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Evaluation of Hargreaves equations for estimating of 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 Hargreaves equation is an alternative method compared with the FAO-56 PM equation. In the present study, different forms of the Hargreaves equation were compared with the FAO-56 PM equation for estimating reference evapotranspiration (ET_0) from 15 meteorological stations in central Iran under semi-arid and arid conditions. Also, calibrated Hargreaves (CHS) equation based on the FAO-56 PM equation was compared with new versions of this equation. The lowest and highest ratios of monthly ET_0 of Hargreaves equations and CHS to the FAO-56 PM reference method over all the stations were in July and December, respectively. Furthermore, a similar equation based on the mean monthly ET_0 calculation is derived for all selected stations. The results showed that the CHS equation gave better estimates of ET_0 compared to the other types of Hargreaves equations and new equation in all stations when compared to the FAO-56 PM equation as the reference equation. Also, the original Hargreaves equation was only better than the other versions of this equation in one station with high humidity and low value of wind speed during the year.

1. Introduction

Water resource scarcity is a great problem attended by experts, decision makers and managers of developing countries. Due to droughts in recent years, suitable management of existing water resources and better solutions for their usage are essential (Heydari and Heydari, 2014a, 2014b).Reference evapotranspiration (ET_0) of each region is generally affected by different climatic parameters as well as geographical attributes. Because a large volume of water can be lost through the soil surface, the estimation ET_0has played an important role in water resource management, e.g., in irrigation engineering to define crop water requirements. (Di Stefano and Ferro, 1997; García et al. 2007; Trajkovic and Kolakovic, 2009; Marti et al., 2011; Tabari et al., 2011, 2013; Thepadia and Martinez, 2012).The measurement of the changes in $ET_0$is very important for predicting Eco hydrological changes and natural plant communities (Monteith, 1964, 1965; Huxman et al., 2005; Mielnick et al., 2005; Prater and DeLucia, 2006). When 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 in many areas of the world. However, the major drawback of FAO-56 PM method is that air temperature; relative humidity, wind speed, and solar radiation are required which are not easily detectable in many meteorological stations.

The largest part of Iran is located in semi-arid and arid climates. On average, about 50% of all precipitation is lost by evaporation processes. Therefore, estimation of ET_0 is very important (Heydari and Heydari, 2014a, 2014b; Heydari et al., 2013, 2015).

At most stations of Iran, meteorological data are often incomplete and/or not available and only maximum and minimum air temperatures are recorded, and the Hargreaves model is recommended for computation of ET_0 when only air temperature data are available (Allen et al., 1998). Therefore, Hargreaves equation is an alternative method and one of the simplest equations to determinate ET_0 (Hargreaves and Samani, 1985) that only requires average, maximum and minimum daily

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values of temperature and extraterrestrial radiation (Ra).

This method behaves best for weekly or longer predictions, although some accurate daily ET_0estimations have been reported in literature (Hargreaves and Allen, 2003). However, this method usually overestimates ET_0 at humid locations (Jensen et al., 1990, Amatya et al., 1995, Itenfisu et al., 2003, Temesgen et al., 2005; Trajkovic, 2005) and underestimates it in very dry zones, semi-arid and arid locations (Jensen et al., 1990; Allen et al., 1998; Droogers and Allen 2002; RahimiKhoob, 2008; Weiß and Menzel, 2008; Benli et al., 2010; Azhar and Perera, 2010). Moreover, the local calibration and validation of ET_0 models are 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).

Several studies attempted to improve the accuracy of the Hargreaves equation. Chuanyan et al. (2004) tested three commonly used models to estimate monthly potential evapotranspiration (PET) values including Behnk-Maxey, Priestley-Taylor and Hargreaves in a semiarid region of China. They also provided a spatial distribution of PET and found that the Hargreaves model was the best model to estimate PET in the semiarid region of China. Martinez-Cob and Tejero-Juste (2004) showed that no local calibration would be required for windy locations (where monthly average wind speeds >2 m s^{-1} are frequent), but the C coefficient of 0.0020 instead of original 0.0023 should be used in the HS equation for non- windy locations. Vanderlinden et al. (2004) found that according to regression analysis that the C coefficient of HS equation increased to 0.0029 at coastal stations, and decreased to 0.0022 at inland stations. Both studies were made in two different semi-arid areas in Spain using data from limited number of meteorological stations, the first in the Ebro River valley, in Aragon (Northeastern Spain, 9 stations); and the second in Andalusia (southern Spain, 16 stations). Furthermore, the HS equation has been evaluated under semi-arid conditions in southern Spain from 86 meteorological stations, comparing ET_0 daily estimates with calculated data from the Penman Monteith equation used as standard (Gavilan et al., 2006). The results of this study showed that a regional calibration can be carried out considering only temperature and wind conditions. Trajkovic (2007) calibrated the C coefficient of HS equation using weather measurements from 10 stations in the western Balkan region (southeast Europe) and reported that in humid regions HS overestimates ET_0 values. Kisi (2008) compared the HS and Penman–Monteith methods in Los Angeles, USA and concluded that the calibrated HS method is the best approach for estimating evapotranspiration. Sentelhas et al. (2010) examined different reference evapotranspiration methods in Ontario, Canada and they showed by considering the amount of available weather data that the HS method can be a good alternative to the Penman-Monteith method in Ontario, Canada. Lee (2010) found that the HS equation provides excellent results for the Korea Peninsula after local calibration as well as Jamshidi et al. (2010) and Ghamarnia et al. (2012) for different climates (dry sub-humid, moist sub-humid, semi-arid and humid) in Iran. 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). Moreover, extensive research was required to assess the validity of different types of the Hargreaves equation for estimating ET_0 in these semi-arid and arid locations.Therefore, the objective of this research was to compare the original Hargreaves equation and three new versions of this equation reported by Droogers and Allen (2002) and calibrated original Hargreaves equation (CHS) for estimating monthly ET_0 for 15 meteorological stations in central Iran under semi-arid and arid conditions, to complete the previous study carried out by Heydari and Heydari (2014a) in which they only considered the original Hargreaves equation.

2. Materials and methods

2.1. Site description

The study area are located in Isfahan, Ghom, Markazy, Yazd and Semnan Provinces in center 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. Water in these areas is greatly important and over 90 % of water is used in agriculture and industry. 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). Fig. 1 shows the study area (center of Iran).

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

2.2. PM equation

In this paper, the FAO-56 PM equation (Allen et al., 1998) is suggested as the standard method for estimating ET_0. This equation is accepted by the ASCE Task Committee on standardization of ET_0, The International Commission on Irrigation and Drainage and FAO.

The suitability of this equation has been confirmed for different climates (Ravelli and Rota, 1999; Irmak et al., 2003; Garcia et al., 2004, 2007; Zhao et al., 2005; Temesgen et al., 2005; Allen et al., 2005, 2006; Gao et al., 2006; Jabloun and Sahli, 2008) and similar studies (Jensen et al., 1990; Allen et al., 1994a, 1994b, 1998, 2000; Smith et al., 1996; Walter et al., 2000; Gundekar et al., 2008). The FAO-56 PM method for predicting ET_0 where applied on 24-h calculation time steps has the form (Allen et al., 1998):

Table 1: Summary of weather station sites in this Study

No.	Weather station	Latitude (N)	Longitude (E)	Altitude (m)	Record (months)	T (°C)	V (ms^{-1})	RH_{mean} (%)	Rain (mmy^{-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	KhoorBiabanak	33°-47'	55°-05'	845.00	168	20.30	2.0	33.8	86.30	Arid
S9	KoshkNosrat	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

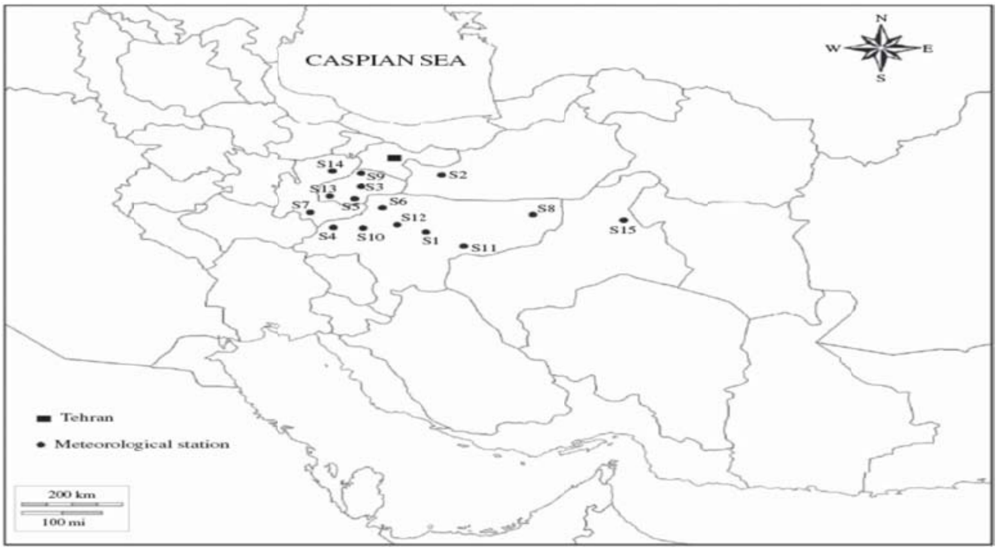

Fig. 1: Spatial distribution of the meteorological stations used in this study

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

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

2.3. Hargreaves equations

The Hargreaves equation (Hargreaves and Samani, 1985) as original version can be written as:

$$ET_0 = 0.0023 \times R_a \times (T_{mean} + 17.80) \times (T_{max} - T_{min})^{0.50} \quad (2)$$

where ET_0 is computed (mmd^{-1}); R_a is the extraterrestrial radiation (mmd^{-1}), depends on the Julian day number and latitude, and can be computed as described by Allen et al. (1998); T_{max}

and T_{min} are the daily maximum, minimum and mean air temperature (ºC), 0.0023 is the original empirical coefficient proposed by Hargreaves and Samani (1985).

Droogers and Allen (2002) reported three new types of the Hargreaves equation (Hargreaves and Samani, 1985) as follows:

$$ET_0 = 0.0030 \times R_a \times (T_{mean} + 20) \times (T_{max} - T_{min})^{0.40} \quad (3)$$

$$ET_0 = 0.0025 \times R_a \times (T_{mean} + 16.80) \times (T_{max} - T_{min})^{0.50} \quad (4)$$

$$ET_0 = 0.0013 \times R_a \times (T_{mean} + 17) \times (T_{max} - T_{min} - 0.0123 P)^{0.76} \quad (5)$$

where ET_0 is in mm day^{-1} and P is monthly rainfall (mm) and the other parameters are as presented for Equation (2).

Heydari and Heydari (2014a) calibrated C coefficient of the Hargreaves equation [Eq. 2] 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). The ET_0 obtained in this study is referred to hereafter as CHS.

2.4. Statistical analysis

For each station, statistical parameters like root mean squared error (RMSE), mean bias error (MBE) and the ratio of average ET_0 estimations (R) were used to test the accuracy of ET_0 determination by the following equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - E_i)^2}{n}} \quad (6)$$

$$MBE = \frac{\sum_{i=1}^{n}(O_i - E_i)}{n} \quad (7)$$

$$R = \frac{O_i}{E_i} \quad (8)$$

where RMSE and MBE are in mmd^{-1}; O_i is ET_0 estimated using the Hargreaves equations (Eqs. 2-5) or CHS; E_i is ET_0 estimated with the FAO-56 PM equation (Allen et al., 1998); and n is number of data (months).

3. Results and discussion

Evaluation of the Hargreaves equations [Eqs. 2 to 5] and CHS equation was performed using the FAO-56 PM as reference. The average ratios between the monthly estimated ET_0 with original Hargreaves equation [Eq. 2]and CHS equation to the FAO-56 PM [Eq. 1]are determined and presented in Tables 2 and 3, respectively for each station-month.

As shown in Table 2, in Ardestan, Khomein, Meimeh, Naein and Natanz regions, the average ratios between monthly estimated ET_0 with original Hargreaves equation to the FAO-56 PM were less than one for all months and yearly time step. Therefore, in these stations monthly ET_0 estimates with the original Hargreaves equation was always less than the monthly ET_0 estimates with the FAO-56 PM equation. In Kashan station, the average ratios between monthly estimated ET_0 with this equation to FAO-56 PM equation were more than one for all months and yearly time step. The lowest and highest values of Rwere 0.542 for Ardestan station (high wind speed combined with low humidity) in July and 1.718 for Kashan station (low wind speed combined with high humidity) in December, respectively.

The results show that the ratios between Hargreaves equation [Eq. 2] and FAO-56 PM ET_0 (R) ranged from 0.64 to 1.28, with a mean of 0.90 for all stations and yearly time step. After calibration and yearly time step, R ranged from 1.00 to 1.05 with an average value of 1.01 (Table 3).

Table 2: Average ratios of monthly ET_0 estimated using Eq. 2 and the ET_0 FAO-56 PM [Eq. 1]

NO.	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
S1	0.753	0.681	0.657	0.636	0.643	0.607	0.542	0.552	0.556	0.573	0.656	0.816
S2	1.114	1.018	0.934	0.909	0.910	0.873	0.808	0.842	1.021	1.061	1.198	1.368
S3	1.162	0.998	0.954	0.964	0.909	0.865	0.825	0.892	1.014	1.070	1.217	1.357
S4	1.024	0.832	0.824	0.818	0.861	0.884	0.814	0.894	0.876	0.884	0.972	1.081
S5	1.191	1.021	0.954	0.968	0.971	0.991	0.941	0.968	1.054	1.051	1.197	1.323
S6	1.486	1.235	1.132	1.119	1.129	1.183	1.112	1.121	1.263	1.325	1.525	1.718
S7	0.894	0.881	0.874	0.862	0.875	0.924	0.855	0.890	0.887	0.857	0.865	0.925
S8	1.149	0.983	0.885	0.855	0.847	0.839	0.791	0.863	0.989	1.080	1.168	1.425
S9	1.054	0.905	0.863	0.860	0.839	0.810	0.783	0.832	0.896	0.918	1.024	1.199
S10	0.865	0.796	0.780	0.811	0.813	0.804	0.736	0.793	0.754	0.778	0.810	0.892
S11	0.786	0.729	0.722	0.742	0.769	0.747	0.716	0.732	0.723	0.722	0.730	0.836
S12	0.927	0.801	0.764	0.779	0.808	0.784	0.726	0.744	0.745	0.753	0.815	0.966
S13	1.056	0.915	0.863	0.879	0.881	0.884	0.848	0.881	0.933	0.911	1.023	1.154
S14	0.946	0.812	0.772	0.756	0.770	0.756	0.740	0.773	0.778	0.766	0.831	1.043
S15	1.129	0.977	0.864	0.819	0.767	0.744	0.671	0.699	0.803	0.871	0.987	1.132

Table 3: Average ratios of monthly ET_0 estimated using CHS and the ET_0FAO-56 PM [Eq. 1]

NO.	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
S1	1.212	1.095	1.057	1.024	1.035	0.996	0.895	0.910	0.915	0.921	1.056	1.313
S2	1.163	1.062	0.974	0.949	0.950	0.910	0.843	0.879	1.066	1.107	1.250	1.427
S3	1.162	0.998	0.954	0.964	0.909	0.865	0.825	0.892	1.014	1.070	1.217	1.357
S4	1.157	0.940	0.937	0.943	0.973	0.999	0.935	1.011	0.990	0.990	1.099	1.222
S5	1.137	0.979	0.916	0.936	0.940	0.958	0.911	0.938	1.014	0.999	1.135	1.250
S6	1.163	0.967	0.886	0.876	0.884	0.926	0.871	0.877	0.988	1.036	1.193	1.344
S7	1.028	0.985	0.990	0.988	1.015	1.085	0.983	1.025	1.019	1.002	0.995	1.086
S8	1.199	1.026	0.924	0.892	0.883	0.875	0.826	0.901	1.033	1.127	1.218	1.487
S9	1.177	1.011	0.963	0.958	0.940	0.909	0.879	0.933	0.997	1.018	1.132	1.336
S10	1.090	1.003	0.984	1.023	1.025	1.014	0.958	1.000	0.968	0.981	1.021	1.124
S11	1.060	0.982	0.973	1.000	1.036	1.007	0.965	0.987	0.975	0.973	0.984	1.126
S12	1.169	1.010	0.963	0.982	1.019	0.988	0.916	0.938	0.940	0.949	1.055	1.218
S13	1.144	0.993	0.938	0.957	0.962	0.965	0.927	0.962	1.013	0.981	1.099	1.243
S14	1.193	1.023	0.973	0.954	0.971	0.953	0.933	0.975	0.981	0.966	1.048	1.314
S15	1.352	1.174	1.052	0.997	0.934	0.906	0.816	0.852	0.978	1.060	1.198	1.378

According to the presented results in Table 3, R values for all stations were more and less than one for cold months (December and January) and warm month (July), respectively. For stations located in semiarid regions (Khomein and Golpaigan) mean value of the R coefficient was closeto 0.90. After calibration, this value was 1.01.

The comparisons between the mean monthly ET_0 values computed by the Hargreaves equations [Eqs. 2 to 5] and CHS equation against the ET_0 calculated by the FAO-56 PM equation for the whole recording period of all stations are presented in Fig. 2.

As shown, the Hargreaves equations [Eqs. 2 to 5] and CHS equation performed relatively well with a R^2 higher than 0.80. Table 4 and 5 shows the statistical analysis components for each station-month between ET_0 estimated using the Hargreaves equations [Eqs. 2 to 5] and CHS equation and FAO-56 PM [Eq. 1]. The lowest and highest ratios monthly ET_0 of Hargreaves equations and CHS tothe FAO-56 PM reference method over all the stations were in July and December, respectively.

It was generally found that the Hargreaves equations [Eqs. 2 to 5] under estimates ET_0 with respect to FAO-56 PM ET_0 at 13 stations, and at two stations, namely Kahak and Kashan, it overestimated ET_0.

In these two stations, the monthly ET_0 estimates with the Hargreaves equations [Eqs. 2 to 5] were generally higher than the monthly ET_0 estimates with the FAO-56 PM method. This is due to the low value of wind speed during the year in these stations, which is in agreement with previous results (Martinez-Cob and Tejero-Juste, 2004; Heydari and Heydari, 2014a). The overestimation of ET_0 in these stations can account for larger values of the annual average of daily temperature range ΔT (difference between daily maximum and minimum air temperature). Also, the mean value of MBE was equal to 0.532 mm d^{-1}, ranging from 0.091 to 1.151 mm d^{-1}, whereas RMSE varied between 0.697 and 1.230mm d^{-1}, with an average value of 0.862mm d^{-1}. In the latter case, R was 1.23, indicating a mean overestimation of 23%.

The highest underestimations of the Hargreaves equations were found at Ardestan and Naein stations; the lowest underestimations were obtained at Ghom and Garmsar stations. Moreover, the underestimations of the CHS equation were observed at all stations. As shown in Table 4 and 5, the original Hargreaves equation [Eq. 2] was only better than the other versions of this equation in Kashan region. In another 14 stations, the second version of Hargreaves equation [Eq. 3] was better than the other types of this equation except Ghom, Garmsar and Meimeh. In Ghom with arid climate the Equation (4) and in Garmsar and Meimeh with their arid climate the fourth type of Hargreaves equation [Eq. 5] which contains monthly rainfall data, was better than the other types of this equation. Considering all locations and Hargreaves equations [Eqs. 2 to 5], the maximum MBE and RMSE was in Ardestan. The minimum MBE and RMSE were in Golpaigan and Ghom, respectively. Also, the maximum and minimum R was obtained in Kashan and Ardestan, respectively.

RMSE: root mean squared error (mm d^{-1}); MBE: mean bias error (mm d^{-1}); R: ratio of average estimations of ET_0; R^2: coefficient of determination.

The values of RMSE, MBE and R corresponding to the comparison of ET_0 FAO-56 PM and ET_0 Hargreaves equation [Eq. 3] as the best equation among other Hargreaves equations for all stations ranged from 0.509 to 2.382, with a mean of 0.932 and from -2.310 to 0.897, with a mean of -0.510 and from 0.702 to 1.372, with a mean of 0.983, respectively.

Ratios of ET_0 estimated using the original Hargreaves equation [Eq. 2] was closer to 1 when compared with the other versions of this equation and CHS at Ghom, Garmsar and KhoorBiabanak stations.

The Hargreaves equations [Eqs. 2 to 5] had a RMSE of less than 1.0 mm d^{-1} only at the 7 out of 15 stations, suggesting that the model provides fairly good approximations of the FAO-56 PM method. The CHS model had a RMSE of less than 1.0 mm d^{-1} at the all of the stations. Hence, local calibration would be required for the Hargreaves equation, especially at windy locations in the arid region.

When considering all stations in a single group, no method is clearly better than others; However, a similar equation based on mean monthly ET_0 calculation with the FAO-56 PM method and other parameters used in Equation (3), was derived for all selected stations in this study as follows:

$$ET_0 = 0.0028 \times R_a \times (T_{mean} + 15.44) \times (T_{max} - T_{min})^{0.517} \quad (9)$$

The mean value of ET_0 estimates using FAO-56 PM and the new equation (Equation (9)) for 15 stations is shown in Fig. 3. Average ratios between estimates using Equation (9) and mean value ET_0 estimates by FAO-56 PM are presented in Tables 5. The ratios were better compared with the Hargreaves equations [Eqs. 2 to 5].

As shown in Table 5, in Ghom, Golpaigan, Kahak, Kashan and Salafchegan stations, the average ratios between monthly estimated ET_0 with Equation (9) to the FAO-56 PM were more than one, while were less than one for regions of Ardestan, Meimeh and Naein for all months and yearly time step.

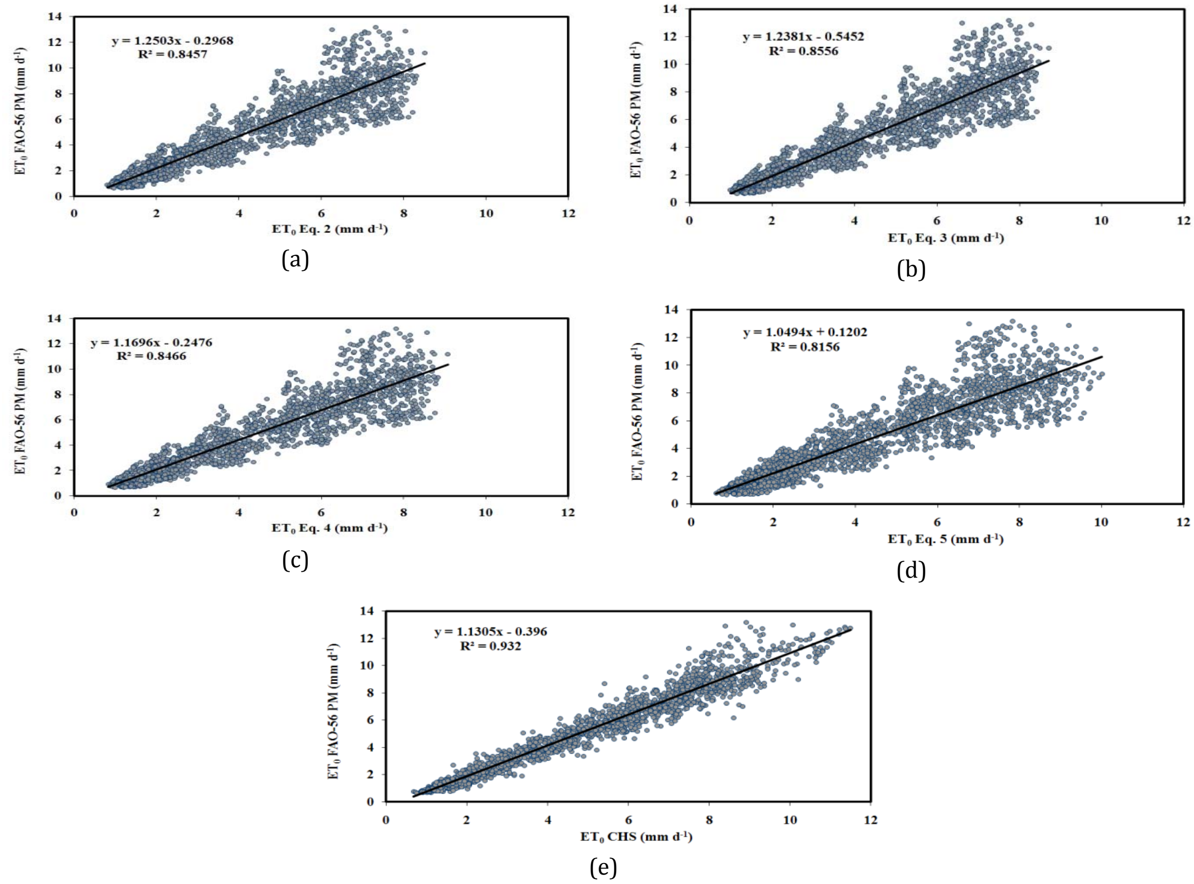

Fig. 2: Comparison of ET_0 estimated by FAO-56 PM reference method and different Hargreaves equations for all stations. (a) Equation (2); (b) Equation (3); (c) Equation (4); (d) Equation (5)and (e) CHS

Table 4: Comparison of statistical indices in estimating ET_0 values using different types of the Hargreaves equations [Eq. 2-5] and CHS equation and FAO-56 PM reference method [Eq. 1]

No.	Equation (2)				Equation (3)				Equation (4)			
	RMSE	MBE	R	R²	RMSE	MBE	R	R²	RMSE	MBE	R	R²
S1	2.661	-2.603	0.639	0.889	2.382	-2.308	0.702	0.893	2.428	-2.367	0.676	0.890
S2	0.814	-0.421	1.005	0.935	0.780	-0.216	1.074	0.938	0.707	-0.167	1.058	0.942
S3	0.678	-0.324	1.019	0.959	0.662	-0.147	1.081	0.962	0.588	-0.063	1.072	0.965
S4	0.661	-0.553	0.897	0.919	0.509	-0.294	0.978	0.931	0.515	-0.343	0.942	0.929
S5	0.712	-0.091	1.052	0.945	0.613	0.116	1.127	0.949	0.697	0.155	1.107	0.946
S6	0.774	0.672	1.279	0.931	0.969	0.897	1.373	0.926	1.002	0.931	1.348	0.920
S7	0.682	-0.621	0.882	0.945	0.510	-0.401	0.928	0.958	0.523	-0.403	0.902	0.953
S8	0.839	-0.489	0.990	0.922	0.716	-0.232	1.061	0.941	0.774	-0.245	1.045	0.936
S9	1.065	-0.772	0.915	0.925	0.913	-0.519	0.983	0.934	0.923	-0.529	0.964	0.933
S10	1.062	-1.031	0.803	0.957	0.899	-0.848	0.861	0.962	0.862	-0.825	0.842	0.958
S11	1.543	-1.454	0.746	0.944	1.305	-1.211	0.802	0.953	1.317	-1.220	0.786	0.951
S12	1.051	-0.992	0.801	0.922	0.788	-0.664	0.898	0.936	0.880	-0.803	0.842	0.928
S13	0.882	-0.561	0.936	0.935	0.752	-0.346	1.005	0.953	0.761	-0.327	0.984	0.948
S14	1.453	-1.234	0.812	0.891	1.244	-0.951	0.885	0.905	1.258	-0.996	0.855	0.901
S15	1.512	-1.282	0.872	0.905	1.155	-0.913	0.937	0.921	1.303	-0.998	0.922	0.917

Table 5: Continue of Table 4

No.	Equation (5)				CHS			
	RMSE	MBE	R	R^2	RMSE	MBE	R	R^2
S1	2.448	-2.400	0.654	0.889	0.672	-0.212	1.036	0.919
S2	0.671	-0.119	1.095	0.959	0.739	-0.234	1.048	0.942
S3	0.644	-0.108	1.131	0.963	0.674	-0.324	1.019	0.959
S4	0.519	-0.321	0.933	0.930	0.382	-0.072	1.016	0.942
S5	0.796	0.429	1.140	0.939	0.534	-0.185	1.009	0.961
S6	1.230	1.151	1.372	0.895	0.525	-0.269	1.001	0.951
S7	0.524	-0.194	0.915	0.954	0.373	-0.051	1.017	0.973
S8	0.757	-0.287	1.058	0.936	0.752	-0.303	1.033	0.954
S9	0.949	-0.332	0.982	0.932	0.741	-0.273	1.021	0.936
S10	0.533	-0.452	0.899	0.971	0.273	-0.024	1.016	0.978
S11	1.358	-1.257	0.804	0.945	0.486	-0.064	1.006	0.961
S12	1.051	-1.000	0.773	0.922	0.384	-0.132	1.012	0.953
S13	0.802	-0.127	1.005	0.940	0.595	-0.161	1.015	0.951
S14	1.253	-0.993	0.834	0.900	0.802	-0.212	1.024	0.912
S15	1.218	-0.916	0.925	0.915	0.953	-0.291	1.058	0.924

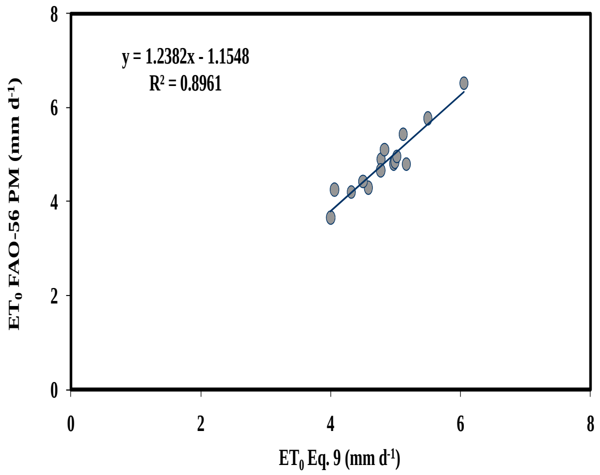

Fig. 3: Comparison of ET_0 estimated by FAO-56 PM reference method and Equation (9) for 15 stations

The Equation (9) was more accurate with respect to the original Hargreaves equation and the other modified versions tested in this study, showing a reduction of nearly 10-15% in RMSE on the entire area with respect to the original Hargreaves equation. The average of RMSE for all the station months between the estimated ET_0 with FAO-56 PM and Equation (9) was obtained equal to 0.840 mm d^{-1} which was less than RMSE presented by Equation (3).

The average of RMSE was obtained 0.567 mm d^{-1} using CHS equation. The results showed that the CHS equation gave better estimates of ET_0 compared to the other types of Hargreaves equations and new equation in all stations when compared to the FAO-56 PM equation as the reference equation. Using calibration and local coefficients for the most stations of this area, water consumption was reduced by 14% if the CHS equation was used instead of the original Hargreaves equation and the other modified versions. The results of this study also revealed that in arid and semiarid climates, the Hargreaves methods can be an alternative method (instead of recommended FAO-56 PM method) in estimating the regional ET_0, but local calibration the coefficient of Hargreaves equation (CHS) is the best approach, where meteorological data are sparse.

Table 5: Average ratios of monthly ET_0 estimated using Eq. 9 and the ET_0 FAO-56 PM [Eq. 1].

NO.	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
S1	0.853	0.783	0.768	0.756	0.771	0.732	0.656	0.696	0.670	0.681	0.765	0.933
S2	1.261	1.168	1.089	1.083	1.094	1.058	0.982	1.023	1.234	1.266	1.402	1.563
S3	1.316	1.146	1.115	1.148	1.093	1.049	1.003	1.084	1.226	1.278	1.425	1.552
S4	1.132	1.115	1.095	1.087	1.074	1.063	1.025	1.079	1.051	1.075	1.122	1.224
S5	1.340	1.167	1.132	1.148	1.164	1.198	1.125	1.174	1.273	1.253	1.397	1.508
S6	1.685	1.420	1.326	1.353	1.358	1.435	1.324	1.362	1.527	1.583	1.787	1.966
S7	0.966	0.960	0.961	0.955	0.961	1.006	0.944	0.972	1.066	0.947	0.953	1.112
S8	1.242	1.141	1.064	1.035	1.035	1.026	0.956	1.035	1.081	1.279	1.359	1.633
S9	1.194	1.038	1.007	1.022	1.008	0.981	0.950	1.010	1.082	1.096	1.197	1.372
S10	0.969	0.935	0.936	0.952	0.967	0.968	0.917	0.957	0.944	0.921	0.929	0.978
S11	0.885	0.891	0.905	0.886	0.913	0.902	0.880	0.886	0.900	0.892	0.889	0.925
S12	1.031	0.905	0.880	0.915	0.960	0.940	0.872	0.894	0.890	0.887	0.938	1.089
S13	1.186	1.044	1.026	1.041	1.055	1.068	1.015	1.068	1.125	1.086	1.192	1.314
S14	1.071	0.930	0.899	0.896	0.923	0.913	0.896	0.936	0.938	0.913	0.968	1.191
S15	1.302	1.138	1.020	0.981	0.927	0.904	0.815	0.850	0.973	1.047	1.167	1.314

4. Conclusions

In this work the FAO-56 PM model was considered as the reference standard method for validating the predicted ET_0 data. Because of the lack of meteorological data for estimating monthly ET_0 with the FAO-56 PM method for most weather stations in the centre of Iran, original Hargreaves and different versions of this equation and calibrated Hargreaves equation (CHS) should be used for estimating monthly ET_0. Application of versions of the Hargreaves equation proposed does not improve significantly or even worsen performances. The second version of Hargreaves equation [Eq. 3] was better than the other types of this equationin most of the stations. The new modified equation [Eq. 9] showed improvement in estimating ET_0 compared to the original and different versions of Hargreaves equation, but the CHS model presented the best performance for estimation of monthly ET_0 values in arid and semiarid regions (centre of Iran).Overall, calibration of the Hargreaves equation resulted in improvements of the equations by reducing the errors of the ET_0 estimates.

References

Allen RG, Clemmens AJ, Burt CM, Solomon K and O'Halloran T (2005). Prediction accuracy for project wide evapotranspiration using crop coefficients and reference evapotranspiration. Journal of Irrigation and Drainage Engineering, 131(1): 24–36.

Allen RG, Pereira LS, Raes D and Smith M (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome, 300(9): D05109.

Allen RG, Pruitt WO, Wright JL, Howell TA, Ventura F, Snyder R, Itenfisu D, Steduto P, Berengena J, Beselga J, Smith M, Pereira LS, Raes D, Perrier A, Alves I, Walter I and Elliott R (2006). A recommendation on standardized surface resistance for hourly calculation of reference ET0 by the FAO-56 Penman–Monteith method. Agricultural Water Management, 81(1):1–22.

Allen RG, Smith M, Pereira LS and Perrier A (1994a). An update for the calculation of reference evapotranspiration. ICID Bull, 43(2): 35– 92.

Allen RG, Smith M, Perrier A and Pereira LS (1994b). An update for the definition of reference evapotranspiration. ICID Bull, 43(2): 1–34.

Allen RG, Walter IA, Elliott R, Mecham B, Jensen ME, Itenfisu D, Howell TA, Snyder R, Brown P, Echings S, Spofford T, Hattendorf M, Cuenca RH, Wright JL and Martin D (2000). Issues, requirements and challenges in selecting and specifying a standardized ET equation. Proceedings of the 4th National Irrigation Symposium. Phoenix: ASAE:. 201–208

Amatya DM, Skaggs RW and Gregory JD (1995). Comparison of methods for estimating Ref-ET. Journal of irrigation and drainage engineering, 121(6): 427-435.

Azhar AH and Perera BJC (2010). Evaluation of reference evapotranspiration estimation methods under south east Australian conditions. Journal of Irrigation and drainage engineering, 137 (5): 268-279.

Benli B, Bruggeman A, Oweis T and Üstün H (2010). Performance of Penman-Monteith FAO-56 in a Semi-arid Highland Environment. Journal of Irrigation and drainage engineering, 136(11): 757-765.

Chuanyan Z, Zhongren N, and Zhaodong F (2004). GIS-assistedspatially distributed modeling of the potential evapotranspiration insemi-arid climate of the Chinese Loess Plateau. Journal of Arid Environ, 58(3): 387–403.

DehghaniSanij H, Yamamoto T and Rasiah V (2004). Assessment of evapotranspiration estimation models for use in semi-arid environments. Agricultural water management, 64(2): 91-106.

Di Stefano C and Ferro V (1997). Estimation of evapotranspiration by Hargreaves formula and remotely sensed data in semi-arid Mediterranean areas. Journal of agricultural engineering research, 68(3): 189-199.

Droogers P and Allen RG (2002). Estimating reference evapotranspiration under inaccurate data conditions. Irrigation and drainage systems, 16(1): 33-45.

Garcia M, Raes D, Allen R and Herbas C (2004). Dynamics of reference evapotranspiration in the Bolivian highlands (Altiplano). Agricultural and forest meteorology, 125(1): 67-82.

Garcia M, Raes D, Jacobsen SE, Michel T. (2007). Agro climatic constraints for rain fed agriculture the Bolivian (Altiplano). Journal of Arid Environments, 71(1): 109-121.

Gavilan P, Lorite IJ, Tornero S and Berengena J (2006). Regional calibration of Hargreaves equation for estimation of reference ET in a semi-arid environment. Journal of Arid Environments, 71(1): 109-121.

Gao G, Chen D, Ren G, Chen Y and Liao Y (2006). Spatial and temporal variations and controlling factors of potential evapotranspiration in China: 1956–2000. Journal of Geographical Sciences, 16(1): 3-12.

Ghamarnia H, Rezvani V, Khodaei E and Mirzaei H (2012). Time and Place Calibration of the Hargreaves Equation for Estimating Monthly Reference Evapotranspiration under Different Climatic Conditions, Journal of Agricultural Science. 4(3): 111-122.

Gundekar HG, Khodke UM, Sarkar S and Rai RK. (2008). Evaluation of pan coefficient for reference crop evapotranspiration for semi-arid region. Irrigation Science, 26(2): 169-175.

Hargreaves GH, Allen RG. (2003). History and evaluation of Hargreaves evapotranspiration equation. Journal of Irrigation and Drainage Engineering, 129(1): 53-63.

Hargreaves GH and Samani ZA (1985). Reference crop evapotranspiration from temperature. Applied engineering in agriculture, 1(2): 96–99.

Heydari MM, Abbasi A and Heydari M (2013). Estimation of Evapotranspiration in Ardestan, Center of Iran. World Applied Sciences Journal, 21 (2): 230-236.

Heydari MM and Heydari M (2014a). Calibration of Hargreaves–Samani equation for estimating reference evapotranspiration in semiarid and arid regions. Archives of Agronomy and Soil Science, 60(5): 695-713.

Heydari MM and Heydari M (2014b). Evaluation of pan coefficient equations for estimating reference crop evapotranspiration in the arid region. Archives of Agronomy and Soil Science, 60(5): 715-731.

Heydari MM, Tajamoli A, Ghoreishi SH, Darbe-Esfahani MK and Gilasi H (2015). Evaluation and calibration of Blaney–Criddle equation for estimating reference evapotranspiration in semiarid and arid regions. Environmental Earth Sciences, 74(5): 4053-4063.

Huxman TE, Bradford P, Davis W, Breshears D, Scot RL, Snyder KA, Small EE, Hultine K, Pockman WT and Jacson RB. (2005). Ecohydrological implications of woody plant encroachment. Ecology, 86(2): 308-319.

Irmak S, Allen RG and Whitty EB (2003). Daily Grass and alfalfa-reference evapotranspiration estimates and alfalfa to grass evapotranspiration ratios in Florida. Journal of Irrigation and Drainage Engineering, 129(5):360-370.

Itenfisu D, Elliott RL, Allen RG and Walter IA (2003). Comparison of reference evapotranspiration calculation as part of the ASCE standardization effort, Journal of Irrigation and Drainage Engineering. 129 (6): 440–448.

Jabloun M and Sahli A (2008). Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data, Application to Tunisia. Agricultural water management, 95(6): 707-715.

Jamshidi H, Khalili D, Zadeh MR and Hosseinipour EZ (2010). Evaluation of Hargreaves Equation for ET0 Calculations at Selected Synoptic Stations in Iran. World Environmental and Water Resources Congress, Challenges of Change. Section of Planning and Management Council. 2791-2801.

Jensen ME, Burman RD and Allen RG (1990). Evaporation and irrigation water requirement. ASCE Manual and Report on Engineering Practice, New York, USA: 70

Kisi O (2008). The potential of different ANN techniques in evapotranspiration modeling. Hydrological Processes, 22(14): 2449-2460.

Lee K. (2010). Relative Comparison of the Local Recalibration of the Temperature-Based Evapotranspiration Equation for the Korea Peninsula. Journal of Irrigation and Drainage Engineering, 136(9): 585-594.

Marti P, Gonzalez-Altozano P and Gasque M (2011). Reference evapotranspiration estimation without local climatic data. Irrigation Science, 29 (6): 479-495.

Martínez-Cob A and Tejero-Juste M (2004). A wind-based qualitative calibration of the Hargreaves ET_0 estimation equation in semi-arid regions. Agricultural Water Management, 64(3): 251-264.

Mielnick P, Dugas WA, Mitchell K and Havstad K (2005). Long-term measurements of CO_2 flux and evapotranspiration in Chihuahuan desert grassland. Journal of Arid Environments, 60(3): 423-436.

Monteith JL (1964). Evaporation and environment. The state and movement of water in living organisms. 19th Symposium Society of Experimental Biology, Academic Press, New York, USA: 205-234.

Monteith JL (1965). Evaporation and the environment. In: The state and movement of water in living organisms. Proceedings of the 19th Symposium, Society of Experimental Biology, Cambridge University Press, London.

Prater MR and DeLucia EH (2006). Non-native grasses alter evapotranspiration and energy balance in Great Basin sagebrush communities. Agricultural and Forest Meteorology, 139(1): 154-163.

RahimiKhoob A (2008). Comparative study of Hargreaves's and artificial neural network's methodologies in estimating reference evapotranspiration in a semi-arid environment. Irrigation Science, 26(3): 253-259.

Ravelli F and Rota P (1999). Monthly frequency maps of reference evapotranspiration and crop Water deficits in Southern Italy. Rome: Irrigation Experimentation Office of the Former Southern Italy Development Agency.

Sentelhas PC, Gillespie TJ and Santos EA (2010). Evaluation of FAO Penman –Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada. Agricultural Water Management, 97(5): 635–644.

Smith M, Allen RG and Pereira L (1996). Revised FAO methodology for crop water requirements. In: Camp CR, Sadler EJ, Yoder RE (eds) Proceedings of the evapotranspiration and irrigation scheduling conference, American Society of Agricultural Engineers, St. Joseph: 116–123.

Tabari H, Grismer EM and Trajkovic S (2013). Comparative analysis of 31 reference evapotranspiration methods under humid conditions. Irrigation Science, 31 (2): 107-117.

Tabari H, Marofi S, Aeini A, HosseinzadehTalaee P and Mohammadi K (2011). Trend analysis of reference evapotranspiration in the western half of Iran. Agricultural and Forest Meteorology, 151(2): 128-136.

Temesgen B, Eching S, Davidoff B and Frame K (2005). Comparison of some reference evapotranspiration equations for California. Journal of irrigation and drainage engineering, 131(1): 73-84.

Thepadia M and Martinez CJ (2012). Regional calibration of solar radiation and reference evapotranspiration estimates with minimal data in Florida. Journal of irrigation and drainage engineering, 138 (2): 111-119.

Trajkovic S and Kolakovic S (2009). Wind-adjusted Turc equation for estimating reference evapotranspiration at humid European locations. Hydrology Research, 40(1): 45-52.

Trajkovic S (2005). Temperature-based approaches for estimating reference evapotranspiration. Journal of irrigation and drainage engineering, 133(4): 316-323.

Trajkovic S (2007). Hargreaves versus Penman-Monteith under humid conditions. Journal of irrigation and drainage engineering, 133(1): 38-42.

Vanderlinden K, Giraldez JV and Van Meirvenne M (2004). Assessing reference evapotranspiration by the Hargreaves method in southern Spain. Journal of irrigation and drainage engineering, 130(3): 184-191.

Walter IA, Allen RG, Elliott R, Jensen ME, Itenfisu D, Mecham B, Howell TA, Snyder R, Brown P, Eching S, Spofford T, Hattendorf M, Cuenca RH, Wright JL and Martin D (2000). ASCE's standardized reference evapotranspiration equation. In: Proceedings of the 4th National Irrigation Symposium, November 2000, Phoenix: ASAE: 209-215.

Weiß M and Menzel L (2008). A global comparison of four potential evapotranspiration equations and their relevance to stream flow modeling in semi-arid environments. Advances in Geosciences, 18(18): 15-23.

Zhao C, Nan Z and Cheng G (2005). Evaluating methods of estimating and modelling spartial distribution of evapotranspiration in the middle heihe river basin, China. American journal of environmental sciences, 1(4): 278-285.