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ORIGINAL ARTICLE

# Calibration of mass transfer-based models to predict reference crop evapotranspiration

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**Abstract** The present study aims to compare mass transfer-based models to determine the best model under different weather conditions. The results showed that the Penman model estimates reference crop evapotranspiration better than other models in most provinces of Iran (15 provinces). However, the values of $R^2$ were less than 0.90 for 24 provinces of Iran. Therefore, the models were calibrated, and precision of estimation was increased (the values of $R^2$ were less than 0.90 for only ten provinces in the modified models). The mass transfer-based models estimated reference crop evapotranspiration in the northern (near the Caspian Sea) and southern (near the Persian Gulf) Iran (annual relative humidity more than 65 %) better than other provinces. The best values of $R^2$ were 0.96 and 0.98 for the Trabert and Rohwer models in Ardabil (AR) and Mazandaran (MZ) provinces before and after calibration, respectively. Finally, a list of the best performances of each model was presented to use other regions and next studies according to values of mean, maximum, and minimum temperature, relative humidity, and wind speed. The best weather conditions to use mass transfer-based equations are 8–18 °C (with the exception of Ivanov), <25.5 °C, <15 °C, >55 % for mean, maximum, and minimum temperature, and relative humidity, respectively.

**Keywords** Calibration · Evapotranspiration · FAO Penman–Monteith · Humidity · Iran

## Introduction

The maximum precision of actual evapotranspiration could be obtained using lysimeter (Xu and Chen 2005; Valipour 2012a, b; Valipour 2015b, c) or imaging techniques (Hart et al. 2009) that their costs are too high. Thus, the FAO Penman–Monteith model (Allen et al. 1998) has been replaced to estimate reference crop evapotranspiration. Although the FAO Penman–Monteith (FPM) has been applied in various regions of the world (Rahimi et al. 2015; Valipour 2014m, n, o; Valipour and Eslamian 2014), but it needs too many parameters to estimate reference crop evapotranspiration. In the most regions, as weather data are limited, it is not possible to use the FPM. Therefore, empirical methods including mass transfer-, radiation-, temperature-, and pan evaporation-based methods have been developed for estimation of the reference crop evapotranspiration using limited data. The mass transfer-based model is one of the most widely used models for estimating reference crop evapotranspiration. Valipour (2014p, q, r, s, t) studied estimation of evapotranspiration in Iran. The results showed that each province of Iran needs to a specified evapotranspiration equation, if the highest accuracy is desirable. Further examination of the performance resulted in the following rank of precision as compared with the FPM estimates: Priestley-Taylor, Makkink, Hargreaves, Blaney-Criddle, and Rohwer (Xu and Singh 2002). Adjusted Dalton model gives the better estimation of reference crop evapotranspiration compared with adjusted Penman–Monteith model for the Kendall subwatershed (Rim 2000). The top six ranked methods obtained for the average as well as for central Saudi Arabia ratings are ranked in the following order of merit: Jensen-Haise, class A pan, Ivanov, adjusted class A pan, Behnke-Maxey, and Stephens-Stewart (Al-Sha'lan and Salih 1987). Azhar

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and Perera (2011) calibrated the Meyer model as well as nine other (temperature and radiation-based) models under Southeast Australian Conditions successfully. Zhai et al. (2010) calibrated the Hargreaves, Makkink, Turc, Priestley–Taylor, Jensen–Haise, Doorenbos-Pruitt, Abtew, McGuinness-Bordne, Rohwer, and Blaney–Criddle. It can be concluded that calibration can be used to modify reference crop evapotranspiration equations with multi-station data to improve the precision of reference crop evapotranspiration estimates in northwest China. Singh and Xu (1997) evaluated the Meyer, Dalton, and Rohwer for determining free water evaporation at four climatological stations in north-western Ontario, Canada. The results of comparison showed that all equations were in reasonable agreement with observed evaporation. More accurate estimation of potential evapotranspiration can help other studies including surface and pressurized irrigation water management (Mahdizadeh Khasraghi et al. 2014; Valipour 2012c, e, f, g, h, 2013a, b, c, d, 2014a, b, c, d, e, f, g, h, i, j, k, l, y, 2015a, b; Valipour and Montazar 2012a, b, c), drainage engineering (Valipour 2012i, j, 2013g, h, 2014v, w), environmental studies (Valipour 2012d, 2013a, b, 2014x), and water resources management (Banihabib et al. 2012; Valipour 2012a, b, c, d, 2013c, e, f, 2014u, 2015a). In the previous studies, one or more of the mass transfer-based models are compared with temperature, radiation, or pan evaporation-based models. In other cases, there are some models which can estimate reference crop evapotranspiration better than the mass transfer-based models. This is because the previous studies focus on specific weather conditions (not suitable for applying the mass transfer-based model) or/and do not consider mass transfer-based models. Moreover, the results of the previous studies are not useable for estimating reference crop evapotranspiration in other regions, because they are recommended for one or more climatic conditions. However, a climatic condition contains various value of weather parameters (e.g., temperature, relative humidity, wind speed, solar radiation, etc.), and results of each research (for a region with specific weather variations) are not applicable for other regions without determining specified ranges of each weather parameter even if climatic conditions (e.g., humid, arid, semi-arid, temperate, etc.) are the same for both regions. In addition, the governments cannot schedule for irrigation and agricultural water management when reference crop evapotranspiration is estimated for a basin, wetland, watershed, or catchment instead a state or province (different parts of them are located at more than one state or province) and/or number of weather station used is low (increasing uncertainty). Therefore, this study aims to estimate reference crop evapotranspiration for 31 provinces of Iran (considering their usability for long-term and macroeconomic policies of governments and adaptability to various weather conditions) using average data of 181 synoptic station (decreasing uncertainty) and by 11 mass transfer-based models to determine the best model based on the weather conditions of each province (for which the best weather parameters are determined to use other regions and next researches) as well as increasing precision of the models by calibration of them for each province.

## Materials and methods

In this study, weather information (from 1951 to 2010) is gathered from 181 synoptic stations of 31 provinces in Iran. Table 1 shows the number of years that data were

**Table 1** Position of all provinces and synoptic stations

| Province | Latitude (N) | Longitude (E) | Recorded length (year) | No. of station |
|---|---|---|---|---|
| AL | 35°55′ | 50°54′ | 20 | 1 |
| AR | 38°15′ | 48°17′ | 30 | 4 |
| BU | 28°59′ | 50°50′ | 55 | 5 |
| CB | 32°17′ | 50°51′ | 51 | 4 |
| EA | 38°05′ | 46°17′ | 55 | 10 |
| ES | 32°37′ | 51°40′ | 55 | 12 |
| FA | 29°32′ | 52°36′ | 55 | 9 |
| GH | 36°15′ | 50°03′ | 47 | 2 |
| GI | 37°15′ | 49°36′ | 50 | 4 |
| GO | 36°51′ | 54°16′ | 54 | 3 |
| HA | 34°52′ | 48°32′ | 55 | 4 |
| HO | 27°13′ | 56°22′ | 49 | 9 |
| IL | 33°38′ | 46°26′ | 20 | 3 |
| KB | 30°50′ | 51°41′ | 19 | 1 |
| KE | 30°15′ | 56°58′ | 55 | 8 |
| KH | 31°20′ | 48°40′ | 55 | 14 |
| KO | 35°20′ | 47°00′ | 47 | 7 |
| KS | 34°21′ | 47°09′ | 55 | 6 |
| LO | 33°26′ | 48°17′ | 55 | 9 |
| MA | 34°06′ | 49°46′ | 51 | 4 |
| MZ | 36°33′ | 53°00′ | 55 | 7 |
| NK | 37°28′ | 57°16′ | 24 | 1 |
| QO | 34°42′ | 50°51′ | 20 | 1 |
| RK | 36°16′ | 59°38′ | 55 | 12 |
| SB | 29°28′ | 60°05′ | 55 | 8 |
| SE | 35°35′ | 53°33′ | 55 | 4 |
| SK | 32°52′ | 59°12′ | 51 | 3 |
| TE | 35°41′ | 51°19′ | 55 | 8 |
| WA | 37°32′ | 45°05′ | 55 | 8 |
| YA | 31°54′ | 54°17′ | 54 | 6 |
| ZA | 36°41′ | 48°29′ | 51 | 4 |

measured and number of stations along with latitude and longitude.

In each station, average weather data in years measured are considered as value of that weather parameter in each month (e.g., value of relative humidity in July for NK is average of 24 data gathered). A spatial interpolation method is usually used to obtain an averaged value from stations. However, the most of synoptic stations have been distributed in north, south, west, and east of each province based on different weather conditions and considering equal spatial distances to skip spatial interpolation method. Therefore, average of data in all stations has been considered as value of that weather parameter in each month for provinces with more than one station (e.g., value of relative humidity in July for KH is average of 55 × 14 = 770 data gathered). All of the data mentioned were used for estimating reference crop evapotranspiration using 11 mass transfer-based models and compared with FAO Penman–Monteith (FPM) model to determine the best model based on the weather conditions of each province (Table 2).

The parameters of each model indicate that each model apply how many parameters to estimate evapotranspiration. In addition, in some synoptic stations, there is no access to all of them; therefore, the researchers can select the best model based on available data and error of each model. The best model for each province and the best performance of each model were determined using the coefficient of determination [Eq. (1)] and mean bias error [Eq. (2)]:

$$R^2 = 1 - \sum\left(\mathrm{ET}_{\mathrm{FPM}_i} - \mathrm{ET}_{\mathrm{m}_i}\right)^2 \Big/ \sum\left(\mathrm{ET}_{\mathrm{FPM}_i} - \frac{\sum \mathrm{ET}_{\mathrm{FPM}_i}}{12}\right)^2 \qquad (1)$$

$$\mathrm{MBE} = \left(\sum \mathrm{ET}_{\mathrm{FPM}_i} - \mathrm{ET}_{\mathrm{m}_i}\right)/12 \qquad (2)$$

In which, $i$ indicates month, $\mathrm{ET_{FPM}}$ indicates reference crop evapotranspiration calculated for FAO Penman–Monteith (FPM) model, $\mathrm{ET_m}$ indicates reference crop evapotranspiration calculated for mass transfer-based models, and MBE is mean bias error (MBE). These formulae were selected due to wide use in previous works as well as their capability to compare with other studies. The best model for each province was modified to increase precision of estimating by calibration of the coefficients (Table 2) similar to the studies of Irmak et al. (2003) and Xu and Singh (2000) and using multiplication linear regressions in which the FPM values were used as the dependent variable, and other parameters (Table 2) were the independent variables. In each province, two-third of the data were used for development of the equations and one-third of the data were applied for validation. This partitioning is due to need to more data for training the models based on previous works (e.g., Xu and Singh 2000). Then, reference crop evapotranspiration calculated using new formulas was compared with FPM, and variations of the errors were investigated. Finally, map of annual average of solar radiation, mean, maximum, and minimum temperature, relative humidity, and wind speed was provided, and the best performance of each model based on these values was determined. Meanwhile, the map of the best model for each province and the map of the error calculated for each province have been presented.

**Table 2** Model used and parameters applied in each model

| Model | References | Formula | Parameters |
|---|---|---|---|
| FAO Penman–Monteith | Allen et al. (1998) | $\mathrm{ET}_o = \frac{0.408(R_n - G) + \gamma\frac{900}{T+273}u\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34u)}$ | $H$, $\varphi$, $T$, $T_{\min}$, $T_{\max}$, RH, $u$, $n$ |
| Albrecht | Albrecht (1950) | $\mathrm{ET}_o = (1.005 + 2.97u)\,(e_s - e_a)$ | $T$, $T_{\min}$, $T_{\max}$, RH, $u$ |
| Brockamp-Wenner | Brockamp and Wenner (1963) | $\mathrm{ET}_o = 5.43u^{0.456}(e_s - e_a)$ | $T$, $T_{\min}$, $T_{\max}$, RH, $u$ |
| Dalton | Dalton (1802) | $\mathrm{ET}_o = (3.648 + 0.722u)(e_s - e_a)$ | $T$, $T_{\min}$, $T_{\max}$, RH, $u$ |
| Ivanov | Romanenko (1961) | $\mathrm{ET}_o = 0.00006(25 + T)^2(100 - \mathrm{RH})$ | $T$, RH |
| Mahringer | Mahringer (1970) | $\mathrm{ET}_o = 2.86u^{0.5}(e_s - e_a)$ | $T$, $T_{\min}$, $T_{\max}$, RH, $u$ |
| Meyer | Meyer (1926) | $\mathrm{ET}_o = (3.75 + 0.503u)(\mathrm{e}_s - e_a)$ | $T$, $T_{\min}$, $T_{\max}$, RH, $u$ |
| Papadakis | Papadakis (1966) | $\mathrm{ET}_o = 2.5(e_{\mathrm{ma}} - e_a)$ | $T_{\min}$, $T_{\max}$, RH |
| Penman | Penman (1948) | $\mathrm{ET}_o = (2.625 + 0.000479/u)(\mathrm{e}_s - e_a)$ | $T$, $T_{\min}$, $T_{\max}$, RH, $u$ |
| Rohwer | Rohwer (1931) | $\mathrm{ET}_o = (3.3 + 0.891u)\,(e_s - e_a)$ | $T$, $T_{\min}$, $T_{\max}$, RH, $u$ |
| Trabert | Trabert (1896) | $\mathrm{ET}_o = 3.075u^{0.5}(e_s - e_a)$ | $T$, $T_{\min}$, $T_{\max}$, RH, $u$ |
| WMO | WMO (1966) | $\mathrm{ET}_o = (1.298 + 0.934u)(e_s - e_a)$ | $T$, $T_{\min}$, $T_{\max}$, RH, $u$ |

*$ET_o$* reference crop evapotranspiration (mm $\mathrm{day}^{-1}$), $R_n$ net radiation (MJ $\mathrm{m}^{-2}$ $\mathrm{day}^{-1}$), $G$ soil heat flux (MJ $\mathrm{m}^{-2}$ $\mathrm{day}^{-1}$), $\gamma$ psychrometric constant (kPa/ °C), $e_s$ saturation vapor pressure (kPa), $e_a$ actual vapor pressure (kPa), $\Delta$ slope of the saturation vapor pressure–temperature curve (kPa/ °C), $T$ average daily air temperature (°C), $u$ mean daily wind speed at 2 m (m $\mathrm{s}^{-1}$), $H$ elevation (m), $\varphi$ latitude (rad), $T_{min}$ minimum air temperature (°C), $T_{max}$ maximum air temperature (°C), *RH* average relative humidity (%), $n$ actual duration of sunshine (hr), $R_s$ solar radiation (MJ $\mathrm{m}^{-2}$ $\mathrm{day}^{-1}$), $e_{ma}$ saturation vapor pressure at the monthly mean daily maximum temperature

## Results and discussion

### Estimating reference crop evapotranspiration for the 31 provinces of Iran

Table 3 and Eq. (2) indicate that in all models (in the most cases), the estimations are more than reference crop evapotranspiration calculated using the FPM, except the Penman. The Albrecht model provided the greatest overestimate 17.7 mm day$^{-1}$, while the Papadakis and Penamn models yielded the least overestimate 0.03 mm day$^{-1}$ both for AR and QO, respectively (Table 3). This underlines that mass transfer-based models should be used carefully in accordance with weather conditions of each province. Because according to the $R^2$ values, each model estimates reference crop evapotranspiration for only one or few provinces as acceptable. In the other words, precision of estimating by mass transfer-based models is very sensitive to variations of the parameters used in each model (Table 2).

**Table 3** Average error of the model used for all provinces

| Model | Evaluation index | Average of all provinces |
|---|---|---|
| Al. | MBE | −6.29 |
| | $R^2$ | 0.71 |
| BW | MBE | −6.05 |
| | $R^2$ | 0.69 |
| Da. | MBE | −2.82 |
| | $R^2$ | 0.73 |
| Iv. | MBE | −1.80 |
| | $R^2$ | 0.38 |
| Ma. | MBE | −1.54 |
| | $R^2$ | 0.45 |
| Me. | MBE | −2.28 |
| | $R^2$ | 0.70 |
| Pa. | MBE | −2.05 |
| | $R^2$ | 0.78 |
| Pe. | MBE | 0.65 |
| | $R^2$ | 0.83 |
| Ro. | MBE | −2.89 |
| | $R^2$ | 0.49 |
| Tr. | MBE | −1.95 |
| | $R^2$ | 0.79 |
| WMO | MBE | −0.51 |
| | $R^2$ | 0.39 |

The underlines show the best value of each method, and the bolds show the best value of each province

*Al.* Albrecht, *BW* Brockamp–Wenner, *Da.* Dalton, *Iv.* Ivanov, *Ma.* Mahringer, *Me.* Meyer, *Pa.* Papadakis, *Pe.* Penman, *Ro.* Rohwer, *Tr.* Trabert

### Comparison of the best models for each province

Figure 1 compares reference crop evapotranspiration using FPM with values estimated using the best method (based on Table 3) for each province.

The Trabert for AR ($R^2 = 0.96$ and $\mathrm{MBE} = -0.01$), Mahringer for West Azerbaijan (WA) ($R^2 = 0.93$ and $\mathrm{MBE} = 0.20$), Brockamp-Wenner for Gilan (GI) ($R^2 = 0.92$ and $\mathrm{MBE} = -0.27$), and Ivanov for Bushehr (BU) ($R^2 = 0.92$ and $\mathrm{MBE} = -0.43$) yielded the best reference crop evapotranspiration as compared to that from the FPM. However, the Penman has been introduced as the best model in the most provinces (15 provinces). In general, mass transfer-based models are more suitable ($R^2$ more than 0.90) for East Azerbaijan (EA), WA, AR, Gorgan (GO), GI, MZ, (north of Iran), and BU (south of Iran). However, preciseness of estimating is not desirable ($R^2$ less than 0.80) in Khuzestan (KH), Semnan (SE), Sistan and Baluchestan (SB), Kerman (KE), Kohkiluyeh and Boyerahmad (KB), Lorestan (LO), and Hormozgan (HO), and it is less than 0.90 for 24 provinces of Iran. These values indicate very different performance of the mass transfer-based models for a specific weather condition in each province. For instance, an impressive difference between the World Meteorological Organization (WMO) and Brockamp–Wenner models is observable in comparison Zanjan (ZA), Ghazvin (GH), and Hamedan (HA) (the Brockamp–Wenner is the worst model and the WMO is the best model) with GI (the WMO is the worst model and the Brockamp–Wenner is the best model). However, according to Table 2, the Ivanov model is a function of mean temperature and relative humidity, the Papadakis is a function of minimum and maximum temperature and relative humidity, and the other models are a function of mean, minimum, and maximum temperature, relative humidity,

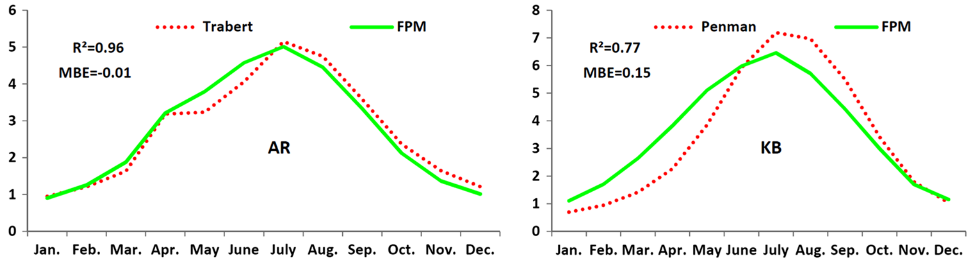

**Fig. 1** Comparison of evapotranspiration (mm day$^{-1}$) calculated using FAO Penman-Montieth (*FPM*) with the best model for the best (AR) and the worst (KB) accuracy

and wind speed. In addition, the only difference among the Albrecht, Dalton, Meyer, Rohwer, and WMO models is coefficients used in each model (Table 2) as well as the only difference among the Brockamp–Wenner, Mahringer, and Trabert models is also coefficients used in each model (Table 2). Thus, the coefficients of the mass transfer-based models need to be adjusted based on weather conditions of each province.

## Calibration of the best models based on their coefficients

The best models for each province (Table 2 and Fig. 1) are calibrated similar to the studies of Irmak et al. (2003) and Xu and Singh (2000). Table 4 shows the new formulas with the coefficients calibrated for each province.

According to Table 4, all models calibrated estimate reference crop evapotranspiration less than the FPM (with the exception of the Ivanov and Rohwer for BU and MZ, respectively). Figure 2 compares reference crop evapotranspiration using the FPM with values estimated using the models calibrated (based on Table 4) for each province.

According to Figs. 1 and 2, preciseness of the models calibrated has been increased in all provinces. The $R^2$ values are less than 0.90 for ten provinces [Esfahan (ES), Ilam (IL), SB, Fars (FA), Qom (QO), Kordestan (KO), Kermanshah (KS), KB, LO, and Yazd (YA)]. In the

**Table 4** Formula calibrated and their error for each province

| Province | Method calibrated | New formula | $R^2$ | MBE |
|---|---|---|---|---|
| CB | Mahringer | $ET_o = 2.385u^{0.955}(e_s - e_a)$ | 0.94 | 0.20 |
| EA | Papadakis | $ET_o = 2.206(e_{ma} - e_a)$ | 0.96 | 0.05 |
| WA | Mahringer | $ET_o = 1.922u^{1.536}(e_s - e_a)$ | 0.96 | 0.15 |
| AR | Trabert | $ET_o = 4.027u^{0.293}(e_s - e_a)$ | 0.96 | 0.02 |
| ES | Penman | $ET_o = (4.313 - 3.510/u)(e_s - e_a)$ | 0.87 | 0.39 |
| IL | Penman | $ET_o = (2.346 + 0.555/u)(e_s - e_a)$ | 0.86 | 0.30 |
| BU | Ivanov | $ET_o = 0.0000556(25 + T)^2(100 - RH)$ | 0.96 | −0.04 |
| TE | Penman | $ET_o = (5.119 - 6.510/u)(e_s - e_a)$ | 0.92 | 0.38 |
| AL | WMO | $ET_o = (0.719 + 0.970u)(e_s - e_a)$ | 0.92 | 0.22 |
| SK | Penman | $ET_o = (3.352 - 0.947/u)(e_s - e_a)$ | 0.95 | 0.16 |
| RK | WMO | $ET_o = (3.231 + 0.00251u)(e_s - e_a)$ | 0.93 | 0.23 |
| NK | WMO | $ET_o = (3.074 + 0.215u)(e_s - e_a)$ | 0.93 | 0.21 |
| KH | Penman | $ET_o = (2.559 - 0.876/u)(e_s - e_a)$ | 0.91 | 0.38 |
| ZA | WMO | $ET_o = (1.966u - 0.440)(e_s - e_a)$ | 0.91 | 0.23 |
| SE | Penman | $ET_o = (2.555 - 0.555/u)(e_s - e_a)$ | 0.90 | 0.25 |
| SB | Penman | $ET_o = (4.097 - 3.616/u)(e_s - e_a)$ | 0.88 | 0.34 |
| FA | Penman | $ET_o = (4.315 - 3.948/u)(e_s - e_a)$ | 0.84 | 0.43 |
| QO | Penman | $ET_o = (3.082 - 1.440/u)(e_s - e_a)$ | 0.89 | 0.35 |
| GH | WMO | $ET_o = (1.215 + 0.834u)(e_s - e_a)$ | 0.91 | 0.26 |
| KO | Penman | $ET_o = (5.456 - 5.664/u)(e_s - e_a)$ | 0.85 | 0.39 |
| KE | Penman | $ET_o = (3.965 - 2.681/u)(e_s - e_a)$ | 0.91 | 0.30 |
| KS | Penman | $ET_o = (6.436 - 9.027/u)(e_s - e_a)$ | 0.85 | 0.42 |
| KB | Penman | $ET_o = (3.351 - 1.239/u)(e_s - e_a)$ | 0.79 | 0.39 |
| GO | Trabert | $ET_o = 3.097u^{0.543}(e_s - e_a)$ | 0.94 | 0.09 |
| GI | Brockamp-Wenner | $ET_o = 1.779u^{0.835}(e_s - e_a)$ | 0.94 | 0.12 |
| LO | Penman | $ET_o = (7.236 - 8.377/u)(e_s - e_a)$ | 0.84 | 0.45 |
| MZ | Rohwer | $ET_o = (4.098u - 3.227)(e_s - e_a)$ | 0.98 | −0.01 |
| MA | WMO | $ET_o = (2.061u - 0.656)(e_s - e_a)$ | 0.90 | 0.24 |
| HO | WMO | $ET_o = (1.353 + 0.762u)(e_s - e_a)$ | 0.95 | 0.07 |
| HA | WMO | $ET_o = (2.048u - 0.127)(e_s - e_a)$ | 0.95 | 0.16 |
| YA | Penman | $ET_o = (7.236 - 8.377/u)(e_s - e_a)$ | 0.87 | 0.44 |

$ET_o$ reference crop evapotranspiration (mm day$^{-1}$), $e_s$ saturation vapor pressure (kPa), $e_a$ actual vapor pressure (kPa), $T$ average daily air temperature (°C), $u$ mean daily wind speed at 2 m (m s$^{-1}$), $RH$ average relative humidity (%), $e_{ma}$ saturation vapor pressure at the monthly mean daily maximum temperature

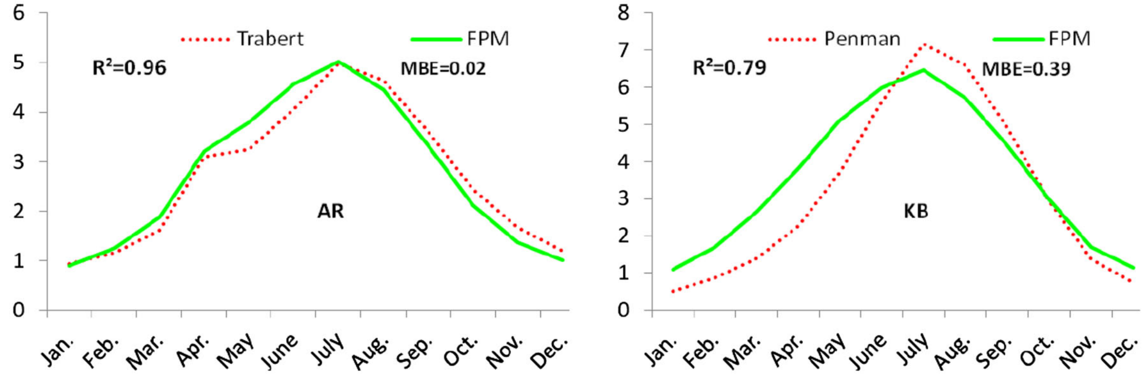

**Fig. 2** Comparison of evapotranspiration (mm day$^{-1}$) calculated using FAO Penman-Montieth (*FPM*) with the best model calibrated for the best (AR) and the worst (KB) accuracy

**Table 5** The best range to use the models based on the results of current study

| Model | $T$ | $T_{\max}$ | $T_{\min}$ | RH | $u$ | $R^2$ | MBE |
|---|---|---|---|---|---|---|---|
| Albrecht | 14–16 | 19.5–21.0 | 11–13 | >80 | 1.25–1.50 | 0.86 | 0.30 |
| Brockamp–Wenner | 14–16 | 19.5–21.0 | 11–13 | >80 | 1.25–1.50 | 0.92 | −0.27 |
| Dalton | 8–10 | <16.5 | <3 | 70–75 | >3.50 | 0.94 | −0.19 |
| Ivanov | 24–26 | – | – | 65–70 | – | 0.92 | −0.43 |
| Mahringer | 8–10 | <16.5 | <3 | 70–75 | >3.50 | 0.94 | 0.19 |
| Meyer | 8–10 | <16.5 | <3 | 70–75 | >3.50 | 0.94 | 0.15 |
| Papadakis | – | <16.5 | <3 | 70–75 | – | 0.94 | −0.03 |
| Penman | 16–18 | 24.0–25.5 | 7–9 | 35–40 | 2.50–2.75 | 0.87 | 0.76 |
| Rohwer | 16–18 | 21.0–22.5 | 13–15 | 75–80 | 1.75–2.00 | 0.91 | −0.13 |
| Trabert | 8–10 | <16.5 | <3 | 70–75 | >3.50 | 0.96 | −0.01 |
| WMO | 12–14 | 19.5–21.0 | 5–7 | 55–60 | 2.25–2.50 | 0.88 | 0.04 |

*T* average daily air temperature (°C), *u* mean daily wind speed at 2 m (m s$^{-1}$), $T_{min}$ minimum air temperature (°C), $T_{max}$ is the maximum air temperature (°C), *RH* is the average relative humidity (%)

Papadakis model (for EA), the coefficient of the model has been decreased 11.8 %, and $R^2$ has been increased 6.7 %. In the Mahringer model, the multiplication coefficients have been decreased 16.6 and 32.8 %, power coefficients have been increased 91 and 207.2 %, and $R^2$ has been increased 11.9 and 3.2 % (average of 7.5 %) for CB and WA, respectively. In the Trabert model, the multiplication coefficients have been increased 31 and 0.7 %, power coefficients have been decreased 41.4 and −8.6 % (increasing), but $R^2$ has not been changed for AR and GO, respectively (the Trabert model does not need to calibration for its the best performance in Iran). In the Ivanov model (for BU), the multiplication coefficient has been decreased 7.3 %, and $R^2$ has been increased 4.3 %. In the Brockamp–Wenner model (for GI), multiplication coefficient has been decreased 67.2 %, power coefficient has been increased 83.1 %, and $R^2$ has been increased 2.1 %. Similarly, in the Rohwer, WMO, and Penman models, we can see a considerable change in the coefficients (increasing or decreasing) and $R^2$ (increasing) of the models after calibration (Figs. 1, 2; Tables 2, 4). Therefore, calibration is a necessary tool for modification of mass transfer-based models to increase preciseness of estimation and to adapt the best models to weather conditions (local conditions) of each province. In the models calibrated (Fig. 2), the Rohwer estimates reference crop evapotranspiration for MZ better than the other models.

## Determining the best values of weather parameters for the best models to become applicable for next studies

According to Table 5, the best performance of the Albrecht and Brockamp–Wenner models is in similar weather conditions ($T = 14$–$16$ °C, $T_{\max} = 19.5$–$21.0$ °C, $T_{\min} = 11$–$13$ °C, RH $> 80$ %, and $u = 1.25$–$1.50$ m s$^{-1}$). This is true for the Dalton, Mahringer, Meyer, and Trabert ($T = 8$–$10$ °C, $T_{\max} < 16.5$ °C, $T_{\min} < 3$ °C, RH $= 70$–$75$ %,

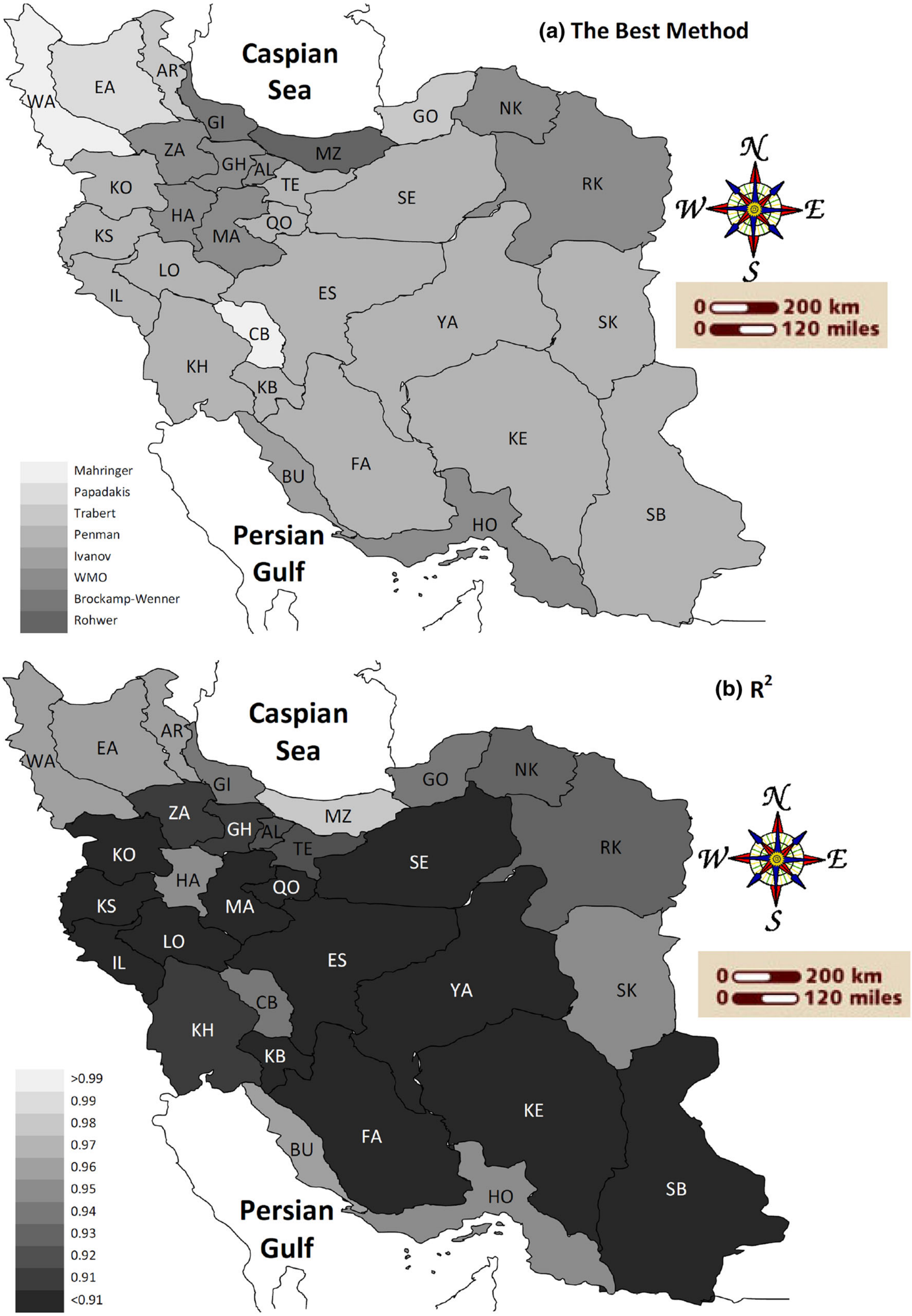

Fig. 3 The best model for each province (a) and their error after calibration (b)

and $u > 3.50$ m s$^{-1}$). However, the precision of them is different (e.g., 0.86 and 0.92 for the Albrecht and Brockamp–Wenner models, respectively). This underlines the important role of selection of the best model for a specified weather condition. Furthermore, we can see different ranges in the Ivanov, Penman, Rohwer, Papadakis, and WMO models (Table 5). This is due to different coefficient of these models that obtained for the best performance of each model (Table 4). Therefore, we can use the mass transfer-based models for other regions (in other countries) based on Table 5 with respect to their errors. The best weather conditions to use mass transfer-based equations are 8–18 °C (with the exception of Ivanov), <25.5 °C, <15 °C, and >55 % (with the exception of Penman) for mean, maximum, and minimum temperature, and relative humidity, respectively. The results are also useful for selecting the best model when we must apply mass transfer-based models based on available data.

### Comparison of the best models with their errors for each province

Figure 3 was plotted to detect the best model for each province versus its error (after calibration). According to Table 3, the best models (before calibration) for each province were selected, and their coefficients were calibrated (Table 4) to increase accuracy of estimation (Figure 3).

First, although the Penman model is the most useful model for provinces of Iran (15 provinces), but it is not suitable for four of the categories [near the Persian Gulf, near the Caspian Sea, north east of Iran, and Chaharmahal and Bakhtiari (CB)]. This confirms that the categories are reliable, and these four categories need to receive more attention due to specific weather conditions. Moreover, precision of the Penman models calibrated is less than 0.91 [with the exception of South Khorasan (SK), Tehran (TE), and KH]. It reveals that the Penman model is a general model for estimating reference crop evapotranspiration (high application and low precision). Thus, we require other temperature, radiation, and pan evaporation-based models to estimate reference crop evapotranspiration in these 15 provinces. For instance, values of solar radiation are more than 25.0 MJ m$^{-2}$ day$^{-1}$ for SB, KE, FA, and KB; hence, the radiation-based models may be useful for these provinces (Fooladmand 2008; Fooladmand 2011). The second favorite (selected for eight provinces) model is the WMO for which precision of estimating is less than 0.94 (with the exception of HA and HO both 0.95). However, the less favorite (selected for only one or two provinces) models including Rohwer, Papadakis, Mahringer, Brockamp–Wenner, Trabert, and Ivanov estimate reference crop evapotranspiration with $R^2$ more than 0.94. It is revealed that only if we use the mass transfer-based models for suitable (based on Table 5) and specific weather conditions, the highest precision of estimating is obtained. Meanwhile, precision of estimating is more than 0.94 for the categories I–IV (with the exception of ZA 0.91). Although the average value of weather parameters in a certain province is used for evapotranspiration estimation of that province, the evapotranspiration is a function of many weather parameters and a significant underestimation or overestimation of evapotranspiration for a province occurs for considerable variations of weather parameters. Therefore, possibility of simultaneous difference of some weather parameters with their average values which leads to a significant underestimation or overestimation of evapotranspiration for a province is poor. However, it is better to spatially distribute the weather parameters first and then to estimate the water requirements for each province for better estimation of crop water requirement of each province. In a study by Basharat and Tariq (2013), for example, they observed that the tail reaches require 33 % (maximum) more water than the head reaches due to variation of rainfall in LBDC canal command in Pakistan. Also in some studies, the Penman–Monteith method shows the 10 % variation when compared with the lysimeter data. Therefore, replacement of FPM model with lysimeter data can be recommended for next studies.

## Summary and conclusions

In this study, 11 mass transfer-based models were used to estimate reference crop evapotranspiration in 31 provinces of Iran. In summary, the precision of estimation by mass transfer-based models is very sensitive to variations of the parameters used in each model. Thus, the coefficients of the mass transfer-based models need to be adjusted based on weather conditions of each province. According to the results, calibration is a tool required to modify mass transfer-based models the precision of estimation and to adapt the best models to weather conditions (local conditions) of each province. In the models calibrated, the Rohwer estimates reference crop evapotranspiration for MZ better than the other models. The provinces of Iran are divided into five categories (at least): the provinces near the Persian Gulf (KH, BU, and HO), the provinces near the Caspian Sea (GI, MZ, and GO), the provinces of northeast of Iran (WA, EA, AR, and ZA), CB (due to the difference weather conditions compared to the near provinces), and the other provinces. These categories are useful for future studies over Iran. It is possible to use radiation-based models for other regions (in other countries) based on the best values of each weather parameter for best models with respect to their errors. Only if the radiation-based methods are used for suitable and specific weather conditions (based on weather conditions and the categories), the highest precision of estimation is obtained. The best weather conditions to use mass transfer-based equations are 8–18 °C (with the exception of Ivanov), <25.5 °C, <15 °C, and >55 % (with the exception of Penman) for mean, maximum, and minimum temperature, and relative humidity, respectively. In addition, the results indicate that the Penman model is a general model for estimating reference crop evapotranspiration (high application and low precision).

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