

Time and Place Calibration of the Hargreaves Equation for Estimating Monthly Reference Evapotranspiration under Different Climatic Conditions

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Abstract

The standardized FAO-56 Penman–Monteith (PM) equation requires a great number of input parameters that are difficult to record. The Hargreaves method is another approach. It has high accuracy, while it requires fewer input parameters. In the present study, the Hargreaves-Samani method was calibrated by the PM equation under different climate conditions, in the western Iran. Different correction coefficients were used for each station under study instead of the constant coefficient 0.0023 in the Hargreaves equation based on monthly and annual scales. The corrected coefficients obtained for different regions can be used to estimate ETo for the PM method under the same climates where reliable data are available. The results also showed that as a larger study area with more weather stations is used and a larger amount of data is obtained, the coefficient of 0.0023 in the Hargreaves equation does not need further corrections for local calibration purposes.

Keywords: Reference evapotranspiration, FAO-56 Penman –Monteith, Hargreaves method

1. Introduction

The estimation of evapotranspiration is the first and the most important step towards designing, planning and managing different irrigation networks, water distribution systems, water application, calculation of lake surface evaporation losses, implementation of hydrological and agro-hydrological models, environmental studies, water balance, and water management practices (Landras et al, 2008). In semiarid climates where water resources are

limited and seriously overexploited, precise estimation of crop water requirements is needed for effective management and planning of available water resources (Jabloun and Sahli, 2008).

The different methods applied to estimate evapotranspiration are categorized into two main groups, namely direct and indirect, or computational methods (Alizadeh and Kamali, 2007). The simplest tool to determine evapotranspiration on a small-scale is the lysimetric method. A lysimeter is a tank of a given size that is embedded in soil and water, and its input and output values are measurable (Alizadeh and Kamali, 2007). By using different climate factors in an indirect method, the potential evapotranspiration is calculated, and then by considering different crop coefficients at different crop growth stages, the desired plant evapotranspiration can be calculated (Allen et al, 1998; Savana and Frenken, 2002; Alizadeh and Kamali, 2007).

Reference crop evapotranspiration is generally a reflection of climate effects. A surface evapotranspiration with no water shortages is called a "reference plant evapotranspiration". The reference level is a hypothetical grass reference crop with a height of 0.12 m and a surface resistance of 70 m/sec with reflection coefficient of 0.23. No lack of water in soil should exist under such circumstances. A similar reference definition for alfalfa with a height of 20 cm has also been defined (Allen et al, 1998; Alizadeh, 2006; Alizadeh and Kamali, 2007; Trajkovic and Kolakovic, 2009).

The Penman–Monteith method proposed by Allen et al. (1998) as a standardized method needs different climatological data such as relative humidity, air temperature, solar radiation, and wind speed. However, at many weather stations around the world, especially in developing countries such as Iran, not all the required parameters can be measured; hence, an alternative method should be used to estimate reference evapotranspiration with higher accuracy and requiring fewer input parameters. Allen et al. (1998) suggested that should insufficient data be available to resolve the Penman–Monteith equation, the Hargreavess-Samani equation (Hargreaves et al., 1985) can be used instead.

A number of studies have been performed to compare the Penman-Monteith and the Hargreavess-Samani approaches. The Hargreaves equation was used to estimate monthly ETo in the Bajgah region in Fars province, Iran, by Fooladmand and Spaskhah (2005). They reported that during different months of the year, different coefficients should be used instead of the 0.0023 value in the Hargreaves equation. The results obtained with the Hargreaves model were reported to be satisfactory in computing weekly or monthly reference evapotranspiration (Hargreaves and Allen 2003). Martinez-Cob and Tejero-Juste (2004) and Gavilan et al., (2006) suggested that the Hargreavess-Samani method needs specific local calibration to achieve an acceptable performance.

Rahimi Khoob (2008) compared the Penman-Monteith and Hargreaves methods for reference evapotranspiration calculation. For this purpose, data from 12 weather stations located across the Khuzestan plain (southwest Iran) were selected to calculate reference evapotranspiration. He reported that the Hargreavess-Samani method gave significantly higher or lower results than those of the Penman-Monteith method. Kisi (2008) compared the Hargreaves-Samani and Penman–Monteith methods in Los Angeles, USA. He concluded that the calibrated Hargreaves-Samani method is the best approach to estimate evapotranspiration.

Landras et al., (2008) compared various equations for reference evapotranspiration using the Penman-Monteith method for a study area in the northern part of Spain. They reported that the Hargreaves-Samani method had the weakest performance, with a 32.2% overestimation. Sentelhas et al., (2010) examined different reference evapotranspiration methods in Ontario, Canada. They showed that by considering the amount of available weather data, the Hargreaves-Samani method can be a good alternative to the Penman-Monteith method. Saghravani, et al., (2009) suggested that if the Hargreaves method was used to study a region in the absence of sunshine hours, humidity and wind-speed data, corrections were needed to obtain results that were as reliable and accurate as those obtained with the Penman-Monteith method.

Sabziparvar and Tabari (2010) evaluated the performance of the Makkink, Priestley-Taylor, and Hargreaves models compared to that of the Penman-Monteith FAO-56 method for arid and semiarid regions in northeastern Iran. They reported that the Hargreaves model had the best performance in estimating monthly ETo values. Moreover, in different parts of Iran, the total number of weather stations is too small for the extent of the country, and the analogue instruments used at most of the existing stations do not record all of the necessary meteorological parameters because of lack of proper facilities and poor management. Therefore, it is not possible to estimate reference evapotranspiration based on the Penman-Monteith method because of insufficient data. At most stations, only maximum and minimum air temperatures are recorded, and according to Allen et al. (1998), the Hargreaves model is recommended for computation of reference evapotranspiration when only maximum and minimum air temperature data are available.

Correct reference evapotranspiration and crop water requirement computations are very important for dam operation and design of irrigation and drainage schemes. Also, the western parts of Iran play a key role in producing agricultural commodities, and a large number of dam construction schemes and irrigation and drainage projects are under study or in progress in these areas. The main objective of the present study was to determine the correction coefficients for each station based on a monthly scale instead of the 0.0023 coefficient of the Hargreaves equation for semi-arid regions in west Iran, for which only maximum and minimum air temperature were recorded and for which comprehensive measurements of meteorological data were unavailable.

2. Materials and Methods

The study area is located in west Iran at 32° 06' to 36°33' N and 45° 24' to 50° 02' E. The region extends over five provinces, Kermanshah, Lorestan, Ilam, Kurdistan, and Hamadan, covering an area of approximately 106,508 square kilometers. The average annual rainfall is about 480 mm, and based on the Thornthwaite classification, the regional climates are dry sub-humid, moist sub-humid, semi-arid, and humid. Figure (1) and Table (1) show the spatial distributions, meteorological data and climate information of 24 selected stations. As shown in Table (1), this area is dominated by dry sub-humid climate.

The data included maximum temperature (Tmax), minimum temperature (Tmin), dew point temperature (Tdew), maximum relative humidity (RHmax), minimum relative humidity (RHmin), average relative humidity (RHmean), wind speed (U), and sunshine hours (n).

To calculate wind speed at two-meter height, the equation proposed by Allen et al. (1998) was:

$$U_2 = \frac{4.87 \cdot U_{10}}{\ln(67.8 \cdot 10 - 5.42)} \quad (1)$$

where U_2 is the average 24-hour wind speed at a height of 2 m and U_{10} is average 24-hour wind speed at a height of 10 m.

The solar radiation was calculated by using the following formula:

$$R_s = \left(0.25 + 0.5 \frac{n}{N} \right) \cdot R_a \quad (2)$$

where R_s is the net solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), N is the maximum possible sunshine hours (h), n is the number of actual sunshine hours (h), and R_a is the extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).

2.1 ET Reference Methods

Allen et al., (1998) proposed the FAO-Penman-Monteith method as a standard method to estimate, evaluate and calibrate the ET reference value. This method has been used by many researchers (Gavilan et al, 2006; Rahimikhoob, 2008; Fooladmand and Haghghat, 2007 Noori mohammadieh et al, 2009; Sabziparvar and Tabari, 2010), and the equation can be rewritten following Allen et al (1998):

$$ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} v_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 v_2)} \quad (3)$$

where ET_o is the reference evapotranspiration (mm day^{-1}), R_n , G , and T are net radiation values at the crop surface ($\text{MJ m}^{-2} \text{ day}^{-1}$), soil heat flux density ($\text{MJ m}^{-2} \text{ day}^{-1}$), and mean daily air temperature at 2 m height ($^{\circ}\text{C}$), respectively. Also, u_2 , e_s , e_a , $(e_s - e_a)$, Δ , and γ are wind speed at 2 m height (m s^{-1}), saturation vapor pressure (kPa), actual vapor pressure (kPa), saturation vapor pressure deficit (kPa), slope of the saturation vapor pressure curve ($\text{kPa}/^{\circ}\text{C}$), and psychrometric constant ($\text{kPa}/^{\circ}\text{C}$), respectively.

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

$$ET_o = 0.0023 (T_{mean} + 17.8) (T_{max} - T_{min}) 0.5 R_a \quad (4)$$

where T_{mean} , T_{max} and T_{min} are mean, maximum and minimum temperatures ($^{\circ}\text{C}$), respectively, and R_a is extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$) converted to equivalent evaporation in mm day^{-1} with a factor of 0.408.

The climate of each region was determined by using the Thorontwhiet model as below (Shahid et al., 2005):

$$PEI = \sum_{n=1}^{12} 115 \left(\frac{P}{T-10} \right)^{10/9} \quad (5)$$

where P is monthly precipitation (inch), T is average monthly temperature (Fahrenheit), and n is the number of months (n=12).

2.2 Calibration

In order to calibrate the Hargreavess-Samani equation using monthly data, the Penman-Monteith method was used as follows:

$$ET_{0-PM} = \lambda \times ET_{0-Hargreaves} \quad (6)$$

where λ is the slope of the correlation of evapotranspiration by the Hargreavess-Samani and Penman Monteith methods. Finally, the Hargreaves equation for each region and each month of the year was corrected:

$$C = \lambda \times 0.0023 \quad (7)$$

where C is the monthly corrected value for each station.

2.3 Model comparison

ETo estimates by the PM and HG models were compared using simple error analysis and the linear regression method. Both methods were compared before and after adjustments were applied. For each location, the following parameters were also calculated (Willmott, 1982): root mean square error (RMSE), mean bias error (MBE), and the ratio of average estimations of ETo (R).

$$RMSE = \left[\frac{\sum_{i=1}^n (X_{Harg} - X_{PM})^2}{n} \right]^{1/2} \quad (8)$$

$$MBE = \left[\frac{\sum_{i=1}^n (X_{Harg} - X_{PM})}{n} \right] \quad (9)$$

$$R = \frac{X_{Harg}}{X_{PM}} \quad (10)$$

where X_{Harg} , X_{pm} , and n are the evaporation values estimated by the Hargreaves and Penman-Monteith methods and data number, respectively.

3. Results and discussion

Monthly ETo values for all the stations were estimated by the FAO-Penman-Monteith (PM) and Hargreavess-Samani (HG) methods, and the results were compared. The monthly and annual slope values (λ) for the different stations based on the regression between ET_{0-Harg} and ET_{0-PM} are shown in Table (2).

Table (3) shows the monthly and annual values of RMSE (Root mean square error). A comparison shows that the lowest monthly RMSE index belonged to the Aleshtar Station, with dry sub-humid climate and with a value of 0.095 in December. The highest RMSE, with a value of 3.132, was recorded at the Baneh Station under a moist sub-humid climate in August. Annually, the highest and lowest RMSE values of 1.946 and 0.334 were at the Baneh and Azna stations, with moist sub-humid and dry sub-humid climates, respectively. The results showed that the RMSE values in warm months were higher than those in cold months of the year, causing differences between evapotranspiration values calculated by the Hargreaves and Penman-Monteith methods. In the warmest months of the year, including May, June, July and August, the differences between ET_{0-Harg} and ET_{0-PM} values were the highest, while in the coldest months of the year, including October, November, December, January, February, March and April, the differences between ET_{0-Harg} and ET_{0-PM} values were the lowest.

The MBE (Mean bias error) values for different meteorological stations are shown in Table (4). A comparison of the results showed overestimated (positive) values or underestimated (negative) values for ETo predicted by the Hargreaves and Penman-Monteith methods. The results of the MBE comparison in Table (4) showed that the minimum and maximum values of MBE were obtained at Ravansar Station, with a value of -1.819 in July, and Kouhdasht Station, with a value of +1.546 in August, both under dry sub-humid climates. Negative and positive values of MBA indicate underestimated and overestimated values for the Hargreaves and Penman-Monteith methods, respectively. As Table (4) shows, for annual results, the minimum and maximum values of MBE were obtained at Banah Station, with a value of -1.634, and Kouhdasht Station, with a value of +0.678, for moist sub-humid and dry sub-humid climates, respectively.

As presented in Table (5), the monthly and yearly values of the C coefficients were estimated. For the monthly results, the lowest value of C was 0.0018 for Eslamabad Gharb Station in December, while it was for Kuhdasht Station in August. Both stations were located in dry sub-humid climates. Also, as shown in Table (5), the highest C value, 0.0042, was obtained for Banah Station under a moist sub-humid climate in October.

The annual results showed that the lowest and highest C values were obtained for Kohdasht and Baneh Stationed, 0.0019 and 0.0035, respectively. Table (5) shows that the annual C coefficients for each station differ. The lowest C value was obtained at Dorud Station with a value of 0.00011 in a moist sub-humid climate, while the greatest difference was obtained at Dehloran, west Islamabad, Ilam, Kangavar, Kermanshah, Khoramabad, Kohdasht, Marivan, and Sanandaj Stations, with a value of 0.0003. The climate at the Marivan Station is humid, that of Dehloran is semi-arid, and that of the rest is dry sub-humid.

As Table (5) shows, C coefficients were lower than 0.0023 for Islam Abad Gharb, Kangavar, Khoramabad, Kohdasht, Saghez, and Sanadnaj Stations, all with dry sub humid climate, and Marivan station with humid climate. This implies that the ETo values estimated by the Hargreaves method were higher than those by the Penman-Monteith method. For stations with C coefficient higher than 0.0023, the ETo values estimated by the Hargreaves method were lower than those by Penman-Monteith method. Figures (2) and (3) show the place and time in which C distribution coefficients were obtained for monthly and annual results at all stations under study.

Different R index values are shown in Table (6). The indexes show that the ratio of the Hargreaves ETo values have been either overestimated or underestimated as compared to those by the Penman-Monteith method. The greatest overestimate was obtained for Kuhdasht Station, 25.2% in August, while the greatest underestimate was obtained for Banah Station, 45.1% in October. For annual results, the greatest overestimate, 17.9%, was obtained for Kuhdasht Station, while the greatest underestimate, 34.41%, was obtained for Banah Station. These differences probably were caused by the higher wind speed of 4.93 m/s at Banah Station as compared to the wind speed of 1.75 m/s at Kuhdasht Station. The annual results at Nahavand Station estimated by the Hargreaves method equal those estimated by the Penman-Monteith method. Figure (4) shows that for annual results, the Hargreaves ETo values were either overestimated or underestimated as compared to the Penman-Monteith method at all stations.

Figure (5) shows the mean monthly ETo values calculated by the PM method along with those estimated by the HG method for all meteorological stations from 1986–2005. The HG method gave a correlation of $R^2 = 0.861$ and the relationship equation $y = 1.008x$. Based on this equation, the value of parameter λ was obtained as 1.008, and the C value was determined to be 0.0023 using Eq.(6). One can conclude that when the investigation area is more extensive and a larger number of weather stations and available data are used, the coefficient of 0.0023 in the Hargreaves equation does not require any local calibrations. The results of the present study differ from those suggested by Noori Mohammadi et al. (2009), who reported satisfactory ETo estimations for 18 locations.

Salako (2008) found that the daily means of PM ETo values were significantly correlated with those of the HG method ($P < 0.0001$, r^2 from 0.72-0.93) and pan ETo values ($P < 0.0001$, r^2 from 0.91-0.93). He also reported that the regression equations developed for three agroecological zones of Nigeria can be used to estimate PM ETo values for similar climatic zones where data requirements cannot be met but data for the HG or pan method are available.

Jabloun and Sahli (2008) evaluated the Hargreaves equation. They reported that the results obtained from the comparison of ETo daily estimates by the Hargreaves equation with FAO-56 PM, estimates taken as reference throughout different Tunisian locations showed a systematic overestimation at inland sites but that at coastal sites, the Hargreaves equation tended to underestimate ETo values. They suggested that further research would be required to adjust the Hargreaves coefficients to local conditions for obtaining better accuracy.

4. Conclusions

The main objective of this study was to evaluate the Hargreaves temperature-based method to estimate daily ETo values for western semi-arid parts of Iran. Monthly data were used for monthly ETo calculations at all 24 meteorological stations by the Hargreaves and Penman-Monteith methods. For this purpose, the calibration process was based on monthly and yearly data. The calibration results of two ETo estimated methods showed either high or low results at different stations. Finally, for all the selected stations, the monthly and yearly Hargreaves C coefficients were calculated.

For monthly results, the lowest and highest C values were 0.0018 and 0.0042. For annual results, the lowest and highest C values were 0.0019 and 0.0035. Finally, at all 24 meteorological stations, C coefficients were determined. By using corrected C coefficients and temperature measurements, one can suggest that the values of ETo by the Hargreaves method can be simply obtained.

The overall results also showed that when the study area is larger, more weather stations are used, and reliable data are available, the coefficient of 0.0023 used in the Hargreaves method does not need any corrections for local calibrations and can be applied with confidence.

Moreover, the results indicated that both monthly and yearly means by the Hargreaves method were significantly correlated with those of the Penman-Monteith method at all available recording stations in western Iran; hence, it is possible to predict monthly and yearly ETo values precisely in other areas where the required data for the Penman-Monteith estimations are unavailable and only maximum and minimum air temperatures have been recorded.

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Table 1. Localization, meteorological data and climate of the 24 selected stations in this study

Station name	Latitude (degree)*	Longitude (degree)*	Elevation (m)	Record Period	Precipitation (mm)	T _{max} (°C)	T _{min} (°C)	T _{dew} (°C)	U ₁₀ (Knot)	RH _{mean} (%)	n (hr)	Climate**
Aleshtar	33° 49'	48° 15'	1567.2	2000-2005	497.25	22.1	3.0	0.9	4.8	49.6	260.4	Dry sub-humid
Aligoodarz	33° 24'	49° 42'	2022	1986-2005	398.82	19.0	5.6	-2.9	7.1	40.2	266.3	Dry sub-humid
Azna	33° 27'	49° 25'	1871.9	2001-2005	438.58	20.4	4.5	-0.3	4.3	46	262.7	Dry sub-humid
Baneh	36° 00'	45° 54'	1600	2000-2005	708	18.6	8.7	-0.1	9.6	44.3	240.1	Moist sub-humid
Bijar	35° 53'	47° 37'	1883.4	1987-2005	339.9	16.5	5.3	-1.7	8	47.8	250.6	Dry sub-humid
Broujerd	33° 55'	48° 45'	1629	1993-2005	463.6	21.4	8.2	-1	6.9	42	259	Dry sub-humid
Dehloran	32° 41'	47° 16'	232	1996-2005	288.7	32.3	20.2	8.6	4.3	38.2	265.1	Semi-arid
Doroud	33° 29'	49° 04'	1526.7	2000-2005	679.5	22.4	9.9	-1.4	5.7	37.7	263	Moist sub-humid
Eslamabad Gharb	34° 07'	46° 28'	1348.8	1987-2005	483.6	22.1	5.1	1.1	3.2	50.4	255.7	Dry sub-humid
Ghorveh	35° 10'	47° 48'	1906	1992-2005	341.4	17.4	5.4	-1.8	6.3	45.3	252.9	Dry sub-humid
Ilam	33° 38'	46° 26'	1337	1995-2005	554.2	22.7	11.6	0.7	4.7	40.6	264.6	Dry sub-humid
Kangavar	34° 30'	47° 59'	1468	1987-2005	400.2	21.3	4.3	1	3.4	51.6	253.5	Dry sub-humid
Kermanshah	34° 21'	47° 09'	1318.6	1983-2005	433.3	23.2	6.5	0.3	4.3	45.3	243.3	Dry sub-humid
Khorramabad	33° 26'	48° 17'	1147.8	1982-2005	491.9	24.7	8	2.4	3.3	48.1	249.9	Dry sub-humid
Kouhdasht	33° 32'	47° 38'	1199.8	1998-2005	391.7	24.8	6.9	2.7	3.4	47.3	270.8	Dry sub-humid
Malayer	34° 15'	48° 51'	1777.8	1994-2005	305.1	20.6	6.2	-0.3	5.2	45.7	260.5	Dry sub-humid
Marivan	35° 31'	46° 12'	1286.8	1994-2005	957	20.9	5.2	2.2	3.7	53.9	247.9	Humid
Nahavand	34° 09'	48° 25'	1680.9	1997-2005	368.4	21	6.7	1	4.6	44.9	271.7	Dry sub-humid
Noorabad	34° 03'	48° 00'	1859.1	2001-2005	478.3	18.9	4.8	-1.7	7.8	45.2	256	Dry sub-humid
Poldokhtar	33° 09'	47° 43'	713.5	1999-2005	372.2	29	16.6	3.5	5.6	36.3	266	Semi-arid
Ravansar	34° 43'	46° 39'	1379.7	1991-2005	537.5	21.6	8.1	-0.2	5.5	45.3	253.8	Dry sub-humid
Saghez	36° 15'	46° 16'	1522.8	1983-2005	482.4	18.8	2.9	0.5	3.8	54.2	240.8	Dry sub-humid
Sanandaj	35° 20'	47° 00'	1373.4	1982-2005	441.6	21.6	5.5	0.3	3.6	48.9	237.7	Dry sub-humid
Zarneh Obato	36° 04'	46° 55'	2142.6	1991-2005	409.5	14	1.7	-2.5	7.3	54.3	255	Dry sub-humid

*Degrees, minutes; T_{min}=minimum air temperature, T_{max}=maximum air temperature, T_{dew}=dew point temperature, U₁₀=wind speed at 10 m height, RH_{mean}=mean relative humidity, n=mean monthly total sunshine hours. **The classification of the climatic regions based on Thornthwaite's method.

Table 2. The value slope of (λ) based on regression between ET0-Harg and ET0-PM

Station	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Yearly
Aleshtar	0.907	0.990	1.027	0.928	0.915	0.890	0.920	0.909	0.981	1.073	1.025	0.935	0.932
Aligoodarz	1.418	1.326	1.276	1.190	1.188	1.157	1.188	1.265	1.338	1.466	1.460	1.490	1.235
Azna	0.947	1.101	1.027	1.021	1.009	0.943	0.961	0.960	0.972	1.128	0.999	0.944	0.979
Baneh	1.440	1.388	1.476	1.419	1.398	1.501	1.415	1.536	1.715	1.820	1.756	1.669	1.509
Bijar	1.454	1.463	1.387	1.328	1.276	1.224	1.158	1.219	1.371	1.524	1.614	1.567	1.254
Broujerd	1.355	1.389	1.286	1.181	1.146	1.140	1.154	1.177	1.270	1.411	1.487	1.512	1.192
Dehloran	1.002	1.074	1.060	1.040	1.015	1.065	1.036	1.021	1.065	1.089	1.107	0.995	1.044
Doroud	1.294	1.496	1.357	1.224	1.170	1.070	1.030	1.057	1.089	1.412	1.387	1.430	1.117
Eslamabad Gharb	0.808	0.846	0.872	0.845	0.854	0.875	0.861	0.914	0.926	0.883	0.883	0.802	0.879
Ghorveh	1.286	1.304	1.306	1.253	1.197	1.154	1.095	1.160	1.262	1.382	1.383	1.356	1.180
Ilam	1.140	1.175	1.161	1.127	1.161	1.185	1.192	1.197	1.236	1.249	1.228	1.119	1.191
Kangavar	0.895	0.953	0.962	0.891	0.874	0.851	0.812	0.814	0.871	0.927	0.899	0.878	0.850
Kermanshah	0.970	1.038	0.996	0.945	0.914	0.922	0.909	0.938	0.959	1.004	1.017	0.980	0.935
Khorramabad	0.830	0.931	0.899	0.814	0.837	0.836	0.826	0.843	0.871	0.923	0.857	0.841	0.850
Kouhdasht	0.866	0.950	0.909	0.865	0.865	0.832	0.819	0.798	0.819	0.928	0.869	0.837	0.836
Malayer	1.179	1.204	1.131	1.084	1.031	1.007	0.991	0.997	1.099	1.183	1.212	1.231	1.036
Marivan	0.861	0.907	0.934	0.904	0.898	0.904	0.881	0.872	0.974	1.011	0.934	0.917	0.905
Nahavand	1.139	1.158	1.165	1.051	0.998	0.931	0.918	0.946	0.969	1.070	1.090	1.134	0.970
Noorabad	1.198	1.258	1.266	1.185	1.144	1.178	1.140	1.191	1.269	1.480	1.439	1.291	1.199
Poldokhtar	1.128	1.213	1.188	1.156	1.213	1.129	1.123	1.105	1.200	1.415	1.403	1.101	1.165
Ravansar	1.056	1.097	1.056	0.993	1.035	1.150	1.254	1.246	1.210	1.247	1.181	1.000	1.177
Saghez	0.898	0.971	0.954	0.930	0.894	0.855	0.861	0.888	0.934	1.020	0.963	0.968	0.892
Sanandaj	0.898	0.987	0.970	0.904	0.893	0.868	0.885	0.867	0.881	0.948	0.937	0.963	0.889
Zarneh Obato	1.293	1.265	1.228	1.178	1.181	1.166	1.115	1.178	1.343	1.437	1.377	1.374	1.189

Table 3. The values of RMSE between ET0-Harg and ET0-PM

Station	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Yearly
Aleshtar	0.142	0.154	0.291	0.384	0.499	0.815	0.714	0.682	0.623	0.537	0.150	0.095	0.489
Aligoodarz	0.433	0.489	0.672	0.767	1.056	1.198	1.554	1.835	1.754	1.494	0.825	0.586	1.159
Azna	0.128	0.377	0.253	0.228	0.300	0.494	0.491	0.309	0.350	0.492	0.134	0.116	0.334
Baneh	0.349	0.422	0.980	1.294	1.722	2.862	2.575	3.132	3.026	2.121	0.971	0.572	1.946
Bijar	0.294	0.486	0.771	1.082	1.289	1.438	1.140	1.428	1.650	1.352	0.794	0.456	1.101
Broujerd	0.397	0.625	0.717	0.748	0.855	1.018	1.158	1.214	1.431	1.351	0.851	0.656	0.968
Dehloran	0.198	0.457	0.468	0.958	1.186	1.405	1.414	1.316	1.018	0.912	0.619	0.354	0.952
Doroud	0.368	0.890	1.015	0.869	0.915	0.691	0.406	0.463	0.646	1.482	0.747	0.496	0.808
Eslamabad Gharb	0.239	0.268	0.358	0.662	0.864	1.058	1.237	0.817	0.605	0.548	0.362	0.290	0.684
Ghorveh	0.239	0.387	0.637	0.844	0.962	1.037	0.782	1.027	1.246	1.089	0.576	0.371	0.826
Ilam	0.185	0.309	0.464	0.507	0.869	1.208	1.348	1.264	1.210	0.840	0.447	0.198	0.849
Kangavar	0.156	0.179	0.270	0.482	0.785	1.167	1.492	1.463	0.722	0.458	0.289	0.221	0.799
Kermanshah	0.184	0.176	0.248	0.313	0.585	0.755	0.858	0.579	0.498	0.285	0.247	0.128	0.467
Khorramabad	0.356	0.322	0.469	0.916	1.195	1.619	1.816	1.490	1.181	0.725	0.460	0.321	1.047
Kouhdasht	0.216	0.205	0.404	0.625	0.892	1.382	1.552	1.593	1.185	0.485	0.303	0.302	0.918
Malayer	0.238	0.353	0.346	0.380	0.254	0.356	0.671	0.417	0.668	0.678	0.397	0.384	0.455
Marivan	0.184	0.188	0.282	0.431	0.652	0.778	1.071	1.120	0.537	0.451	0.238	0.171	0.606
Nahavand	0.174	0.344	0.477	0.373	0.505	0.820	1.014	0.903	0.582	0.565	0.360	0.259	0.588
Noorabad	0.200	0.379	0.663	0.647	0.711	1.193	1.143	1.354	1.373	1.550	0.686	0.292	0.955
Poldokhtar	0.216	0.451	0.642	0.786	1.413	1.112	1.132	0.893	1.302	1.624	0.906	0.189	0.991
Ravansar	0.197	0.197	0.262	0.360	0.526	1.215	1.987	1.799	1.210	0.943	0.461	0.204	0.995
Saghez	0.176	0.154	0.258	0.407	0.665	1.198	1.314	1.100	0.778	0.471	0.255	0.123	0.707
Sanandaj	0.195	0.162	0.267	0.505	0.715	1.223	1.180	1.195	0.890	0.375	0.254	0.184	0.724
Zarneh Obato	0.227	0.263	0.395	0.532	0.843	1.081	0.992	1.261	1.482	1.137	0.469	0.290	0.857

Table 4. The values of MBE between ET0-Harg and ET0-PM

Station	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Yearly
Aleshtar	0.112	0.022	-0.077	0.298	0.470	0.785	0.618	0.657	0.093	-0.272	-0.048	0.080	0.228
Aligoodarz	-0.400	-0.424	-0.570	-0.632	-0.870	-0.977	-1.269	-1.629	-1.609	-1.347	-0.741	-0.503	-0.914
Azna	0.042	-0.114	-0.070	-0.072	-0.042	0.376	0.264	0.264	0.140	-0.426	0.002	0.002	0.031
Baneh	-0.335	-0.407	-0.933	-1.232	-1.680	-2.820	-2.563	-3.072	-3.015	-2.103	-0.938	-0.507	-1.634
Bijar	-0.273	-0.402	-0.636	-0.989	-1.155	-1.295	-1.001	-1.262	-1.567	-1.268	-0.737	-0.419	-0.917
Broujerd	-0.364	-0.575	-0.666	-0.652	-0.732	-0.934	-1.110	-1.182	-1.373	-1.277	-0.804	-0.551	-0.852
Dehloran	0.001	-0.158	-0.190	-0.224	-0.114	-0.540	-0.294	-0.170	-0.395	-0.356	-0.270	-0.017	-0.227
Doroud	-0.302	-0.767	-0.950	-0.845	-0.863	-0.482	-0.220	-0.382	-0.467	-1.333	-0.637	-0.467	-0.643
Eslamabad Gharb	0.205	0.247	0.333	0.626	0.821	0.946	1.066	0.616	0.401	0.426	0.307	0.231	0.519
Ghorveh	-0.216	-0.329	-0.574	-0.793	-0.826	-0.883	-0.615	-0.949	-1.154	-1.006	-0.496	-0.307	-0.679
Ilam	-0.165	-0.279	-0.387	-0.462	-0.807	-1.150	-1.265	-1.217	-1.138	-0.776	-0.402	-0.147	-0.683
Kangavar	0.089	0.075	0.103	0.417	0.680	1.050	1.445	1.321	0.692	0.248	0.172	0.136	0.536
Kermanshah	0.019	-0.057	0.020	0.229	0.489	0.577	0.731	0.453	0.228	-0.015	-0.038	0.017	0.221
Khorramabad	0.213	0.133	0.298	0.779	0.945	1.213	1.377	1.145	0.704	0.248	0.287	0.201	0.629
Kouhdasht	0.173	0.095	0.258	0.593	0.836	1.315	1.471	1.546	1.065	0.279	0.266	0.243	0.678
Malayer	-0.182	-0.298	-0.317	-0.303	-0.149	-0.048	0.038	0.011	-0.510	-0.564	-0.341	-0.280	-0.245
Marivan	0.153	0.141	0.168	0.360	0.540	0.650	0.871	0.895	0.131	-0.033	0.119	0.096	0.341
Nahavand	-0.144	-0.236	-0.387	-0.198	0.000	0.450	0.580	0.347	0.150	-0.226	-0.172	-0.162	0.000
Noorabad	-0.182	-0.318	-0.624	-0.598	-0.670	-1.118	-0.958	-1.210	-1.302	-1.466	-0.666	-0.286	-0.783
Poldokhtar	-0.183	-0.444	-0.600	-0.724	-1.356	-1.004	-0.986	-0.786	-1.197	-1.613	-0.849	-0.147	-0.824
Ravansar	-0.072	-0.135	-0.131	0.031	-0.175	-1.007	-1.819	-1.666	-1.093	-0.788	-0.315	-0.013	-0.598
Saghez	0.059	0.025	0.107	0.246	0.528	0.956	0.978	0.733	0.305	-0.055	0.045	0.026	0.329
Sanandaj	0.083	0.023	0.080	0.359	0.567	0.916	0.863	0.928	0.622	0.166	0.107	0.048	0.397
Zarneh Obato	-0.183	-0.221	-0.311	-0.471	-0.670	-0.854	-0.684	-0.995	-1.368	-0.990	-0.413	-0.249	-0.618

Table 5. The monthly C values for different months for investigated stations

Station	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Yearly
Aleshtar	0.0021	0.0023	0.0024	0.0021	0.0021	0.0020	0.0021	0.0021	0.0023	0.0025	0.0024	0.0022	0.0021
Aligoodarz	0.0033	0.0030	0.0029	0.0027	0.0027	0.0027	0.0027	0.0029	0.0031	0.0034	0.0034	0.0034	0.0028
Azna	0.0022	0.0025	0.0024	0.0023	0.0023	0.0022	0.0022	0.0022	0.0022	0.0026	0.0023	0.0022	0.0023
Baneh	0.0033	0.0032	0.0034	0.0033	0.0032	0.0035	0.0033	0.0035	0.0039	0.0042	0.0040	0.0038	0.0035
Bijar	0.0033	0.0034	0.0032	0.0031	0.0029	0.0028	0.0027	0.0028	0.0032	0.0035	0.0037	0.0036	0.0029
Broujerd	0.0031	0.0032	0.0030	0.0027	0.0026	0.0026	0.0027	0.0027	0.0029	0.0032	0.0034	0.0035	0.0027
Dehloran	0.0023	0.0025	0.0024	0.0024	0.0023	0.0024	0.0024	0.0023	0.0024	0.0025	0.0025	0.0023	0.0024
Doroud	0.0030	0.0034	0.0031	0.0028	0.0027	0.0025	0.0024	0.0024	0.0025	0.0032	0.0032	0.0033	0.0026
Eslamabad Gharb	0.0019	0.0019	0.0020	0.0019	0.0020	0.0020	0.0020	0.0021	0.0021	0.0020	0.0020	0.0018	0.0020
Ghorveh	0.0030	0.0030	0.0030	0.0029	0.0028	0.0027	0.0025	0.0027	0.0029	0.0032	0.0032	0.0031	0.0027
Ilam	0.0026	0.0027	0.0027	0.0026	0.0027	0.0027	0.0027	0.0028	0.0028	0.0029	0.0028	0.0026	0.0027
Kangavar	0.0021	0.0022	0.0022	0.0020	0.0020	0.0020	0.0019	0.0019	0.0020	0.0021	0.0021	0.0020	0.0020
Kermanshah	0.0022	0.0024	0.0023	0.0022	0.0021	0.0021	0.0021	0.0022	0.0022	0.0023	0.0023	0.0023	0.0022
Khorramabad	0.0019	0.0021	0.0021	0.0019	0.0019	0.0019	0.0019	0.0019	0.0020	0.0021	0.0020	0.0019	0.0020
Kouhdasht	0.0020	0.0022	0.0021	0.0020	0.0020	0.0019	0.0019	0.0018	0.0019	0.0021	0.0020	0.0019	0.0019
Malayer	0.0027	0.0028	0.0026	0.0025	0.0024	0.0023	0.0023	0.0023	0.0025	0.0027	0.0028	0.0028	0.0024
Marivan	0.0020	0.0021	0.0021	0.0021	0.0021	0.0021	0.0020	0.0020	0.0022	0.0023	0.0021	0.0021	0.0021
Nahavand	0.0026	0.0027	0.0027	0.0024	0.0023	0.0021	0.0021	0.0022	0.0022	0.0025	0.0025	0.0026	0.0022
Noorabad	0.0028	0.0029	0.0029	0.0027	0.0026	0.0027	0.0026	0.0027	0.0029	0.0034	0.0033	0.0030	0.0028
Poldokhtar	0.0026	0.0028	0.0027	0.0027	0.0028	0.0026	0.0026	0.0025	0.0028	0.0033	0.0032	0.0025	0.0027
Ravansar	0.0024	0.0025	0.0024	0.0023	0.0024	0.0026	0.0029	0.0029	0.0028	0.0029	0.0027	0.0023	0.0027
Saghez	0.0021	0.0022	0.0022	0.0021	0.0021	0.0020	0.0020	0.0020	0.0021	0.0023	0.0022	0.0022	0.0021
Sanandaj	0.0021	0.0023	0.0022	0.0021	0.0021	0.0020	0.0020	0.0020	0.0020	0.0022	0.0022	0.0022	0.0020
Zarneh Obato	0.0030	0.0029	0.0028	0.0027	0.0027	0.0027	0.0026	0.0027	0.0031	0.0033	0.0032	0.0032	0.0027

Table 6. The R values (ratio between ET0-Harg and ET0-PM)

Station	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Yearly
Aleshtar	1.101	1.013	0.974	1.080	1.093	1.123	1.086	1.100	1.017	0.929	0.975	1.068	1.058
Aligoodarz	0.701	0.758	0.789	0.843	0.844	0.865	0.840	0.790	0.747	0.684	0.686	0.677	0.792
Azna	1.047	0.927	0.974	0.980	0.992	1.059	1.038	1.041	1.027	0.886	1.001	1.002	1.008
Baneh	0.694	0.723	0.679	0.708	0.717	0.665	0.707	0.651	0.583	0.549	0.571	0.609	0.656
Bijar	0.686	0.694	0.732	0.754	0.785	0.815	0.863	0.821	0.729	0.657	0.623	0.638	0.770
Broujerd	0.736	0.722	0.780	0.848	0.875	0.877	0.866	0.849	0.786	0.709	0.673	0.666	0.815
Dehloran	1.001	0.934	0.946	0.958	0.983	0.938	0.966	0.979	0.939	0.919	0.897	0.990	0.955
Doroud	0.775	0.673	0.733	0.814	0.856	0.933	0.970	0.945	0.917	0.706	0.724	0.699	0.855
Eslamabad Gharb	1.224	1.182	1.149	1.185	1.172	1.143	1.160	1.094	1.079	1.132	1.194	1.235	1.144
Ghorveh	0.770	0.770	0.772	0.798	0.839	0.867	0.912	0.861	0.789	0.723	0.728	0.740	0.825
Ilam	0.876	0.851	0.861	0.886	0.862	0.844	0.837	0.834	0.806	0.798	0.814	0.893	0.841
Kangavar	1.097	1.051	1.042	1.120	1.144	1.174	1.231	1.226	1.147	1.080	1.106	1.127	1.155
Kermanshah	1.016	0.966	1.008	1.060	1.095	1.084	1.100	1.065	1.042	0.996	0.981	1.014	1.056
Khorramabad	1.188	1.076	1.119	1.221	1.189	1.187	1.203	1.178	1.136	1.072	1.153	1.164	1.166
Kouhdasht	1.153	1.053	1.096	1.158	1.157	1.201	1.219	1.252	1.218	1.078	1.148	1.203	1.179
Malayer	0.847	0.833	0.882	0.922	0.971	0.993	1.005	1.002	0.907	0.846	0.828	0.826	0.939
Marivan	1.155	1.100	1.075	1.107	1.115	1.106	1.134	1.146	1.026	0.991	1.071	1.092	1.096
Nahavand	0.877	0.867	0.864	0.950	1.000	1.073	1.089	1.056	1.031	0.934	0.906	0.876	1.000
Noorabad	0.835	0.802	0.792	0.847	0.875	0.848	0.876	0.839	0.788	0.675	0.695	0.775	0.818
Poldokhtar	0.887	0.824	0.842	0.864	0.823	0.885	0.889	0.905	0.833	0.707	0.714	0.906	0.846
Ravansar	0.936	0.914	0.948	1.009	0.967	0.870	0.796	0.800	0.824	0.801	0.843	0.988	0.863
Saghez	1.079	1.023	1.055	1.075	1.121	1.171	1.159	1.125	1.066	0.982	1.031	1.030	1.101
Sanandaj	1.090	1.015	1.034	1.100	1.117	1.147	1.127	1.144	1.130	1.054	1.064	1.045	1.110
Zarneh Obato	0.765	0.787	0.824	0.852	0.852	0.861	0.897	0.848	0.746	0.702	0.731	0.730	0.823



Figure 1. Spatial distribution of the 24 meteorological stations used in the study

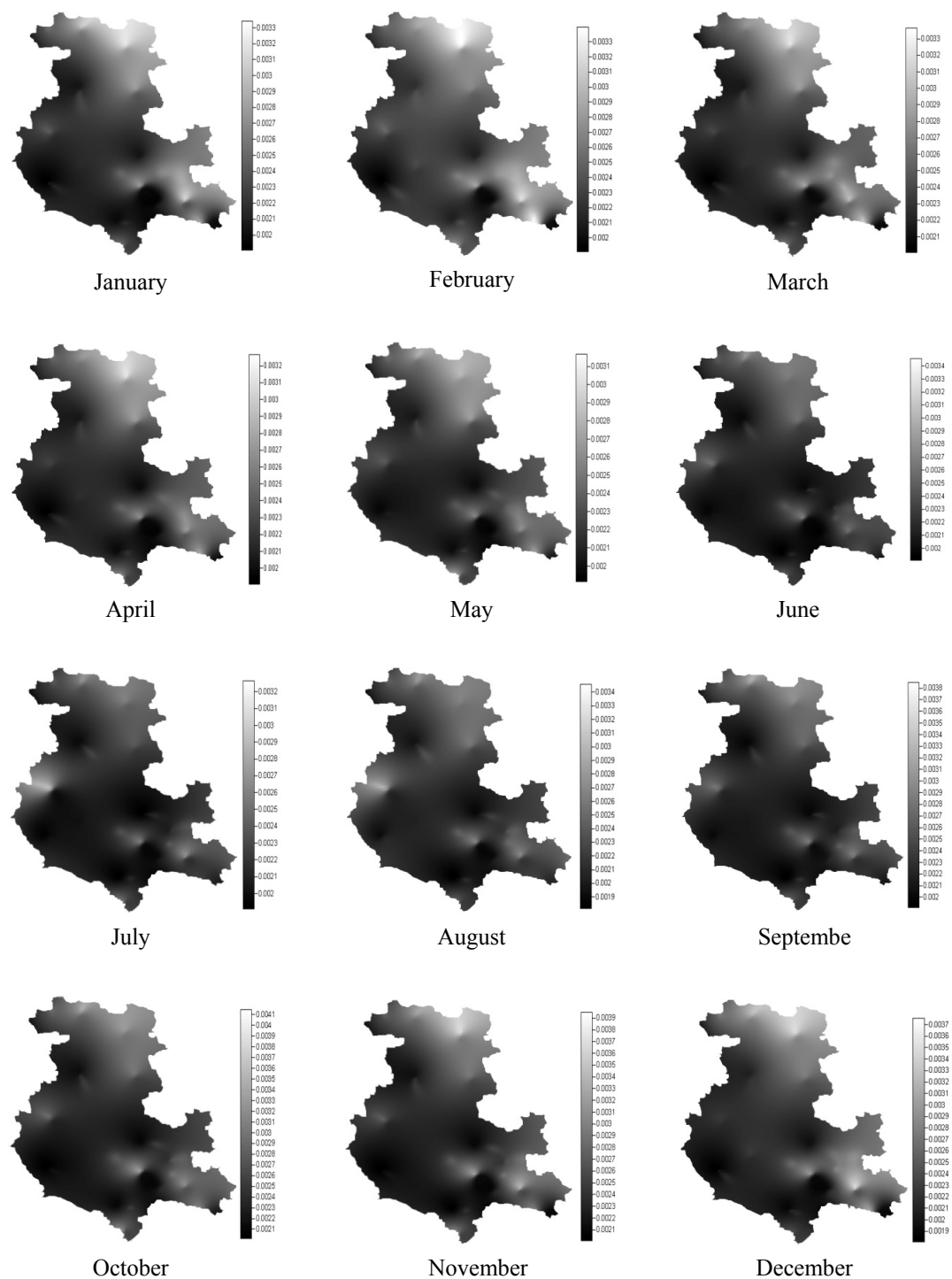


Figure 2. Place distribution of C coefficient based of monthly scale

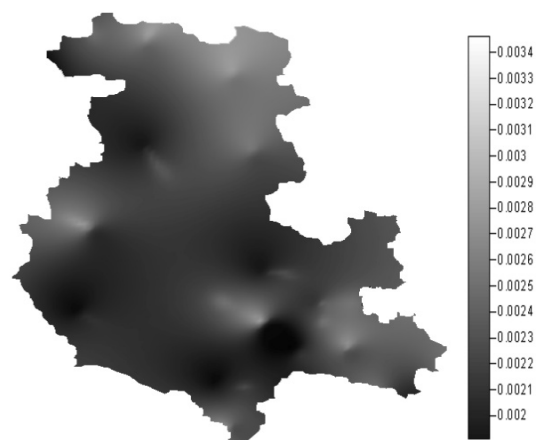


Figure 3. Place distribution of C coefficient based of yearly scale

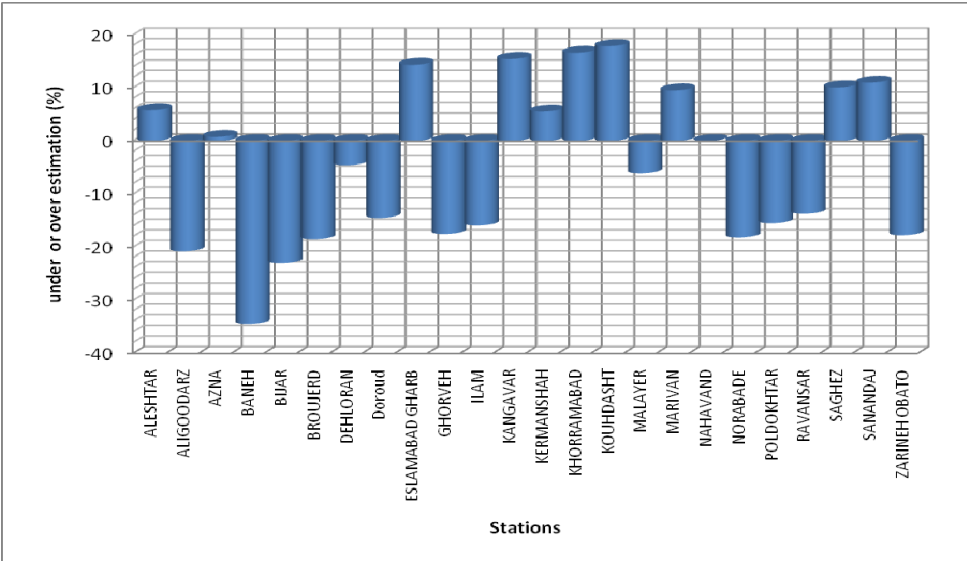


Figure 4. The percentage of under or over ETo estimation on yearly scale

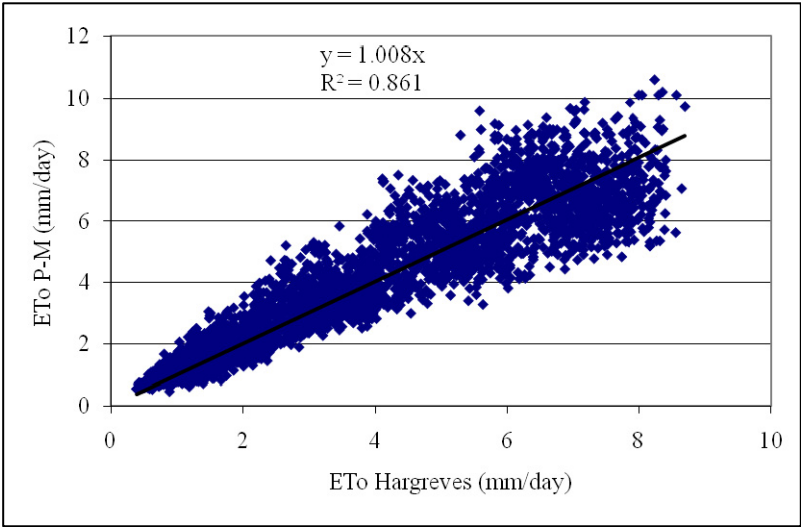


Figure 5. Regression models of ETo estimations by PM vs Harg for different meteorological stations