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ORIGINAL ARTICLE

Evaluation and calibration of Blaney–Criddle equation for estimating reference evapotranspiration in semiarid and arid regions

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Abstract Penman–Monteith (FAO-56 PM) equation is suggested as the standard method for estimating evapotranspiration by the International Irrigation and Drainage Committee and FAO. On the other hand, the Blaney–Criddle (BC) temperature-based equation is an alternative and simple method compared with the FAO-56 PM equation. In the present study, the original coefficients BC equation (*a* and *b*) were calculated and calibrated spatial and temporal calibration at each station for each month based on the FAO-56 PM method for estimating reference evapotranspiration (ET_0) from 15 meteorological stations in central Iran (about 170,000 km^2) under semi-arid and arid conditions. The values of *a* and *b* in BC equation were negative and positive for all months of any station, respectively. Highest and lowest *a* values were obtained in December and August, respectively. December showed the lowest b values while August showed the highest. Therefore, the values of *a* and *b* were greater in cold and warm months of the year, respectively. After calibration, the root mean square error, mean bias error and percentage error values were obtained lower than 0.50, 0.015 mm day^{-1} and 10 % for the whole stations and months, respectively. The calibrated *b* values (b_{cal}) were proportional and inversely to the calibrated *a* values (a_{cal}). The ET_0 values based on the calibrated Blaney–Criddle equation were better than the results of the BC equation when compared to the FAO-56 PM equation as the reference model.

Keywords Reference evapotranspiration · Blaney–Criddle equation · Calibration · Semi-arid and arid regions · FAO Penman–Monteith

Introduction

Reference evapotranspiration (ET_0) of each region is generally affected by different climatic parameters as well as its geographical attributes. ET_0 can be either estimated with lysimeter measurements or water balance approach, or estimated from climatological data. Because a large volume of water can be lost through the soil surface, the estimation of ET_0 has played an important role in water resource management, e.g., in irrigation engineering to define crop water requirements. (Di Stefano and Ferro 1997; Garcia et al. 2007a, b; Trajkovic and Kolakovic 2009a, b; Marti et al. 2011; Thepadia and Martinez 2012; Heydari and Heydari 2014a, b; Heydari et al. 2014a). Most of Iran areas have been located in semi-arid and arid climates. In these areas, ET_0 can achieve till 96 % of annual precipitation. In average, about 50 % of all precipitation is lost by evaporation process in Iran. Therefore, investigation of ET_0 estimation could be very important in this country (Heydari et al. 2013, 2014b). In the recent years, the Penman–Monteith model has been studied and

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improved. If lysimeter data of ET_0 are not available, Allen et al. (1998) suggested the use of Penman–Monteith equation (FAO-56 PM) as standard method for many areas of the world. The FAO-56 PM equation has two advantages over many other equations. First, it can be used globally without any local calibrations due to its physical basis. Second, it is a well-documented equation that has been tested using a variety of lysimeters (Gocic and Trajkovic 2010). However, the major disadvantage of this method is that air temperature, relative humidity, wind speed and solar radiation are required, which are not easily detectable in many meteorological stations.

The Blaney–Criddle (BC) temperature-based equation is one of the earliest methods for estimating ET_0. The BC equation is still used for ET_0 estimation in many areas in developing countries, because of the advantage of its simplicity in requiring only air temperature data. Interpolating air temperature data results in spatially distributed values of BC ET_0 that can be used to produce ET_0 maps (Temesgen et al. 2005a, b). Several studies attempted to improve the accuracy of the BC equation. Chiew et al. (1995) indicated that the BC equation gave similar ET_0 estimates as the FAO-56 PM method at 16 Australian locations with a wide range of climate conditions. Abu Rizaiza and Al-Osaimy (1996) indicated that irrigation water requirements for vegetables and perennial crops are close to the values estimated by the BC equation in the western region of Saudi Arabia. The results of another study showed that the Hargreaves and BC equations were the best ones for Davis in California and Jagdalpur in India with arid and humid climates, respectively (George et al. 2002a, b). Good performance of the BC equation may stem from its original development for humid areas where the advective effect is usually negligible and has been reported by several researchers (Irmak et al. 2003a, b; Ali and Shui 2009). About inverse modelling of hydrological models, Vrugt et al. (2003) presented an efficient and effective Markov Chain Monte Carlo sampler, entitled the Multiobjective Shuffled Complex Evolution Metropolis (MOSCEM) algorithm, which is capable of solving the multiobjective optimization problem for hydrological models. The inverse problem of water flow and multicomponent reactive solute transport has been addressed and solved in a systematic manner by Dai and Samper (2004). The inverse methodology has been found to be useful in investigating the relevance of calcite dissolution/precipitation under both local equilibrium and kinetic conditions (Dai and Samper 2004). The study by DehghaniSanij et al. (2004) for a semi-arid region in Iran also showed similar results which indicate that BC method overestimate the ET_0 and Hargreaves method underestimate the ET_0 for the reference crop of grass. The result of a recent study to find the best alternative method to estimate ET_0 showed that BC equation was identified as the best method among other climate-based methods used in the study when compared with FAO-56 PM for the Mahanadi Reservoir project at Raipur in India (Chauhan and Shrivastava 2009). Mostafazadeh-Fard et al. (2009) validated nine methods for estimation of daily to mean monthly ET_0 by drainage lysimeter data in an arid region. The results of this study showed that the BC, FAO-Radiation and Turc-Radiation Grass methods estimate the lysimeter ET_0 values most closely. Mohawesh (2010) calibrated coefficients of the BC equation using three methods and weather measurements from 12 stations across Jordan. Moreover, the local calibration and validation of ET_0 models is more important in semi-arid and arid regions because most of the models have already been calibrated and validated in temperate environments (DehghaniSanij et al. 2004). Heydari and Heydari (2014a) calibrated C coefficient of the Hargreaves equation in these regions based on the FAO-56 PM method. The results indicated that for each station-month different coefficients should be used instead of the original coefficient of the Hargreaves equation (0.0023). On the other hand, no study has been reported so far about calibrated original coefficients BC equation (*a*, *b*) to improve the estimations of the ET_0. Therefore, the calibration of the coefficients of BC equation under local conditions is an alternative and important operation for improving the ET_0 estimates. Hence, the objectives of this paper were (1) to assess the performance of the original BC equation against FAO-56 PM as the reference standard, and (2) to calibrate the BC (CBC) equation for every month at semi-arid and arid regions of Iran based on the FAO-56 PM equation for calculating monthly ET_0.

Materials and methods

PM equation

In this paper, FAO-56 PM equation (Allen et al. 1998) is suggested as reference to evaluate and calibrate the BC (CBS) equation for estimating ET_0. This equation is accepted by American Society of Civil Engineers (ASCE) Task Committee on standardisation of ET_0, the International Irrigation and Drainage Committee and the food and Agriculture Organization of the United Nations (FAO) and the suitability of this equation are confirmed for different climates (Ravelli and Rota 1999; Irmak et al. 2003a; Garcia et al. 2004, 2007a; Zhao et al. 2005; Temesgen et al. 2005a; Allen et al. 2005, 2006; Ge et al. 2006; Lopez-Urrea et al. 2006a, b; Jabloun and Sahli 2008; Gundekar et al. 2008; Trajkovic and Kolakovic 2009a, b; Mohawesh and Talozi 2011; Ghamarnia et al. 2012; Ravazzani et al. 2012; Heydari and Heydari 2014a, 2014b). The FAO-56 PM method for predicting ET_0 applied on 24-h calculation time steps has the form (Allen et al. 1998)

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left[\frac{900}{(T+273)}\right]U_2(e_s - e_d)}{\Delta + \gamma(1.0 + 0.34U_2)}, \quad (1)$$

where ET_0 = reference crop evapotranspiration (mm day^{-1}); Δ = slope of the saturation vapour pressure in function of temperature (kPa $(°C)^{-1}$); R_n = net radiation (MJ m^{-2} day^{-1}); G = soil heat flux density (MJ m^{-2} day^{-1}); T_{mean} = mean air temperature (°C); U_2 = average 24-h wind speed at two metres height (m s^{-1}); $e_s - e_d$ = vapour pressure deficit (kPa); and γ = psychometric constant (kPa $(°C)^{-1}$). The factor 0.408 = $1/\lambda$ (λ = latent heat of vaporisation in MJ kg^{-1}) converts units from MJ m^{-2} day^{-1} to mm day^{-1}.

The computation of all data required for the calculation of the ET_0 followed the method of Allen et al. (1998).

BC equation

The usual form of the BC equation converted to metric units is written as (Blaney and Criddle 1950, 1962; Doorenboss and Pruitt 1977a, b)

$$ET_0 = a + b[P(0.46T_{mean} + 8.13)], \quad (2)$$

where ET_0 is in mm day^{-1}, a and b are the parameters of the equation and P is the mean annual percentage of daytime hours for different latitudes that can be obtained from Doorenbos and Pruitt (1977b). The a and b coefficients were computed based on the procedure of Doorenbos and Pruitt (1977b) using daily wind speed, daily minimum relative humidity and the ratio of daily actual sunshine hours to daily maximum sunshine hours.

Local calibration

In order to calibrate the original coefficients BC equation (a, b) using monthly data, a linear regression procedure was adopted. Considering the linear regression between ET_0 as the dependent variable obtained from the FAO-56 PM method as reference, T_{mean} as the independent variable and obtaining the P value from the appropriate Table (James 1988), the slope and intercept of the regression line can be calculated for each region and each month of the year. Using the local calibrated coefficients (a_{cal}, b_{cal}) instead of the original coefficients, Eq. (2) can be rewritten (hereafter as CBC)

$$ET_0 = a_{cal} + b_{cal}[P(0.46T_{mean} + 8.13)]. \quad (3)$$

Using the geographical coordinates of the stations and considering the a_{cal} and b_{cal} values, the spatial and temporal distribution maps of these coefficients were drawn for each month of the year. To obtain these maps, geographic information system (GIS)-assisted methods were used. Contour maps of coefficients (a_{cal}, b_{cal}) were obtained by inverse distance weighting (IDW) with power of one used for interpolation (Kravchenko and Bullock 1999).

Statistical analysis

ET_0 estimates from both methods (BC vs. FAO-56 PM and CBC vs. FAO-56 PM) were compared by using simple error analysis and linear regression. For each station, the following statistical parameters were calculated: percentage error (PE), root mean squared error (RMSE), mean bias error (MBE) and coefficient of determination (R^2). The PE, RMSE, MBE and R^2 are defined as

$$PE = \left|\frac{ET_{K,i} - ET_{0,i}}{ET_{0,i}}\right| \times 100, \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{M}\left(ET_{K,i} - ET_{0,i}\right)^2}{M}} \quad (5)$$

$$MBE = \frac{\sum_{i=1}^{M}\left(ET_{K,i} - ET_{0,i}\right)}{M} \quad (6)$$

$$R^2 = \left[\frac{\sum_{i=1}^{1}(ET_{K,i} - \overline{ET_{K,i}})(ET_{0,i} - \overline{ET_{0,i}})}{\sqrt{\sum_{i=1}^{M}(ET_{K,i} - \overline{ET_{K,i}})^2 \sum_{i=1}^{M}(ET_{0,i} - \overline{ET_{0,i}})^2}}\right]^2, \quad (7)$$

where RMSE and MBE are mm day^{-1}, $ET_{K,i}$ and $ET_{o,i}$ are the ET_0 values based on different equations and FAO-56 PM (Allen et al. 1998), respectively, and M is the total number of data. Perfect equation will have PE = 0.0, RMSE = 0.0, R^2 = 1.0 and MBE = 0.0.

Site description

The study area are located in Isfahan, Ghom, Markazy, Yazd and Semnan Provinces in centre of Iran (about 12 % of the total area of Iran) and with almost the same latitude (N 32°–35°) and semi-arid and arid regions. The monthly climatic data of the 15 stations, including wind speed, the mean, maximum and minimum monthly air temperature (°C) and mean, maximum and minimum monthly air relative humidity (%) and monthly sunny hours are used with full data set from 1978 to 2007. Also, the quality of weather data such as air humidity, solar radiation, sunshine hours and wind speed was checked using the method proposed by Allen et al. (1998). Figure 1 shows the study area (centre of Iran). Water in these areas is greatly important and 90 % of water is used in agriculture and industry.

Number of data (months), the mean annual temperature and mean annual rain and climate of all selected stations have been reported in Table 1.

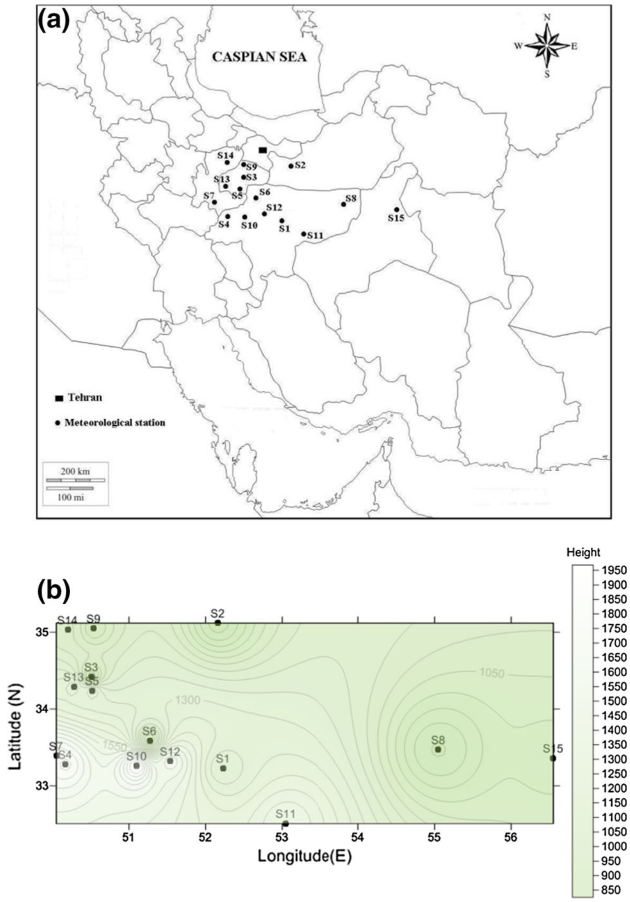

Fig. 1 **a** Spatial distribution and **b** altitude of the meteorological stations used in this study

Results and discussion

FAO-56 PM versus BC ET_0

The ET_0 values estimated by the original BC equation and corrected by the CBC equation are compared with those of FAO-56 PM method for the semi-arid and arid climates, such as Iran. Mean monthly ET_0 values calculated with the BC and FAO-56 PM methods are presented in Fig. 2 for all stations considered in this study.

According to the monthly results, the lowest and highest values of FAO-56 PM ET_0 and BC equations were found in December and July, respectively. Results of F-test (Snedecor and Cochran 1968) showed that both slope and intercept were significantly different ($\alpha < 0.05$) from one and zero, respectively, for ET_0 FAO-56 PM and ET_0 BC equation. The mean monthly values of T are plotted against FAO-56 PM ET_0 and BC ET_0 in Fig. 3. For a definite T, the range of BC ET_0 was equal to FAO-56 PM ET_0. Also, it shows that the values of FAO-56 PM ET_0 and BC ET_0 increased with increasing T.

The statistical analyses for each station between the estimated ET_0 by the FAO-56 PM and BC equations are presented in Table 2. As shown, the BC equation significantly overestimated ET_0 with respect to FAO-56 PM ET_0 at 12 stations, and three clearly underestimated it.

At Ardestan, Meimeh and Naein stations with the wind speed above 3 m s^{-1}, the monthly ET_0 estimates with the BC equation are generally lower than the monthly ET_0 estimates with the FAO-56 PM method. The ET_0 is

Table 1 Summary of weather station sites in this study

No.	Weather station	Latitude (N)	Longitude (E)	Altitude (m)	Record (months)	T (°C)	V (m s^{-1})	RH_{mean} (%)	Rain (mm $year^{-1}$)	Climate
S1	Ardestan	33°–23′	52°–23′	1252.40	168	18.90	3.6	30.7	115.80	Arid
S2	Garmsar	35°–12′	52°–16′	825.20	180	17.40	2.0	42.3	118.70	Arid
S3	Ghom	34°–42′	50°–51′	877.40	252	18.00	2.1	41.5	151.10	Arid
S4	Golpaigan	33°–28′	50°–17′	1870.00	132	14.20	2.2	38.9	273.70	Semi-arid
S5	Kahak	34°–24′	50°–52′	1403.20	60	16.30	1.7	39.5	173.60	Arid
S6	Kashan	33°–59′	51°–27′	982.30	348	19.10	0.6	40.0	138.40	Arid
S7	Khomein	33°–39′	50°–05′	1835.00	72	14.00	2.5	39.4	347.90	Semi-arid
S8	Khoor Biabanak	33°–47′	55°–05′	845.00	168	20.30	2.0	33.8	86.30	Arid
S9	Koshk Nosrat	35°–05′	50°–54′	948.00	24	19.80	2.1	41.0	116.60	Arid
S10	Meimeh	33°–26′	51°–10′	1980.00	96	12.30	4.1	37.3	163.70	Arid
S11	Naein	32°–51′	53°–05′	1549.00	168	16.60	3.1	30.0	98.70	Arid
S12	Natanz	33°–32′	51°–54′	1684.90	168	15.50	2.0	35.6	195.30	Arid
S13	Salafchegan	34°–29′	50°–28′	1380.50	60	16.80	2.1	42.0	187.40	Arid
S14	Saveh	35°–03′	50°–20′	1108.00	156	18.20	2.5	36.4	206.50	Arid
S15	Tabas	33°–36′	56°–55′	976.00	264	21.70	1.8	31.0	83.20	Arid

T annual mean of air temperature, *V* average wind speed, RH_{mean} average relative humidity, *Rain* annual average precipitation, *climate* with the De Martonne method

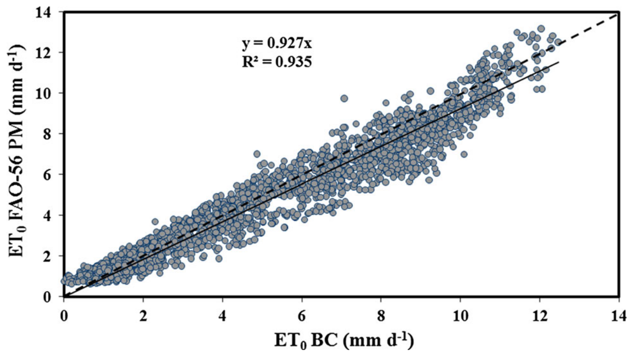

Fig. 2 Comparison of ET_0 calculated by FAO-56 PM (Eq. 1) and BC (Eq. 2) for 15 stations

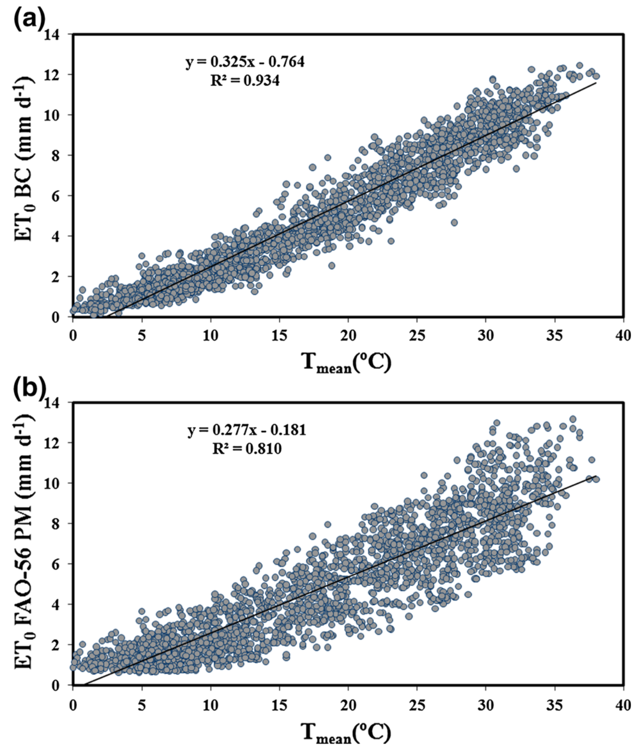

Fig. 3 Relationship between mean temperature (T_{mean}) and **a** BC equation and **b** ET_0 calculated (FAO-56 PM)

sensitive to wind and the performance of the estimation method may also be influenced (Wang et al. 2007). In general, the lowest and highest overestimations of the BC equation were obtained at Kashan and Khomein stations. Also, the evaluation the Hargreaves equation (temperature-based) in these regions based on the FAO-56 PM method showed that the Kashan and Ardestan stations overestimated and underestimated ET_0, respectively (Heydari and Heydari 2014a). Overestimations of the BC equation with respect to the FAO-56 PM method were also reported in the dry tropical climate of Burkina Faso (Wang et al. 2007), in the arid climate of California, USA (George et al. 2002a), in semi-arid climates of Spain (Gavilan 2002; Lopez-Urrea et al. 2006a). Considering all locations, the RMSE ranged from 0.456 to 1.132 mm days^{-1}, with an average value of 0.794 mm days^{-1} (Table 2). The MBE values ranged from −0.651 to 0.969 mm days^{-1}, with a mean of 0.157 mm days^{-1}. The PE values ranged from 11.922 to 29.371 %, with a mean of 20.645 %. The R^2 values ranged from 0.942 to 0.985 and considering all stations, the mean of R^2 was 0.929.

Original coefficients (*a*, *b*)

The values of *a* and *b* (coefficients BC equation) for different months and stations are presented in Tables 3 and 4. The values of *a* were negative for all months of any station and ranged between −2.231 and −1.770. The lowest and highest values of *a* were found in August and December for 15 stations, respectively. The results show that the *a* values in the warm and dry months (including July and August) are lower than those in the cold and rainy months (including December, and January) of the year caused by differences between ET_0 values calculated by the BC and PM method. The lowest values of *a* were obtained in August in Khoor Biabanak (−2.231) and Tabas (−2.224) with an arid climate. The highest values of *a* were obtained in December in Khomein (−1.770) with a semi-arid climate. The ranges between the minimum and maximum values of *a* at the whole stations were between 0.287 (Golpaigan) to 0.413 (Khomein). Tabas had the lowest values of *a* (−2.078) while the highest values of *a* were obtained in Kashan (−1.941) in yearly time step.

Table 2 Comparison of statistical indices in estimating ET_0 values using BC (Eq. 2) and FAO-56 PM (Eq. 1)

No.	RMSE (mm day^{-1})	MBE (mm day^{-1})	PE (%)	R^2
S1	0.715	−0.651	13.645	0.952
S2	0.668	0.353	15.945	0.965
S3	0.609	0.362	14.400	0.974
S4	0.636	0.176	18.254	0.978
S5	0.776	0.431	21.178	0.968
S6	1.132	0.969	29.371	0.942
S7	0.586	0.038	19.764	0.986
S8	0.935	0.823	20.781	0.962
S9	0.639	0.206	14.112	0.963
S10	0.456	−0.369	17.845	0.985
S11	0.476	−0.202	11.922	0.981
S12	0.684	0.175	19.456	0.975
S13	0.660	0.201	17.291	0.970
S14	0.668	0.050	13.823	0.952
S15	0.775	0.484	15.889	0.963

The values of b were positive for all months of any station and ranged between 1.097 and 1.908. The highest and lowest values of b were found in August and December for 15 stations, respectively. The results show that the b was greater in warm months than in cold months of the year. The highest and lowest value of b was in August in Ardestan (1.908) and in December in Kashan (1.097) with a semi-arid climate. Also, in yearly time step, Meimeh had the highest values of b (1.630), while the lowest values of b were obtained in Kashan (1.331). The ranges between the minimum and maximum values of b at the whole stations were between 0.394 (Naein) to 0.655 (Ardestan). It is interesting that Kashan station showed the highest and lowest values of a and b, respectively for all months. This is due to the low value of wind speed and high temperature during the year in this station.

The values of a were proportional and inversely to b. A linear regression was calculated to verify the correlation between a versus b values. The following equation was obtained:

$$b = -0.742a \quad (R^2 = 0.710) \tag{8}$$

Table 3 The monthly a values for different months for investigated stations (Eq. 2)

No.	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Yearly
S1	−1.886	−1.930	−1.958	−1.930	−2.062	−2.166	−2.152	−2.215	−2.132	−2.137	−1.951	−1.873	−2.033
S2	−1.876	−1.859	−1.896	−1.921	−2.029	−2.132	−2.145	−2.166	−2.133	−2.102	−1.935	−1.848	−2.004
S3	−1.842	−1.865	−1.918	−1.901	−2.030	−2.146	−2.161	−2.183	−2.163	−2.100	−1.935	−1.803	−2.004
S4	−1.881	−1.943	−1.949	−1.918	−2.073	−2.137	−2.092	−2.164	−2.149	−2.136	−1.918	−1.877	−2.020
S5	−1.814	−1.849	−1.904	−1.870	−2.016	−2.112	−2.119	−2.163	−2.140	−2.078	−1.903	−1.783	−1.979
S6	−1.777	−1.808	−1.852	−1.866	−1.966	−2.061	−2.088	−2.123	−2.084	−2.032	−1.863	−1.775	−1.941
S7	−1.826	−1.873	−1.942	−1.842	−2.053	−2.129	−2.109	−2.183	−2.172	−2.102	−1.912	−1.770	−1.993
S8	−1.955	−1.971	−1.986	−1.991	−2.114	−2.138	−2.177	−2.231	−2.181	−2.196	−2.023	−1.913	−2.073
S9	−1.839	−1.872	−1.915	−1.881	−2.022	−2.132	−2.150	−2.175	−2.155	−2.101	−1.920	−1.791	−1.996
S10	−1.893	−1.994	−2.021	−1.918	−2.097	−2.143	−2.100	−2.171	−2.168	−2.156	−1.975	−1.851	−2.041
S11	−1.892	−1.954	−1.932	−1.945	−2.061	−2.139	−2.143	−2.205	−2.160	−2.164	−2.008	−1.870	−2.039
S12	−1.833	−1.873	−1.868	−1.882	−1.999	−2.095	−2.131	−2.189	−2.140	−2.096	−1.901	−1.821	−1.986
S13	−1.846	−1.890	−1.930	−1.880	−2.043	−2.132	−2.125	−2.170	−2.161	−2.110	−1.917	−1.807	−2.001
S14	−1.836	−1.879	−1.911	−1.860	−2.014	−2.117	−2.138	−2.166	−2.146	−2.101	−1.904	−1.779	−1.988
S15	−1.932	−1.947	−1.961	−1.995	−2.105	−2.152	−2.192	−2.224	−2.187	−2.202	−2.062	−1.928	−2.074

Table 4 The monthly b values for different months for investigated stations (Eq. 2)

No.	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Yearly
S1	1.287	1.427	1.507	1.541	1.699	1.839	1.831	1.908	1.765	1.690	1.403	1.253	1.596
S2	1.241	1.275	1.346	1.428	1.547	1.680	1.689	1.698	1.595	1.517	1.316	1.195	1.461
S3	1.203	1.299	1.388	1.423	1.577	1.718	1.721	1.730	1.663	1.547	1.334	1.160	1.480
S4	1.223	1.380	1.427	1.437	1.599	1.665	1.600	1.674	1.648	1.629	1.313	1.218	1.484
S5	1.161	1.266	1.371	1.367	1.527	1.632	1.643	1.671	1.624	1.534	1.299	1.136	1.436
S6	1.099	1.173	1.241	1.286	1.387	1.490	1.526	1.560	1.494	1.412	1.212	1.097	1.331
S7	1.180	1.325	1.485	1.391	1.617	1.688	1.672	1.733	1.714	1.644	1.352	1.150	1.496
S8	1.293	1.383	1.440	1.480	1.623	1.665	1.705	1.731	1.645	1.620	1.416	1.261	1.522
S9	1.206	1.318	1.402	1.421	1.578	1.701	1.702	1.704	1.659	1.559	1.328	1.152	1.477
S10	1.319	1.534	1.651	1.557	1.785	1.823	1.763	1.819	1.806	1.747	1.472	1.285	1.630
S11	1.405	1.474	1.480	1.531	1.654	1.749	1.741	1.799	1.734	1.696	1.495	1.309	1.589
S12	1.159	1.279	1.319	1.355	1.480	1.600	1.639	1.699	1.617	1.525	1.280	1.151	1.425
S13	1.202	1.335	1.429	1.418	1.593	1.689	1.670	1.696	1.677	1.598	1.330	1.169	1.484
S14	1.208	1.336	1.415	1.419	1.579	1.684	1.679	1.680	1.655	1.571	1.322	1.144	1.474
S15	1.310	1.339	1.417	1.495	1.649	1.719	1.781	1.788	1.708	1.677	1.481	1.283	1.554

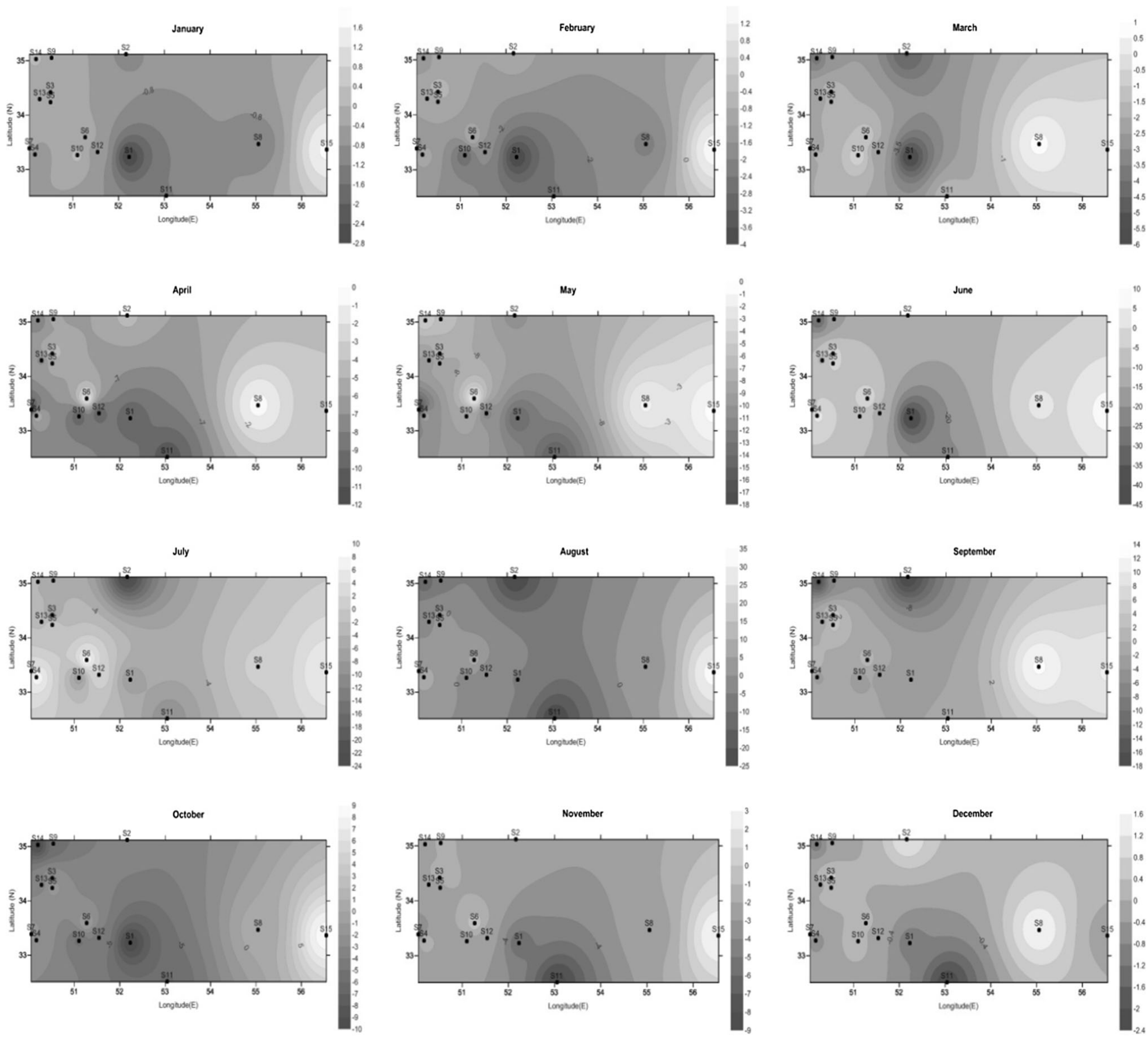

Fig. 4 Monthly spatial distribution of the a_{cal} coefficient (Eq. 3)

On average, Naein, Meimeh and Ardestan stations, with the highest wind speeds, showed the greatest *b* values, whereas the lowest *b* values were obtained at Kashan and Kahak stations. The results of *a* and *b* revealed that *a* values varied more than *b* values. This could be revealed that ET_0 calculated by BC equation is more sensitive to *a* values than *b* values.

Calibrated coefficients (a_{cal}, b_{cal})

Figures 4, 5, 6, 7 show the monthly and yearly spatial and temporal distribution map of the a_{cal} and b_{cal} values, respectively. The results of all 24 monthly spatial distribution maps of a_{cal} and b_{cal} coefficients for different months are shown here. When considering monthly values of a_{cal} for all stations, December and January had the highest values of a_{cal} and the lowest a_{cal} values were obtained in May to August. It is concluded that the values of a_{cal} were greater in warm or high temperature months than in cold or low temperature months of the year. December and January showed the lowest b_{cal} values while May and June showed the highest. Therefore, the values of b_{cal} were greater in cold or low temperature months than warm or high temperature months of the year.

The values of b_{cal} were proportional and inversely to a_{cal} A linear regression was calculated to verify the correlation

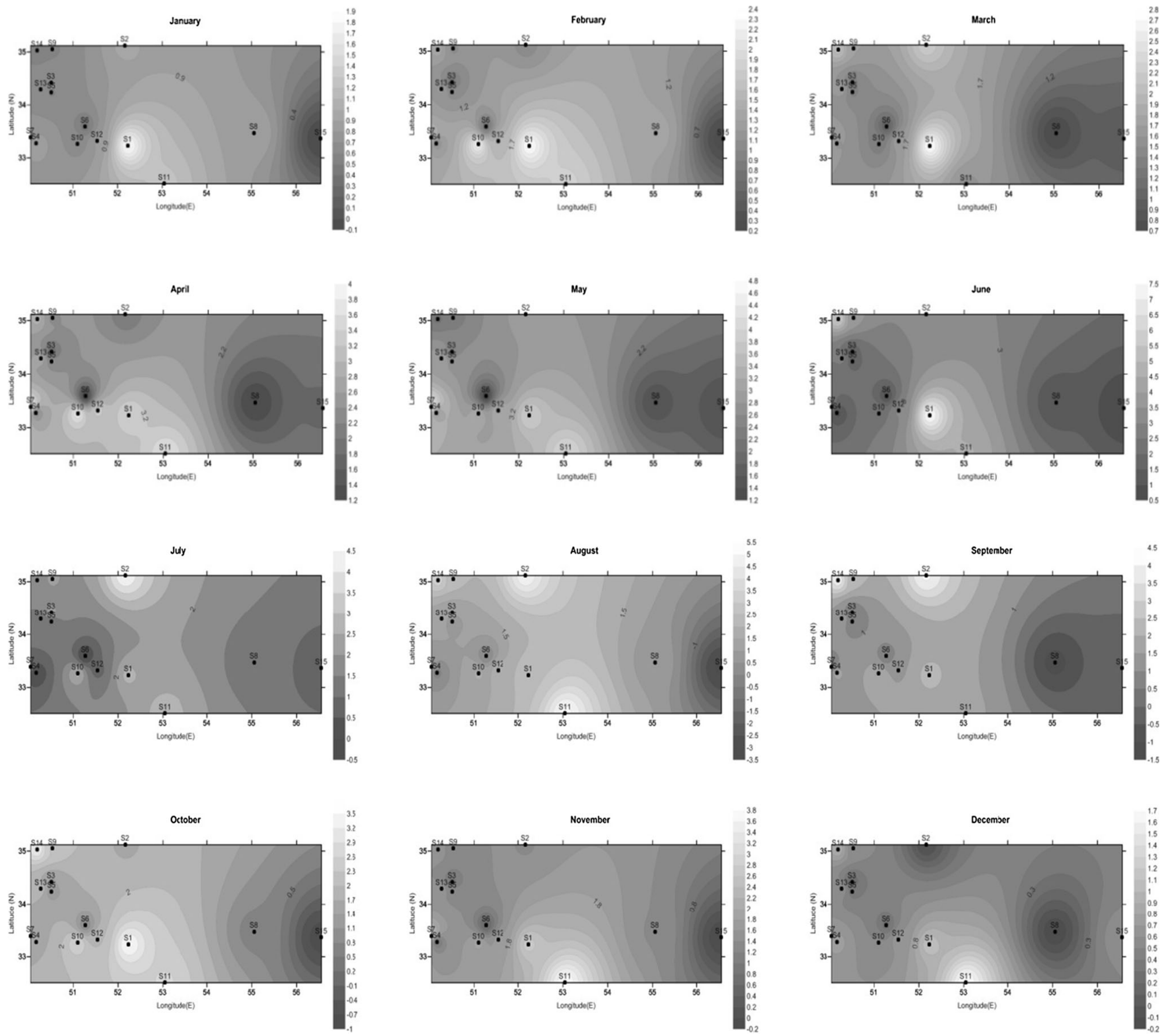

Fig. 5 Monthly spatial distribution of the b_{cal} coefficient (Eq. 3)

between b_{cal} versus a_{cal} values. The following equation was obtained

$$b_{\mathrm{cal}} = -0.713 a_{\mathrm{cal}} \quad (R^2 = 0.927). \tag{9}$$

It is clearly seen that Tabas station has the highest and lowest values of a_{cal} and b_{cal}, and Ardestan station experienced the lowest and highest values of a_{cal} and b_{cal}, respectively, in yearly time step. This showed that even with the short distance and same altitude between the two stations, quite variations in meteorological parameters were noticed. Comparing the range of variations of a_{cal} and b_{cal} values, it may be concluded that a_{cal} values varied more

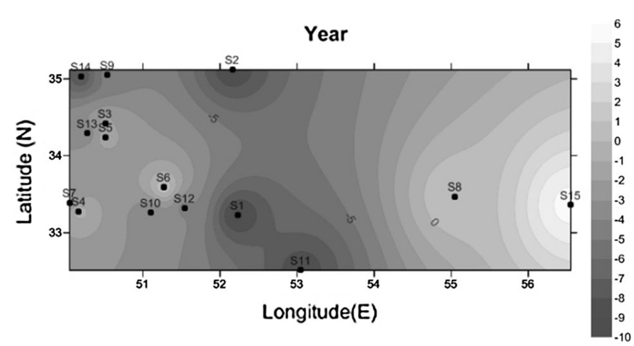

Fig. 6 Yearly spatial distribution of the a_{cal} coefficient (Eq. 3)

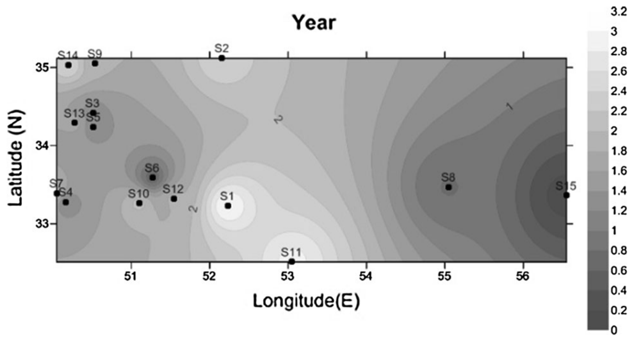

Fig. 7 Yearly spatial distribution of the b_{cal} coefficient (Eq. 3)

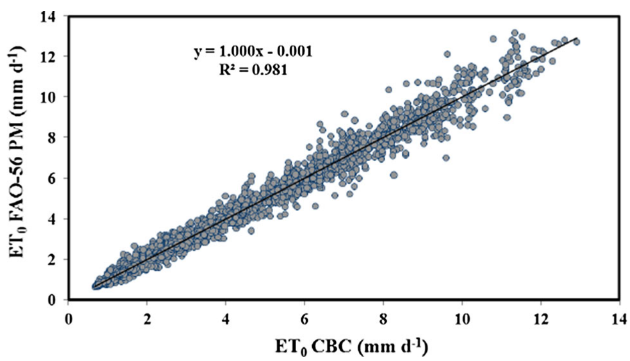

Fig. 8 Comparison of ET_0 calculated by FAO-56 PM (Eq. 1) and CBC (Eq. 5) for 15 Stations

than b_{cal} values in different months. These maps clearly show that a_{cal} and b_{cal} varied considerably in the study area, and being aware of the spatiotemporal variations of climatological parameters is important in managing the limited water resources.

FAO-56 PM versus CBC ET_0

Mean monthly ET_0 values calculated with the FAO-56 PM method and the CBC equation are presented in Fig. 8. A better scattering of the points with high correlation ($R^2 = 0.981$) can be seen in Fig. 8 compared to Fig. 2. Using CBC, better monthly and annual estimations of ET_0 are obtained in all meteorological stations.

The statistical analysis components for each station-month between ET_0 estimated using the FAO-56 PM and CBC equations are presented in Table 5. The ranges of RMSE, MBE and PE for monthly estimated ET_0 using the CBC equation were 0.195–0.489 mm day^{-1} with an average value of 0.342 mm day^{-1}, −0.0003 to 0.015 mm day^{-1} with an average value of 0.007 mm day^{-1} and 3.953–9.986 %, with a mean of 6.968 %, respectively. The R^2 values ranged from 0.963 to 0.993 and considering all stations, the mean of R^2 was 0.981.

Table 5 Comparison of statistical indices in estimating ET_0 values using CBC (Eq. 3) and FAO-56 PM (Eq. 1)

No.	RMSE (mm day^{-1})	MBE (mm day^{-1})	PE (%)	R^2	a_{cal}	b_{cal}
S1	0.396	0.015	6.313	0.988	−9.161	3.021
S2	0.405	0.0002	8.242	0.977	−8.755	2.385
S3	0.395	−0.0001	8.448	0.985	−1.723	1.247
S4	0.309	−0.0002	7.279	0.980	−0.436	1.183
S5	0.304	0.0002	6.296	0.981	−1.428	1.246
S6	0.321	0.00001	6.486	0.973	0.758	0.633
S7	0.195	0.0006	3.953	0.991	−3.319	1.857
S8	0.329	−0.0002	7.381	0.985	0.883	0.788
S9	0.442	0.0004	9.217	0.968	−4.774	1.842
S10	0.219	−0.0003	4.612	0.993	−3.840	2.069
S11	0.315	0.0000	6.789	0.984	−8.617	2.877
S12	0.275	0.0007	6.433	0.985	−4.215	1.839
S13	0.346	0.0004	7.171	0.972	−3.574	1.681
S14	0.489	0.0008	9.986	0.963	−7.825	2.438
S15	0.470	−0.0003	9.557	0.968	5.378	0.121

The greatest overestimations occurred mainly for Ardestan station with the highest values of b_{cal} (3.021) and the lowest values of a_{cal} (−9.161) in yearly time step. In this station, high Wind speed (V), average daily temperature range (ΔT) and small RH_{min} values are found.

After calibration and considering all stations, average RMSE, MBE and PE are decreased by 55, 86, and 67 %, respectively. Therefore, CBC equation can be used for ET_0 estimates in different places in centre of Iran instead of using the FAO-56 PM method.

Validation

The BC equation is calibrated by using data from 1978 until 2006. Furthermore, the calibrated equation (CBC) is validated by using independently measured monthly ET_0 data from 2007 to 2009. To illustrate this, two stations Meimeh and Kashan located in semi-arid and arid, respectively, are taken.

Figure 9 shows the relative comparison of the evolution of cumulative ET_0 at two representative stations according to FAO-56 PM, BC and CBC model. BC equation shows underestimation at the Meimeh station at higher elevation and lower temperature and overestimation at the Kashan station at lower elevation and higher temperature. The calibrated BC equation (CBC) shows good performance.

These results show the importance of calibrating empirical equations such as the BC equation used in the present study to calculate ET_0 which can affect yield and water logging.

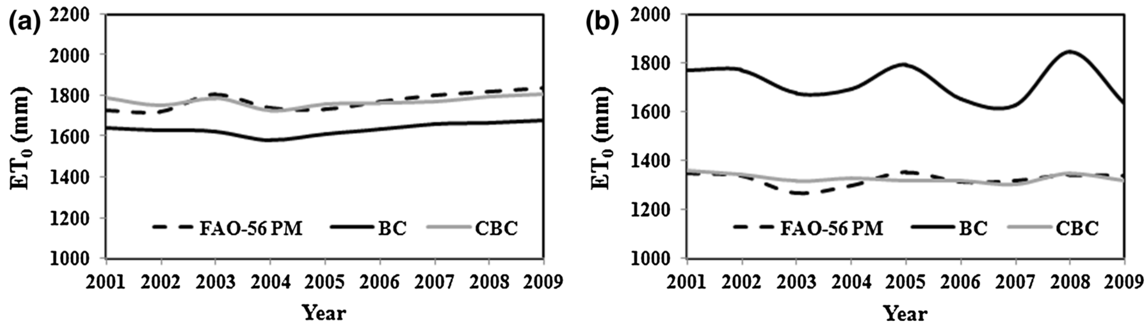

Fig. 9 Comparison of evolution of cumulative ET_0 according to FAO-56 PM (Eq. (1)), BC (Eq. (2)), and CBC (Eq. (3)) methods in two stations: **a** Meimeh, **b** Kashan

Conclusions

In this study, the BC equation was evaluated and calibrated to estimate ET_0 using weather data from 15 arid and semi-arid stations in central Iran. The FAO-56 PM method was assumed as the standard for comparing ET_0 estimates by the BC and calibrated BC equation (CBC) equations for all locations. The CBC equation resulted in decreasing the RMSE values from 0.794 to 0.342 mm day^{-1}, the MBE values from 0.157 to 0.007 mm day^{-1} and the PE values from 20.645 to 6.968 %, indicating that the performance of the BC equation significantly improved after it was calibrated at the study stations.The values of a were negative for all months of any station and ranged between -2.231 and -1.770. The lowest and highest values of a were found in August and December for 15 stations, respectively. The values of b were positive for all months of any station and ranged between 1.097 and 1.908. The highest and lowest values of b were found in August and December for 15 stations, respectively. The results showed that the values of b were proportional and inversely to a. Also, these results were obtained between a_{cal} and b_{cal}. Moreover, the spatial and temporal maps of a_{cal} and b_{cal} values help managers to apply these maps for calculating reliable and precise ET_0 across the study area that actually lead to precise and elevate water resource management. Based on this research, monthly and annual ET_0 can be easily estimated for any region in central Iran with the most available meteorological data (mean air temperature) for irrigation scheduling. It is suggested that the same procedure might be conducted in other parts of the country or the world, especially in arid and semi-arid regions, where no meteorological data are available to compute ET_0 for agricultural purposes.

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