Journal of Hydrology 399 (2011) 422–433

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# Trends in reference crop evapotranspiration over Iran

Yagob Dinpashoh[a,b,*], Deepak Jhajharia[c], Ahmad Fakheri-Fard[a], Vijay P. Singh[d,e], Ercan Kahya[f,1]

[a] Department of Water Engineering, Faculty of Agriculture, University of Tabriz, Iran
[b] Department of Soil Science, Faculty of Agriculture, University of Maragheh, Iran
[c] Department of Agricultural Engineering, North Eastern Regional Institute of Science and Technology, Nirjuli, Itanagar 791 109, Arunachal Pradesh, India
[d] Department of Biological and Agricultural Engineering, Texas A and M University, Scoates Hall, 2117 TAMU, College Station, TX 77843-2117, USA
[e] Department of Civil & Environmental Engineering, Texas A and M University, Scoates Hall, 2117 TAMU, College Station, TX 77843-2117, USA
[f] Department of Civil Engineering, Istanbul Technical University, Istanbul, Turkey

ARTICLE INFO

*Article history:*
Received 15 May 2010
Received in revised form 6 January 2011
Accepted 19 January 2011
Available online 2 February 2011

This manuscript was handled by A. Bardossy, Editor-in-Chief, with the assistance of Efrat Morin, Associate Editor

*Keywords:*
Evapotranspiration
Iran
Mann–Kendall
Theil–Sen's estimator

SUMMARY

This study examined the trends in reference crop evapotranspiration ($ET_0$) on monthly and annual time scales in Iran. $ET_0$ was estimated using the globally accepted Food and Agriculture Organization (FAO) Penman Monteith method (FAO-56 PM) over the 16 weather stations located in the different regions of Iran. The trends in $ET_0$ were detected by using the Mann–Kendall (MK) test after the removal of the significant lag-1 serial correlation effect from all the $ET_0$ time series by pre-whitening. The slopes of trend lines were computed using the Theil–Sen's slope estimator. The spatial and temporal homogeneity of trends were tested as well. The multiple regression analysis was performed in each time series of the governing meteorological variables to identify the cause of observed trends in $ET_0$. Results showed that both statistically significant increasing and decreasing trends were observed in the annual and monthly $ET_0$. The increasing trends in $ET_0$ were more pronounced than the decreasing trends. In annual time scale, the strong positive (negative) trend in $ET_0$ over Iran of the magnitude of about 186 (−65) mm/year per decade was observed. In monthly time scale there was greater number of increasing trends than that of the decreasing trends in most of the warm months. The most strong positive (negative) trend magnitude was found in April (July) with Theil–Sen's slope equal to 14 (−8.7) mm/year per decade. The results of homogeneity test indicated no homogeneity in $ET_0$ trends between the stations and months when the entire study domain is considered. Wind speed was found to be the most dominant variable influencing $ET_0$ in all the months except the winter months in Iran.



## 1. Introduction

It is now widely accepted that the concentration of greenhouse gases (GHG) of the Earth's atmosphere have increased in recent decades. The main effect of increase in the (GHG) concentration has been the increase in air temperature. The increased air temperature over different parts of the world has caused different effects on elements of the hydrologic cycle. Some of the researchers (Tayanc et al., 1997; Zhang et al., 2001; Kahya and Kalayci, 2004; Lins and Slack, 1999, 2005; Partal and Kahya, 2006; Aziz and Burn, 2006; Burn, 2008; Basistha et al., 2009; Jhajharia et al., 2009; Sahoo and Smith, 2009; Deni et al., 2010; and many others) have investigated the trends in different types of hydrological and hydro-meteorological parameters such as air temperature, precipitation, streamflow, water pollutant concentration, drought characteristics, Pan evaporation ($E_{pan}$) and reference crop evapotranspiration ($ET_0$) over different parts of the world.

$ET_0$ is one of the main elements in the hydrological cycle, which is affected by the changes in air temperature, sunshine duration, and wind speed and so on. Changes in air temperature can alter the saturation vapor pressure, which in turn changes the evaporation and $ET_0$ rate. It is well known that $ET_0$ is a nonlinear complex function of many parameters and change in any one parameter can change the other parameter(s) and therefore, the effect of such changes on $ET_0$ is very difficult to understand. Most of the meteorological variables can influence $ET_0$; however, sunshine duration and wind speed are the two important meteorological parameters controlling $ET_0$ in different regions of the world (Thomas, 2000; Jhajharia et al., 2009).

Many investigators have studied trends in $ET_0$ across the different regions of the world. In contrast to the global warming, most of the investigators have reported decreasing trends in $ET_0$ in several countries. For example, Chattopadhayay and Hulme (1997) studied $E_{pan}$ and potential $ET_0$ trends over different parts of India and

* Corresponding author at: Department of Water Engineering, Faculty of Agriculture, University of Tabriz, Iran. Tel.: +98 0411 339 2774, fax: +98 0411 335 6007.
*E-mail address:* dinpashoh@yahoo.com (Y. Dinpashoh).
[1] Present address: Department of Civil Engineering, American University of Sharjah, Sharjah, United Arab Emirates.

0022-1694/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2011.01.021

reported decreasing trends in both $E_{pan}$ and potential $ET_0$. Gan (1998) reported decreasing trends in $ET_0$ at 13 stations in Alberta. Xu et al. (2006) investigated trends in $E_{pan}$ and $ET_0$ in Changjiang (Yangtze River) catchment and found decreasing trends in both $E_{pan}$ and $ET_0$ for the whole catchment. Bandyopadhayay et al. (2009) also studied $ET_0$ trends in India and reported decreases in $ET_0$ all over India. Tebakari et al. (2005) conducted trend analysis of the $E_{pan}$ in the Chao Phraya River basin located in Thailand and observed decreasing trend in $E_{pan}$. Jhajharia et al. (2009) reported decreasing $E_{pan}$ trends mainly in pre-monsoon and monsoon seasons over the northeast India. They showed that sunshine duration followed by wind speed strongly influenced the observed $E_{pan}$ changes in the northeast India. Similarly, Shen et al. (2010) found statistically significant decreasing trends in $E_{pan}$ in the arid regions of China.

On the other hand, several researchers also reported increases in ET0 trends. Yu et al. (2002) observed increasing trends in ET at Kao-Hsiung, south Taiwan, using 48 years of data. Hess (1998) reported an increasing trend in $ET_0$, which was caused primarily due to the observed increases in wind speed in the northeast arid zone of Nigeria. Burn and Hesch (2007) analyzed trends in $E_{pan}$ at 48 stations of the Canadian Prairies and found both increasing and decreasing trends in $E_{pan}$ during the period of 1971–2000. They observed that the wind speed (vapor pressure deficit) had more influence on decreasing (increasing) trends in $E_{pan}$ over the Canadian Prairies.

Spatial and temporal homogeneity of trends is an important aspect of trend analysis of any hydro-meteorological parameter in any region. Van Belle and Hughes (1984) developed a method to test the homogeneity of trends by Mann–Kendall (MK) test. Homogeneity test is performed on a data set obtained by combining the data of several stations to obtain a possible single global trend. This test was previously applied for homogeneity of trends in different variables, such as rainfall (Kampata et al., 2008), streamflow (Kahya and Kalayci, 2004), precipitation and air temperature (Gan, 1995 and Gan, 1998), and groundwater levels (Panda et al., 2007). To our best knowledge, no such study concerning homogeneity of trend using $ET_0$ time series is available in the literature.

Iran, mainly an agrarian society is seriously vulnerable to the anthropogenic-induced climate change as most of the geographical area falls under the arid and semi-arid type of climate. It seems very likely that any change in the availability of water will play a key role in the sustainable development of agriculture and environment in Iran. Few studies are available in the literature on the trend analysis of mean annual air temperature (Ghahraman, 2006) and precipitation (Ghahraman and Taghvaeian, 2008; and Modarres and da Silva, 2007) in Iran. However, very little information is available on the trend analysis of $ET_0$, an important component of hydrologic cycle, on temporal and spatial basis over Iran. Therefore, the present study is undertaken with the four objectives, which are as follows: (1) to estimate the monthly and annual $ET_0$ using the Food and Agriculture Organization (FAO-56) Penman Monteith (PM) method, and to detect the monotonic linear trends in the $ET_0$ time series using the MK non-parametric test; (2) to estimate the slopes of trend lines of $ET_0$ times series using the Theil–Sen's estimator method; (3) to test the homogeneity of trends of $ET_0$ series over Iran; and (4) to identify the most dominating and important meteorological variables affecting the $ET_0$ time series using multiple (stepwise) regression analysis.

## 2. Study area and data

The study area encompasses the entire region of Iran's geographical area of about 1650,000 km$^2$. Iran is located in Asia, approximately between 25°00′N and 38°39′N latitudes and between 44°00′E and 63°25′E longitudes (Fig. 1). The mean annual precipitation of Iran is about 224 mm. The two main mountain chains in Iran are Alborz and Zagros. Alborz Mountains extends from the north to the west and east Iran, while, Zagros Mountains extends from the northwest to the southern part of Iran. Generally, Iran is categorized as having arid (BW) and semi-arid (BS) climates based on the Koppen climatic classification (Ahrens, 1998).

The data were compiled from the Iran Meteorological Organization (Tehran), and only 16 stations with sufficient length of records during the period of 1965–2005 were selected for the present analysis. The details of these stations were given in Table 1. The compiled data were comprised of the daily values of the following six variables $T_{max}$ (°C), $T_{min}$ (°C), $RH_{max}$ (%), $RH_{min}$ (%), wind speed (Knot) and sunshine duration (h), which were averaged over each calendar month in order to get the monthly values of each meteorological variable. The 24-h wind speed was recorded in km/h at a 10 m height, and the necessary corrections was applied to convert it to m/s at a 2 m height to confirm to its application in the PM equation. During the period of 1965–2005, the monthly data of six meteorological parameters (i.e., the mean maximum and minimum air temperature ($T_{max}$ and $T_{min}$), maximum and minimum relative humidity ($RH_{max}$ and $RH_{min}$), sunshine hours ($n$) and wind speed (w.s.) were collected from the weather stations to estimate $ET_0$ by the PM method. The stations were equipped with the mercury and alcohol thermometers, a cup anemometer, a Campbell sunshine recorder, and a wet-bulb thermometer and some other meteorological instruments. Some stations were also equipped with the automatic and/or semi-automatic instruments in recent years. However, such records were not used in this study due to the short duration data length and the non-availability of these data. It is worthy to mention that the records from the automatic thermometer and hair hygrometer were used in weather stations of Iran to validate the temperature and the relative humidity estimates obtained from dry-bulb temperature and wet-bulb depression in the weather stations of Iran. All the instruments in the weather stations of Iran were checked for the proper installation and operation during observations. The observer might change them if any instrument seems to do not operate well. Quality of data were checked prior to the analysis. For this purpose, we plotted the time series and then visually inspected them for possible errors for all meteorological variables used in this study. If there were any unusual point we then relook at nearby stations plot for the same series and corrected the possible errors. Furthermore, we plotted the time series of $T_{max}$ and $T_{min}$ for each month and

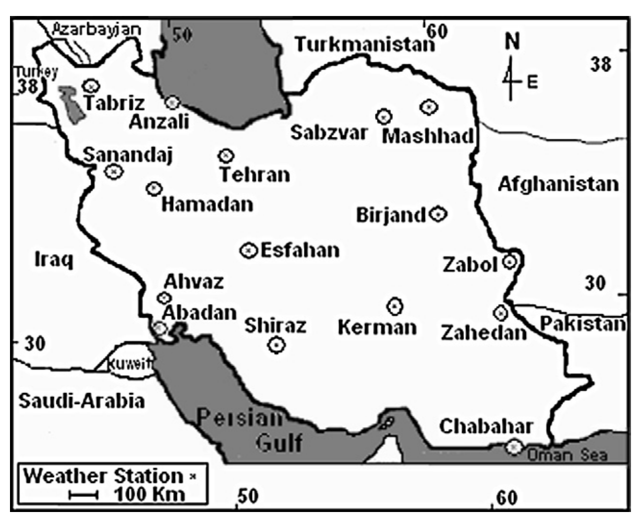


Fig. 1. Study area and location of stations.

**Table 1**
Details of selected synoptic stations of Iran.

| S. No. | Name of site | Koopen's climatic class | Lat. (N) | Long. (E) | Alt., m amsl | Available duration of data | Percent of missing data |
|---|---|---|---|---|---|---|---|
| 1 | Shiraz | C | 29°32′ | 52°36′ | 1484 | 1959–2005 | 1.77 |
| 2 | Tehran | Bs | 35°41′ | 51°19′ | 1191 | 1951–2005 | 0.60 |
| 3 | Tabriz | C | 38°05′ | 46°17′ | 1361 | 1962–2005 | 1.23 |
| 4 | Mashhad | C | 36°16′ | 59°38′ | 999 | 1959–2005 | 0.41 |
| 5 | Zabol | Bw | 31°02′ | 61°29′ | 489 | 1963–2005 | 3.51 |
| 6 | Sanandaj | D | 35°20′ | 47°00′ | 1373 | 1961–2005 | 1.74 |
| 7 | Ahvaz | Bw | 31°20′ | 48°40′ | 22 | 1962–2005 | 3.68 |
| 8 | Birjand | Bs | 32°52′ | 59°12′ | 1491 | 1967–2005 | 2.64 |
| 9 | Chabahar | Bw | 25°17′ | 60°37′ | 8 | 1963–2005 | 9.48 |
| 10 | Sabzvar | Bs | 36°12′ | 57°43′ | 978 | 1967–2005 | 2.48 |
| 11 | Abadan | Bw | 30°22′ | 48°15′ | 7 | 1951–2005 | 4.06 |
| 12 | Anzali | C | 37°28′ | 49°28′ | −26 | 1962–2005 | 0.06 |
| 13 | Esfahan | Bs | 32°37′ | 51°40′ | 1550 | 1964–2005 | 1.47 |
| 14 | Zahedan | Bs | 29°28′ | 60°53′ | 1663 | 1965–2005 | 1.69 |
| 15 | Kerman | Bw | 30°15′ | 56°58′ | 1754 | 1965–2005 | 1.03 |
| 16 | Hamadan | C | 35°12′ | 48°43′ | 1680 | 1965–2005 | 5.47 |

Lat., long., alt., m amsl and N denote latitude, longitude, altitude, meter above mean sea level and north, respectively.

station, separately, to see if there is any bisection point. This procedure was repeated for the $RH_{max}$ and $RH_{min}$ time series as well. As a result, we found no noticeable error. There were few missing observations in the time series of $T_{max}$, $T_{min}$, $RH_{max}$ and $RH_{min}$. These missing data were substituted with the corresponding long-term mean. In the case of the sunshine duration and the wind speed parameters, the missing data were mainly observed for almost all the stations during the specific years from 1977 to 1982, in which the Islamic revolution took place and few starting years of Iran–Iraq war. Since nearly all the stations had complete data for $T_{max}$ and $T_{min}$ time series; therefore, in the first step the monthly $ET_0$ were computed using the Hargreaves and Samani (1982) method in the period of analysis. Then, we computed the $ET_0$ by the PM method for those years, in which all the data needed for analyze were available. Then the two $ET_0$ time series having the pair wise data were considered. The $ET_0$ time series estimated by the PM method was regarded as dependent variable, while, the corresponding $ET_0$ time series obtained by Hargreaves and Samani (1982) method was considered as independent variable. Simple linear regression analysis was conducted to model the $ET_0$. The parameters of the model were estimated using the least square method. Then, for those cases having the missing values in the $ET_0$ series in PM method, the $ET_0$ values were estimated using the above-mentioned model. Similar procedures were used to complete all the $ET_0$ time series. After completing the $ET_0$ time series for all the months, the trend analysis was conducted for each time series, separately over Iran.

## 3. Methodology

### 3.1. FAO-56 Penman–Monteith (PM) method

For estimating $ET_0$, Allen et al. (1998) derived the FAO-56 Penman–Monteith equation from the original Penman–Monteith equation and the equations of aerodynamic and surface resistance. The FAO-56 Penman–Monteith method, designated as PM in the present study, is now universally accepted for calculating $ET_0$ in various climates. The PM method can be expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{\bar{T}+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where $ET_0$ is the reference crop evapotranspiration (mm/day), $\Delta$ is the slope of vapor pressure versus temperature curve at temperature $T$ (kPa/°C), $\gamma$ is the psychrometric constant (kPa/°C), $u_2$ is the wind speed at a 2 m height (m s$^{-1}$), $R_n$ is the net radiation at crop surface (MJ m$^{-2}$ d$^{-1}$), $G$ is the soil heat flux density (MJ m$^{-2}$ d$^{-1}$), $\bar{T}$ is the mean daily air temperature at 2 m height (°C), and ($e_s$–$e_a$) is the saturation vapor pressure deficit (kPa). The reference crop was assumed as green grass. A complete set of equations, proposed by Allen et al. (1998) according to the available weather data and time step computation, constitutes the PM method. We used $G = 0.14(T_{j+1} - T_j)$ for estimating soil heat flux density, where $T_j$ is the mean air temperature in the present month and $T_{j+1}$ is the mean air temperature in °C in the next month. Since no actual solar radiation data were available, we estimated $R_n$ from the sunshine hour record, assuming the recommended (Shuttleworth, 1993) values for albedo equal to 0.23 and angstrom coefficients a and b equal to 0.25 and 0.5, respectively. The FAO Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements accepted the definition as "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m$^{-1}$ and an albedo of 0.23" for reference surface. The reference surface closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water. The requirements that the grass surface should be extensive and uniform result from the assumption that all fluxes are one-dimensional upwards (Allen et al., 1998). Such an assumption is often hard to achieve in most weather stations located in the arid and semi-arid countries like Iran. Fig. 2 shows a sample picture of a weather station of Iran showing different types of recording equipments for measuring different types of meteorological parameters.

**Fig. 2.** A sample weather station located in the north of Iran.

### 3.2. Trend analysis

We applied the non-parametric Mann–Kendall (MK) method (Mann, 1945; Kendall, 1975) in this study as it is distribution-free, robust against outliers, and has a higher power than many other commonly used tests (Hess et al., 2001). One of the main problems in testing and interpretation of trends in data is the effect of serial dependence. If there is a positive correlation (persistence) in the time series, then the non-parametric test will suggest a significant trend in a time series that is, in fact, random more than specified by the significance level (Zhang et al., 2001). Therefore, to eliminate the effect of serial correlation from data we first tested the significance of lag-1 serial correlation ($r_1$) for all $ET_0$ time series at the 1% significance level. For this purpose, the absolute value of $r_1$ was compared with the critical threshold, which depends on the number of data. If the absolute value of $r_1$ was greater than the critical value at a certain level, then it was considered significant; otherwise, it was regarded insignificant. The original MK test was employed for the $ET_0$ time series having insignificant $r_1$. The effect of serial correlation was removed from the time series by pre-whitening prior to applying the MK test. The pre-whitening method is described in the Section 3.2.3.

#### 3.2.1. Original Mann–Kendall (MK) test

The original MK trend test was first carried out by computing an $S$ statistic as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{2}$$

where $n$ is the number of observations, $x_j$ is the $j$th observation, and $\mathrm{sgn}(\cdot)$ is the sign function which can be computed as:

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if} \quad (x_j - x_i) > 0 \\ 0 & \text{if} \quad (x_j - x_i) = 0 \\ -1 & \text{if} \quad (x_j - x_i) < 0 \end{cases} \tag{3}$$

Under the assumption that the data are independent and identically distributed, the mean and variance of the $S$ statistic in Eq. (2) are given by (Kendall, 1975) as:

$$E(S) = 0 \tag{4}$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \tag{5}$$

where $m$ is the number of groups of tied ranks, each with $t_i$ tied observations. The original MK statistic, designated by $Z$, was computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \tag{6}$$

If $-Z_{1-\alpha/2} \leqslant Z \leqslant Z_{1-\alpha/2}$ then the null hypothesis of no trend was accepted at the significance level of $\alpha$. Otherwise, the null hypothesis was rejected and the alternative hypothesis was accepted at the significance level of $\alpha$.

#### 3.2.2. Theil–Sen's estimator

The slope of $n$ pairs of data points was estimated using the Theil–Sen's estimator (Theil, 1950 and Sen, 1968) which is given by the following relation:

$$\beta = Median\left(\frac{x_j - x_l}{j - l}\right) \quad \forall 1 < l < j \tag{7}$$

According to Yue et al. (2002), the slope computed by Theil–Sen's estimator is a robust estimate of the magnitude of a trend, which has been widely used in identifying the slope of the trend line in hydrological time series.

#### 3.2.3. Modified Mann–Kendall method

In the presence of serial correlation in a time series, application of the original MK procedure cannot be recommended for the data set, because the effect of lag-1 serial correlation on trend statistic is a major source of uncertainty. To eliminate the influence of serial correlation on the MK test we removed the lag-1 serial correlation component from the time series prior to applying the MK test to assess the influence of trend. This treatment is called "pre-whitening". The MK test was then used to detect trends in the residual (or pre-whitened) series. For this purpose the new time series as proposed by Kumar et al. (2009) was obtained as:

$$x'_i = x_i - (\beta \times i) \tag{8}$$

The $r_1$ value of this new time data set was computed and used to determine the residual series as:

$$y'_i = x'_i - r_1 \times x'_{i-1} \tag{9}$$

The value of $\beta \times i$ was added again to the residual data set as follows:

$$y_i = y'_i + (\beta \times i) \tag{10}$$

The $y_i$ series was subjected to trend analysis.

### 3.3. Test of homogeneity of trends

A procedure, proposed by van Belle and Hughes (1984) based on the partitioning of the sum of squares, was used to test for the $ET_0$ trend homogeneity of stations. This method uses the chi-square tests to determine the trend homogeneity between months, between stations and station–month interactions. The first step in testing homogeneity is to calculate the MK statistics $Z_j$ ($j$ = 1, 2, ..., 12) for all months, and later its squares $\left(Z_j^2\right)$ are considered in the analysis. Under the null hypothesis of no trend for month $j$, each $\left(Z_j^2\right)$ has approximately a chi-square distribution with 1 degree of freedom (d.f.). Furthermore, if the seasonal observations are far enough apart, then the $Z_j$ will be nearly independent. The overall statistics for $m$ months is

$$x^2_{\text{Total}} = \sum_{j=1}^{m} Z_j^2 \tag{11}$$

which follows approximately a chi-square distribution with $m$ d.f. under the null hypothesis of no trends for all $m$ months. A large value of such statistics in (11) is not very meaningful as it still fails to distinguish heterogeneity between the individual $Z_j^2$'s from the overall trend. This problem can be solved by partitioning $x^2_{\text{Total}}$ by the following procedure:

$$x^2_{\text{Total}} = x^2_{\text{homog.}} + x^2_{\text{trend}} \tag{12}$$

where

$$x^2_{\text{trend}} = mZ^2 \tag{13}$$

where $Z$ is an average over subscript j and $x^2_{\text{homog.}}$ can be found by subtracting the $x^2_{\text{trend}}$ from the $x^2_{\text{Total}}$. Under the null hypothesis of equal $Z$'s for all months, $x^2_{\text{homog.}}$ and $x^2_{\text{trend}}$ have a chi-square distribution with $(m-1)$ and 1 d.f., respectively. The homogeneity of trends can be tested by comparing the calculated $x^2_{\text{homog.}}$ by the corresponding $x^2_{m-1}$ from the chi-square tables. If $x^2_{\text{homog.}}$ is not significant, then a valid test for the common trend is possible by referring $x^2_{\text{trend}}$ to the corresponding tabulated value. If $x^2_{\text{homog.}}$ is significant, then evaluation of $x^2_{\text{trend}}$ is not appropriate. In such a condition, the trend was

**Table 2**
Partitioning of sums of squares for testing trend heterogeneity.

| Source | Chi-square | Degrees of freedom* | Remarks |
|---|---|---|---|
| Total | $\sum_{j=1}^{m}\sum_{p=1}^{k}Z_{jp}^2$ | $mk$ | |
| Homogeneity | $\sum_{j=1}^{m}\sum_{p=1}^{k}[(Z]_{jp}-Z_{...})^2$ | $mk-1$ | Can be obtained by subtraction |
| Month | $k\sum_{j=1}^{m}[(Z_{j.}-Z_{...}])^2$ | $m-1$ | |
| Station | $m\sum_{p=1}^{km}[(Z_{.p}-Z_{...}])^2$ | $k-1$ | |
| Station–month | $\sum_{j=1}^{m}\sum_{p=1}^{k}[(Z]_{jp}-Z_{j.}-Z_{.p}+Z_{...})^2$ | $(m-1)(k-1)$ | Obtained by subtraction |
| Trend | $mkZ_{...}{}^2$ | 1 | |

* $m$, Number of months; $k$, number of stations.

tested for each month from the individual $Z_j$. The total chi-square in this condition is $x^2_{\text{Total}}=\sum_{j=1}^{m}\sum_{p=1}^{k}Z_{jp}^2$, which has approximately, a chi-square distribution with d.f. equal to $mk$. Table 2 shows the partitioning of this statistic. The following steps were followed to test the homogeneity of trends.

*Step* 1: The chi-square values in Table 2 are calculated. Note that $x^2_{\text{station-month}}$ can be found by subtracting the sum of $x^2_{\text{month}}+x^2_{\text{station}}$ from the $x^2_{\text{homog.}}$
*Step* 2: Test the homogeneity of stations using the statistic $x^2_{\text{station}}$.
*Step* 3: Test the homogeneity of months using the statistic $x^2_{\text{month}}$.
*Step* 4: Test the homogeneity of month-station interaction using the statistic $x^2_{\text{station-month}}$.
*Step* 5: If the test results from steps 2, 3 and 4 are all non-significant, then the test for the overall trend using $x^2_{\text{trend}}$ is performed with d.f. = 1. If months are heterogeneous but stations are homogeneous, trend tests are run for individual months from $kZ_j^2$ ($j$ = 1, 2, ..., $m$). If stations are heterogeneous but months are homogeneous, trend tests are done for individual stations using $mZ_p^2$ ($p$ = 1, 2, ..., $k$). However, if both stations and months are heterogeneous or there is a significant station–month interaction, then only meaningful trend tests are possible for the individual station–months using $Z_{jp}$.

### 3.4. Influence of meteorological variables on $ET_0$ changes in Iran

In order to identify the primary and the leading meteorological variables that are responsible for observed $ET_0$ trends at various stations of Iran, a multiple stepwise regression method was applied to monthly and annual time series. Using SPSS, multiple regression analysis, was carried out by considering the monthly $ET_0$ time series as a dependent variable and seven meteorological parameters (namely, $T_{max}$, $T_{min}$, $T_{mean}$, $RH_{min}$, $RH_{max}$, wind speed and sunshine duration) as independent variables.

## 4. Results

### 4.1. Temporal Trends in $ET_0$ in Iran

Table 3 shows the $ET_0$ trend results in terms of $Z$ statistic for all months and the year. It is important to emphasize that any $Z$ statistic within the confidence limits (insignificant $Z$) presents a value due to random fluctuations, meaning not much in inferring existence of a trend from the statistical standpoint. Herein we perceived and treated insignificant $Z$ statistics, particularly for its greater values, just as a tendency for trend-type behavior of the time series under consideration. Fig. 3 shows the annual $ET_0$ time series of selected stations in the period of 1965–2005. In annual time scale, both the increasing and decreasing trends were observed for the $ET_0$ time series across Iran. Five out of the 16 stations exhibited statistically significant positive trends ($p < 0.10$) for the annual $ET_0$ time series. On the other hand, four stations exhibited statistically significant negative trends ($p < 0.10$) for the same time series in Iran. Positive trends were more pronounced than negative ones.

The magnitude of trend in the annual $ET_0$ in Zabol station located in the eastern Iran near Afghanistan borderline revealed

**Table 3**
Trend tests, $Z$ statistic, obtained through the MK method for reference crop evapotranspiration over Iran.

| Station | January | February | March | April | May | June | July | August | September | October | November | December | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abadan | −**1.99*** | 0.17 | −1.04 | 1.18 | 0.37 | **1.94*** | 1.34 | 0.69 | **1.76** | −0.53 | −0.06 | −**2.53**** | 0.69 |
| Anzali | 0.21 | 1.09 | 1.47 | 0.57 | −0.33 | −1.40 | 0.53 | 1.04 | 0.86 | **2.71**** | 1.04 | −0.08 | 0.98 |
| Ahvaz | −0.06 | 0.39 | −0.33 | 0.86 | −0.47 | 1.45 | 0.91 | 0.58 | 0.03 | −**2.37**** | 1.09 | −0.66 | 1.45 |
| Birjand | −1.09 | 0.19 | −**1.65** | −1.20 | −1.52 | −0.95 | −0.75 | −**1.83** | −**2.01**** | −**3.76**** | −**1.81** | −0.71 | −**1.92** |
| Chabahar | **1.90** | 1.53 | −**1.98*** | −0.36 | −**2.57**** | −**2.17*** | −**3.20**** | −**2.46**** | −**4.03**** | −**1.72** | **2.28*** | 1.01 | −**1.67** |
| Esfahan | −0.19 | 0.55 | −**1.74** | −1.07 | −0.91 | −**3.67**** | −**3.54**** | −**3.65**** | −**2.64**** | −**1.83** | −1.38 | −1.58 | −**2.66**** |
| Hamadan | −0.08 | 0.73 | 0.73 | 0.42 | 0.01 | 0.91 | −0.98 | 0.53 | 0.57 | −0.01 | −1.22 | −**1.76** | 0.10 |
| Kerman | 0.39 | 0.60 | −0.26 | −0.89 | −0.86 | −**2.01*** | −**2.03*** | −**2.37**** | −**2.71**** | −**1.81** | −0.78 | −**1.74** | −**1.83** |
| Mashhad | **3.61**** | **2.26*** | **2.24*** | **2.37**** | **1.97*** | **3.11**** | **3.90**** | **3.79**** | **4.05**** | **4.03**** | **3.45**** | **3.16**** | **4.44**** |
| Sabzvar | 1.09 | 1.09 | −0.33 | 1.02 | 0.62 | 0.53 | −0.55 | −0.93 | 0.93 | 0.91 | −0.91 | −0.53 | 1.02 |
| Sanandaj | **1.81** | **2.57**** | **1.92** | **1.97*** | **2.66**** | **1.94*** | **2.57**** | 0.78 | 0.33 | 0.33 | −0.10 | 0.89 | **2.06*** |
| Shiraz | 0.57 | 0.62 | −0.73 | 1.61 | 1.45 | −0.86 | −0.57 | −0.57 | −**2.30*** | −**1.94*** | −**1.65** | −1.56 | −0.39 |
| Tehran | 1.34 | 0.57 | −0.17 | 0.44 | −0.01 | −1.54 | 0.44 | 0.01 | −**2.37**** | −0.62 | −1.09 | −**1.92** | −.42 |
| Zabol | **2.30*** | **3.83**** | **3.02**** | **3.13**** | **2.15*** | 0.98 | **2.64**** | **2.12*** | **2.98**** | **2.89**** | **3.76**** | **3.72**** | **3.52**** |
| Tabriz | 0.53 | **2.84**** | **2.95**** | **2.75**** | **2.73**** | 1.20 | −**1.70** | −0.86 | 0.24 | **3.09**** | 1.20 | **1.94*** | **1.85** |
| Zahedan | **2.41**** | **1.92** | 0.62 | 0.71 | **2.03*** | **2.06*** | **2.59**** | **2.10*** | 1.16 | 0.35 | **2.26*** | 1.29 | **3.02**** |
| +Trends no. | 11(5) | 16(5) | 7(4) | 12(4) | 9(5) | 9(4) | 8(4) | 9(3) | 10(2) | 7(4) | 7(4) | 6(3) | 10(5) |
| −Trends no. | 5(0) | 0(0) | 9(3) | 4(0) | 7(1) | 7(3) | 8(4) | 7(4) | 6(6) | 9(6) | 9(2) | 10(4) | 6(4) |

Note that values in Table are $Z$ statistic. Significant trends (10%) indicated by bold numbers, significant trends (5%) indicated by bold numbers and an asterisk, significant trends (1%) indicated by bold numbers and two asterisks. In the last two rows, two numbers, in each cell, denote the number of trends with positive or negative sign, and the number of statistically significant trends at 10% level.

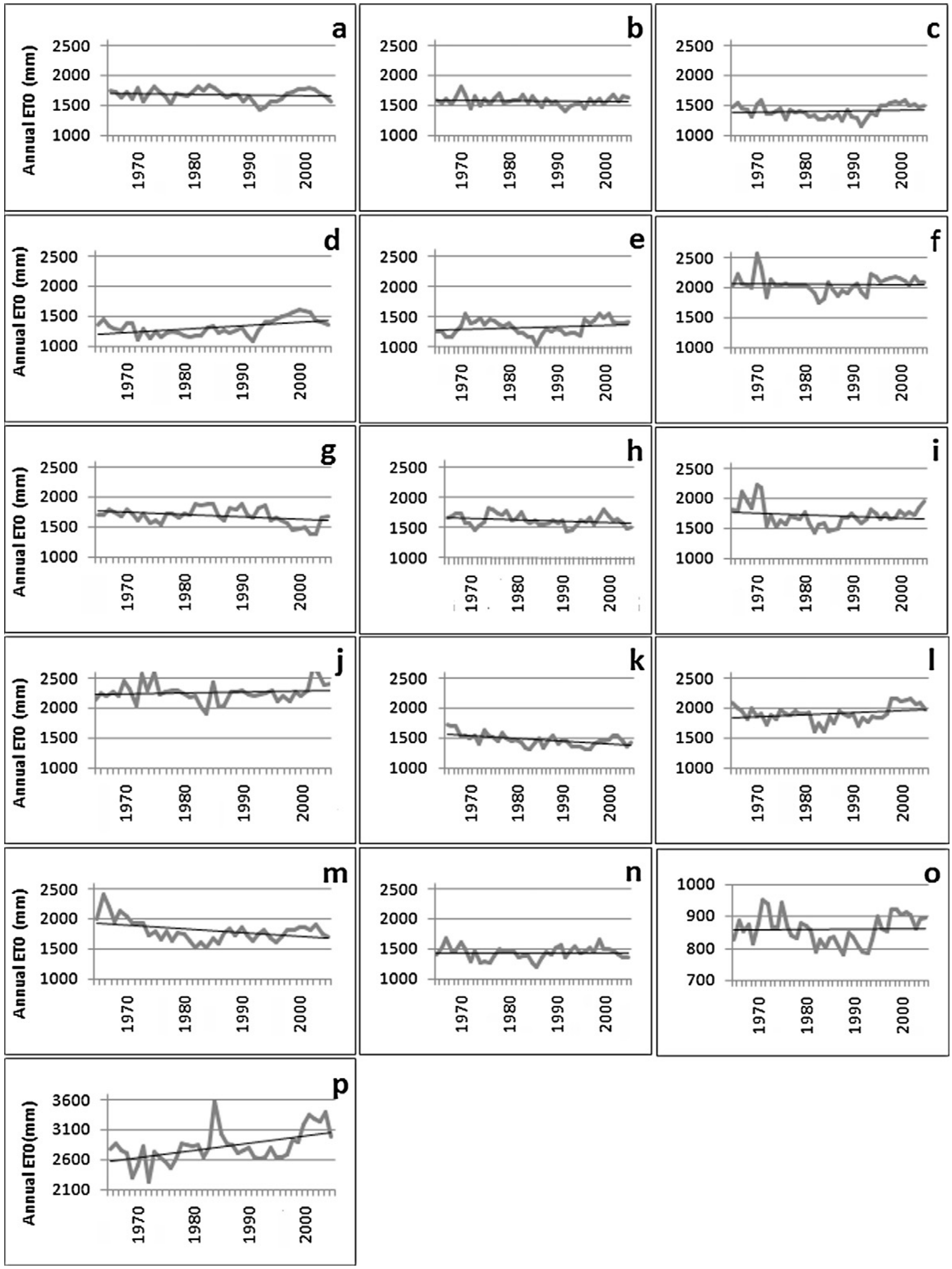

**Fig. 3.** The time series of annual $ET_0$ for 16 stations in Iran (1965–2005). (a) Shiraz; (b) Tehran; (c) Tabriz; (d) Mashhad; (e) Sanandaj; (f) Ahvaz; (g) Birjand; (h) Chabahar; (i) Sabzvar; (j) Abadan; (k) Esfahan; (l) Zahedan; (m) Kerman; (n) Hamadan; (o) Anzali; and (p) Zabol.

the highest positive trend line slope with a value of 186 mm per decade. On the other hand, the strongest negative trend (−65 mm/year per decade) was observed in Esfahan station located in the central Iran and Birjand station located in the eastern part of Iran.

In all months (except February), all the stations exhibited either positive or negative trend characteristics. However, all the stations showed solely positive trend characteristics in February, and 5 out of 16 stations exhibited statistically significant trends at $\alpha < 0.10$. For 7 out of 12 months, the number of statistically significant positive trends was more than that of the negative trends; however, this was not true for the months of July, August, September, October and December. We observed more or less similar number of significant increasing or decreasing trends, that is, either at three or four stations during the months of March, June, July, August and December.

Estimation of the magnitude of trends in $ET_0$ by Theil–Sen's estimator for all the 16 stations in Iran revealed that the steep downward $ET_0$ trend slopes were belonged to Esfahan station during July and August and to Kerman station during September with a value of (−) 8.7 mm/year per decade. In contrast, a steep upward slope appeared at Zabol station during April with a value of (+) 14 mm/year per decade.

### 4.2. Spatial trends in $ET_0$ in Iran

Fig. 4 shows the spatial distribution of annual $ET_0$ trends in Iran during the period of 1965–2005. As it can be seen from Fig. 4 both positive and negative significant ($p < 0.10$) trends were observed in different stations over Iran. Positive trends were located in the northwest, northeast and eastern borderlines of Iran. The two former regions are the main agricultural producing regions of Iran. Negative trends were observed in the central areas of Iran and coastal regions of Oman Sea. Most of these areas were nonagricultural regions located in deserts called "Dashte Kavir".

Fig. 5 shows the spatial distribution of monthly $ET_0$ trends for each month in Iran during the period of 1965–2005. Both the upward and downward significant trends were evident in different stations and months. Most of the stations located in the central areas of Iran and Caspian Sea shoreline exhibited no significant trends in monthly $ET_0$. In the northwestern Iran, significant increasing trends were found in all twelve months. It is thus reasonable to conclude that stations in the region enclosing northwest and northeast of Iran beside the borderlines of Afghanistan and Pakistan exhibited upward significant trends in $ET_0$. On the other hand, decreasing trends were detected in stations, located in the fringes of extent large infertile deserts of central Iran. Moreover, Oman Sea coast in the southeastern Iran showed decreasing trends in $ET_0$ in seven months. Thus, it could be concluded that significant negative trends in $ET_0$ series prevailed in the mid-southern Iran for nearly half of the year. It is also worthwhile to note that most of the eastern and northwestern stations demonstrated statistically significant increasing trends in the cold months.

Fig. 6 shows the Box-Plot of Theil–Sen's slopes for $ET_0$ time series. The medians of slopes for all the months (except March, October and December) are located above the zero line. The maximum value of slopes in $ET_0$ (about 40 mm/year per decade) was observed in April whereas a minimum value (−27 mm/year per decade) was observed in July. It is interesting to note that the $ET_0$ slopes of all stations in February were above the zero line (Fig. 6), implying that all stations in February had a positive $ET_0$ slope. In July, the median of slopes was close to zero line. This implies that about half of the stations experienced a positive $ET_0$ slope as the other half experienced a negative $ET_0$ trend during warm months in Iran. However, the variation of slopes was not the same for these two groups of stations in July.

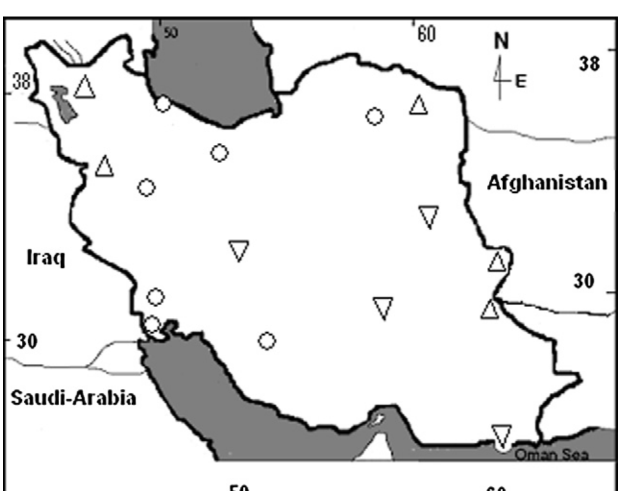


**Fig. 4.** Location of sites with increasing trends (up pointing triangles), decreasing trends (down pointing triangles) and no trends (circles) at the 10% significance level for the annual $ET_0$ time series for the period of 1965–2005.

### 4.3. Homogeneity of trends in $ET_0$ in Iran

Table 4 presents the results of homogeneity test of monthly $ET_0$ trends. The value of $x^2_{\text{Total}}$ equal to 645 (i.e., $\sum_{j=1}^{m}\sum_{p=1}^{k} Z_{jp}^2$) was higher than the corresponding chi-square table value (225), indicating that the other four tests provide the existence of overall significant trend in Iran, which was heterogeneous across the country. The $x^2_{\text{Total}}$ was partitioned into two major sources of variation as $x^2_{\text{homog.}}$ and $x^2_{\text{trend}}$ with $(mk-1)$ and 1 d.f., respectively. Again, $x^2_{\text{homog.}}$ was partitioned into assignable sources such as $x^2_{\text{station},k-1}$, $x^2_{\text{month},m-1}$ and $x^2_{\text{station-month},(m-1)(k-1)}$ for the $ET_0$ time series of Iran. At $\alpha = 0.05$ level, $x^2_{\text{homog.}}$ was found to be 625. Referring to the table of the $x^2$ distribution with 191 d.f. (calculated from $(mk-1)$), the critical value at $\alpha = 0.05$ is 224. Since $x^2_{\text{homog.}}$ was greater than the critical value at $\alpha = 0.05$, the null hypothesis of homogeneity of stations is rejected. It is concluded that the stations are also heterogeneous for the trends of $ET_0$ time series. By partitioning $x^2_{\text{homog.}}$ into the other three sources as seen in Table 4, it was found that stations are heterogeneous for $ET_0$ data, since $x^2_{\text{station},k-1}$ is greater than $x^2_{.95,15}$ (numerically 378 > 25). The heterogeneous nature of stations means that some stations showed upward trends while some others showed downward trends in the same study domain. As a result, an overall conclusion can be drawn so that there exists trend heterogeneity for the entire study area. Since $ET_0$ trends across stations are not homogeneous, we cannot further test the significance of the overall $ET_0$ trend of each month. This is because such test for the overall trend across Iran in the mentioned condition would be misleading. Similarly, it was found that months are heterogeneous for $ET_0$ data, since $x^2_{\text{month},m-1}$ is greater than $x^2_{.95,11}$ (numerically 378 > 25)(numerically 36.52 > 19.68). In other words, we cannot assume a monotonic trend between months. Non-existence of homogeneity of $ET_0$ trends between months implies that some months exhibited upward trends whereas others showed downward trends. Consequently, no particular trend is possible to define for a year from the overall perspective. Since $ET_0$ trends for months are not homogeneous, we cannot further test the significance of the overall $ET_0$ trend in each station, which may yield misleading results. In addition, the value of the interaction between station and month, namely $x^2_{\text{station-month},(0.95,165)} = 210.51$, was greater than the corresponding tabulated value ($x^2_{.95,165} = 195.59$), indicating that this term is significant. It is reasonable to conclude that the only meaningful trend tests are valid for the individual site-seasons, i.e. $Z_{jp}$ ($j = 1, \ldots, 12$; and $P = 1, \ldots, 16$). In other words, there is no homogeneity in $ET_0$ trends between stations and months.

### 4.4. Dominant meteorological variables

Fig. 7 shows the first and the most important meteorological variable entered in the linear multiple stepwise regression model for all the 16 stations in annual time scale. Wind speed were found to be the most important and dominant variable influencing the rate of $ET_0$ over almost entire Iran (i.e., 13 out of total 16 sites at annual time scale (Fig 7). However, $T_{\max}$ ($T_{\min}$) was found to be the most important and dominant variable influencing the rate of annual $ET_0$ in the coastal region of Caspian Sea (in the coastal

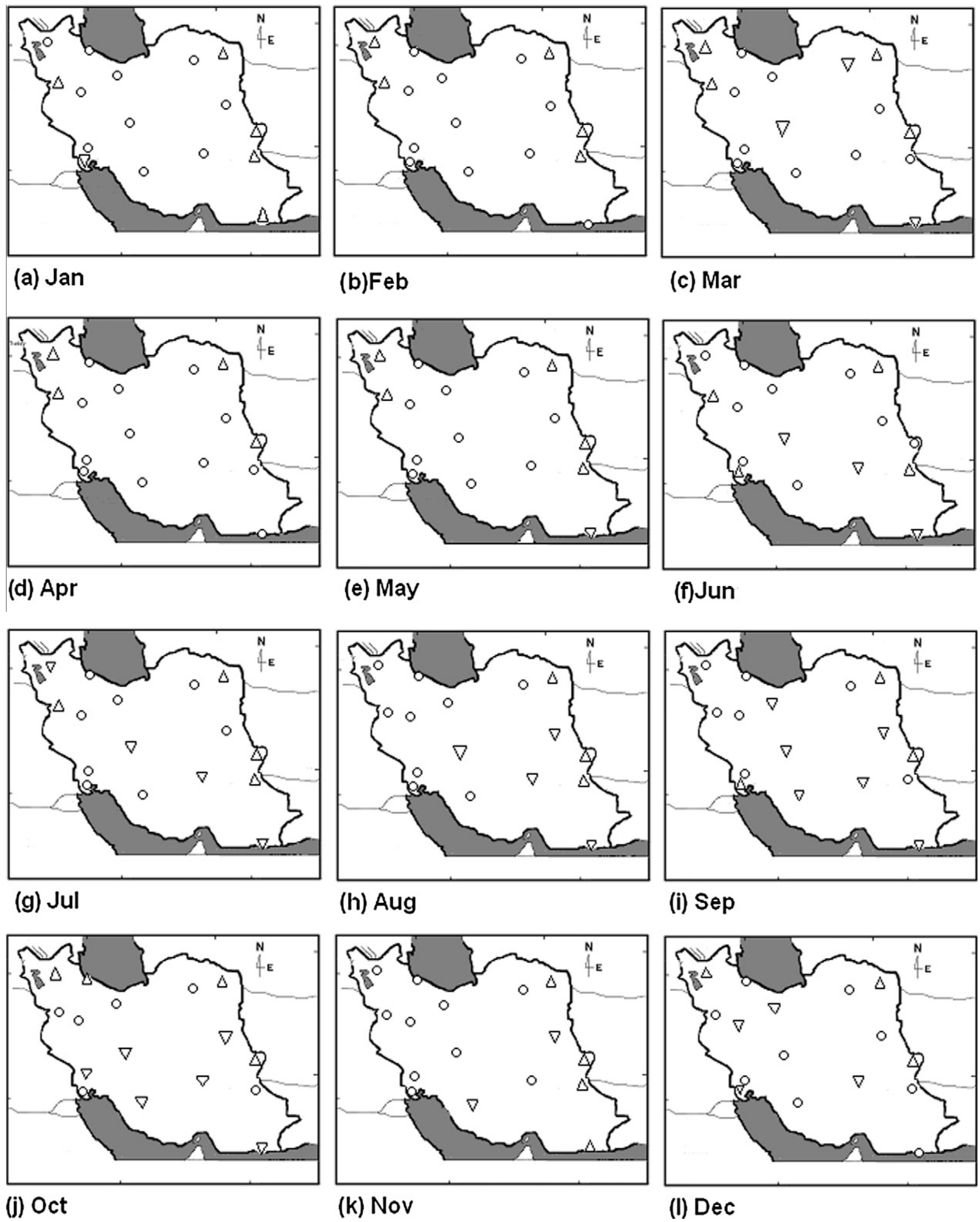


**Fig. 5.** Location of sites with increasing trends (up pointing triangles), decreasing trends (down pointing triangles) and no trends (circles) at the 10% significance level for the monthly $ET_0$ time series for the period of 1965–2005.

region of Oman Sea). Similarly, the annual $ET_0$ in a station located in the southeast part of Iran was found to be affected by $T_{max}$ followed by wind speed. Therefore, the stepwise multiple regression analysis indicates that wind speed was found to be the foremost dominant variable influencing the $ET_0$ in Iran in annual duration. $T_{min}$ followed by the $RH_{max}$ were found to be the other two variables, which influenced the $ET_0$, to some extent in annual duration over Iran.

We also prepared maps similar to Fig. 7 for each month (not shown here). $RH_{min}$ followed by wind speed and $RH_{max}$ were the main meteorological parameters affecting monthly $ET_0$ in January (Table 5). In February and March, $RH_{min}$ followed by wind speed were found to be the two main dominating variables influencing the rate of $ET_0$ in Iran. Wind speed appeared to be the most dominating variable among all the meteorological parameters affecting $ET_0$ from April to December (Table 5). We concluded that wind

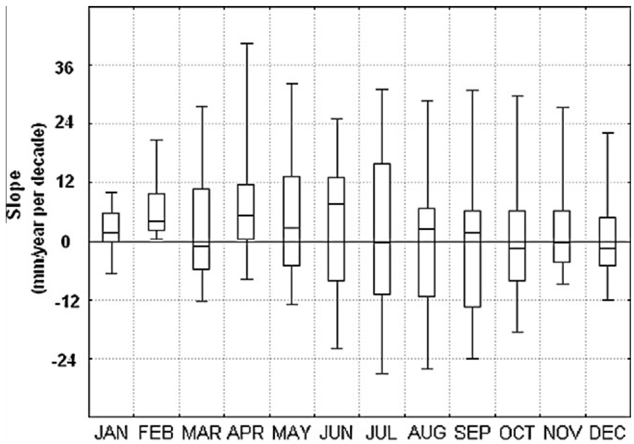


**Fig. 6.** Box and Whisker plots of monthly $ET_0$ trend slope values for the 1965–2005 analysis period. Note: The line inside the boxes represents the median and the upper and lower lines of the boxes indicate the 75% and 25% percentile, respectively. Furthermore, the upper and lower part of the whiskers indicates the respective maximum and minimum values of the slopes of $ET_0$.

**Table 4**
Partitioning of sums of squares for testing monthly $ET_0$ trend heterogeneity of Iran.

| Source | Chi-square (calculated) | d.f. | Critical chi-sq. in 5% (from table) | Significance |
|---|---|---|---|---|
| Total | 645.38 | 192 | 224.94 | S |
| Homogeneity | 624.77 | 191 | 223.86 | S |
| Month | 36.52 | 11 | 19.68 | S |
| Station | 377.74 | 15 | 25.00 | S |
| Station–month | 210.51 | 165 | 195.59 | S |
| Trend | 20.61 | 1 | 3.84 | S |

S: significant; NS: not significant; d.f.: degrees of freedom.

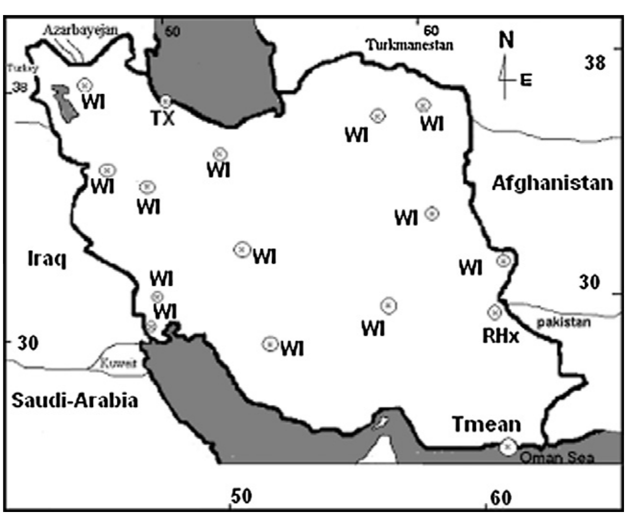


**Fig. 7.** Contribution of meteorological variables to annual $ET_0$ rates over Iran (1965–2005). Note: The most dominant variables affecting annual $ET_0$ rate of stations are shown. WI, TX, Tmean and RHx indicate wind speed, maximum air temperature, mean air temperature and maximum relative humidity, respectively.

speed is the most dominant variable influencing changes in the monthly $ET_0$ in Iran during all the months except winter months.

## 5. Discussion

Based on the PM estimates (1965–2005), $ET_0$ in annual time scale exhibited both upward and downward trends in different locations of Iran. Most of the positive trends were observed for northwest and northeast parts of Iran, covering large areas of mountainous dry-farming regions of Iran. This implies that crop water requirements for production of various crops in these areas will increase in view of increases in $ET_0$. A large portion of spring rainfall in these regions, originated from the Mediterranean systems in west, supply crop water requirements of dry land areas. Ghahraman and Taghvaeian (2008) reported significant decreases in annual rainfall over the northwest Iran by using the linear regression method. Such a decrease in precipitation and increase in $ET_0$ may cause serious adverse effects on food production, especially in the northwest dry farming areas of Iran, which may affect Iran's economy adversely. Most of the areas exhibiting decrease in $ET_0$ were located in the arid and semi-arid region of the central Iran. According to Dinpashoh (2006), in these areas, the ratio of annual precipitation to corresponding $ET_0$ was found to be less than 0.1. Furthermore, annual precipitation of such areas mainly varied between 50 to 200 mm with a considerable high CV varying between 35% and 55% in these areas (Dinpashoh et al., 2004). No significant trends were found in the annual precipitation of stations located in the central Iran based on the available data (Ghahraman and Taghvaeian, 2008). Decrease in annual $ET_0$ in the central arid areas of Iran, having infertile bare soil, and occurrence of no significant trends for annual precipitation series seems to be not effective in improving the food production in Iran.

**Table 5**
Number of times meteorological variables, in order of dominance (i–iii), were significantly (at the 0.05 level) related to $ET_0$ in multiple stepwise regression analysis over Iran.

| Meteorological variables | January | | | February | | | March | | |
|---|---|---|---|---|---|---|---|---|---|
| | i | ii | iii | i | ii | iii | i | ii | iii |
| $T_{max}$ | 0 | 0 | 7 | 0 | 1 | 10 | 2 | 3 | 7 |
| $T_{min}$ | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 3 |
| $T_{mean}$ | 0 | 1 | 3 | 0 | 1 | 2 | 0 | 1 | 1 |
| $RH_{max}$ | 3 | 0 | 1 | 0 | 1 | 0 | 2 | 1 | 2 |
| $RH_{min}$ | 7 | 6 | 1 | 14 | 1 | 0 | 7 | 3 | 0 |
| w.s. | 6 | 9 | 1 | 1 | 12 | 0 | 3 | 8 | 3 |
| *n* | 0 | 0 | 0 | 0 | 0 | 4 | 2 | 0 | 0 |
| | April | | | May | | | June | | |
| $T_{max}$ | 3 | 3 | 6 | 4 | 3 | 1 | 1 | 7 | 5 |
| $T_{min}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $T_{mean}$ | 0 | 0 | 1 | 0 | 1 | 3 | 1 | 0 | 0 |
| $RH_{max}$ | 3 | 1 | 1 | 3 | 5 | 0 | 1 | 2 | 0 |
| $RH_{min}$ | 4 | 2 | 2 | 1 | 0 | 3 | 1 | 0 | 2 |
| w.s. | 5 | 10 | 0 | 7 | 7 | 1 | 12 | 2 | 2 |
| *n* | 1 | 0 | 6 | 1 | 0 | 8 | 0 | 5 | 7 |
| | July | | | August | | | September | | |
| $T_{max}$ | 0 | 7 | 5 | 1 | 10 | 2 | 0 | 7 | 3 |
| $T_{min}$ | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 3 |
| $T_{mean}$ | 1 | 1 | 1 | 0 | 2 | 0 | 1 | 2 | 0 |
| $RH_{max}$ | 0 | 3 | 1 | 0 | 1 | 1 | 0 | 2 | 3 |
| $RH_{min}$ | 1 | 0 | 4 | 1 | 0 | 5 | 0 | 1 | 3 |
| w.s. | 13 | 1 | 1 | 13 | 0 | 1 | 13 | 1 | 0 |
| *n* | 1 | 4 | 3 | 1 | 3 | 6 | 1 | 3 | 4 |
| | October | | | November | | | December | | |
| $T_{max}$ | 1 | 3 | 9 | 0 | 2 | 5 | 0 | 1 | 11 |
| $T_{min}$ | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| $T_{mean}$ | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 |
| $RH_{max}$ | 2 | 2 | 3 | 0 | 3 | 1 | 1 | 0 | 3 |
| $RH_{min}$ | 0 | 4 | 2 | 2 | 9 | 1 | 5 | 8 | 1 |
| w.s. | 12 | 3 | 1 | 14 | 2 | 0 | 9 | 7 | 0 |
| *n* | 0 | 4 | 1 | 0 | 0 | 2 | 0 | 0 | 0 |

i, ii and iii indicate the step at which the meteorological variable was selected in the stepwise regression model (i first, i.e. most dominant variable; iii third). Only variables significantly related to $ET_0$ at 95% level were included, so the number of variables counted in each matrix is not constant.
w.s. and *n* denote wind speed and actual sunshine hours, respectively.

Based on the PM estimates (1965–2005), the monthly $ET_0$ time series exhibited both upward and downward trends in different stations and months in Iran. Increasing trends in monthly $ET_0$ in the northwest of Iran during spring months may lead to increase in the water demand for the growth of crops. These areas are the main dry farming cereal crop production of Iran as mentioned earlier. On the other hand, examining monthly precipitation trends (not shown here) in these months in the northwest of Iran revealed that these series exhibited decreasing trends during the spring months. Therefore, it seems that such changes in $ET_0$ and precipitation would lead to decrease in vegetation and dry farming crop production of Iran. Moreover, the natural vegetation in these mountainous areas of Iran will diminish due to the changes in $ET_0$ and precipitation. Ultimately, it may lead to the adverse affect on the production of meat, and therefore on agricultural economy of Iran.

Increasing trends in annual $ET_0$ in the northwestern Iran seems to be the combined effect of increasing trends in monthly $ET_0$ values in the months of April, May and June. Although, in February and March, increasing trends are observed in $ET_0$, however, due to low values of incoming solar radiation in these cold months crop water requirements can not be changed considerably. In the far northeastern region of Iran, increase in annual $ET_0$ seems to be a result of the occurrence of similar type of significant trends in monthly $ET_0$ in all the twelve months in northeast Iran, which is the main rain-fed cropped mountainous area of Iran. Similarly increasing trends in annual $ET_0$ series of sites located in the east Iran, nearby Afghanistan and Pakistan borderlines, seems to be a result of increasing trends of $ET_0$ in all the months, especially the warm months. This is because the two stations located in that part of Iran, i.e. Zabol and Zahedan, experienced positive Z statistic in all twelve months (see Table 3). Decrease in annual $ET_0$ in the central arid region of Iran besides in the coastal region of Oman Sea is due to the occurrence of the decreasing trends in most warm months, especially June, July, August and September. However, such downward monthly trends in $ET_0$ in this part of Iran, where there are less rain and alkaline and/or salty infertile soils, are not important from the point of view of agriculture in Iran.

According to Sabziparvar et al. (2009), Zahedan (Tabriz) station experienced the lowest (highest) amount of $E_{pan}$ in the year 2004 (2001). Such results are in accordance with our findings for Zahedan (Fig. 3l) and Tabriz $ET_0$ (Fig. 3c), respectively. In the year 1999, $E_{pan}$ reaches to a highest value (i.e. about 2230 mm/year) in the Hamadan province during the period of 1982–2003 (Tabari and Marofi, 2010), which is in total agreement with our findings for Hamadan station (Fig. 3n). Goyal (2004) reported that an increase in ET demand due to global warming would have a larger impact on resource-poor, fragile arid zone ecosystem of Rajasthan (India). He further reported that a small increase (of 1%) in temperature could result in an increase of ET by 15 mm, which might lead to an additional water requirement of 313.12 million cubic meters for the arid zone of Rajasthan. The arid and semi-arid regions of Iran could similarly require careful planning for water resources development due to increase in water demand in view of the observed increases in $ET_0$ over various stations of Iran.

Homogeneity tests in the present study revealed that both the stations and months trends are heterogeneous. This means that similar direction of trends for average value of $Z$ statistics for months is not shown for all stations. This implies that some stations experienced upward trends, whereas some other experienced downward trends in $ET_0$. Moreover, heterogeneous nature of monthly trends suggests that trends for all months were not in the same direction for average values of $Z$'s for station. Such a conclusion has not surprised us for the evapotranspiration variable since the nature of $ET_0$ is very complex involving many highly random processes, and the stations with remote distances to each other are all scattered around a big country like Iran.

In the present study, stepwise regression analysis was used to identify the most important meteorological variable among seven variables used to estimate $ET_0$ by the PM method. The first variable entered to the model known as the most important variable, which affects the particular $ET_0$ time series either in monthly or in annual time scale. Chattopadhayay and Hulme (1997) used similar approach to find the variables responsible for changes in potential ET over different parts of India. Jhajharia et al. (2009) recently used the similar approach to find dominant variables associated with the $E_{pan}$ changes in northeastern India.

Decreasing annual $ET_0$ trends observed in four stations in central and northeast of Iran (see Fig. 3). Stepwise regression analysis results indicate that in a large area of Iran, mainly located in center of the country, decreasing trends in annual $ET_0$ is due to wind speed decreasing trend but in Oman Sea coast, it is due to the mean air temperature decreases.

Bandyopadhayay et al. (2009) reported RH and wind speed are to be the two main meteorological parameters responsible for $ET_0$ decreases in India. The net radiation followed by wind speed was the main two variables responsible for the observed decreasing trends in $ET_0$ in the Yangtze River catchment (Xu et al., 2006). Thomas (2000) reported sunshine duration is the main parameter, which affects PET in South China. However, in northwest, central and northeast China wind speed, relative humidity and maximum temperature are the most important factors, respectively. Wind was most strongly associated with PET in all but one (winter) season at Hami, the station with the highest absolute annual PET decrease in China (Thomas, 2000). Thomas (2000) reported that the sunshine duration (wind speed, relative humidity and maximum temperature) is (are) found to be the main parameter (parameters) affecting the PET in South China (northwest, central and northeast China, respectively). Also, wind was found to be most strongly associated with PET in all but one (winter) season at Hami in China, the station with the highest absolute annual PET decrease (Thomas, 2000). Thomas (2000) tried to explain the dominant influence of wind on PET in the desert regions of west China on the basis of an 'oasis effect'. Doorenbos and Pruitt (1977) stated that the advection of hot air from the surrounding bare lands create an oasis effect, which affect PET rates more than that under the undisturbed conditions. Ubiquitous windy conditions in the desert regions generally may have dominant influence on the observed PET changes. The observed decreasing wind speed in Chine may be due to the changes in the regional circulation system (Thomas, 2000).

Increasing annual $ET_0$ trends were observed in six stations in northwest and east of Iran (Fig. 3). Stepwise regression analysis results indicate that in the northwest of Iran, increasing trends in annual $ET_0$ is due to the effect of increasing trends in wind speed too (see Fig. 7). In the east of Iran stations located in the upper parts of latitudes 30°N exhibited increasing trends in annual $ET_0$, which attributed to wind speed increases. However, $RH_{max}$ and mean air temperature series are the main meteorological parameters, which affect $ET_0$ trend direction (Fig. 7).

Goyal (2004) found that temperature followed by radiation; wind speed and vapor pressure had an effect on $ET_0$ over an arid zone of Rajasthan in India. Yu et al. (2002) reported that increase in $ET_0$ was due to changes in temperature and RH in Paddy fields in southern Taiwan. Hess (1998) also reported that increasing trends in wind speed at Maiduguri, an arid station in East Nigeria, were responsible for the increasing trends in $ET_0$. In the same context, decrease in wind speed was noted to be one of the main meteorological parameters, which caused decline in evapotranspiration in Australia (Roderick et al., 2007), the Tibetan Plateau (Chen et al., 2006; and Zhang et al., 2007) and the south of Canada (Burn and Hesch, 2007). These findings are consistent with our results that wind speed is the main factor, which affects $ET_0$ changes in Iran. It is worthy to mention that in this study we also examined the correlation between the altitude and trend line slope of $ET_0$. This carried out both in annual and seasonal time scales for $ET_0$, separately. Meanwhile, it examined for different climatic classes of stations according to Koppen's classification system (Table 1). Results indicated that there is no significant correlation between trend magnitudes and altitudes of all station. This is true for Iran as whole and specific climatic classes of stations in annual and seasonal time scales. Similarly, Thomas (2000) found no significant correlation between the station altitude and PET trends for China as a whole. However, Thomas (2000) witnessed a positive relation between PET change and station altitude over the eight stations (above 1650 m altitude) located in the mountains of the southwest China and East Tibet.

In order to find a possible link between the atmospheric circulation changes and the observed changes in the meteorological variables in Iran, Nazemosadat and Cordery (2000) found that the north-west Iran's autumn rainfalls were strongly influenced by the Southern Oscillation (SO) phenomenon during extreme phases of El Nino-Southern Oscillation (ENSO). They reported that droughts in the northwest of Iran occurred during the positive SOI, however, abundant autumn precipitation occurred when SOI was negative. They reported that, there is no significant correlation between the SOI and wind speed time series in Iran and concluded that the ENSO was not connected to the near surface pressure system, although it might be related to the upper atmospheric circulation over Iran. According to Alijani (2002) Syrian trough affects western mountainous area of Iran climate, while the Caspian trough affects central and eastern parts of the country. He found that precipitation increases in Iran, when a trough forms in the eastern Mediterranean. It seems that in dry periods, especially in active vegetation growth season, vegetation growth decreases in comparison to the normal rainfall condition. This may cause increase for the near surface wind speed due to decrease plants growth and surface roughness. Furthermore, in dry conditions, crop water requirements may be increases due to decrease in sky cloudiness and therefore, increases in the duration of sunshine hours. Increasing wind speed and sunshine hours in dry periods may increase $ET_0$ rate. The reverse can be anticipated in the periods having rainfall greater than the normal. For stations located in the Zagros Mountainous area of Iran, Masih et al. (2010) demonstrated that very weak correlations existed between the winter precipitation and NAO, while better correlations were found with winter temperatures for some mountainous stations of Iran. The influence of Arctic Oscillation (AO) on winter temperatures of Iran was studied by Ghasemi and Khalili (2006). They showed that the summer AO index is found to be one of the essential components affecting the winter sea air temperature (SAT) in Iran. They showed that, when the negative phase of AO prevails, westerly winds that originate from the warm Atlantic regions, usually increase winter air temperature of Iran. However, when the AO is in its positive phase and is accompanied by the northerly winds, the continental polar and arctic cold air masses move into Iran. They concluded that the sensitivity of the winter SAT to the AO index is higher for western half of the country than the eastern half. On the other hand, the five pressure centers over Khazakhstan, Syria, the Indian Peninsula, the North Sea and the northwestern African coast make a strong effect on wind circulation over Iran in winter (Ghasemi and Khalili, 2008). Recently, the variability of $ET_0$ association to ENSO, in some warm climates of Iran, was addressed by Sabziparvar et al. (2010). They found that about 74% of the SOI-$ET_0$ correlations in spring and summer months were statistically significant. They concluded that the time lag between El-Nina events and the observed maximum effects on $ET_0$ at the warm sites of Iran was about 5 months. Therefore, the SOI values of winter (spring) months significantly influenced the crop ET values of the following summer (autumn) months. It is obvious that the data of sufficiently longer duration are needed to get the precise answer for one of the most important question, i.e. how the air circulation patterns affect the $ET_0$ and/or other meteorological variables in the different climatic conditions of Iran.

## 6. Conclusions

The $ET_0$ trends in the annual and monthly time scales during the period of 1965–2005 carried out using the Mann–Kendall method over Iran. The effect of significant lag-1 serial correlation removed from data by pre-whitening prior to trend analysis. Results indicated that both positive and negative trends detected in the annual and monthly $ET_0$ series at different stations located in different regions of Iran. Increasing $ET_0$ trends prevailed in rain-fed agricultural areas in northwest and northeast of Iran. However, decreasing trends exhibited in sites located in large non-productive area in the center of Iran. The results of the Theil–Sen's slope analysis indicated that the slope of annual trend lines in different stations varied from (−) 63 to 186 mm/year per decade. In monthly scale it is varied from (−) 8.7 to 14 mm/year per decade. Steep upward slope detected in the east of Iran near Afghanistan borderline. Countrywide and season-wide homogeneity of $ET_0$ trends tested using the method proposed by Van Belle and Hughes (1984). There was no evidence for the homogeneity of $ET_0$ trends between stations, months and station–month interaction. In examining the results of stepwise regression analysis in order to find the physical mechanisms behind $ET_0$ changes, wind speed appeared to be the most influencing variable responsible for decreasing and increasing trends in $ET_0$ at most of stations.

On the account of the observed increases in $ET_0$ series at various regions in Iran, an increase in the water demand of various sectors, like, agriculture, reservoir operation, etc., expected to take place in most parts of Iran. It will become highly imperative for the irrigation planners in Iran to adopt some suitable policy for the future development of agriculture and water resources in Iran on the account of the anthropogenic-induced global warming.

## Acknowledgements

The authors are grateful to the anonymous reviewers for their useful comments and suggestions that have led to improved quality of the paper. We also appreciate Dr. Damadi for his useful comments. This work financially supported by the Office of Vice Chancellor for Research of University of Maragheh, gratefully acknowledged.

## References

Ahrens, C.D., 1998. Essentials of Meteorology, An Introduction to The Atmosphere, 2nd ed. Wadsworth, Publishing Company.
Alijani, B., 2002. Variation of 500 hPa flow patterns over Iran and surrounding areas and their relationship with the climate of Iran. Theoretical and Applied Climatology 72, 41–54.
Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy.
Aziz, O.I.A., Burn, D.H., 2006. Trends and variability in the hydrological regime of the Mackenzie River basin. Journal of Hydrology 319, 282–294.
Bandyopadhayay, A., Bhadra, A., Raghuwanshi, N.S., Singh, R., 2009. Temporal trends in estimates of reference evapotranspiration over India. Journal of Hydrologic Engineering 14 (5), 508–518.
Basistha, A., Arya, D.S., Goel, N.K., 2009. Analysis of historical changes in rainfall in the Indian Himalayas. International Journal of Climatology 29, 555–572.
Burn, D.H., 2008. Climatic influences on streamflow timing in the headwaters of the Mackenzie River basin. Journal of Hydrology 352, 225–238.
Burn, D.H., Hesch, N.M., 2007. Trends in evaporation for the Canadian Prairies. Journal of Hydrology 336, 61–73.
Chattopadhayay, N., Hulme, M., 1997. Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. Agricultural Forest Meteorology 87, 55–73.

Chen, S., Liu, Y., Thomas, A., 2006. Climatic change on the Tibetan Plateau: potential evapotranspiration trend from 1961–2006. Climate Change 76, 291–319.
Deni, S.M., Suhaila, J., Zin, W.Z.W., Jemain, A.A., 2010. Spatial trends on dry spells over Peninsular Malaysia during monsoon seasons. Theoretical and Applied Climatology 99, 357–371.
Dinpashoh, Y., 2006. Study of reference crop evapotranspiration in I.R. of Iran. Agricultural Water Management 84, 123–129.
Dinpashoh, Y., Fakheri-Fard, A., Moghaddam, M., Jahanbakhsh, S., Mirnia, M., 2004. Selection of variables for the purpose of regionalization of Iran's precipitation climate using the multivariate methods. Journal of Hydrology 297, 109–123.
Doorenbos, J., Pruitt, O.W., 1977. Crop Water Requirements, FAO Irrigation and Drainage Paper 24, Land and Water Development Division, FAO, Rome, p. 144.
Gan, T.W., 1995. Trends in air temperature and precipitation for Canada and north-eastern USA. International Journal of Climatology 15, 1115–1134.
Gan, T.W., 1998. Hydroclimatic trends and possible climatic warming in the Canadian prairies. Water Resources Research 34 (11), 3009–3015.
Ghahraman, B., 2006. Time trend in the mean annual temperature of Iran. Turkish Journal of Agricultural Forestry 30, 439–448.
Ghahraman, B., Taghvaeian, S., 2008. Investigation of annual rainfall trends in Iran. Journal of Agricultural Science and Technology 10, 93–97.
Ghasemi, A.R., Khalili, D., 2006. The influence of the Arctic Oscillation on winter temperatures in Iran. Theoretical and Applied Climatology 85, 149–164.
Ghasemi, A.R., Khalili, D., 2008. The association between regional and global atmospheric patterns and winter precipitation in Iran. Atmospheric Research 88, 116–133.
Goyal, R.K., 2004. Sensitivity of evapotranspiration to global warming: a case study of arid zone of Rajasthan (India). Agricultural Water Management 69, 1–11.
Hargreaves, G.H., Samani, Z.A., 1982. Estimating potential evapotranspiration. Journal of Irrigation and Drainage Engineering 108 (3), 225–230.
Hess, T.M., 1998. Trends in reference evapo-transpiration in the North East Arid Zone of Nigeria, 1961–1991. Journal of Arid Environment 38, 99–115.
Hess, A., Lyer, H., Malm, W., 2001. Linear trend analysis: a comparison of methods. Atmospheric Environment 35, 5211–5222.
Jhajharia, D., Shrivastava, S.K., Sarkar, D., Sarkar, S., 2009. Temporal characteristics of pan evaporation trends under the humid conditions of northeast India. Agricultural Forest Meteorology 149, 763–770.
Kahya, E., Kalaycı, S., 2004. Trend analysis of streamflow in Turkey. Journal of Hydrology 289, 128–144.
Kampata, J.M., Parida, B.P., Moalafhi, D.B., 2008. Trend analysis of rainfall in the headstreams of the Zambezi River in Zambia. Physics and Chemistry of the Earth 33, 621–625.
Kendall, M.G., 1975. Rank Correlation Methods, 4th ed. Charles Griffin, London.
Kumar, S., Merwade, V., Kam, J., Thurner, K., 2009. Streamflow trends in Indiana: Effects of long term persistence, precipitation and subsurface drains. Journal of Hydrology 374 (1–2), 171–183.
Lins, H.F., Slack, J.R., 1999. Streamflow trends in the United States. Geophysical Research Letters 26 (2), 227–230.
Lins, H.F., Slack, J.R., 2005. Seasonal and regional characteristics of US streamflow trends in the United States from 1940 to 1999. Physical Geography 26 (6), 489–501.
Mann, H.B., 1945. Non-parametric tests against trend. Econometrica 33, 245–259.
Masih, I., Uhlenbrook, S., Maskey, S., Smakhtin, V., 2010. Streamflow trends and climate linkages in the Zagros Mountains, Iran. Climate Change. doi:10.1007/s10584-009-9793-x.
Modarres, R., da Silva, R.V.P., 2007. Rainfall trends in arid and semi-arid regions of Iran. Journal of Arid Environment 70, 344–355.
Nazemosadat, M.J., Cordery, I., 2000. On the relationships between ENSO and autumn rainfall in Iran. International Journal of Climatology 20, 47–61.
Panda, D.K., Mishra, A., Jena, S.K., James, B.K., Kumar, A., 2007. The influence of drought and anthropogenic effects on groundwater levels in Orissa, India. Journal of Hydrology 343, 140–153.
Partal, T., Kahya, E., 2006. Trend analysis in Turkish precipitation data. Hydrological Processes 20, 2011–2026.
Roderick, M.L., Rotstayn, L.D., Farquhar, G.D., Hobbins, M.T., 2007. On the attribution of changing pan evaporation. Geophysical Research Letters 34, L17403. doi:10.1029/2007GL031166.
Sabziparvar, A.A., Tabari, A., Aeini, A., Ghafouri, M., 2009. Evaluation of class A pan coefficient models for estimation of reference crop evapotranspiration in cold semi-arid and warm arid climates. Water Resources Management. doi:10.1007/s11269-009-9478-2.
Sabziparvar, A.A., Mirmasoudi, H.S., Tabari, H., Nazemosadat, M., Maryanaji, Z., 2010. ENSO teleconnection impacts on reference evapotranspiration variability in some warm climates of Iran. International Journal of Climatology. doi:10.1002/joc.2187.
Sahoo, D., Smith, P.K., 2009. Hydroclimatic trend detection in a rapidly urbanizing semi-arid and coastal river basin. Journal of Hydrology 367, 217–224.
Sen, P.K., 1968. Estimates of the regression coefficients based on Kendall's tau. Journal of the American Statistical Association 63, 1379–1389.
Shen, Y., Liu, C., Liu, M., Zeng, Y., Tian, C., 2010. Change in pan evaporation over the past 50 years in the arid region of China. Hydrological Processes 24, 225–231.
Shuttleworth, W.J., 1993. Evaporation. In: Maidment, D.R. (Ed.), Handbook of Hydrology. McGraw-Hill, New York, pp. 4.1–4.53.
Tabari, A., Marofi, S., 2010. Changes of pan evaporation in the west of Iran. Water Resources Management. doi:10.1007/s11269-010-9689-6.
Tayanc, M., Karaca, M., Yenigun, O., 1997. Annual and seasonal air temperature trend patterns of climate change and urbanization effects in relation to air pollutants in Turkey. Journal of Geophysical Research 102 (D2), 1909–1919.
Tebakari, T., Yoshitani, J., Suvanpimol, C., 2005. Time–space trend analysis in pan evaporation over kingdom of Thailand. Journal of Hydrologic Engineering 10 (3), 205–215.
Theil, H., 1950. A rank invariant method of linear and polynomial regression analysis, Part 3. Netherlands Akademie van Wettenschappen, Proceedings 53, 1397–1412.
Thomas, A., 2000. Spatial and temporal characteristics of potential evapotranspiration trends over China. International Journal of Climatology 20, 381–396.
Van Belle, G., Hughes, J.P., 1984. Nonparametric tests for trend in water quality. Water Resources Research 20 (1), 127–136.
Xu, C.-Y., Gong, L., Jiang, T., Chen, D., Singh, V.P., 2006. Analysis of spatial distribution and temporal trend of reference evapotranspiration and pan evaporation in Changjiang (Yangtze River) catchment. Journal of Hydrology 327, 81–93.
Yu, P.-S., Yang, T.-C., Chou, C.-C., 2002. Effects of climate change on evapotranspiration from paddy fields in southern Taiwan. Climate Change 54, 165–179.
Yue, S., Pilon, P., Phinney, B., Cavadias, G., 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrological Processes 16, 1807–1829.
Zhang, X., Harvey, K.D., Hogg, W.D., Yuzyk, T.R., 2001. Trends in Canadian streamflow. Water Resources Research 37 (4), 987–998.
Zhang, Y.Q., Liu, C.M., Tang, Y.H., Yang, Y.H., 2007. Trends in pan evaporation and reference and actual evapotranspiration across the Tibetan Plateau. Journal of Geophysical Research 112, D12110. doi:12110.11029/12006JD0081-61.