Pan evaporation and reference evapotranspiration trend detection in western Iran with consideration of data persistence

P. Hosseinzadeh Talaee, Hossein Tabari and Hirad Abghari

ABSTRACT

It is important to identify the spatiotemporal trends of evaporation and evapotranspiration under the changing climate for use in regional water resources planning. This work aimed to investigate the trends of the Hargreaves reference evapotranspiration (ET_o), pan evaporation (E_{pan}) and pan coefficient (K_{pan}) series at 12 stations in the west of Iran by using the sequential Mann–Kendall, Kendall and Spearman tests after eliminating the influence of the significant lag-1 serial correlation from the time series by the pre-whitening method for the period 1982–2003. The approximate year of the beginning of the significant trends was detected by using the Mann–Kendall rank statistic. The spatial distribution of the trend magnitudes was obtained from the Inverse-Distance-Weighted (IDW) interpolation method. No significant trends were found in the ET_o time series, while an upward trend of 16 mm/year was observed in the E_{pan} series which began in 1998. Moreover, a downward trend was obtained in the K_{pan} series which started in 1994.

Key words | evaporation and evapotranspiration, Hargreaves equation, pan coefficient, serial correlation, spatial distribution, trend analysis

P. Hosseinzadeh Talaee (corresponding author)
Young Researchers & Elites Club,
Hamedan Branch,
Islamic Azad University,
Hamedan,
Iran
E-mail: p.hosseinzadeh@iauh.ac.ir

Hossein Tabari
Department of Water Engineering,
Ayatollah Amoli Branch,
Islamic Azad University,
Amol,
Iran

Hirad Abghari
Department of Watershed Management,
Faculty of Natural Resources,
Urmia University,
Urmia,
Iran

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) reported that the global mean land-surface-air temperature has risen by about 0.74 °C over the past 100 years (1906–2005), and it was predicted to increase by 1.1–6.4 °C by 2100 (IPCC 2007). The global warming leads to higher evaporation rates and enables the atmosphere to transport higher amounts of water vapor, which will accelerate the hydrological cycle and cause uneven distribution of water resources (Menzel & Burger 2002). Most water resources projects are planned, designed and operated based on the historical pattern of water availability, quality and demand assuming constant climatic behavior. It is important to investigate present and probable future climatic change patterns and their impacts on water resources so that appropriate adaptation strategies may be implemented (Abdul Aziz & Burn 2006).

There is a general need to study the climate change that has actually occurred over the past few decades and its impact on evaporation and evapotranspiration (ET), as the most basic components of the hydrological cycle, under the existing trend (Bandyopadhyay et al. 2009). Hence, the analysis of the spatiotemporal trends of evaporation and ET under the changing climate is particularly important for improving the utilization of agricultural water resources, and helpful for understanding the spatiotemporal variation of ecological and environmental water requirements, etc. (Zuo et al. 2012).

Several studies have been carried out to analyze trends in pan evaporation (E_{pan}) and reference evapotranspiration (ET_o) over different parts of the world since the mid-1990s (e.g., Ramirez & Finnerty 1996; da Silva 2004; Goyal 2004; Hobbins et al. 2004; Roderick & Farquhar 2004, 2005; Xu et al. 2006; Burns et al. 2007; Wang et al. 2007; Zhang et al. 2007; Bandyopadhyay et al. 2009; Song et al. 2010). Recently, Yin et al. (2010) studied

the changes of ET_o in China during the period 1961–2008 and found decreasing trends of ET_o in the whole country and in most climate regions, except the cold temperate humid region in Northeast China. In the other study in China, Zuo et al. (2012) analyzed the spatiotemporal variations of potential evapotranspiration (PET) at 21 meteorological stations in the Wei River basin over the period 1959–2008. The results indicated that mean annual and seasonal PET was generally decreasing from northeast to southwest. In addition, summer and spring made the major contributions to the annual values, and annual and seasonal PET series in most parts of the basin exhibited increasing trends. Abtew et al. (2011) showed that South Florida is experiencing an increase in evaporation and ET. Jhajharia et al. (2012) analyzed the trends in ET_o series at eight stations in the humid region of northeast India for the period 1979–2000. They found a significant decreasing ET_o trend at annual and seasonal time scales for six sites in NE India and NE India as a whole.

Iran with a land area of about 1.65 million km^2 is situated in the Middle East region of south-western Asia. The country has arid and semi-arid climates, with an average annual precipitation of about 250 mm or less (Alizadeh & Keshavarz 2005). Two main mountain chains consist of the Zagros and the Alborz Mountains located in the northwest, the west and the northern parts of Iran and the central parts of the country are covered by two very dry deserts, the Dasht-e-Kavir and the Dasht-e-Lut (Ghasemi & Khalili 2008). Air temperature in Iran has high spatial variability due to the above mentioned topographic features (Ghasemi & Khalili 2006). The temperature variability in different parts of the country and the multiplicity of climatic zones make it possible to cultivate a diverse variety of crops. About one-third of the country's total surface area is suited for farmland, but because of poor soil and lack of adequate water distribution in many areas, most of it is not under cultivation and only 12% of the total land area is under cultivation (arable land, orchards and vineyards). Iran's agriculture is highly vulnerable to climate variability (Bannayan et al. 2010), because the observed changes in climatic regimes due to warming of the earth-atmosphere system (Tabari & Hosseinzadeh Talaee 2011b, 2011c, 2011d; Tabari et al. 2011b) may affect

ET and consequently agricultural water demand in the region.

There are some studies available regarding spatiotemporal trends of E_{pan} and ET_o in Iran. Tabari & Marofi (2011) studied the temporal variations of pan evaporation at 12 stations located in western Iran for the period 1982–2003. They found a significant increasing trend at 67% of the stations at the average rate of (+)160 mm/month per decade. Dinpashoh et al. (2011) examined the trends in ET_o over the 16 weather stations and found that the increasing trends in ET_o were more pronounced than the decreasing trends. Tabari et al. (2011a, 2012) also showed an increasing ET_o trend at the majority of the Iranian stations, but the trends were found to be significant at about 30% of the stations.

Most of the above mentioned researches mainly focused on non-parametric trend identification methods, particularly the non-parametric Mann–Kendall test, without paying adequate attention to the serial structure of the time series. However, it is worthwhile to note that the existence of serial correlation in time series can adversely impact the power of the trend tests (von Storch 1995; Yue & Wang 2002; Yue et al. 2002, 2003; Yue & Hashino 2003; Khaliq et al. 2009). Thus, it is necessary to investigate the effect of serial correlation on trend detection tests. Several methods have been proposed in the literature to account for the effect of serial correlation in the data. One of the methods used to prevent false indication of trend is known as 'pre-whitening', where serial correlation is removed from the data by assuming a certain correlation model, usually a Markovian one (Hamed 2009).

The work is an extension of the previous analysis of E_{pan} trends in the west of Iran by Tabari & Marofi (2011) for exploring the spatial trends and change points of the ET_o, E_{pan} and pan coefficient (K_{pan}) series. The purpose of this study includes: (1) to estimate ET_o using the calibrated Hargreaves equation over 12 stations located in the west of Iran; (2) to calculate K_{pan} using the estimated ET_o and observed E_{pan} at each station; (3) to detect the temporal trends in the annual ET_o, E_{pan} and K_{pan} time series using the Kendall and Spearman tests for the period 1982–2003; (4) to identify the serial structure of the data and consider the influence of lag-1 serial correlation on the trend tests with the pre-whitening method;

(5) to obtain the magnitudes of trends through Theil-Sen's estimator; (6) to map the spatial distributions of the trend magnitudes and per cent changes of the ET_o, E_{pan} and K_{pan} series using the Inverse-Distance-Weighted (IDW) method; and (7) to determine the approximate year of the beginning of the significant ET_o, E_{pan} and K_{pan} trends by the sequential Mann–Kendall test.

DATA AND METHODS

Data

The monthly class A pan evaporation and air temperature data were obtained from 12 stations located in the west of Iran for the period 1982–2003 (Table 1). The geographical position of the selected stations is shown in Figure 1. Long-term E_{pan} data are available for a few stations in Iran. The class A pan was chosen as the standard for measuring evaporation in Iran due to it being the international preference. The class A pan is a circular pan made of galvanized iron, with a 121 cm diameter and a 25.5 cm depth which is supported by a wood frame stand.

Because of the absence of the solar radiation and wind speed data at the stations, the Hargreaves method calibrated by Tabari & Hosseinzadeh Talaee (2011a) was used

to estimate ET_o in the study area. The Hargreaves method (Hargreaves & Samani 1982) for computing ET_o is a simple, empirical approach that has been used in cases where only air temperature data are available (Itenfisu *et al.* 2003). Many researchers (e.g., Chuanyan *et al.* 2004; Lopez-Urrea *et al.* 2006; Sabziparvar & Tabari 2010; Tabari 2010) introduced the Hargreaves model as a proper model to estimate ET_o for semi-arid regions. Tabari and Hosseinzadeh Talaee (2011a) calibrated the Hargreaves equation for the cold climate of western Iran as follows:

$$ET_o = 0.408 \times 0.0029 \times R_a \times (T_{mean} + 17) \times \sqrt{T_{max} - T_{min}}$$
(1)

where ET_o is in mm d^{-1}, and T_{max}, T_{min} and T_{mean} are the maximum, minimum and mean air temperature ($^\circ$C), respectively. R_a depends on the Julian day number and latitude, and can be computed as described by Allen *et al.* (1998). The coefficient of 0.408 is for converting MJ m^{-2} d^{-1} into mm d^{-1} (Allen *et al.* 1998).

After estimating ET_o, the pan coefficient (K_{pan}) was calculated by comparing the measured E_{pan} with the estimated ET_o:

$$K_{pan} = \frac{ET_o}{E_{pan}}$$
(2)

Table 1 | Climatic characteristics of the stations used in the study

| Station name	Station type	T_{max} ($^\circ$C)	T_{mean} ($^\circ$C)	T_{min} ($^\circ$C)	P (mm)
1. Dargezin	Climatological	18.2 ± 0.8	11.0 ± 1.0	4.0 ± 0.8	325.9 ± 101.6
2. Ekbatan	Research	19.1 ± 1.1	11.0 ± 1.1	2.9 ± 1.1	310.0 ± 71.4
3. Ekbatan dam	Evaporimeter	18.3 ± 0.8	10.7 ± 0.9	3.1 ± 1.0	337.0 ± 79.8
4. Ghahavand	Raingauge	19.7 ± 1.4	11.3 ± 1.2	2.9 ± 1.2	233.7 ± 51.4
5. Kangavar	Synoptic	21.0 ± 1.1	13.3 ± 0.9	4.7 ± 1.1	401.6 ± 101.4
6. Kheir-Abad	Evaporimeter	19.6 ± 1.3	12.8 ± 1.1	5.6 ± 0.9	312.2 ± 72.5
7. Khomigan	Evaporimeter	17.8 ± 1.0	10.6 ± 2.0	4.3 ± 1.6	273.3 ± 69.9
8. Khosro-Abad	Evaporimeter	21.8 ± 1.3	12.5 ± 1.1	2.7 ± 1.8	329.7 ± 84.0
9. Malayer	Synoptic	20.0 ± 1.1	14.0 ± 1.5	6.0 ± 0.8	307.8 ± 75.4
10. Nahavand	Synoptic	20.5 ± 0.9	13.5 ± 1.2	5.9 ± 1.1	421.7 ± 116.9
11. Nozheh	Synoptic	19.3 ± 1.0	10.9 ± 0.9	2.5 ± 1.0	331.5 ± 74.0
12. Varayeneh	Evaporimeter	19.8 ± 1.2	9.8 ± 1.8	0.1 ± 2.8	517.9 ± 142.4
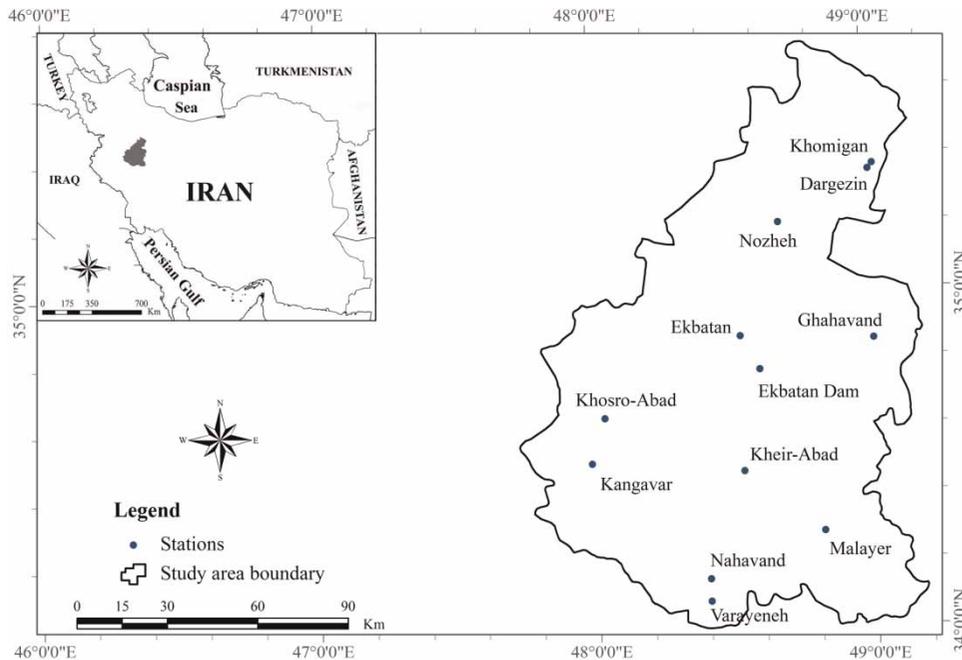
Figure 1 | Geographic location of the study region and the stations.

Statistical analyses

Spearman test

A quick and simple test to determine whether correlation exists between two classifications of the same series of observations is the Spearman's rank correlations test (Kahya & Kalayci 2004). Since Spearman's rank correlation coefficient is a non-parametric test, it does not depend upon the assumptions given for a parametric test. Hence it is distribution free. In contrast, some difficulties of calculating Spearman's rank correlation coefficient arise, when the sample is large. For large data, it can be hard to rank the data for both variables and consequently it is time consuming to perform the Spearman's rank correlation coefficient test (Göktaş & İşçi 2011).

In the Spearman test, there is a significant trend only if the correlation between time steps and ET_o, E_{pan} and K_{pan} series are found to be significant (Kahya & Kalayci 2004). The Spearman coefficient, r_s, is the correlation coefficient of the linear regression between the series i and y_i and it is

obtained from the expression:

$$r_s = 1 - \left[6 \sum (y_i - i)^2\right] / \left[n(n^2 - 1)\right] \qquad (3)$$

where n is the number of data items in the series and i is the order of the elements in the original series. The distribution of r_s tends towards a normal distribution (bell curve) with a mean of zero.

In order to examine whether the null hypothesis, that there is no trend, can be rejected or not, it is necessary to calculate the probability

$$\alpha = P(|u| > |u(r_s)|) \qquad (4)$$

$$u(r_s) = r_s(n - 1)^{1/2} \qquad (5)$$

This is calculated using a table of reduced normal distribution. If $\alpha < \alpha_0$, the null hypothesis is rejected for a significance level of α_0. If a trend is detected, it will be an increasing or decreasing trend, depending on whether $r_s > 0$ or $r_s < 0$ (del Rio *et al.* 2005).

Kendall test

Kendall's rank correlation (or τ test) is a commonly used test to assess the significance of trends in hydro-meteorological time series which is based on the proportionate number of subsequent observations that exceed a particular value (Kendall & Stuart 1973; Kottegoda 1980). Similar to the Spearman test, the Kendall test is designed to capture the association between two ordinal (not necessarily interval) variables. The Kendall test is even less sensitive to outliers and is often preferred due to its simplicity and ease of interpretation. Comparing with the Spearman test, the Kendall test leads to a somewhat less powerful test (Chok 2010). For a sequence $x_1, x_2, \ldots, x_n$, the standard procedure is to determine the number of times, say, p, in all pairs of observations ($x_i, x_j; j > i$) that x_j is greater than x_i; the ordered (i, j) subsets are ($i = 1, j = 2, 3, \ldots, n$), ($i = 2, j = 3, 4, \ldots, n$), $\ldots$, ($i = n - 1, j = n$), n is the data set record length. There is a rising trend where succeeding values are throughout greater than preceding ones and p is given by $(n - 1) + (n - 2) + \ldots + 1$ which is the sum of an arithmetic progression and is given by $n(n - 1)/2$. If the observations are totally reversed, $p = 0$ and, hence it follows that, for a trend free series,

$$E(p) = \frac{n(n - 1)}{4} \tag{6}$$

The test is based on the statistic τ,

$$\tau = \frac{4p}{n(n - 1)} - 1 \tag{7}$$

A positive τ indicates an increasing trend in the time series, and a negative τ indicates a decreasing trend (Ma *et al.* 2008). Under the null hypothesis, the test statistic τ approximately follows a standard normal distribution.

Sequential Mann–Kendall test

The sequential Mann–Kendall test proposed by Sneyers (1990) is used for determining the approximate year of the beginning of the significant trend. In particular, the sequential Mann–Kendall test calculates all $u(d_i)$, $1 \leq i \leq n$,

through a formula similar to the one referred by Mitchell *et al.* (1966). Before applying the test, the number m_i of terms Y_i in the series preceding each term Y_i ($i > j$), is calculated such that $Y_j < Y_i$. The statistical test d_i is then given by the sum of the i first terms:

$$d_i = \sum_i m_i \tag{8}$$

and its distribution function under the null hypothesis is asymptotically normal, with mean and variance:

$$E(d_i) = \frac{i(i - 1)}{4} \tag{9}$$

$$\text{var}(d_i) = \frac{i(i - 1)(2i + 5)}{72} \tag{10}$$

Finally, the test calculates all $u(d_i)$, $1 \leq i \leq n$, given by the equation (Feidas *et al.* 2004):

$$u(d_i) = \frac{d_i - E(d_i)}{\sqrt{\text{var}(d_i)}} \tag{11}$$

The sequential Mann–Kendall test, consisting of the application of the test to all series starting with the first term and ending with the ith, and to those starting with the ith and ending with the last one, was also used as a progressive analysis of the series (Dufek & Ambrizzi 2008). The sequential behavior of $u(d)$ fluctuates around the zero level. $u(d)$ is the same as the Z values that are found from the first to last data point. This test considers the relative values of all terms in the time series ($x_1, x_2, \ldots, x_n$). The values of $u'(d)$ are computed backward, starting from the end of the series (Partal & Kahya 2006). If the $u(d)$ and $u'(d)$ curves cross each other, and then diverge and acquire specific threshold values, then there is a statistically significant trend (Croitoru *et al.* 2012; Tabari *et al.* 2011b). The point where they cross each other shows the approximate year at which the trend begins (Mosmann *et al.* 2004). In the absence of any trend, the graphical representation of the direct $u(d_i)$ and the backward $u'(d_i)$ series obtained with this method gives curves which overlap several times (Dufek & Ambrizzi 2008).

Theil-Sen's estimator

The magnitude of the significant trends in the time series was estimated using the non-parametric Theil-Sen's estimator (Theil 1950; Sen 1968) as follows:

$$\beta = \text{Median}\left(\frac{X_i - X_j}{i - j}\right) \tag{12}$$

in which $1 < j < i < n$. The estimator β is the median over all combinations of record pairs for the whole data set and is thereby resistant to the effect of extreme values in the observations (Xu *et al.* 2003).

Relative change

Relative change (RC) was calculated using the following formula:

$$\text{RC} = \frac{n \times \beta}{|\bar{x}|} \times 100 \tag{13}$$

where n is the data set record length, β is the trend of the time series (Equation (12)) and $|\bar{x}|$ is the absolute average value of the time series. The RC index is a useful tool for comparing the changes in parameters with very different values, such as K_{pan} and E_{pan}.

Pre-whitening approach

The Kendall and Spearman tests require time series to be serially independent. von Storch (1995) suggested the use of a pre-whitening approach to eliminate the influence of serial correlation on the Mann–Kendall test. Later, the pre-whitening approach was used for removing the effect of serial correlation on the other trend tests such as Mann–Whitney (Yue & Wang 2002) and Sen's slope estimator (Tabari & Hosseinzadeh Talaee 2011b). In this study, the pre-whitening method was used to eliminate the influence of serial correlation on the Kendall and Spearman tests and the Theil-Sen's estimator. A serially correlated series is pre-whitened using the following formula (Yue & Wang 2002):

$$Y_t = X_t - r_1 X_{t-1} \tag{14}$$

where r_1 is the lag-1 sample serial correlation coefficient, which is estimated using the following formula:

$$r_1 = \frac{(1/(n-1))\sum_{t=1}^{n-1}[X_t - E(X_t)][X_{t+1} - E(X_t)]}{\frac{1}{n}\sum_{t=1}^{n}[X_t - E(X_t)]^2} \tag{15a}$$

$$E(X_t) = \frac{1}{n}\sum_{t=1}^{n}X_t \tag{15b}$$

RESULTS AND DISCUSSION

The ET_o values were estimated by using the calibrated Hargreaves equation at the study stations. The results (not shown) indicated that the mean annual ET_o varied from 1,323 mm at Varayeneh station in southern parts of the study area to 1,608 mm at Kangavar station in western parts. After calculating the ET_o values, the K_{pan} values were obtained as the ratio of the estimated ET_o values to the observed E_{pan} values (Equation (2)). An average K_{pan} of 0.81 was found for the whole study area. The inter-annual variations of the areal means of the ET_o, E_{pan} and K_{pan} are shown in Figure 2.

The consideration of the serial structure of the time series is necessary prior to trend analysis. The lag-1 serial correlation coefficients of the ET_o, E_{pan} and K_{pan} time series are illustrated in Figure 3. The majority of the time series had a positive serial correlation. A significant positive serial correlation at the significance level of 0.05 was observed in the ET_o series of Kangavar, Malayer and Varayeneh stations. The E_{pan} series of Dargezin, Ekbatan, Ekbatan dam, Kheir-Abad, Khomigan, Nahavand, Nozheh and Varayeneh stations showed a significant positive serial correlation. Furthermore, a significant positive serial correlation was found in the K_{pan} series of Dargezin, Ekbatan, Kangavar, Khomigan, Khosro-Abad, Nozheh and Varayeneh stations. As already discussed, the significant serial correlation in time series can adversely impact the power of the trend tests. From a statistical point of view, the existence of positive serial correlation (persistence) increases the possibility of the Kendall and Spearman tests to reject the null hypothesis of no trend while it is true; while negative
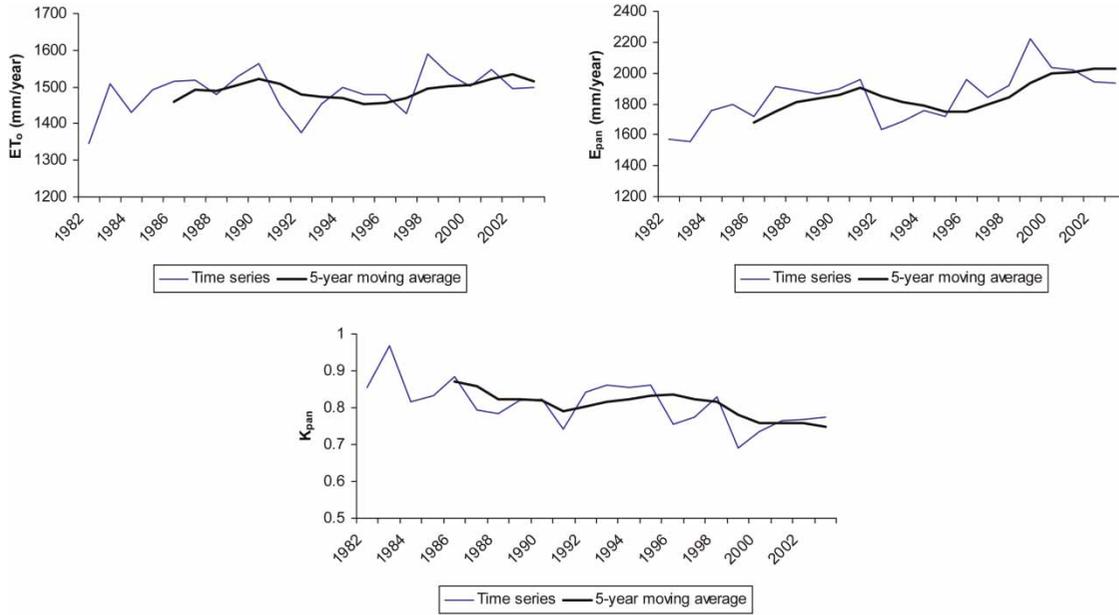
Figure 2 │ Observed and 5-year moving average of annual ET_o, E_{pan} and K_{pan} series for the period 1982–2003.
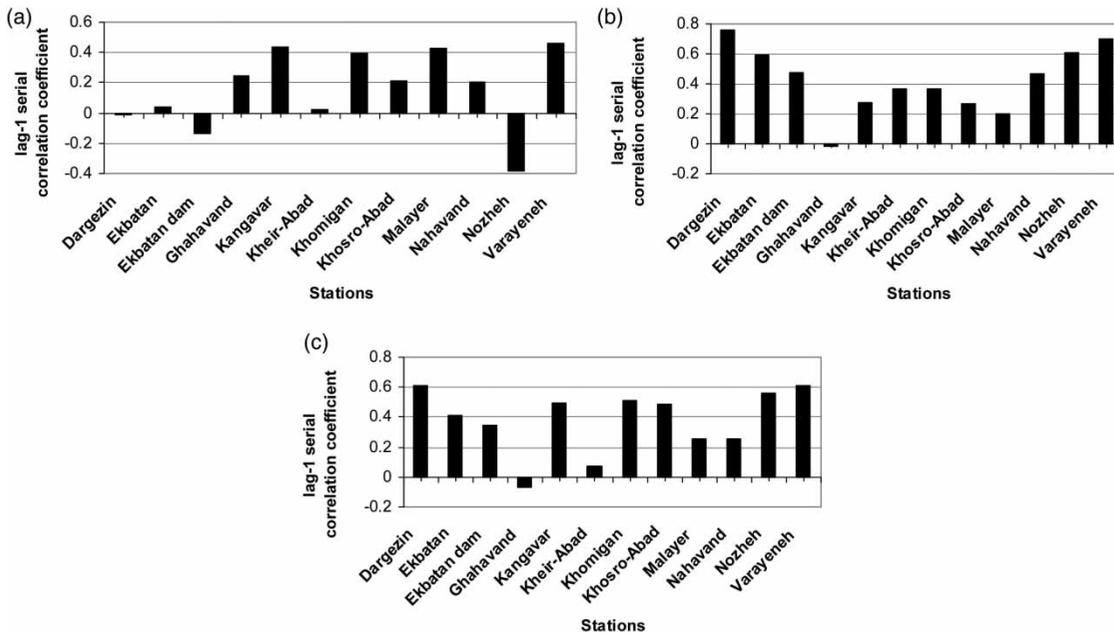

Figure 3 │ Lag-1 serial correlation coefficient for the considered parameters at the stations: (a) ET_o; (b) E_{pan}; and (c) K_{pan}.

serial correlation will decrease the possibility of rejecting the null hypothesis (Tabari & Aghajanloo 2013).

The effect of serial correlation was removed from the time series by the pre-whitening method prior to applying the Kendall and Spearman tests and the Theil-Sen's estimator. The analysis indicated that the pre-whitening method can effectively remove the serial correlation from the ET_o, E_{pan} and K_{pan} time series. The results of the trend tests after removal of the serial correlation effect from the data are presented in this paper. The results of the Spearman

test on the ET_o time series are presented in Figure 4. In this study, the trends are considered statistically significant at the 95% confidence level when identified by the two Kendall and Spearman trend tests. According to the results, five out of the 12 stations exhibited an upward ET_o trend. No significant ET_o trends were detected by both statistical tests. On average, annual ET_o increased at the rate of 0.464 mm/year (0.68%) in the study area.

The spatial distribution maps of the trend magnitude (mm/year) obtained by the Theil-Sen's estimator of annual ET_o for the period 1982–2003 are illustrated in Figure 4. For preparing the maps, the contours were generated using an IDW algorithm with a power of 2.0 for each grid point in ArcGIS 9.3 software media, and data from locations within a 45 km radius were used. As the maps show, there is no general spatial pattern of upward and downward ET_o

magnitudes, and the positive and negative changes can be observed in different parts of the study area.

ET plays an important role in supporting regional water resources assessment and water management (Zuo *et al.* 2012). The upward ET_o trends obtained in this study combined with the decreasing trends of precipitation in the west of Iran (Tabari & Hosseinzadeh Talaee 2011c) will influence crop water requirements and surface water resources in the study region.

Figure 5 illustrates the outputs of the Spearman test on the E_{pan} time series. As shown, an upward trend was detected in the E_{pan} series for about 75% of the stations. A significant upward trend of E_{pan} was only found at Varayeneh station. According to the Theil-Sen's estimator, the magnitude of the significant E_{pan} trend at Varayeneh station was 16 mm/year (Figure 5). The E_{pan} trend averaged over all
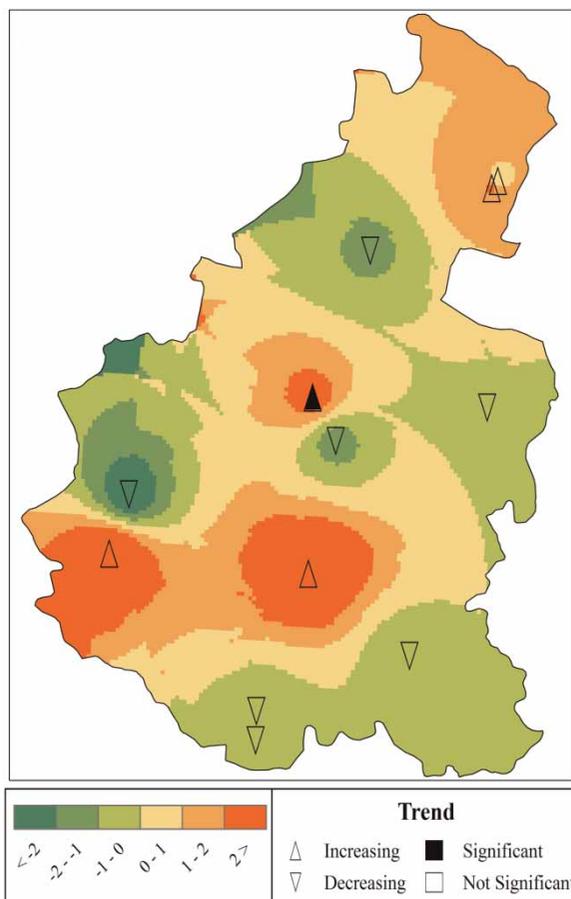
Figure 4 │ Spatial distribution of the trend magnitude (mm/year) of annual ET_o obtained through Theil-Sen's estimator for the period 1982–2003 (markers show upward and downward trends detected by the Spearman test).
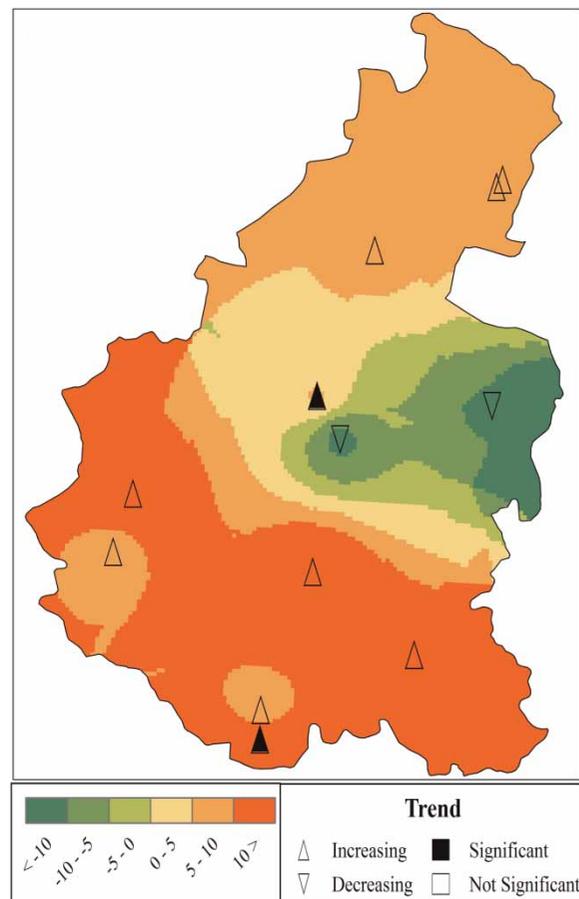
Figure 5 │ Spatial distribution of the trend magnitude (mm/year) of annual E_{pan} obtained through Theil-Sen's estimator for the period 1982–2003 (markers show upward and downward trends detected by the Spearman test).

12 stations for the period 1982–2003 was (+)6.73 mm/year or (+)7%.

The spatial distribution of the trend magnitude (mm/year) obtained by the Theil-Sen's estimator of annual E_{pan} for the period 1982–2003 are plotted in Figure 5. As can be seen from Figure 5, the trend magnitude of annual E_{pan} was positive for the whole study area, except a small part in the eastern region. Generally speaking, the positive changes of annual E_{pan} for the southern half of the study area (more than 10%) were greater than those for the northern parts (5–10%).

The results of the progressive application of the Mann–Kendall test allow the detection of the beginning year of trend or change in the series. As stated earlier, the point where the $u(d)$ and $u'(d)$ curves cross each other indicates the approximate year at which the trend begins. Figure 6 shows the curves for annual E_{pan} series at Varayeneh station. As the plots indicate, the E_{pan} trend at Varayeneh station began around 1998.

Evaporation has great effect on the water balance of the earth surface (Ogolo 2011). The positive trends of E_{pan} observed in the study area imply that the evaporation component of the hydrological cycle has been increasing which has great effect on the water balance of the study area (Fang & Imura 2005; Ogolo 2011). The E_{pan} increases will affect the volume, spatial distribution and temporal characteristics of surface runoff, river runoff and available water resources (Fang & Imura 2005). The implication of the increasing E_{pan} trend also suggests the increase of aridity in the study area during the last 22 years, because more volumes of water escaped through evaporation from the earth surface than were replenished through rainfall from the atmosphere.
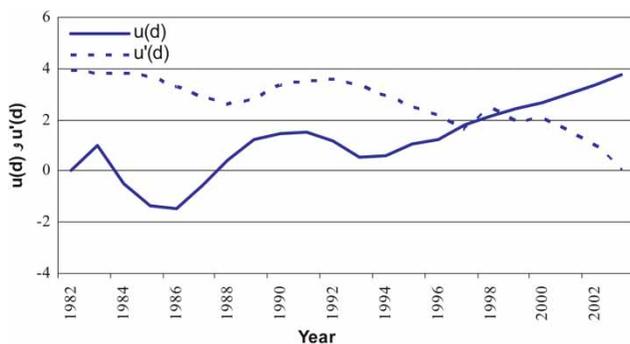
The results of the Spearman trend test on the K_{pan} series are shown in Figure 7. As expected, the majority of the K_{pan} trends at the study stations were downward. Only the downward K_{pan} trend of Varayeneh station was statistically significant. The annual K_{pan} of Varayeneh station decreased at the rate of 20% during the study period. The K_{pan} trend averaged over all 12 stations for the period 1982–2003 was about (−)5%. Broadly speaking, the ratio of ET_o to pan evaporation was not constant over time in the study area and had a downward tendency during the last 22 years. The variation of pan coefficient depends on (1) the type of pan used, (2) the pan environment (fallow or cropped area) and (3) the climate (humidity and wind speed) (Allen *et al.* 1998).
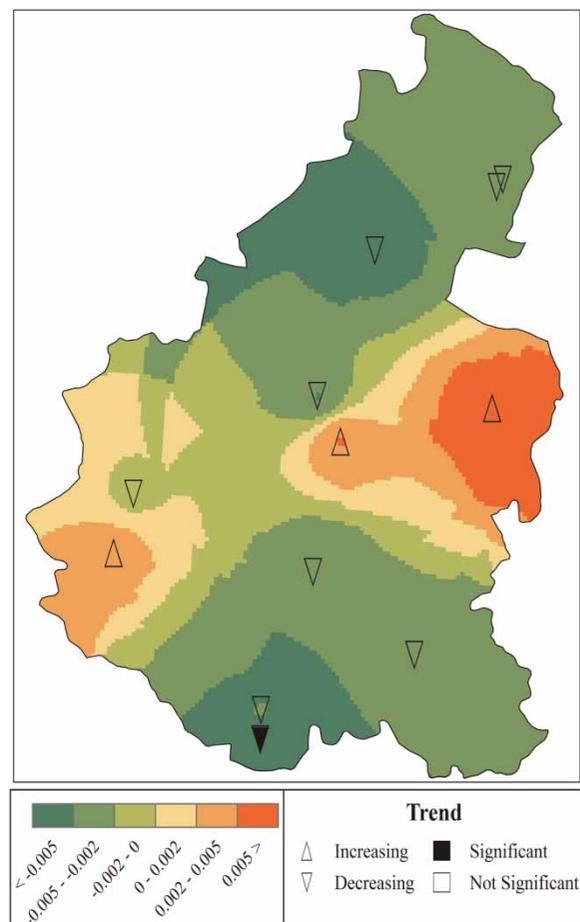

Figure 6 | Progressive values of $u(d)$ and $u'(d)$ for annual E_{pan} at Varayeneh station for the period 1982–2003.

Figure 7 | Spatial distribution of the trend magnitude (dimensionless) of annual K_{pan} obtained through Theil-Sen's estimator for the period 1982–2003 (markers show upward and downward trends detected by the Spearman test).

Figure 7 shows the spatial distribution map of the trend magnitude (dimensionless) of annual K_{pan} for the period 1982–2003. A negative change of annual K_{pan} was found for the whole study area except for a small part in the eastern and western regions. The negative change clearly increased from the central part to northern and southern parts (Figure 7).

Figure 8 shows the $u(d)$ and $u'(d)$ curves for annual K_{pan} series at Varayeneh station. The $u(d)$ and $u'(d)$ curves intersected at about 1994 when K_{pan} begins to decrease. So, the decreasing K_{pan} trend at Varayeneh station began around 1994.

To take the influence of serial correlation on the results of the trend tests into consideration, the number of significant trends before and after the removal of the lag-1 serial correlation from the ET_o, E_{pan} and K_{pan} time series is given in Table 2. The number of the significant trends detected by both tests decreased in all the series after removing the serial correlation effects: from 1 to 0 in the ET_o series; from 7 to 1 in the E_{pan} series; from 5 to 1 in the K_{pan} series. Furthermore, the sign of the ET_o trend changed at Malayer and Varayeneh stations after the pre-whitening of
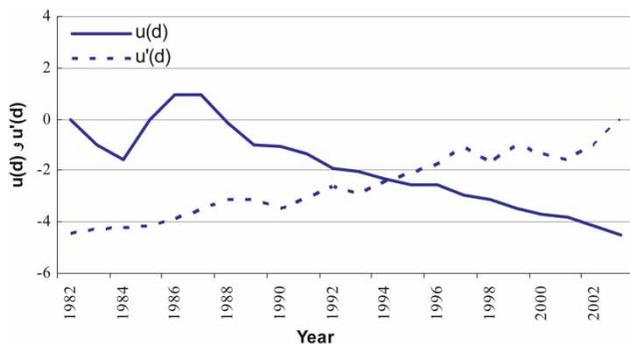
the time series. Overall, the largest difference between the results of the trend tests on the original and pre-whitened time series was observed in the E_{pan} series due to the high serial dependence of the data. After removing the influence of the lag-1 serial correlation by the pre-whitening method, the magnitudes of the ET_o, E_{pan} and K_{pan} trends decreased by about 3, 12 and 8%, respectively.

SUMMARY AND CONCLUSIONS

In this study, the ET_o estimated through the calibrated Hargreaves equation, pan evaporation (E_{pan}) and pan coefficient (K_{pan}), i.e., the ratio of ET_o to E_{pan}, time series were analyzed over 12 stations located in the west of Iran for the period 1982–2003. The trend analysis was performed by using the Kendall and Spearman tests after eliminating the effect of the significant lag-1 serial correlation from the ET_o, E_{pan} and K_{pan} time series by the pre-whitening method. The approximate year of the beginning of the significant trends was detected by using the sequential Mann–Kendall test. The spatial distribution of the trend magnitudes was obtained using the IDW interpolation method. The results showed that the significant trends in the time series were very infrequent, and the significant trends were found only in the E_{pan} and K_{pan} series of Varayeneh station. The significant upward E_{pan} trend of 16 mm/year at Varayeneh station began in 1998. Furthermore, the significant downward K_{pan} trend of Varayeneh station, with the relative change of -20%, started in 1994. Generally, the relative changes of the E_{pan} (average increment of 7.03%) and K_{pan} (average decrement of 5.36%) time series were very much greater than that of the ET_o series (average increment of 0.68%).

The number of the significant trends detected by the trend tests decreased in all the series after eliminating the influence of the lag-1 serial correlation by the pre-whitening method. Additionally, the magnitudes of the ET_o, E_{pan} and K_{pan} trends decreased by about 3, 12 and 8%, respectively, after the removal of the serial correlation. These results confirmed the necessity of investigating the serial structure of the time series prior to trend analysis as stated by von Storch (1995), Yue and Wang (2002), Yue *et al.* (2002, 2003), Yue & Hashino (2003) and Khaliq *et al.* (2009).

Figure 8 | Progressive values of $u(d)$ and $u'(d)$ for annual K_{pan} at Varayeneh station for the period 1982–2003.

Table 2 | Number of statistically significant trends at the 95% confidence level before and after removing the influence of lag-1 serial correlation

Time series	Original time series		Pre-whitened time series	
	Kendall test	Spearman test	Kendall test	Spearman test
ET_o	2	2	1	1
E_{pan}	8	7	1	2
K_{pan}	5	5	1	1

The results presented in this paper will contribute to a better understanding of current climate change and its impact on the hydrological cycle and water resources in the study area. The previous analysis in the study area (Tabari & Marofi 2011) showed that the increasing trends of E_{pan} were attributed to significant increasing trends in minimum temperature. Study of other possible explanatory variables such as land-use changes may result in much more significant changes of E_{pan}, ET_o and K_{pan} which merit future studies.

ACKNOWLEDGEMENTS

REFERENCES

Abdul Aziz, O. I. & Burn, D. H. 2006 Trends and variability in the hydrological regime of the Mackenzie River Basin. *J. Hydrol.* **319**, 282–294.

Abtew, W., Obeysekera, J. & Iricanin, N. 2011 Pan evaporation and potential evapotranspiration trends in South Florida. *Hydrol. Process.* **25**, 958–969.

Alizadeh, A. & Keshavarz, A. 2005 Status of agricultural water use in Iran. In: *Water Conservation, Reuse, and Recycling: Proceedings of an Iranian-American Workshop*. The National Academies Press, Washington, DC, pp. 96–97.

Allen, R. G., Periera, L. S., Raes, D. & Smith, M. 1998 Crop evapotranspiration: Guideline for computing crop water requirement. FAO Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the UN, Rome, Italy, 301 pp.

Bandyopadhyay, B., Bhadra, A., Raghuwnshi, N. S. & Singh, R. 2009 Temporal trends in estimates of reference evapotranspiration over India. *J. Hydrol. Eng. ASCE* **14** (5), 508–515.

Bannayan, M., Sanjani, S., Alizadeh, A., Sadeghi Lotfabadi, S. & Mohamadian, A. 2010 Association between climate indices, aridity index, and rainfed crop yield in northeast of Iran. *Field Crops Res.* **118**, 105–114.

Burns, D. A., Klaus, J. & McHale, M. R. 2007 Recent climate trends and implications for water resources in the Catskill Mountain region, New York, USA. *J. Hydrol.* **336** (1–2), 155–170.

Chok, N. S. 2010 Pearson's versus Spearman's and Kendall's Correlation Coefficients for Continuous Data. M.Sc. Thesis, University of Pittsburgh, 53 pp.

Chuanyan, Z., Zhongren, N. & Zhaodong, F. 2004 GIS-assisted spatially distributed modeling of the potential evapotranspiration in semi-arid climate of the Chinese Loess Plateau. *J. Arid Environ.* **58**, 387–403.

Croitoru, A. E., Holobaca, I. H., Lazar, C., Moldovan, F. & Imbroane, A. 2012 Air temperature trend and the impact on winter wheat phenology in Romania. *Clim. Change* **111** (2), 393–410.

da Silva, V. P. R. 2004 On climate variability in northeast of Brazil. *J. Arid Environ.* **58**, 575–596.

del Rio, S., Penas, A. & Fraile, R. 2005 Analysis of recent climatic variations in Castile and Leon (Spain). *Atmos. Res.* **73**, 69–85.

Dinpashoh, Y., Jhajharia, D., Fakheri-Fard, A., Singh, V. P. & Kahya, K. 2011 Trends in reference crop evapotranspiration over Iran. *J. Hydrol.* **399**, 422–433.

Dufek, A. S. & Ambrizzi, T. 2008 Precipitation variability in Sao Paulo State, Brazil. *Theor. Appl. Climatol.* **93**, 167–178.

Fang, W. & Imura, H. 2005 The spatial and temporal changes of pan evaporation from 1971 to 2000 in the Yellow River basin. *Environ. Syst. Res.* **33**, 165–170.

Feidas, H., Makrogiannis, T. & Bora-Senta, E. 2004 Trend analysis of air temperature time series in Greece and their relationship with circulation using surface and satellite data: 1955–2001. *Theor. Appl. Climatol.* **79**, 185–208.

Ghasemi, A. R. & Khalili, D. 2006 The influence of the arctic oscillation on winter temperatures in Iran. *Theor. Appl. Climatol.* **85**, 149–164.

Ghasemi, A. R. & Khalili, D. 2008 The association between regional and global atmospheric patterns and winter precipitation in Iran. *Atmos. Res.* **88**, 116–133.

Göktaş, A. & İşçi, O. 2011 A comparison of the most commonly used measures of association for doubly ordered square contingency tables via simulation. *Metodološki zvezki* **8** (1), 17–37.

Goyal, R. K. 2004 Sensitivity of evapotranspiration to global warming: a case study of arid zone of Rajasthan (India). *Agric. Water Manage.* **69**, 1–11.

Hamed, K. H. 2009 Enhancing the effectiveness of prewhitening in trend analysis of hydrologic data. *J. Hydrol.* **368**, 143–155.

Hargreaves, G. H. & Samani, Z. A. 1982 Estimating potential evapotranspiration. *J. Irrig. Drain. Eng. ASCE* **108** (3), 223–230.

Hobbins, M. T., Ramirez, J. A. & Brown, T. C. 2004 Trends in pan evaporation and actual evapotranspiration across the conterminous US: paradoxical or complementary? *Geophys. Res. Lett.* **31** (13), pL13503.

IPCC 2007 Summary for policymakers. In: M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson (eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the*

Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 23 pp.

Itenfisu, D., Elliott, R. L., Richard, G., Allen, R. G. & Walter, I. A. 2003 Comparison of reference evapotranspiration calculations as part of the ASCE standardization effort. *J. Irrig. Drain. Eng. ASCE* **129** (6), 440–448.

Jhajharia, D., Dinpashoh, Y., Kahya, E., Singh, V. P. & Fakheri-Fard, A. 2012 Trends in reference evapotranspiration in the humid region of northeast India. *Hydrol. Process.* **26** (3), 421–435.

Kahya, E. & Kalayci, S. 2004 Trend analysis of streamflow in Turkey. *J. Hydrol.* **289**, 128–144.

Kendall, M. G. & Stuart, A. 1973 *The Advanced Theory by Statistics*. Griffin, London.

Khaliq, M. N., Ouarda, T. B. M. J. & Gachon, P. 2009 Identification of temporal trends in annual and seasonal low flows occurring in Canadian rivers: the effect of short- and long-term persistence. *J. Hydrol.* **369**, 183–197.

Kottegoda, N. T. 1980 *Stochastic Water Resources Technology*. The Macmillan Press, London.

Lopez-Urrea, R., Martın de Santa Olalla, F., Fabeiro, C. & Moratalla, A. 2006 Testing evapotranspiration equations using lysimeter observations in a semiarid climate. *Agric. Water Manage.* **85**, 15–26.

Ma, Z., Kang, S., Zhang, L., Tong, L. & Su, X. 2008 Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China. *J. Hydrol.* **352**, 239–249.

Menzel, L. & Burger, G. 2002 Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany). *J. Hydrol.* **267**, 53–64.

Mitchell, J. M., Dzezerdzeeskii, B., Flohn, H., Hofmeyer, W. L., Lamb, H. H., Rao, K. N. & Wallen, C. C. 1966 Climatic change. WMO Tech. Note 79, WMO No. 195. TP-100. Geneva, 79 pp.

Mosmann, V., Castro, A., Fraile, R., Dessens, J. & Sanchez, J. L. 2004 Detection of statistically significant trends in the summer precipitation of mainland Spain. *Atmos. Res.* **70**, 43–53.

Ogolo, E. O. 2011 Regional trend analysis of pan evaporation in Nigeria (1970 to 2000). *J. Geog. Reg. Plan.* **4** (10), 566–577.

Partal, T. & Kahya, E. 2006 Trend analysis in Turkish precipitation data. *Hydrol. Process.* **20**, 2011–2026.

Ramirez, J. A. & Finnerty, B. 1996 CO_2 and temperature effect on evapotranspiration and irrigated agriculture. *J. Irrig. Drain. Eng. ASCE* **122**, 155–163.

Roderick, M. L. & Farquhar, G. D. 2004 Change in Australian pan evaporation from 1970 to 2002. *Int. J. Climatol.* **24**, 1077–1090.

Roderick, M. L. & Farquhar, G. D. 2005 Change in New Zealand pan evaporation since the 1970s. *Int. J. Climatol.* **25**, 2031–2039.

Sabziparvar, A. A. & Tabari, H. 2010 Regional estimation of reference evapotranspiration in arid and semi-arid regions. *J. Irrig. Drain Eng. ASCE* **136** (10), 724–731.

Sen, P. K. 1968 Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* **63**, 1379–1389.

Sneyers, R. 1990 On the statistical analysis of series of observations. WMO. Technical Note (143). World Meteorological Organization, Geneva, 192 pp.

Song, Z. W., Zhang, H. L., Snyder, R. L., Anderson, F. E. & Chen, F. 2010 Distribution and trends in reference evapotranspiration in the North China Plain. *J. Irrig. Drain. Eng. ASCE* **136** (4), 240–247.

Tabari, H. 2010 Evaluation of reference crop evapotranspiration equations in various climates. *Water Resour. Manage.* **24**, 2311–2337.

Tabari, H. & Aghajanloo, M.-B. 2013 Temporal pattern of monthly aridity index in Iran with considering precipitation and evapotranspiration trends. *Int. J. Climatol.* **33**, 396–409.

Tabari, H. & Hosseinzadeh Talaee, P. 2011a Local calibration of the Hargreaves and Priestley–Taylor equations for estimating reference evapotranspiration in arid and cold climates of Iran based on the Penman-Monteith model. *J. Hydrol. Eng. ASCE* **16** (10), 1–9.

Tabari, H. & Hosseinzadeh Talaee, P. 2011b Analysis of trends in temperature data in arid and semi-arid regions of Iran. *Glob. Planet. Change* **79**, 1–10.

Tabari, H. & Hosseinzadeh Talaee, P. 2011c Temporal variability of precipitation over Iran: 1966–2005. *J. Hydrol.* **396**, 313–320.

Tabari, H. & Hosseinzadeh Talaee, P. 2011d Recent trends of mean maximum and minimum air temperatures in the western half of Iran. *Meteor. Atmos. Phys.* **111**, 121–131.

Tabari, H. & Marofi, S. 2011 Changes of pan evaporation in the west of Iran. *Water Resour. Manage.* **25**, 97–111.

Tabari, H., Marofi, S., Aeini, A., Hosseinzadeh Talaee, P. & Mohammadi, K. 2011a Trend analysis of reference evapotranspiration in the western half of Iran. *Agric. For. Meteor.* **151**, 128–136.

Tabari, H., Shifteh Somee, B. & Rezaian Zadeh, M. 2011b Testing for long-term trends in climatic variables in Iran. *Atmos. Res.* **100**, 132–140.

Tabari, H., Aeini, A., Hosseinzadeh Talaee, P. & Shifteh Somee, B. 2012 Spatial distribution and temporal variation of reference evapotranspiration in arid and semi-arid regions of Iran. *Hydrol. Process.* **26**, 500–512.

Theil, H. 1950 A rank-invariant method of linear and polynomial regression analysis, Part 3. Proceedings of Koninalijke Nederlandse Akademie van Weinenschatpen A 53, Amsterdam, pp. 1397–1412.

von Storch, H. 1995 Misuses of statistical analysis in climate research. In: *Analysis of Climate Variability: Applications of Statistical Techniques* (H. V. Storch & A. Navarra, eds), Springer, Berlin, pp. 11–26.

Wang, Y., Jiang, T., Bothe, O. & Fraedrich, K. 2007 Changes of pan evaporation and reference evapotranspiration in the Yangtze River basin. *Theor. Appl. Climatol.* **90**, 13–23.

Xu, C., 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. *J. Hydrol.* **327**, 81–93.

Xu, Z. X., Takeuchi, K. & Ishidaira, H. 2003 Monotonic trend and step changes in Japanese precipitation. *J. Hydrol.* **279**, 144–150.

Yin, Y., Wu, S., Chen, G. & Dai, E. 2010 Attribution analyses of potential evapotranspiration changes in China since the 1960s. *Theor. Appl. Climatol.* **101**, 19–28.

Yue, S. & Hashino, M. 2003 Temperature trends in Japan: 1900–1996. *Theor. Appl. Climatol.* **75**, 15–27.

Yue, S., Pilon, P. & Phinney, B. 2003 Canadian streamflow trend detection: impacts of serial and cross-correlation. *Hydrol. Sci. J.* **48** (1), 51–63.

Yue, S., Pilon, P., Phinney, B. & Cavadias, G. 2002 The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrol. Process.* **16**, 1807–1829.

Yue, S. & Wang, C. Y. 2002 The influence of serial correlation on the Mann–Whitney test for detecting a shift in median. *Adv. Water Resour.* **25**, 325–333.

Zhang, Y., Liu, C., Tang, Y. & Yang, Y. 2007 Trends in pan evaporation and reference and actual evapotranspiration across the Tibetan Plateau. *J. Geophys. Res.* **112**, D12110.

Zuo, D., Xu, Z., Yang, H. & Liu, X. 2012 Spatiotemporal variations and abrupt changes of potential evapotranspiration and its sensitivity to key meteorological variables in the Wei River basin, China. *Hydrol. Process.* **26** (8), 1149–1160.