R_H (%)	u_2 (m/s)	ADS (hr)
Jan.	−2.4722	6.456805	1.637849	82.10084	1.948095	4.068556
Feb.	−0.70498	9.119825	3.879202	77.80656	2.03074	5.523926
Mar.	1.35	12.93011	6.869201	71.70399	2.034531	7.231183
Apr.	4.053921	17.7883	10.78143	66.83915	2.001817	9.930079
May.	8.165284	22.66553	15.32273	67.41961	1.775382	12.19247
Jun.	11.8696	27.0969	19.40746	64.06363	1.866984	15.06278
Jul.	14.5894	31.39485	23.09186	53.79854	2.167066	17.45384
Aug.	14.94923	31.59203	23.2353	53.64063	2.175499	17.10661
Sep.	10.8389	27.10262	18.7577	58.67798	1.920651	14.88746
Oct.	6.63318	20.52028	12.95722	70.88963	1.70192	10.8722
Nov.	2.240771	14.53118	7.879095	74.50659	1.753444	7.885
Dec.	−0.49846	8.882181	3.701413	81.21989	1.807204	4.574731

* ADS: actual duration of sunshine.

issue in this process. Thus, stations with missing data have been ignored. Kutahya province is 11.875 km^2 in size. Geographical coordinates and the location of the meteorological stations on the map are given in Table 2 and Fig. (1), respectively.

2. ET_o estimating methods

There are many empirical relations for estimating ET_o values. As mentioned earlier, among evapotranspiration equations, FAO suggested the PMFAO56 equation as the most reliable equation in this field. Therefore, this equation is selected as a base equation to develop new empirical equations or calibrate present empirical. The main reason to look for an alternative empirical formula is that in most countries especially underdeveloped or developing countries or regions, the necessary data to estimate by the PMFAO56 is not available. Therefore, in this branch of science, employing empirical formulas that can determine accurate and reliable outcomes has become popular. The present study has analyzed and calibrated the performance of six temperature-based and solar radiation-based ET_o equations using data from a continental climate in Turkey. Generally speaking, temperature-based equations are the easiest formulas, and gathering the required data for such equations is not a problem. Radiation-based equations are easy-to-use and supply reliable results, too. The equations used include Thornthwaite (1948), Makkink (1957), Turc (1961), Jensen and Haise (1963), Priestley and Taylor (1972), and Hargreaves and Samani (1985) formulas, which are frequently used in the literature and require few weather data inputs. It is clear that ET_o values depend on the geographical, meteorological, and vegetation properties of the territory. Since the effect of these features is also hidden in the empirical equations with the calibrated coefficients, the calibrated coefficients are mainly valid for this study region.

2.1. Penman-Monteith 56

The PMFAO56 formula was admitted as a reference formula for predicting the ET_o values and is given as follows: (Allen et al., 1998):

$$ET_{oPMFAO56} = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T_a+273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

Where, $ET_{oPMFAO56}$, is the reference evapotranspiration [$mm.day^{-1}$] calculated by PMFAO56 method; G, is the soil heat flux density [$MJ.m^{-2}.day^{-1}$]; R_n, is the net radiation at the crop surface [$MJ.m^{-2}.day^{-1}$]; u_2, is the wind speed at 2 m height [$m.s^{-1}$]; and T_a, is the mean daily air temperature at 2 m height [$°C$]. Also, e_s, e_a, and Δ are the saturation vapour pressure [kPa], the actual vapour pressure [kPa], and slope vapour pressure curve [$kPa.°C^{-1}$], respectively. Finally, γ indicates the psychrometric constant [$kPa.°C^{-1}$]. "As the magnitude of the day or ten-day soil heat flux beneath the grass reference surface is relatively small, it may be ignored" Allen et al. (1998). For this reason, in this study, the G value is chosen as zero.

Table 2
Geographical coordinates of meteorological station.

Station	Latitude (N)	Longitude(E)	Elevation(m)
Dumlupinar	38.8526	29.9789	1250
Gediz	38.9947	29.4003	736
Simav	39.0925	28.9786	809
Çavdarhisar	39.1758	29.5878	1056

2.2. The Hargreaves and Samani formula

Hargreaves and Samani (1985) suggested an easy-to-use empirical formula based on the extraterrestrial radiation and minimum, mean, and maximum air temperatures for calculating daily grass ET_o. This equation can express as:

$$ET_{0HS} = C_{HS}R_a(T_a + 17.8)\sqrt{T_{max} - T_{min}} \quad (2)$$

where ET_{0HS} indicates the estimated reference evapotranspiration value with HSF [$mm.day^{-1}$], C_{HS} is a constant coefficient which is equal to 0.0023, T_{min}, T_a, and T_{max} are minimum, mean, and maximum air temperatures (^0C), and R_a is the extraterrestrial radiation $MJm^{-2}day^{-1}$ determined with Allen et al. (1998) equation's as follows:

$$R_a = \frac{24 \times 60}{\pi}G_{sc}d_r[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \quad (3)$$

Where G_{SC} is a solar constant which is equal to 0.082 $MJm^{-2}min^{-1}$, φ is the latitude (rad), ω_s is the sunset hour angle (rad), δ is the solar declination (rad), and d_r is the inverse relative distance Earth-sun.

2.3. The Priestley and Taylor formula

Priestley and Taylor (1972) established an abbreviated form of the Penman (1948) relation to calculate evapotranspiration and published the following one:

$$ET_{0PT} = C_{PT}\frac{\Delta}{\Delta + \gamma}\frac{R_n - G}{\lambda} \quad (4)$$

where ET_{0PT} indicates the estimated reference evapotranspiration value with PTF [$mm.day^{-1}$]. Priestley and Taylor (1972) for open bodies of water offered the value of C_{PT} as 1.26. Also, in this formula, λ is the latent heat of vaporization ($MJkg^{-1}$). Other parameters are the same as the previous equations.

2.4. The Jensen and Haise formula

Jensen and Haise (1963) investigated ET_o values for more than 3000 observations in a 35-year period and finally suggested Eq. (5) in this

Fig. 1. Location of Kutahya province in Turkey and meteorological stations.

field.

$$ET_{0JH} = C_T \frac{R_s \times (T_a - T_x)}{\lambda} \tag{5}$$

where ET_{0JH} indicates the estimated reference evapotranspiration value with JHF [$mm.day^{-1}$], R_s indicates the incoming shortwave solar radiation ($MJ.m^{-2}.day^{-1}$), C_T is the temperature constant (0.025), T_x is equal to -3 when T_a is in degrees Celsius. Other parameters are the same as the previous equations. They assumed these coefficients to be a constant magnitude for a yielded territory (Xu and Singh 2000).

2.5. The Thornthwaite formula

Thornthwaite (1948) introduced a temperature-based method for the prediction of ET_0 based on the average monthly temperature as follows:

$$ET_{0Tw} = 16 \frac{d}{30} \left(10 \frac{T_{av}}{I} \right)^a \tag{6}$$

$$I = \sum_{n=1}^{12} (0.2 T_{av})^{1.514} \tag{7}$$

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.7912 \times 10^{-2} I + 0.49239 \tag{8}$$

where ET_{0Tw} indicates the estimated reference evapotranspiration value with the TwF [$mm.day^{-1}$], d indicates the number of days per month, and T_{av} is the monthly mean air temperature. Meanwhile, the following correction factor (C) was used to transform the predictions from a standard monthly ($mm.month^{-1}$) to a daily time scale ($mm.day^{-1}$):

$$C = \frac{N}{360} \tag{9}$$

where N represents the hourly photoperiod for days.

2.6. The Makkink formula

Makkink (1957) tried to obtain a simplified equation of the Penman equation and consequently suggested the following equation:

$$ET_{0M} = 0.61 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{\lambda} - 0.12 \tag{10}$$

where ET_{0M} indicates the estimated reference evapotranspiration value with the MF [$mm.day^{-1}$].

2.7. The Turc formula

Turc (1961) derived an equation based on relative humidity, air temperature, and solar radiation to estimate evapotranspiration values.

$$\begin{cases} ET_{0T} = 0.0133 \dfrac{T_a}{T_a + 15} (R_s + 50) & R_H > 50\% \\ ET_{0T} = 0.0133 \dfrac{T_a}{T_a + 15} (R_s + 50) \left(1 + \dfrac{50 - R_H}{70} \right) & R_H < 50\% \end{cases} \tag{11}$$

where ET_{0T} indicates the estimated reference evapotranspiration value with TF [$mm.day^{-1}$], and R_H indicates the relative humidity (%). Other parameters are the same as the previous equations.

3. Calibration procedure

In the first step to calibrate the empirical equations, daily ET_o values have calculated with the PMFAO56 equation ($ET_{oPMFAO56}$) and empirical equations (ET_{oEE}). Later, the calibration coefficients have determined by calculating the proportion of the values of the PMFAO56 equation to the empirical equations (except TwF) as follows:

$$C_{C,EE} = ET_{oPMFAO56} / ET_{oEE} \tag{12}$$

Since the ET_o values calculated with the TwF can be zero, it is possible not to determine a calibration coefficient with the above-mentioned approach. Hence, the calibration coefficient for the TwF has calculated as follows:

$$C_{C,EE} = ET_{oPMFAO56} / (1 + ET_{oEE}) \tag{13}$$

In the present study, three ways were followed for determining the local calibration coefficients.

In the first approach, initially, during the observation period, the monthly mean ET_o values for each year were calculated with empirical formulas. Then, the calibration coefficients were calculated for each month during the observation period. In the next step, by taking the averages of the values calculated in a previous step, the coefficients of the station monthly were determined. Finally, by taking the average of the coefficients calculated for all stations, the monthly calibration coefficients of the region were determined.

In the second approach, the average ET_o values of the relevant station were determined by taking the averages of the monthly average ET_o values calculated for each year during the observation period. Then, using these values, the calibration coefficients were calculated. Lastly, by taking the average of the calibration coefficients calculated for each station, the coefficients for the region were determined.

In the third method, by using the monthly average ET_o values of the stations, the local average ET_o values were calculated and after that, the values of local coefficients ($C_{3,EE}$) illustrated in Table 5, were determined using these values.

It is crucial to note that in the following tables, the values of $C_{i,HS}$, $C_{i,PT}$, $C_{i,JH}$, $C_{i,Tw}$, $C_{i,M}$, and $C_{i,T}$, are the calibrated coefficients of Hargreaves and Samani (1985), Priestley and Taylor (1972), Jensen and Haise (1963), Thornthwaite (1948), Makkink (1957), and Turc (1961), respectively, which i indicates the number of methods.

Table 3
Table of calibrated coefficients $C_{1,EE}$ with the first method.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
$C_{1,HS}$	0.3421	0.3785	0.3899	0.3962	0.4157	0.4534	0.4855	0.5232	0.5001	0.4511	0.399	0.3516
$C_{1,PT}$	1.0904	0.9882	0.9264	0.8843	0.8635	0.891	0.9552	0.998	1.0032	1.0115	1.1609	1.2755
$C_{1,JH}$	2.8913	1.5499	1.3146	1.0617	0.9044	0.834	0.8062	0.8133	0.8569	0.9479	1.1208	2.0724
$C_{1,Tw}$	0.6523	0.9999	1.3848	1.5455	1.4425	1.3029	1.2213	1.1196	1.1125	1.0131	0.8337	0.6398
$C_{1,M}$	−73.5928	5.2327	6.4912	5.1108	4.2523	3.7424	3.4985	3.522	3.9422	4.7865	7.1027	21.3441
$C_{1,T}$	−0.9305	15.2514	6.6253	8.4141	8.8576	9.7427	10.3305	10.053	8.5282	6.3798	5.5108	3.1307

Table 4
Table of calibrated coefficients $C_{2,EE}$ with the second method.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
$C_{2,HS}$	0.3403	0.3816	0.3917	0.4009	0.4142	0.4494	0.484	0.5195	0.5023	0.4553	0.4014	0.3518
$C_{2,PT}$	1.0869	0.9823	0.92	0.8709	0.8451	0.8619	0.9129	0.9357	0.9396	0.9542	1.1018	1.25
$C_{2,JH}$	1.9347	1.4875	1.2506	1.0239	0.8865	0.8203	0.7906	0.7946	0.8342	0.9095	1.0429	1.4417
$C_{2,Tw}$	0.6525	1.0068	1.387	1.5125	1.4036	1.2572	1.172	1.0683	1.0661	0.9924	0.8324	0.638
$C_{2,M}$	16.2893	7.8806	6.0534	4.8453	4.1073	3.6505	3.4112	3.4037	3.7577	4.395	5.7834	12.8966
$C_{2,T}$	6.4585	0.3768	8.2943	8.5023	8.978	9.866	10.4647	10.2139	8.7067	6.515	5.125	15.8211

Table 5
Table of calibrated coefficients $C_{3,EE}$ with the third method.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
$C_{3,HS}$	0.342	0.381	0.39	0.399	0.412	0.448	0.484	0.519	0.501	0.454	0.4	0.353
$C_{3,PT}$	1.091	0.985	0.921	0.872	0.846	0.862	0.913	0.936	0.94	0.955	1.103	1.252
$C_{3,JH}$	1.773	1.449	1.236	1.018	0.883	0.818	0.789	0.793	0.833	0.907	1.037	1.425
$C_{3,Tw}$	0.656	1.011	1.389	1.513	1.404	1.257	1.17	1.066	1.066	0.993	0.834	0.642
$C_{3,M}$	14.305	7.775	6.013	4.823	4.089	3.635	3.397	3.386	3.742	4.365	5.722	12.062
$C_{3,T}$	−13.11	12.551	8.038	8.47	8.971	9.866	10.463	10.213	8.706	6.51	5.077	6.716

To determine the best method between the ET_o values calculated using the $C_{1,EE}$, $C_{2,EE}$, and $C_{3,EE}$ coefficients and the ET_o values calculated with the PMFAO56 equation, four methods named the coefficient of determination (R^2), root-mean-square error (RMSE), percentage error of estimate (PE), and mean absolute error (MAE) are applied. The purposes behind choosing these four methods are to see the relations between the results of empirical equations and to calculate the error values with different approaches.

$$R^2 = \frac{\left[\sum_{i=1}^{n}(P_i - \overline{P})(O_i - \overline{O})\right]^2}{\sum_{i=1}^{n}(P_i - \overline{P})^2 \sum_{i=1}^{n}(O_i - \overline{O})^2} \tag{14}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{15}$$

$$PE = \left|\frac{\overline{P} - \overline{O}}{\overline{O}}\right| \times 100\% \tag{16}$$

$$MAE = \frac{\sum_{i=1}^{n}|P_i - O_i|}{n} \tag{17}$$

where P_i, $\overline{P}$, O_i, $\overline{O}$, and n are the estimated values, mean estimated values, observed values, mean observed values, and the total number of data, respectively. For all stations during the observation periods, monthly ET_o values for each year were calculated with PMFAO56 and calibrated empirical formulas. The results of comparison for these four analysis methods are given in Tables 6–8. The values given in the tables show the average values.

When the error values given in Tables 6–8 are examined, it is comprehended that the third of the three different methods used for coefficient calculation would be appropriate. Because in the third method, the errors are very close to each other, it is easier than the first two methods and gives slightly better results than the others. Subsequently,

Table 6
Table of R^2, RMSE, PE, MAE for. $C_{1,EE}$

Calibrated Emp. Equations	R^2	RMSE	PE	MAE
Hargraves and Samani	0.993	0.620	9.433	0.468
Priestley and Taylor	0.990	0.464	7.660	0.402
Jensen and Haise	0.993	0.525	6.860	0.380
Thornthwaite	0.992	1.104	17.779	0.832
Makking	0.866	1.428	7.660	0.890
Turc	0.926	1.001	10.093	0.764

Table 7
Table of R^2, RMSE, PE, MAE for. $C_{2,EE}$

Calibrated Emp. Equations	R^2	RMSE	PE	MAE
Hargraves and Samani	0.992	0.543	8.447	0.418
Priestley and Taylor	0.994	0.384	6.595	0.330
Jensen and Haise	0.992	0.549	7.957	0.425
Thornthwaite	0.992	1.102	17.759	0.832
Makking	0.989	0.583	10.508	0.515
Turc	0.905	1.132	11.236	0.836

Table 8
Table of R^2, RMSE, PE, MAE for. $C_{3,EE}$

Calibrated Emp. Equations	R^2	RMSE	PE	MAE
Hargraves and Samani	0.992	0.544	8.458	0.418
Priestley and Taylor	0.994	0.378	6.498	0.325
Jensen and Haise	0.991	0.523	7.285	0.398
Thornthwaite	0.992	1.101	17.746	0.831
Makking	0.990	0.566	10.219	0.504
Turc	0.865	1.487	11.451	0.925

the third method is selected as a final method.

4. Results and discussion

As highlighted earlier, the PMFAO56 equation is selected to calibrate the other easy-to-use empirical equations. The values of calibrated coefficients of the empirical equations for Kutahya province for every month are illustrated in Tables 3–5. According to the variation of monthly values of the coefficients shown in Table 5, it is possible to say that expressing these values with a solely single value per year is not appropriate. As earlier stated, the outcomes of the third method have been selected as the best ones. For the third method, the minimum values of calibrated coefficients for $C_{3,HS}$, $C_{3,PT}$, $C_{3,JH}$, $C_{3,Tw}$, $C_{3,M}$, and $C_{3,T}$ are as 0.342, 0.846, 0.789, 0.642, 3.386, and −13.11, respectively. Also, the maximum values of calibrated coefficients for $C_{3,HS}$, $C_{3,PT}$, $C_{3,JH}$, $C_{3,Tw}$, $C_{3,M}$, and $C_{3,T}$ are given as 0.519, 1.252, 1.773, 1.513, 14.305, and 12.551, respectively. It is obviously clear that the smallest and greatest differences between maximum and minimum values can be seen in $C_{3,HS}$, and $C_{3,T}$, respectively.

To examine the performance of calibrated coefficients, daily recorded meteorological data of Çavdarhisar station for four years (i.e., 2016–2019), as well as the daily recorded meteorological data for three stations, including Dumlupinar, Gediz, and Simav, for the year 2020 have been applied. It is worthwhile to mention that to test the determined coefficients, these data are not taken into account in the coefficients calculation process. Results of these examinations are demonstrated in Figs. 2 and 3, respectively. In the following Figures and tables, CTw, CM, CT, CJH, CPT, and CHS stands for calibrated results of TwF, MF, TF, JHF, PTF, and HSF, respectively. Meanwhile, to assess the outcomes equations (14)–(17) are applied, and results are illustrated in Tables 9 and 10. The results show that PTF and JHF are the best estimation methods among the uncalibrated and calibrated formulas,

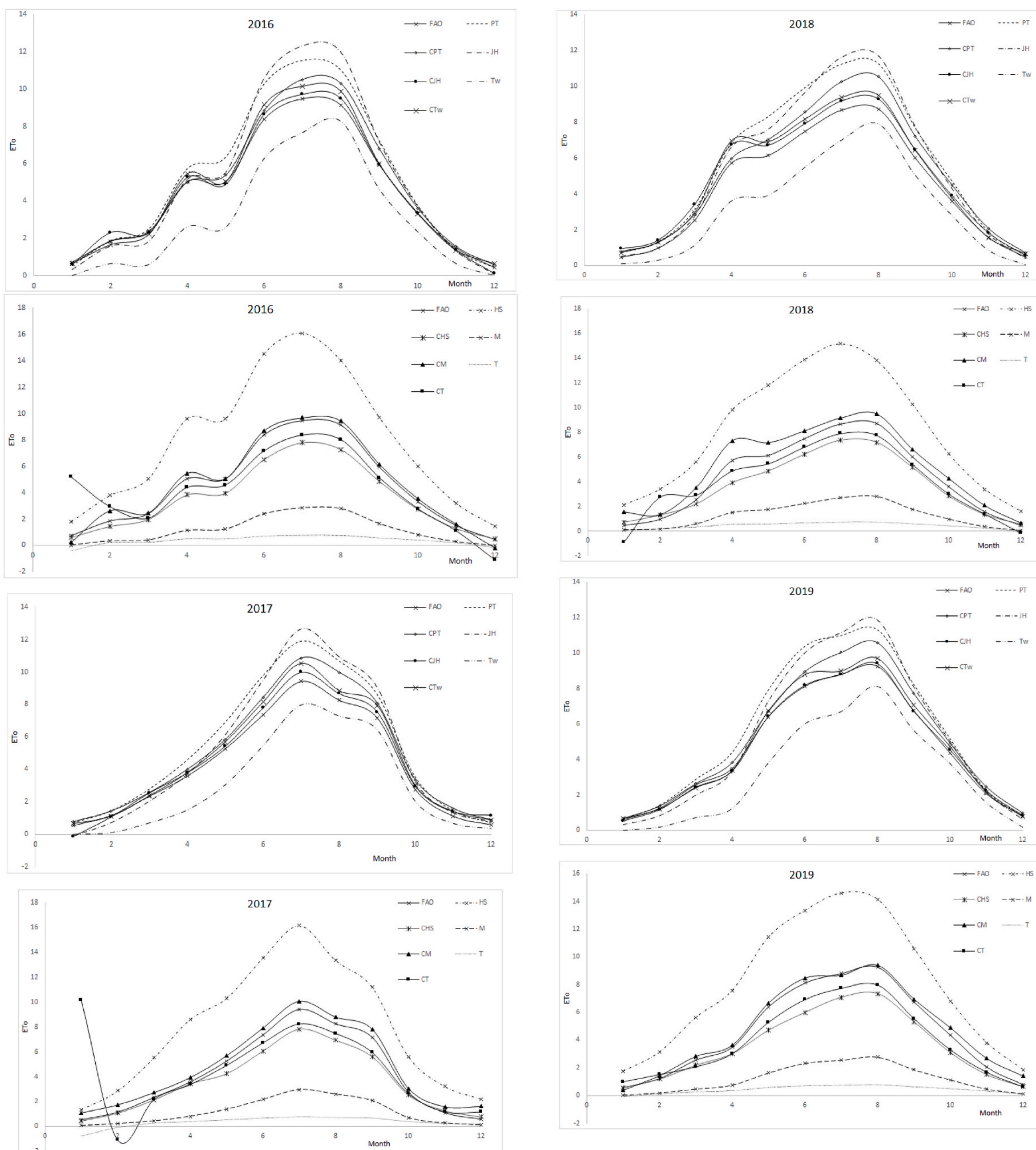

Fig. 2. Prediction of Çavdarhisar station for years between 2016 and 2019.

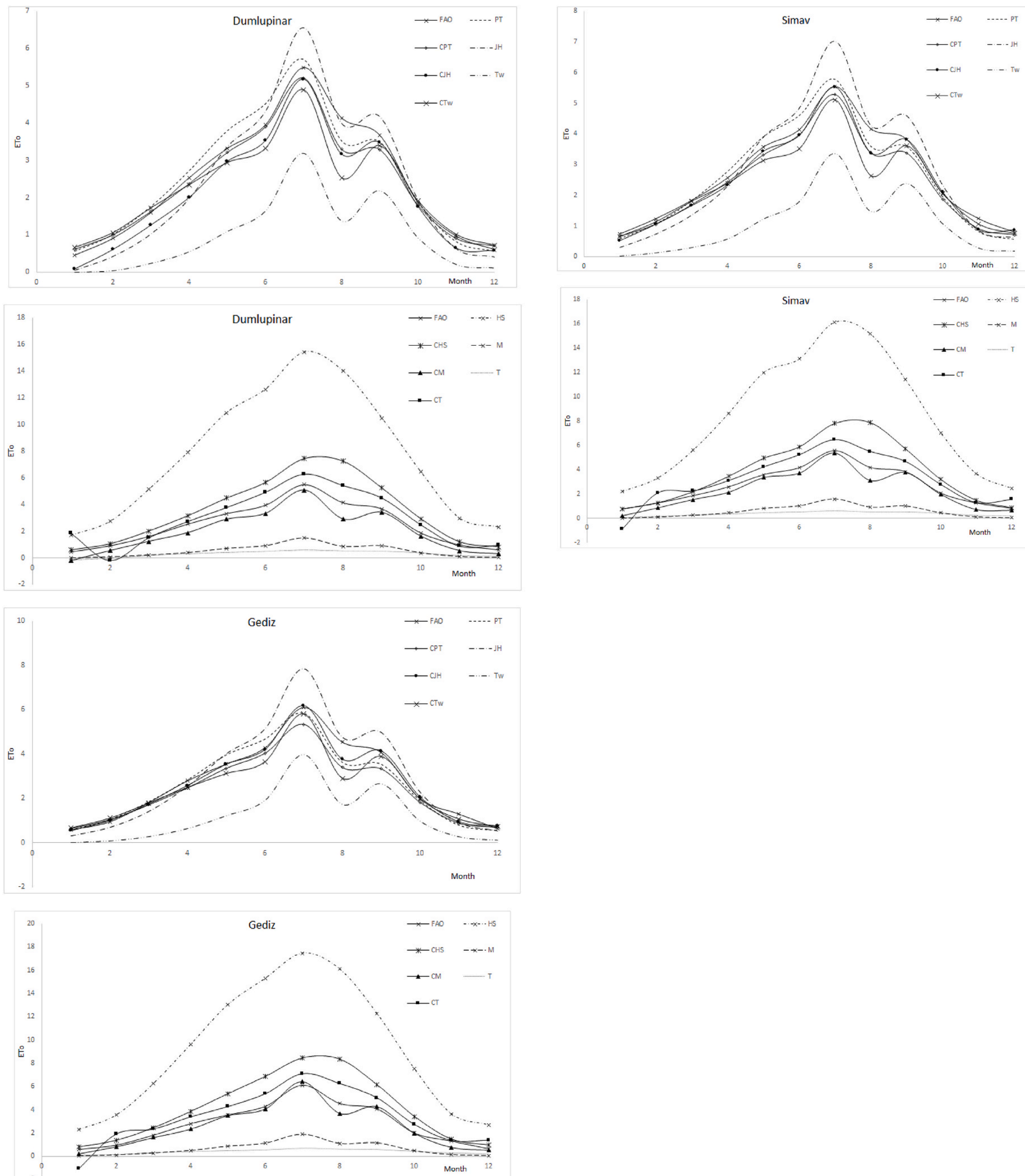

Fig. 3. Prediction of Dumlupinar, Gediz, and Simav stations for year 2020.

respectively. To use the developed coefficients, by employing the coefficients presented in Table 8, the ET_o values calculated using the empirical equations (except TwF) can be calibrated as follows:

$$ET_{o.\ calibrated\ EE} = C_{3,EE} \cdot ET_{o.EE} \tag{18}$$

And the ET_o values calculated with the TwF can be calibrated as:

$$ET_{o.\ calibrated\ Tw} = C_{3,w}(1 + ET_{o.\ Tw}) \tag{19}$$

To modify the ET_o values calculated in other empirical equations, it would be appropriate to multiply them with the given coefficients. According to the presented results on the tables, when the ET_o values estimated by empirical relations are calibrated with the illustrated coefficients, results very close to the results of the PMFAO56 equation can be obtained.

According to the outcomes of six empirical formulas presented in Table 10 for three stations, it can be stated that HSF found the best results in Dumlupinar station. PTF offered the best results in Dumlupinar station. Moreover, JHF, TwF, MF, and, TF's gained the best outcomes in Dumlupinar, Dumlupinar, Gediz, and Dumlupinar stations, respectively.

Based on our best knowledge, the sole attempt to calibrate empirical equations in Turkey was conducted by Cobaner et al. (2017). As mentioned earlier, they exclusively focused on HSF and calibrated it with several combinations. They obtained the values of MAE as (0.8, 1.01, 0.6, 1.39) and values of RMSE as (1.01, 1.15, 0.72, 1.61) for the Central Anatolia region with various combinations. About the results of Table 8 for Kutahya, which is inside the same region, the values of MAE and RMSE presented in this research are 0.418 and 0.544, respectively.

When the obtained results were examined, it was observed that

Table 9
Table of R^2, RMSE, PE, MAE for Çavdarhisar.

Year	Calibrated Emp. Equations	R^2	RMSE	PE	MAE
2016	Hargraves and Samani	0.995652	0.5453	7.59481	0.377997
	Priestley and Taylor	0.996687	0.237349	1.412897	0.201265
	Jensen and Haise	0.996831	0.393568	4.148227	0.285386
	Thornthwaite	0.997562	1.101828	19.78071	0.891285
	Makking	0.990115	0.384529	2.580366	0.309623
	Turc	0.753506	1.565311	5.226482	1.155699
2017	Hargraves and Samani	0.996831	0.831496	16.58044	0.685114
	Priestley and Taylor	0.992902	0.391037	5.210347	0.345471
	Jensen and Haise	0.998072	0.51231	9.567197	0.403039
	Thornthwaite	0.994894	0.896828	14.34803	0.654578
	Makking	0.996464	0.57596	13.20881	0.545796
	Turc	0.336093	2.909193	6.58927	1.436922
2018	Hargraves and Samani	0.993758	0.948946	18.028	0.786526
	Priestley and Taylor	0.994532	0.551398	11.34806	0.495094
	Jensen and Haise	0.994611	0.59778	11.25315	0.497568
	Thornthwaite	0.98544	1.003816	16.51544	0.832627
	Makking	0.986554	0.847192	17.50648	0.763774
	Turc	0.935416	0.883087	9.813842	0.784764
2019	Hargraves and Samani	0.996994	0.690099	11.84105	0.53726
	Priestley and Taylor	0.99888	0.109719	0.418363	0.091527
	Jensen and Haise	0.997584	0.304816	3.915874	0.239079
	Thornthwaite	0.992241	1.244164	21.66716	0.983096
	Makking	0.993823	0.345844	5.365112	0.297867
	Turc	0.990721	0.875732	14.72874	0.772918

Table 10
Table of R^2, RMSE, PE, MAE for 2020.

Stations	Calibrated Emp. Equations	R^2	RMSE	PE	MAE
Dumlupinar	Hargraves and Samani	0.982199	0.292663	5.212749	0.195719
	Priestley and Taylor	0.980591	0.419558	14.31226	0.351632
	Jensen and Haise	0.934423	0.554716	10.21266	0.363814
	Thornthwaite	0.964863	1.362287	41.89855	1.029387
	Makking	0.973419	0.569761	20.66019	0.507591
	Turc	0.910255	0.798383	18.86238	0.672107
Gediz	Hargraves and Samani	0.974894	0.488366	11.77625	0.360589
	Priestley and Taylor	0.979874	0.263294	3.679653	0.163381
	Jensen and Haise	0.938511	0.544524	10.421	0.340225
	Thornthwaite	0.959855	1.780741	51.43007	1.397578
	Makking	0.973428	0.362224	7.287264	0.282133
	Turc	0.920823	0.992426	22.52634	0.889352
Simav	Hargraves and Samani	0.9863	0.320646	9.725412	0.256577
	Priestley and Taylor	0.978543	0.28245	6.674445	0.199551
	Jensen and Haise	0.93742	0.515509	11.76489	0.31372
	Thornthwaite	0.950719	1.571914	43.34112	1.14343
	Makking	0.970323	0.453027	13.99496	0.369216
	Turc	0.914149	0.89659	20.15997	0.803822

calibrated empirical formulas could obtain very close results to the PMFAO56 equation. Since the equations are calibrated with the help of coefficients, the change in the calibration coefficients will affect the results of the original equations at the same ratio. Any variation in meteorological data will affect the results of the uncalibrated equations. This effect will be the same in calibrated equations.

The coefficients obtained in this study are valid for the Kutahya region. In the process of calibration of the equations, coefficients that are valid for other regions can be obtained. For this, the variation of the coefficients from region to region should be examined, the effective parameters should be recognized, and the relations between these parameters should be investigated. In this research, as a preliminary evaluation, the variation of the coefficients according to the months was examined and a strong relation was observed with the second-order polynomial. The results of this assessment are given in Fig. 4 and Table 11. Based on these results, it is clear to state that the coefficients can express as an equation depending on the months. The highest and lowest R^2 values calculated for JHF, and TF, respectively.

Finally, the comparison between mean annual total Et_o values with calibrated formulas used in this study for three synoptic stations and PMFAO56 values is given in Fig. 5.

5. Conclusion

This paper documented the calibration and evaluation of two temperature-based empirical evapotranspiration models, including Thornthwaite (1948), and Hargreaves and Samani (1985) formulas, and four solar radiation-based empirical evapotranspiration models including, Makkink (1957), Turc (1961), Jensen and Haise (1963), and Priestley and Taylor (1972) formulas. These are easy-to-use and widely-used empirical equations in this field that require a small amount of data. The main aims of this study are (i) to determine the ET_o value employing several empirical formulas, (ii) to calibrate the empirical formulas, and (iii) to compare and examine the outcomes of the calibrated formulas for the research field. The values of ET_o estimated by PMFAO56 selected as a reference ET_o and Kutahya in Turkey with a continental climate, including snowy, cold winters, and dry, hot summers, selected as a case study for this research. Three different ways were used to calculate the calibrated coefficients. The third method was chosen considering the results of the evaluation criteria (i.e., R^2, RMSE, PE, and MAE). To evaluate the performance of calibrated coefficients, daily recorded meteorological data of three stations, including Dumlupınar, Gediz, and Simav, for the year 2020, and daily recorded meteorological data of Çavdarhisar station for four years (i.e., 2016–2019)

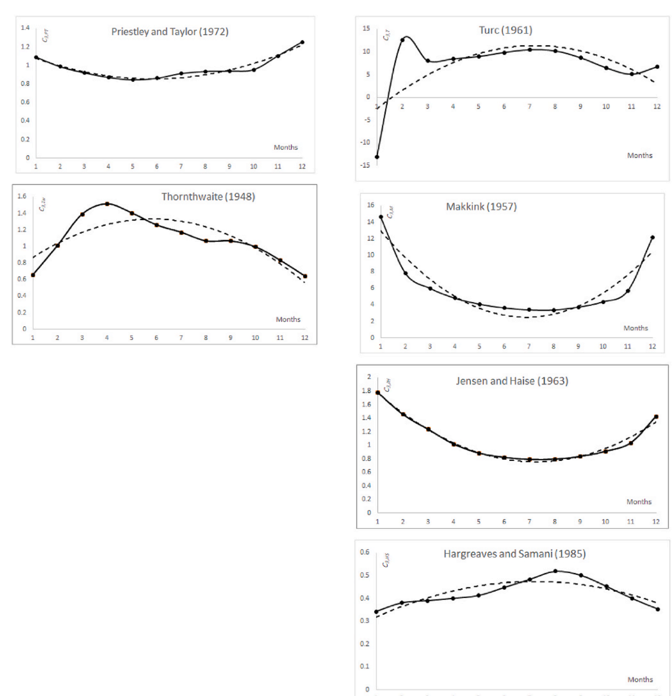

Fig. 4. Illustration of second-order polynomial relations between empirical coefficients ($C_{3,\ EE}$) and months.

Table 11
Second-order polynomial relations between $C_{3,EE}$ coefficients and months.

Calibrated Emp. Equations	Second-order polynomial relations	R^2
Hargraves and Samani	$C_{3,HS} = = -0.0041x^2 + 0.0586x + 0.2634$	0.7388
Priestley and Taylor	$C_{3,PT} = 0.0096x^2 - 0.1114x + 1.1786$	0.937
Jensen and Haise	$C_{3,JH} = 0.0259x^2 - 0.3759x + 2.1184$	0.9834
Thornthwaite	$C_{3,Tw} = -0.0201x^2 + 0.234x + 0.6519$	0.7426
Makking	$C_{3,M} = 0.2971x^2 - 4.0803x + 16.54$	0.8849
Turc	$C_{3,T} = -0.3637x^2 + 5.2373x - 7.4694$	0.4454

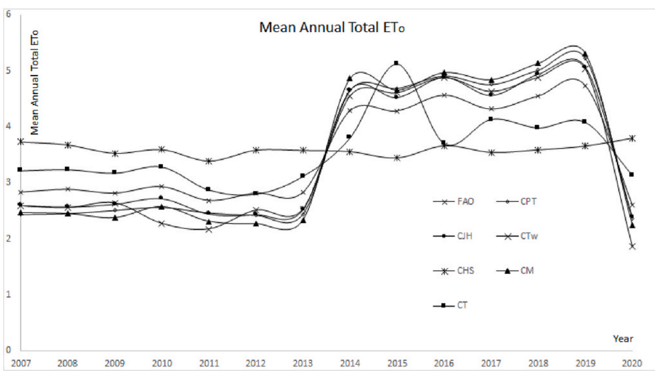

Fig. 5. Illustration of mean annual total Et_o values for three synoptic stations in Kutahya province.

have been applied. According to the outcomes presented in tables and figures, it is clear to say that values very close to the results of the PMFAO56 equation were obtained. Therefore, empirical equations that are easier to use and require fewer data types can easily replace with PMFAO56, where a wide variety of data is required. Overall, based on the results, among uncalibrated and calibrated formulas PTF and JHF have obtained the best estimations over Kutahya province, respectively. In addition, although the calibrated coefficients were close the each other, most of the empirical equations obtained the best results in the Dumlupinar station. Moreover, it has been observed that monthly adjusted empirical equation coefficients should be used instead of annual average calibrated coefficients to obtain reliable results.

The main challenge in this study was related to the availability of the required meteorological data. Some of the required data has not been measured at some stations. To avoid any mistakes, stations with missing data were ignored.

In this study, it has been observed that using the original empirical formulas without local calibration can yield very inaccurate results. The outcomes demonstrated that the precision of the empirical formulas after calibration increased meaningfully. Evapotranspiration is directly dependent on the geographical, meteorological, and vegetation features of the region. Consequently, the coefficients obtained in this study include regional effects. Therefore, the suggested coefficients should be used solely for the province of Kutahya, and the same procedure should be applied in other regions. To generalize coefficients, studies are still in progress and we try to figure out the most affected parameters in variations of the coefficients from region to region. Furthermore, additional studies are required to examine the performance of the calibrated equations in different time scales. Finally, it would be appropriate to compare the results with measurements of the lysimeter.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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