Calibration of Empirical Equations for Estimating Reference Evapotranspiration in Different Climates of Iran

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Calibration of empirical equations for estimating reference evapotranspiration in different climates of Iran

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Abstract

The accurate estimation of reference evapotranspiration (ET_{ref}) is a crucial component for modeling hydrological and ecological cycles. The goal of this study was the calibration of 32 empirical equations used to determine ET_{ref} in the three classes of temperature-based, solar radiation-based and mass transfer-based evapotranspiration. The calibration was based on measurements taken between the years 1990 and 2019 at 41 synoptic stations located in very dry, dry, semidry and humid climates of Iran. The performance of the original and calibrated empirical equations compared to the PM-FAO₅₆ equation was evaluated based on model evaluation techniques including: the coefficient of determination (R^2), the root mean square error (RMSE), the average percentage error (APE), the mean bias error (MBE), the index of agreement (D) and the scatter index (SI). The results show that the calibrated Baier and Robertson equation for temperature-based models, the Makkink equation for solar radiation-based models and the Penman equation for mass transfer-based models performed better than the original empirical equations. The calibrated equations had, respectively, an average $R^2=0.73$, 0.67 and 0.78 ; $RMSE=35.14$, 35.02 and 30.20 mm year⁻¹; and $MBE=-5.6$, -3.89 and 2.57 mm year⁻¹. The original empirical equations had values of average $R^2=0.60$, 0.37 and 0.65 ; $RMSE=68.34$, 66.98 and 52.62 mm year⁻¹; and $MBE=-5.75$, 4.26 and 8.99 mm year⁻¹, respectively. The calibrated empirical equations for very dry climate (e.g. Zabol, Zahedan, Bam, Iranshahr and Chabahar stations) also significantly reduced the SI value from $SI>0.3$ (poor class) to $SI<0.1$ (excellent class). Therefore, the calibrated empirical equations are highly recommended for estimating ET_{ref} in different climates.

Keywords: Calibration, ET_{ref} Estimation, Scatter Index, Water Resource, Zonation

1. Introduction

The estimation of reference evapotranspiration (ET_{ref}) by using hydrological equations can be helpful in agriculture sectors (Celestin et al. 2020; Ndiaye et al. 2020). It has a key role in the management of water resources and the determination of crops' water demands (Berti et al. 2014; Ferreira et al. 2019). The most accurate evaluation of ET_{ref} is computed by the lysimeter method, but this method has high costs and requires complex instruments (Ahooghalandari et al. 2016; Ahooghalandari et al. 2017). Therefore, alternative techniques for indirect estimation of ET_{ref} were developed based on empirical models, including temperature-based, solar radiation-based and mass transfer-based models.

In contrast, the FAO₅₆ Penman-Monteith (PM-FAO₅₆) equation is the standard combination-based model used to estimate the ET_{ref} in different climates and at different time scales (Güçlü et al. 2017; Saggi and Jain 2019; Shiri et al. 2019; Ndiaye et al. 2020; Sharafi and Mohammadi Ghaleni 2021). The accuracy of this equation is due to its consideration of all climatic parameters, including solar radiation, air temperature, wind speed and relative humidity (Ndiaye et al. 2020). While the PM-FAO₅₆ equation shows relatively stable results, the equations for empirical models based on temperature, solar radiation and mass transfer use fewer climatic parameters in the

1 calculation of ET_{ref} . Therefore, the development and calibration of empirical model equations in
2 different climates can be more effective for agricultural and hydrological projects where only a
3 few climatic variables are available (Heydari and Heydari, 2014; Gafurov et al. 2018).

4 Several researchers have evaluated the dependence of different empirical ET_{ref} equations on
5 various meteorological parameters over different climates. Sharafi and Mohammadi Ghaleni
6 (2021) evaluated different empirical equations for ET_{ref} in different climates of Iran. Their results
7 found that the simplest regression model (MLR) based on minimum and maximum temperature
8 data was more precise than the empirical equations. They also recommended the solar radiation–
9 based Irmak equation as the best substitute for the PM-FAO₅₆ model, especially in dry and semidry
10 climates. Celestin et al. (2020) compared the 32 empirical ET_{ref} equations with the PM-FAO₅₆
11 using data on temperature, solar radiation and mass transfer in northwest China. They found that
12 the World Meteorological Organization (WMO) and the Mahringer equations for the mass
13 transfer–based model provided the best results. Gao et al. (2017) also assessed different empirical
14 ET_{ref} equations in various climates and observed that the Priestley-Taylor and Hargreaves
15 equations worked best in dry and semidry climates, while the Makkink equation worked best in
16 the humid climate of China.

17 Water resources in semiarid regions are vulnerable to the impacts of climate change and human
18 activities, and the accurate estimation of ET_{ref} is a primary tool in the management of water
19 resources. Therefore, the goals of this study were to: (I) evaluate the best empirical equation for
20 different climates, (II) find the best substitutes for the PM-FAO₅₆ model in different climates and
21 (III) calibrate each of the 32 empirical ET_{ref} equations for different climates of Iran.

22 **2. Materials and Methods**

23 *2.1. Time and location scales*

24 Iran is in the northern hemisphere between 25 and 40 degrees latitude. For this study,
25 meteorological data recorded between 1990 and 2019 were collected from 41 synoptic stations in
26 the country. These data were collected by the National Meteorological Organization of Iran and
27 include the monthly mean of minimum, mean and maximum air temperature, relative humidity,
28 wind speed measured at 2 m height and solar radiation. The data were complete, and no data
29 needed to be reconstructed.

30 According to the FAO₅₆ index, Iran is classified into four climatic regions: very dry, dry,
31 semidry and humid (Fig. 1). Fig. 1 shows the location and climate for each station used in this
32 study. Six stations were in very dry climate, 17 stations in dry climate, 14 stations in semidry
33 climate and 4 stations in humid climate (Fig. 1).
34
35

2.2. Empirical ET_{ref} equations

Based on the type and importance of input variables used in each empirical equation to calculate the ET_{ref} , the models were divided into 4 categories: combination-based (1 equation), temperature-based (11 equations), solar radiation-based (11 equations) and mass transfer-based (10 equations). Table 1 lists the 33 empirical ET_{ref} equations used in this study and their respective references.

Table 1. The ET_{ref} estimated based on empirical equations

Code	Abs.	Empirical equations	References
<i>Combination-based</i>			
1	PM-FAO ₅₆	$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma[900 / (T_{mean} + 273)]u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$	Allen et al. (2006)
<i>Temperature-based</i>			
2	HASA	$ET_{ref} = [0.0023 \times R_a (T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}] / \lambda$	Hargreaves and Samani (1985)
3	TRAJ	$ET_{ref} = [0.0023 \times R_a (T_{mean} + 17.8)(T_{max} - T_{min})^{0.424}] / \lambda$	Trajkovic (2007)
4	TATA1	$ET_{ref} = [0.0031 \times R_a (T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}] / \lambda$	Tabari and Talaei (2011)
5	TATA2	$ET_{ref} = [0.0028 \times R_a (T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}] / \lambda$	Tabari and Talaei (2011)
6	DRAL1	$ET_{ref} = [0.003 \times R_a (T_{mean} + 20)(T_{max} - T_{min})^{0.4}] / \lambda$	Droogers and Allen (2002)
7	DRAL2	$ET_{ref} = [0.0025 \times R_a (T_{mean} + 16.8)(T_{max} - T_{min})^{0.5}] / \lambda$	Droogers and Allen (2002)
8	BERT	$ET_{ref} = [0.00193 \times R_a (T_{mean} + 17.8)(T_{max} - T_{min})^{0.517}] / \lambda$	Berti et al. (2014)
9	DORJ	$ET_{ref} = [0.002 \times R_a (T_{mean} + 33.9)(T_{max} - T_{min})^{0.296}] / \lambda$	Dorji et al. (2016)
10	BARO	$ET_{ref} = 0.109 \times (R_a / \lambda) + 0.157T_{max} + 0.158(T_{max} - T_{min}) - 5.39$	Baier and Robertson (1965)
11	AHOO1	$ET_{ref} = 0.252 \times (R_a / \lambda) + 0.221T_{mean}(1 - RH / 100)$	Ahooghalandari (2016)
12	AHOO2	$ET_{ref} = 0.29 \times (R_a / \lambda) + 0.15T_{max}(1 - RH / 100)$	Ahooghalandari (2016)
<i>Solar radiation-based</i>			
13	MAKK	$ET_{ref} = 0.7 \times (R_a / \lambda) \times [\Delta / \Delta + \gamma] - 0.12$	Makkink (1957)
14	PRTA	$ET_{ref} = 1.26 \times (R_n - G) [\Delta / \Delta + \gamma] / \lambda$	Priestley and Tayler (1972)
15	JEHA	$ET_{ref} = (0.025T_{mean} + 0.08) / \lambda$	Jensen and Haise (1963)
16	HARG	$ET_{ref} = [0.0135(T_{mean} + 17.8)R_s] / \lambda$	Hargreaves (1975)
17	ABTE1	$ET_{ref} = 0.25T_{max}R_s / \lambda$	Abtew (1996)
18	ABTE2	$ET_{ref} = (T_{max} / 56) \times (R_s / \lambda)$	Abtew (1996)
19	IRMA1	$ET_{ref} = -0.611 + 0.149R_s + 0.079T_{mean}$	Irmak et al. (2003)
20	IRMA2	$ET_{ref} = 0.469 + 0.289R_n + 0.023T_{mean}$	Irmak et al. (2003)
21	TATA3	$ET_{ref} = -0.642 + 0.174R_s + 0.0353T_{mean}$	Tabari and Talaei (2011)
22	TATA4	$ET_{ref} = -0.478 + 0.156R_s - 0.0112T_{max} + 0.0733T_{min}$	Tabari and Talaei (2011)
23	OUDI	$ET_{ref} = (R_s / \lambda) \times [T_{mean} + 5] / 100$	Oudin (2004)
<i>Mass transfer-based</i>			
24	DALT	$ET_{ref} = (3.648 + 0.7223u_2)(e_s - e_a)$	Dalton (1802)
25	MEYE	$ET_{ref} = (3.75 + 0.503u_2)(e_s - e_a)$	Meyer (1926)
26	ROHW	$ET_{ref} = (3.3 + 0.891u_2)(e_s - e_a)$	Rohwer (1931)
27	ALBR	$ET_{ref} = (1.005 + 2.97u_2)(e_s - e_a)$	Albrecht (1950)

28	WMO	$ET_{ref} = (1.298 + 0.934u_2)(e_s - e_a)$	WMO (1966)
29	TRAB	$ET_{ref} = 0.3075 \times u_2^{0.5} (e_s - e_a)$	Trabert (1896)
30	BRWE	$ET_{ref} = 0.543 \times u_2^{0.456} (e_s - e_a)$	Brockamp and Wenner (1963)
31	MAHR	$ET_{ref} = 0.286 \times u_2^{0.5} (e_s - e_a)$	Mahringer (1970)
32	PENM	$ET_{ref} = (2.625 + 0.000479u_2)(e_s - e_a)$	Penman (1948)
33	ROMA	$ET_{ref} = 0.00006(100 - RH)(25 + T_{mean})^2$	Romanenko (1961)

ET_{ref} : reference evapotranspiration (mm day^{-1}), Δ : the slope of saturation vapor pressure curve ($\text{mb } ^\circ\text{C}^{-1}$), R_n : net solar radiation ($\text{MJ m}^{-2} \text{day}^{-1}$); G : soil heat flux density (mm day^{-1}), γ : psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), $T_{\text{mean, max and min}}$: mean, maximum and minimum daily temperature ($^\circ\text{C}$), respectively, u_2 : wind speed measured at 2 m height (m s^{-1}), R_a : extraterrestrial radiation (mm day^{-1}), λ : latent heat of vaporization (MJ kg^{-1}), RH : mean relative humidity (%), R_s : solar radiation ($\text{MJ m}^{-2} \text{day}^{-1}$), e_s : saturation vapor pressure (k Pa), e_a : actual vapor pressure (k Pa) and $(e_s - e_a)$: saturation vapor pressure deficit (k Pa).

To calculate the PM-FAO₅₆, measurements of the amount of total solar radiation at the Earth's surface (R_s , $\text{MJ m}^{-2} \text{d}^{-1}$), maximum and minimum temperature, wind speed (m s^{-1}) and lack of vapor pressure (VPD, kPa) are required. Due to lack of access to R_s and VPD, the FAO method was used (Gholipoor 2008). Daily values of R_s were obtained from Hargreaves and Samani's equation (Mehdizadeh et al. 2017) and the modified Allen et al. (2006) equation. Solar radiation reaching the land surface (R_n , $\text{MJ m}^{-2} \text{d}^{-1}$) was first measured above the Earth's atmosphere for each day of the year based on latitude and longitude and the solar constant (Allen et al. 2006). Then R_s was calculated using Eq. 34:

$$R_s = K_{R_s} \times (1 + 2.7 \times 10^{-5} \times \text{Alt}) \times (T_{\text{max}} - T_{\text{min}})^{0.5} \times R_n$$

where Alt is altitude (m) and K_{R_s} is the empirical constant, considered equal to 0.16 (Gholipoor, 2008). The e_s calculation is obtained from the difference between the daily saturated water vapor pressure (e_{max}) and the actual water vapor pressure (e_a). Relative humidity at temperature was assumed to be at least 100 percent and the values for e_a were obtained from Eq. (35):

$$e_a = 0.6108 \times \exp \frac{(17.27 \times T_{\text{min}})}{(T_{\text{min}} + 237.3)}$$

In very dry and dry climates, the relative humidity at the T_{min} may never reach 100 percent. Therefore, it was assumed that in these regions, e_a values would occur at $T_{\text{min}} > 10^\circ\text{C}$ and it was observed that in this case it had a minor effect on ET_{ref} (1-2%). As a result, the ET_{ref} was calculated assuming that the dew point was equal to the T_{min} . Then the T_{max} saturated vapor pressure during the day (e_{max}) depending on the T_{max} was obtained from Eq. (36).

$$e_{\text{max}} = 0.6108 \times \exp \frac{(17.27 \times T_{\text{max}})}{(T_{\text{max}} + 237.3)}$$

where e_s is obtained from the mean e_a and e_{max} . Finally, e_s is calculated as the average between e_a and e_{max} in a part of the day when the air temperature is not at its maximum. However, other researchers have found that $(e_{\text{max}} - e_a) \times 0.75$ is a more accurate estimate of e_a (Tanner and Sinclair, 1983; Allen et al. 1998). Therefore, this method is used in this current study. Calculations were performed using SAS software (Statistical Analysis System, Version 9.1, SAS Inst., Cary, NC).

The average annual rainfall over the last thirty years in Iran was reported to be 334 mm. The highest annual rainfall occurred at Bandar Anzali station (1791.78 mm) and the lowest annual rainfall occurred at Bam station (61.61 mm). The average annual rainfall in the very dry climate was 92.89 mm, which was 140.74, 266.41 and 1150.05 mm less than in dry, semidry and humid climates, respectively (Fig. 2a). The annual average relative humidity in Iran was reported to be

1 55.34 percent with the highest relative humidity at Bandar Anzali station (84.71%) and the lowest
2 relative humidity at Bam station (28.08%). The relative humidity in the very dry climate was 44.64
3 percent, which was 1.02, 7.9 and 35.93 percent less than in the dry, semidry and humid climates,
4 respectively (Fig. 2b).

5 The 30-year average air temperature in Iran was reported to be 17.54 °C. The hottest and coldest
6 stations in this study were the Bandar Abbas and Ardabil stations (26.63 and 9.14 °C, respectively).
7 The average air temperature in the very dry climate was 20.44 °C, which was 3.4, 10.15 and 6.04
8 °C warmer than in the dry, semidry and humid climates, respectively (Fig. 2c). The average solar
9 radiation received in Iran is reported to be 7.26 MJ m⁻² day⁻¹. The highest and lowest received solar
10 radiation was observed in Bam and Rasht stations (9.06 and 4.17 MJ m⁻² day⁻¹, respectively). The
11 average solar radiation received in the very dry climate was 8.55 MJ m⁻² day⁻¹, which increased by
12 0.36, 1.06 and 3.74 MJ m⁻² day⁻¹ in dry, semidry and humid climates (Fig. 2d). The average wind
13 speed in the country during the last thirty years was reported to be 4.35 m s⁻¹, which has increased
14 by about 0.52 m s⁻¹ compared to the same period. The highest and lowest wind speeds were
15 recorded in Zabol and Gorgan stations, respectively (10.62 and 1.45 m s⁻¹). The mean wind speed
16 in a very dry climate was 6.54 m s⁻¹, which increased by 2.15, 2.63 and 3.97 m s⁻¹ in dry, semidry
17 and humid climates (Fig. 2e).

Fig. 2. The long period values of a) rainfall, b) relative humidity, c) temperature, d) solar radiation and e) wind speed of Iran's climate (1990-2019)

2.3. Evaluation Performance Criteria

Until now, many performance criteria have been used to evaluate the results of the model for prediction of ET_{ref} . In the present study, six statistical measures were used to evaluate the accuracy of each model in estimating the ET_{ref} : the coefficient of determination (R^2), the root mean square error (RMSE), the average percentage error (APE), the mean bias error (MBE), the index of agreement (D) and the scatter index (SI). The explanations for the statistical measures appear in Table 2.

Table 2. The characteristics of evaluation performance criteria used in the study

Code	Criteria	Equation	References
(37)	Coefficient of determination (R^2)	$R^2 = \frac{\sum_{i=1}^N \left(ET_{ref_i}^{PM_{FAO56}} - \overline{ET_{ref}^{PM_{FAO56}}} \right) \left(ET_{ref_i}^{model} - \overline{ET_{ref}^{model}} \right)}{\sqrt{\left[\sum_{i=1}^N \left(ET_{ref_i}^{PM_{FAO56}} - \overline{ET_{ref}^{PM_{FAO56}}} \right)^2 \right] \left[\sum_{i=1}^N \left(ET_{ref_i}^{model} - \overline{ET_{ref}^{model}} \right)^2 \right]}}$	Ma and Iqbal (1984)
(38)	Root mean square error (RMSE)	$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(ET_{ref_i}^{model} - ET_{ref_i}^{PM_{FAO56}} \right)^2}$	Ma and Iqbal (1984)
(39)	Average percentage error (APE)	$APE = \frac{\sum_{i=1}^N \left ET_{ref_i}^{PM_{FAO56}} - ET_{ref_i}^{model} \right }{\sum_{i=1}^N ET_{ref_i}^{PM_{FAO56}}} \times 100\%$	Behar et al. (2015)
(40)	Mean bias error (MBE)	$MBE = \frac{1}{N} \sum_{i=1}^N \left(ET_{ref_i}^{model} - ET_{ref_i}^{PM_{FAO56}} \right)$	Ferreira and da Cunha (2020)
(41)	Index of agreement (D)	$D = 1 - \frac{\sum_{i=1}^N \left(ET_{ref_i}^{model} - ET_{ref_i}^{PM_{FAO56}} \right)^2}{\sum_{i=1}^N \left(\left ET_{ref_i}^{model} - \overline{ET_{ref}^{PM_{FAO56}}} \right + \left ET_{ref_i}^{model} - \overline{ET_{ref}^{PM_{FAO56}}} \right \right)^2}$	Seifi and Riahi-Madvar (2019)
(42)	Scatter Index (SI)	$SI = \frac{RMSE}{\overline{ET_{ref}^{PM_{FAO56}}}}$	Li et al. (2013)

In Eqs. (37) to (42), $ET_{ref_i}^{PM_{FAO56}}$ and $ET_{ref_i}^{model}$ are the ET_{ref} based on PM-FAO₅₆, and modeled ET_{ref} , $\overline{ET_{ref}^{PM_{FAO56}}}$ and $\overline{ET_{ref}^{model}}$ are the mean values of ET_{ref} based on PM-FAO₅₆ and modeled ET_{ref} and N is the number of data sets. According to Li et al. (2013), the range of SI for the accuracy of the models is excellent ($SI < 0.1$), good ($0.1 < SI < 0.2$), fair ($0.2 < SI < 0.3$) and poor ($SI > 0.3$).

2.4. Empirical Equation Calibration

The basis of empirical equations used in estimating ET_{ref} is the regression relationship between the ET_{ref} equation as a dependent variable and meteorological parameters as independent variables. In the process of developing each of the empirical equations, one of two modifications may be made, either a change in meteorological parameters or a change in the coefficients of the equation. In this study, modification (optimization) of constant coefficients in empirical equations is the basis for increasing the accuracy of ET_{ref} estimation in different climates. The objective function of that change has been to minimize the RMSE error criterion by optimizing the constant coefficients of the equations as decision variables. For instance, in the HASA equation, the two

coefficients a and b in Eq. (43) are optimized to minimize the amount of error between the estimated ET_{ref} and the PM-FAO₅₆.

$$(43) \quad ET_{ref} = \left[a \times R_a (T_{mean} + 17.8) (T_{max} - T_{min})^b \right] / \lambda$$

The accuracy of empirical equations in estimating ET_{ref} before and after calibration was evaluated using error evaluation criteria separately for various empirical equations (temperature-based, solar radiation-based and mass transfer-based) and for very dry, dry, semidry and humid climates.

3. Results

3.1. Accuracy evaluation of empirical equations

To assess the 32 empirical equations for temperature-based, solar radiation-based and mass transfer-based models in different climates, meteorological datasets from 1990 to 2019 were evaluated. Table 3 shows the values of R^2 and RMSE for original and calibrated empirical equations based on temperature, solar radiation and mass transfer methods in different climates. According to the results of the best values of R^2 and RMSE in the temperature-based BARO equation for very dry (0.71 and 65.05), dry (0.63 and 74.69), semidry (0.46 and 60.25) and humid (0.59 and 73.35) climates observed in original BARO equation. These values after calibration were 0.82 and 32.79 in very dry climate, 0.73 and 42.12 in dry climate, 0.65 and 30.34 in semidry climate and 0.71 and 35.29 in humid climate. The DRAL1 equation in dry climate (0.73 and 36.4), and BERT equation in semidry (0.66 and 31.16) and humid climates (0.7 and 30.58) had acceptable results (Table 3).

For solar radiation-based methods, the maximum R^2 in very dry, dry and humid climates derived by the original HARG equation was 0.6, 0.47 and 0.45, respectively, but the best RMSE in very dry climate obtained by the original IRMA1 equation was 67.51, and in dry and humid climates as obtained by the original JEHA equation was 65.92 and 66.77, respectively. The result for calibrated equations showed that in very dry ($R^2=0.84$ and $RMSE=33.13$), dry ($R^2=0.74$ and $RMSE=34.9$) and semidry ($R^2=0.63$ and $RMSE=34.36$) climates, the OUDI, ABTE2 and TATA3 equations yielded reliable estimates. In the humid climate calibrated PRTA and MAKK equations showed the maximum $R^2=0.71$ and the minimum $RMSE=33.71$ (Table 3).

The results from mass transfer-based methods showed that the values of R^2 for the original PEMN equation in very dry, dry, semidry and humid climates were acceptable (0.74, 0.7, 0.53 and 0.64, respectively). The values of RMSE for the original PENM equation were reported as 54.17 for very dry, 53.13 for dry and 46.46 for semidry climates, but the best value of RMSE for humid climates, 49.2, was obtained by the original ROMA equation.

The results from mass transfer-based methods showed that the values of R^2 for the calibrated PEMN equation in very dry, dry, semidry and humid climates were acceptable (0.85, 0.79, 0.71 and 0.77, respectively). The values of RMSE for the calibrated PEMN equation were 27.87 for very dry, 31.83 for dry and 29.38 for semidry climates, but the best value of RMSE for humid climates, 30.14, was obtained by the calibrated ROMA equation (Table 3).

Table 3. The original and calibrated values of R^2 and RMSE for empirical ET_{ref} equations in different climates of Iran

		Very dry				Dry				Semidry				Humid			
		R^2		RMSE		R^2		RMSE		R^2		RMSE		R^2		RMSE	
Equation		Ori.	Cal.	Ori.	Cal.	Ori.	Cal.	Ori.	Cal.	Ori.	Cal.	Ori.	Cal.	Ori.	Cal.	Ori.	Cal.
Temperature-based	HASA	0.54	0.77	83.38	43.99	0.44	0.70	82.41	37.67	0.32	0.59	79.99	34.41	0.42	0.67	70.15	37.23
	TRAJ	0.54	0.80	80.48	39.18	0.44	0.69	77.59	40.29	0.28	0.60	77.87	35.63	0.40	0.68	80.81	38.80
	TATA1	0.49	0.78	78.73	40.66	0.34	0.68	76.75	39.46	0.20	0.59	62.12	32.56	0.32	0.68	73.03	34.94
	TATA2	0.53	0.76	73.20	39.97	0.38	0.68	83.42	40.71	0.36	0.61	74.34	34.37	0.39	0.68	85.12	34.05
	DRAL1	0.50	0.75	70.68	38.78	0.41	0.73	82.01	36.40	0.36	0.62	70.43	32.65	0.40	0.70	85.27	37.61
	DRAL2	0.48	0.79	84.88	43.97	0.36	0.67	72.66	41.21	0.23	0.55	69.24	36.91	0.32	0.66	78.29	35.49
	BERT	0.52	0.79	83.42	36.88	0.42	0.70	77.57	37.81	0.27	0.66	82.50	31.16	0.39	0.70	67.92	30.58
	DORJ	0.53	0.78	90.22	41.95	0.40	0.69	82.48	39.61	0.26	0.62	74.14	33.37	0.38	0.69	70.24	32.08
	BARO	0.71	0.82	65.05	32.79	0.63	0.73	74.69	42.12	0.46	0.65	60.25	30.34	0.59	0.71	73.35	35.29
	AHOO1	0.56	0.79	72.75	40.43	0.42	0.72	80.13	38.94	0.31	0.62	73.51	33.57	0.41	0.70	73.69	32.84
	AHOO2	0.54	0.76	65.58	38.36	0.39	0.71	81.70	38.74	0.28	0.59	76.76	39.36	0.39	0.68	67.84	36.71
Radiation-based	MAKK	0.43	0.77	69.82	32.77	0.42	0.71	66.56	37.34	0.24	0.52	56.31	36.24	0.37	0.66	75.22	33.71
	PRTA	0.49	0.83	73.92	37.98	0.41	0.72	74.28	38.43	0.38	0.63	65.67	35.22	0.42	0.71	83.72	35.38
	JEHA	0.50	0.78	71.27	32.39	0.42	0.69	65.92	37.25	0.42	0.60	53.08	34.23	0.44	0.68	66.77	41.86
	HARG	0.60	0.79	71.45	37.54	0.47	0.70	82.83	41.01	0.35	0.57	77.92	36.34	0.45	0.68	69.82	34.75
	ABTE1	0.54	0.82	80.25	33.30	0.43	0.69	71.60	38.40	0.43	0.58	77.11	38.25	0.44	0.67	85.44	37.09
	ABTE2	0.51	0.77	78.60	35.59	0.44	0.74	85.22	34.90	0.35	0.59	75.66	35.93	0.42	0.69	82.89	38.51
	IRMA1	0.53	0.77	88.50	38.48	0.44	0.74	77.14	37.32	0.34	0.60	79.41	37.52	0.43	0.70	71.64	35.71
	IRMA2	0.55	0.80	67.51	32.29	0.45	0.71	77.56	38.52	0.35	0.61	77.79	41.90	0.43	0.69	69.01	38.63
	TATA3	0.51	0.78	79.88	38.96	0.44	0.72	71.85	39.05	0.36	0.63	78.98	34.36	0.42	0.70	74.70	35.57
	TATA4	0.45	0.77	82.61	39.48	0.42	0.70	78.05	54.78	0.28	0.60	76.11	35.62	0.38	0.68	79.58	40.30
	OUDI	0.51	0.84	70.61	33.13	0.45	0.72	73.87	61.40	0.36	0.59	70.91	38.62	0.42	0.70	86.26	33.80
Mass transfer-based	DALT	0.56	0.82	66.53	31.11	0.59	0.71	76.56	53.83	0.36	0.65	66.21	36.12	0.51	0.71	75.23	34.40
	MEYE	0.67	0.80	80.83	36.93	0.60	0.71	72.02	56.87	0.44	0.64	61.90	33.51	0.55	0.70	70.29	35.10
	ROHW	0.68	0.76	72.71	38.88	0.58	0.73	74.26	52.57	0.31	0.63	70.95	38.54	0.50	0.70	67.41	36.73
	ALBR	0.63	0.79	64.30	39.43	0.48	0.72	71.79	65.94	0.30	0.56	65.62	47.00	0.44	0.68	72.52	31.83
	WMO	0.67	0.81	68.91	34.10	0.58	0.74	72.37	53.26	0.27	0.63	70.84	36.75	0.48	0.71	69.69	38.68
	TRAB	0.69	0.82	71.94	36.76	0.62	0.71	73.93	36.43	0.31	0.63	70.26	36.38	0.51	0.71	81.45	38.86
	BRWE	0.56	0.86	87.93	33.20	0.49	0.73	80.31	35.17	0.33	0.64	78.86	38.63	0.44	0.72	77.47	35.62
	MAHR	0.61	0.83	71.85	33.01	0.64	0.75	71.92	35.79	0.32	0.62	75.02	35.87	0.51	0.71	75.93	37.77
	PENM	0.74	0.85	54.17	27.87	0.70	0.79	53.13	31.83	0.53	0.71	46.46	29.38	0.64	0.77	56.72	31.71
	ROMA	0.50	0.76	59.22	30.93	0.45	0.73	69.14	36.09	0.42	0.61	49.03	30.99	0.46	0.70	49.20	30.14

Radar charts in Fig. 3 compare the APE values of the $ET_{ref}^{PM_{FAO56}}$ and the estimated ET_{ref} using the original and calibrated empirical equations for temperature-based, solar radiation-based and mass transfer-based methods from 1990 to 2019. Based on the results of APE plots, calibration greatly improved the performance of all empirical equations in all investigated climates compared with the original empirical equations. After calibration, APE values are closer to zero.

A reduction in values of APE for the calibrated empirical equations was found in very dry, dry, semidry and humid climates in temperature-based (1, 1.5, 2.2 and 3.2%), solar radiation-based (1, 1.4, 1.9 and 3.1%) and mass transfer-based (1, 1.3, 1.6 and 2.8%) methods when compared to the original equations (Fig. 3). This indicates the great effect calibration has relative to other empirical equations on increasing the accuracy of temperature-based methods. This increase confirms the accuracy of calibrated empirical equations in estimating ET_{ref} in humid climate. At the same time, the accuracy of ET_{ref} estimation for all empirical equations decreased from very dry to humid climates, indicating that the process of ET_{ref} estimation in humid climate is more complex due to its greater dependence on multiple climatic parameters.

Fig. 3. The APE performance of original and calibrated empirical equations in different climates

3.2. Bias error evaluation of empirical equations

Figure 4 shows a decrease in MBE for calibrated empirical equations compared to the original empirical equations. This error reduction is evident in all types of equations and in all climates. Figure 4-a shows the overestimation of most empirical temperature-based methods in very dry, semidry and humid climates. The highest accuracy of empirical equations for temperature-based and solar radiation-based methods for estimating ET_{ref} in dry climate (Figs. 4a-2 and b-2) is obtained when the MBE in this climate for all empirical equations is less than 20 mm year^{-1} . Figure 4-c shows the overestimation of ET_{ref} values for mass transfer-based empirical equations in humid climate and underestimation in very dry, dry and semidry climates. The highest accuracy of MBE is acquired by mass transfer-based methods in semidry climate.

Fig. 4. The MBE performance of original and calibrated empirical equations in different climates

3.4. Correlation between $PM-FAO_{56}$ and empirical equations

Based on the results presented in Table 3, the highest accuracy of empirical equations for temperature-based, solar radiation-based and mass transfer-based methods of estimating ET_{ref} in different climates is determined by the BARO, JEHA and PENM equations, respectively. Figure 5 shows the values of D for the best equations of temperature-based, solar radiation-based and mass transfer-based methods in different climates. A better fit between the estimated ET_{ref} and $PM-FAO_{56}$ appears in the calibrated empirical equations when compared to the original empirical equations in all empirical equations and climates.

The best fit between the $PM-FAO_{56}$ and estimated ET_{ref} values is related to the calibrated PENM equation in humid climate and is equal to 0.94 (Fig. 5c-4). Generally, the best and worst fit between the $PM-FAO_{56}$ and estimated ET_{ref} values were related to the mass transfer-based (Fig. 5c) and the solar radiation-based methods (Fig. 5b).

Fig. 5. The D performance of original and calibrated empirical equations in different climates

Figure 6 shows $PM-FAO_{56}$ and estimated ET_{ref} values for the best empirical equations in different climates during 1990 to 2019. The estimated ET_{ref} values using the empirical equations

after calibration are very close to the calculated ET_{ref} values. This can especially be seen in the calibrated PENM equation in semidry climate (Fig. 6c-3).

Fig. 6. The estimated ET_{ref} versus PM-FAO₅₆ values in different climates

3.4. SI map

Figure 7 shows that calibration at stations with very dry climate, such as Zabol, Zahedan, Bam, Iranshahr and Chabahar stations, had a greater effect on the accuracy of ET_{ref} estimation based on the SI value in the excellent class ($SI < 0.1$). The highest amount of error in the SI index is related to stations with humid climates, such as Rasht and Nowshahr. This is due to the complexity of the ET_{ref} process in humid climate.

4. Conclusion

In general, the results show that most of the empirical equations had good accuracy in estimating ET_{ref} in all studied climates. However, the accuracy of the ET_{ref} estimate before and after calibration depended on the classification of the equation in the type and number of input data and the type of climate under study. The results of various empirical equations for temperature-based, solar radiation-based and mass transfer-based ET_{ref} estimation in very dry, dry, semidry and humid climates showed that in each climate, specific empirical equations have the desired accuracy. In other words, each climatic region has its own superior empirical equation. Also, with the complexity of climatic variables, the accuracy of various empirical equations is associated with change.

Based on the lowest value of RMSE and the highest value of R^2 , the empirical equations BARO for temperature-based, JEHA for solar radiation-based and PENM for mass transfer-based

methods showed the best results among the 32 empirical equations studied. The results of APE, MBE and D criteria show that the accuracy of the empirical equations after calibration increased significantly when compared to their original values. At the same time, the results of SI criterion and the effect of factors such as high relative humidity and the balance between air temperature and rainfall mean that the estimation of ET_{ref} is more complex. Considering the dependence of the ET_{ref} process on fewer meteorological parameters, we can conclude that in very dry climates the empirical equations before and after calibration are more accurate.

Availability of data and material: All data used in this article have been prepared from the Meteorological Organization of Iran and after validation, have been used. In this study, meteorological information was used that lacked outdated data.

Code availability: The software used in this research will be available (by the corresponding author), upon reasonable request.

Ethics approval: We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

Consent to participate: Conceptualization, Methodology, Technical Investigation, Writing (Original draft preparation), Supervision: S.S. and Software, Validation: M.M.G. All authors have read and agreed to the published version of the manuscript.

Consent for publication: We confirm that intellectual property associated with this work belong to the Journal of Theoretical and Applied Climatology.

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Figures

Figure 1

Location and classification of studied stations based on the FAO56 method Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

The long period values of a) rainfall, b) relative humidity, c) temperature, d) solar radiation and e) wind speed of Iran's climate (1990-2019)

Figure 3

The APE performance of original and calibrated empirical equations in different climates

Figure 4

The MBE performance of original and calibrated empirical equations in different climates

Figure 5

The D performance of original and calibrated empirical equations in different climates

Figure 6

The estimated ET_{ref} versus PM-FAO56 values in different climates

Figure 7

SI map of the best empirical equations in different climates Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.