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<sub>ref</sub>) 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<sub>ref</sub> 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, semi dry and humid climates of Iran. The performance of the original and calibrated empirical equations compared to the PM-FAO<sub>56</sub> equation was evaluated based on model evaluation techniques including: the coefficient of determination (R<sup>2</sup>), 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<sup>2</sup>=0.73, 0.67 and 0.78; RMSE=35.14, 35.02 and 30.20 mm year<sup>-1</sup>; and MBE=-5.6, -3.89 and 2.57 mm year<sup>-1</sup>. The original empirical equations had values of average R<sup>2</sup>=0.60, 0.37 and 0.65; RMSE=68.34, 66.98 and 52.62 mm year<sup>-1</sup>; and MBE=-5.75, 4.26 and 8.99 mm year<sup>-1</sup>, 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<sub>ref</sub> in different climates.

Keywords: Calibration, ET<sub>ref</sub> Estimation, Scatter Index, Water Resource, Zonation

1. Introduction
The estimation of reference evapotranspiration (ET<sub>ref</sub>) 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<sub>ref</sub> 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<sub>ref</sub> were developed based on empirical models, including temperature-based, solar radiation–based and mass transfer–based models.

In contrast, the FAO<sub>56</sub> Penman-Monteith (PM-FAO<sub>56</sub>) equation is the standard combination-based model used to estimate ET<sub>ref</sub> 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-FAO<sub>56</sub> equation shows relatively stable results, the equations for empirical models based on temperature, solar radiation and mass transfer use fewer climatic parameters in the
calculation of \( \text{ET}_{\text{ref}} \). Therefore, the development and calibration of empirical model equations in different climates can be more effective for agricultural and hydrological projects where only a few climatic variables are available (Heydari and Heydari, 2014; Gafurov et al. 2018).

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

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

2. Materials and Methods

2.1. Time and location scales

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

According to the FAO56 index, Iran is classified into four climatic regions: very dry, dry, semidy dryer and humid (Fig. 1). Fig. 1 shows the location and climate for each station used in this study. Six stations were in very dry climate, 17 stations in dry climate, 14 stations in semidy dryer climate and 4 stations in humid climate (Fig. 1).
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<sub>ref</sub> estimated based on empirical equations

| Code  | Solar Radiation-based | Referential | Empirical equations | References |
|-------|-----------------------|-------------|---------------------|------------|
| 1     | PM-FAO<sub>56</sub>   | ET<sub>ref</sub> | \[0.408\Delta(R_n - G) + \gamma [900 / (T_{mean} + 273)] u_2 (e_s - e_a) / \Delta + \gamma (1 + 0.34u_2)\] | Allen et al. (2006) |
| 2     | HASA                  | ET<sub>ref</sub> | \[0.0023 \times R_a (T_{mean} + 17.8) (T_{max} - T_{min})^{0.5} \] | Hargreaves and Samani (1985) |
| 3     | TRAJ                  | ET<sub>ref</sub> | \[0.0023 \times R_a (T_{mean} + 17.8) (T_{max} - T_{min})^{0.424} \] | Trajkovic (2007) |
| 4     | TATA1                 | ET<sub>ref</sub> | \[0.0031 \times R_a (T_{mean} + 17.8) (T_{max} - T_{min})^{0.5} \] | Tabari and Talaee (2011) |
| 5     | TATA2                 | ET<sub>ref</sub> | \[0.0028 \times R_a (T_{mean} + 17.8) (T_{max} - T_{min})^{0.5} \] | Tabari and Talaee (2011) |
| 6     | DRAL1                 | ET<sub>ref</sub> | \[0.003 \times R_a (T_{mean} + 20) (T_{max} - T_{min})^{0.4} \] | Droogers and Allen (2002) |
| 7     | DRAL2                 | ET<sub>ref</sub> | \[0.0025 \times R_a (T_{mean} + 16.8) (T_{max} - T_{min})^{0.5} \] | Droogers and Allen (2002) |
| 8     | BERT                  | ET<sub>ref</sub> | \[0.00193 \times R_a (T_{mean} + 17.8) (T_{max} - T_{min})^{0.517} \] | Berti et al. (2014) |
| 9     | DORJ                  | ET<sub>ref</sub> | \[0.002 \times R_a (T_{mean} + 33.9) (T_{max} - T_{min})^{0.296} \] | Dorji et al. (2016) |
| 10    | BARO                  | ET<sub>ref</sub> | \[0.109 \times (R_a / \lambda) + 0.157 T_{max} + 0.158 (T_{max} - T_{min}) - 5.39\] | Baier and Robertson (1965) |
| 11    | AHOO1                 | ET<sub>ref</sub> | \[0.252 \times (R_a / \lambda) + 0.22T_{mean} (1 - RH / 100)\] | Ahooghalandari (2016) |
| 12    | AHOO2                 | ET<sub>ref</sub> | \[0.29 \times (R_a / \lambda) + 0.15 T_{mean} (1 - RH / 100)\] | Ahooghalandari (2016) |

| Code  | Temperature-based | Empirical equations | References |
|-------|-------------------|---------------------|------------|
| 13    | MAKK              | ET<sub>ref</sub> | \[0.7 \times (R_a / \lambda) \times \Delta / \Delta + \gamma - 0.12\] | Makkink (1957) |
| 14    | PRTA              | ET<sub>ref</sub> | \[1.26 \times (R_n - G) \times \Delta / \Delta + \gamma / \lambda\] | Priestley and Taylor (1972) |
| 15    | JEHA              | ET<sub>ref</sub> | \[0.25T_{max} R_s / \lambda\] | Jensen and Haise (1963) |
| 16    | HARG              | ET<sub>ref</sub> | \[0.0135(T_{mean} + 17.8) R_s / \lambda\] | Hargreaves (1975) |
| 17    | ABTE1             | ET<sub>ref</sub> | \[0.25(T_{max} / 56) \times (R_s / \lambda)\] | Abtew (1996) |
| 18    | ABTE2             | ET<sub>ref</sub> | \[T_{mean} / (R_s / \lambda)\] | Abtew (1996) |
| 19    | IRMA1             | ET<sub>ref</sub> | \[-0.611 + 0.149 R_s + 0.079T_{mean}\] | Irmak et al. (2003) |
| 20    | IRMA2             | ET<sub>ref</sub> | \[0.469 + 0.289 R_s + 0.023T_{mean}\] | Irmak et al. (2003) |
| 21    | TATA3             | ET<sub>ref</sub> | \[-0.642 + 0.174 R_s + 0.0353T_{mean}\] | Tabari and Talaee (2011) |
| 22    | TATA4             | ET<sub>ref</sub> | \[-0.478 + 0.156 R_s - 0.0112T_{max} + 0.0733T_{min}\] | Tabari and Talaee (2011) |
| 23    | OUDI              | ET<sub>ref</sub> | \[(R_s / \lambda) \times (T_{mean} + 5) / 100\] | Oudin (2004) |

| Code  | Mass transfer-based | Empirical equations | References |
|-------|---------------------|---------------------|------------|
| 24    | DALT                | ET<sub>ref</sub> | \[(3.648 + 0.7223u_2)(e_s - e_a)\] | Dalton (1802) |
| 25    | MEYE                | ET<sub>ref</sub> | \[(3.75 + 0.503u_2)(e_s - e_a)\] | Meyer (1926) |
| 26    | ROHW                | ET<sub>ref</sub> | \[(3.3 + 0.891u_2)(e_s - e_a)\] | Rohwer (1931) |
| 27    | ALBR                | ET<sub>ref</sub> | \[(1.005 + 2.97u_2)(e_s - e_a)\] | Albrecht (1950) |
To calculate the PM-FAO56, measurements of the amount of total solar radiation at the Earth’s surface ($R_s$, MJ m$^{-2}$ 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 ($R_{nr}$, MJ m$^{-2}$ 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:

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

where Alt is altitude (m) and $K_{R_s}$ is the empirical constant, considered equal to 0.16 (Gholipoor, 2008). The $e_a$ 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:

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

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 $T_{\min} > 10$ °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:

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

where $e_a$ is obtained from the mean $e_a$ and $e_{max}$. Finally, $e_a$ 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 ($e_{max} - e_a$) $\times$ 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
55.34 percent with the highest relative humidity at Bandar Anzali station (84.71%) and the lowest relative humidity at Bam station (28.08%). The relative humidity in the very dry climate was 44.64 percent, which was 1.02, 7.9 and 35.93 percent less than in the dry, semidry and humid climates, respectively (Fig. 2b).

The 30-year average air temperature in Iran was reported to be 17.54 °C. The hottest and coldest stations in this study were the Bandar Abbas and Ardabil stations (26.63 and 9.14 °C, respectively). The average air temperature in the very dry climate was 20.44 °C, which was 3.4, 10.15 and 6.04 °C warmer than in the dry, semidry and humid climates, respectively (Fig. 2c). The average solar radiation received in Iran is reported to be 7.26 MJ m⁻² day⁻¹. The highest and lowest received solar radiation was observed in Bam and Rasht stations (9.06 and 4.17 MJ m⁻² day⁻¹, respectively). The average solar radiation received in the very dry climate was 8.55 MJ m⁻² day⁻¹, which increased by 0.36, 1.06 and 3.74 MJ m⁻² day⁻¹ in dry, semidry and humid climates (Fig. 2d). The average wind speed in the country during the last thirty years was reported to be 4.35 m s⁻¹, which has increased by about 0.52 m s⁻¹ compared to the same period. The highest and lowest wind speeds were recorded in Zabol and Gorgan stations, respectively (10.62 and 1.45 m s⁻¹). The mean wind speed 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 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$_{\text{ref}}$. In the present study, six statistical measures were used to evaluate the accuracy of each model in estimating the ET$_{\text{ref}}$: 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 ($R^2$)  | $R^2 = \frac{\sum_{i=1}^{N} (ET_{\text{ref}}^{\text{PM FAO56}} - \overline{ET}_{\text{ref}}^{\text{PM FAO56}})(ET_{\text{ref}}^{\text{model}} - \overline{ET}_{\text{ref}}^{\text{model}})}{\sqrt{\sum_{i=1}^{N} (ET_{\text{ref}}^{\text{PM FAO56}} - \overline{ET}_{\text{ref}}^{\text{PM FAO56}})^2} \sqrt{\sum_{i=1}^{N} (ET_{\text{ref}}^{\text{model}} - \overline{ET}_{\text{ref}}^{\text{model}})^2}}$ | Ma and Iqbal (1984) |
| (38) | Root mean square error (RMSE)         | $RMSE = \frac{1}{N} \sum_{i=1}^{N} (ET_{\text{ref}}^{\text{PM FAO56}} - ET_{\text{ref}}^{\text{PM FAO56}})^2$ | Ma and Iqbal (1984) |
| (39) | Average percentage error (APE)       | $APE = \frac{\sum_{i=1}^{N} |ET_{\text{ref}}^{\text{PM FAO56}} - ET_{\text{ref}}^{\text{model}}|}{\sum_{i=1}^{N} ET_{\text{ref}}^{\text{PM FAO56}}} \times 100\%$ | Behar et al. (2015) |
| (40) | Mean bias error (MBE)                | $MBE = \frac{1}{N} \sum_{i=1}^{N} (ET_{\text{ref}}^{\text{PM FAO56}} - ET_{\text{ref}}^{\text{PM FAO56}})$ | Ferreira and da Cunha (2020) |
| (41) | Index of agreement (D)               | $D = 1 - \frac{\sum_{i=1}^{N} (ET_{\text{ref}}^{\text{model}} - ET_{\text{ref}}^{\text{PM FAO56}})^2}{\sum_{i=1}^{N} (ET_{\text{ref}}^{\text{model}} - ET_{\text{ref}}^{\text{PM FAO56}})^2 + (ET_{\text{ref}}^{\text{model}} - \overline{ET}_{\text{ref}}^{\text{PM FAO56}})^2}$ | Seifi and Riahi-Madvar (2019) |
| (42) | Scatter Index (SI)                   | $SI = \frac{RMSE}{\overline{ET}_{\text{ref}}}$ | Li et al. (2013) |

In Eqs. (37) to (42), $ET_{\text{ref}}^{\text{PM FAO56}}$ and $ET_{\text{ref}}^{\text{model}}$ are the ET$_{\text{ref}}$ based on PM-FAO56, and modeled ET$_{\text{ref}}$, $\overline{ET}_{\text{ref}}^{\text{PM FAO56}}$ and $\overline{ET}_{\text{ref}}^{\text{model}}$ are the mean values of ET$_{\text{ref}}$ based on PM-FAO56 and modeled ET$_{\text{ref}}$ 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$_{\text{ref}}$ is the regression relationship between the ET$_{\text{ref}}$ 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$_{\text{ref}}$ 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 $ET_{\text{ref}}$ and the PM-FAO56.

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

The accuracy of empirical equations in estimating $ET_{\text{ref}}$ 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).
Radar charts in Fig. 3 compare the APE values of the $ET_{\text{ref}}^{PM\text{FAO}56}$ and the estimated $ET_{\text{ref}}$ 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 $ET_{\text{ref}}$ in humid climate. At the same time, the accuracy of $ET_{\text{ref}}$ estimation for all empirical equations decreased from very dry to humid climates, indicating that the process of $ET_{\text{ref}}$ estimation in humid climate is more complex due to its greater dependence on multiple climatic parameters.
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$_{\text{ref}}$ 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$_{\text{ref}}$ 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. 3. The APE 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$_{\text{ref}}$ 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$_{\text{ref}}$ 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$_{\text{ref}}$ 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$_{\text{ref}}$ values were related to the mass transfer–based (Fig. 5c) and the solar radiation–based methods (Fig. 5b).

Figure 6 shows PM-FAO$_{56}$ and estimated ET$_{\text{ref}}$ values for the best empirical equations in different climates during 1990 to 2019. The estimated ET$_{\text{ref}}$ values using the empirical equations
after calibration are very close to the calculated ET$_{\text{ref}}$ values. This can especially be seen in the calibrated PENM equation in semidry climate (Fig. 6c-3).

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$_{\text{ref}}$ 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$_{\text{ref}}$ process in humid climate.
4. Conclusion

In general, the results show that most of the empirical equations had good accuracy in estimating ET\textsubscript{ref} in all studied climates. However, the accuracy of the ET\textsubscript{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\textsubscript{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\textsuperscript{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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