

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

P. Hosseinzadeh Talaei, Hossein Tabari and Hiran 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

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### 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. Abtey *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 north-west, 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 Talaei 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:

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

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  $ET_o$ :

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

**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	$18.2 \pm 0.8$	$11.0 \pm 1.0$	$4.0 \pm 0.8$	$325.9 \pm 101.6$
2. Ekbatan	Research	$19.1 \pm 1.1$	$11.0 \pm 1.1$	$2.9 \pm 1.1$	$310.0 \pm 71.4$
3. Ekbatan dam	Evaporimeter	$18.3 \pm 0.8$	$10.7 \pm 0.9$	$3.1 \pm 1.0$	$337.0 \pm 79.8$
4. Ghahavand	Raingauge	$19.7 \pm 1.4$	$11.3 \pm 1.2$	$2.9 \pm 1.2$	$233.7 \pm 51.4$
5. Kangavar	Synoptic	$21.0 \pm 1.1$	$13.3 \pm 0.9$	$4.7 \pm 1.1$	$401.6 \pm 101.4$
6. Kheir-Abad	Evaporimeter	$19.6 \pm 1.3$	$12.8 \pm 1.1$	$5.6 \pm 0.9$	$312.2 \pm 72.5$
7. Khomigan	Evaporimeter	$17.8 \pm 1.0$	$10.6 \pm 2.0$	$4.3 \pm 1.6$	$273.3 \pm 69.9$
8. Khosro-Abad	Evaporimeter	$21.8 \pm 1.3$	$12.5 \pm 1.1$	$2.7 \pm 1.8$	$329.7 \pm 84.0$
9. Malayer	Synoptic	$20.0 \pm 1.1$	$14.0 \pm 1.5$	$6.0 \pm 0.8$	$307.8 \pm 75.4$
10. Nahavand	Synoptic	$20.5 \pm 0.9$	$13.5 \pm 1.2$	$5.9 \pm 1.1$	$421.7 \pm 116.9$
11. Nozheh	Synoptic	$19.3 \pm 1.0$	$10.9 \pm 0.9$	$2.5 \pm 1.0$	$331.5 \pm 74.0$
12. Varayeneh	Evaporimeter	$19.8 \pm 1.2$	$9.8 \pm 1.8$	$0.1 \pm 2.8$	$517.9 \pm 142.4$

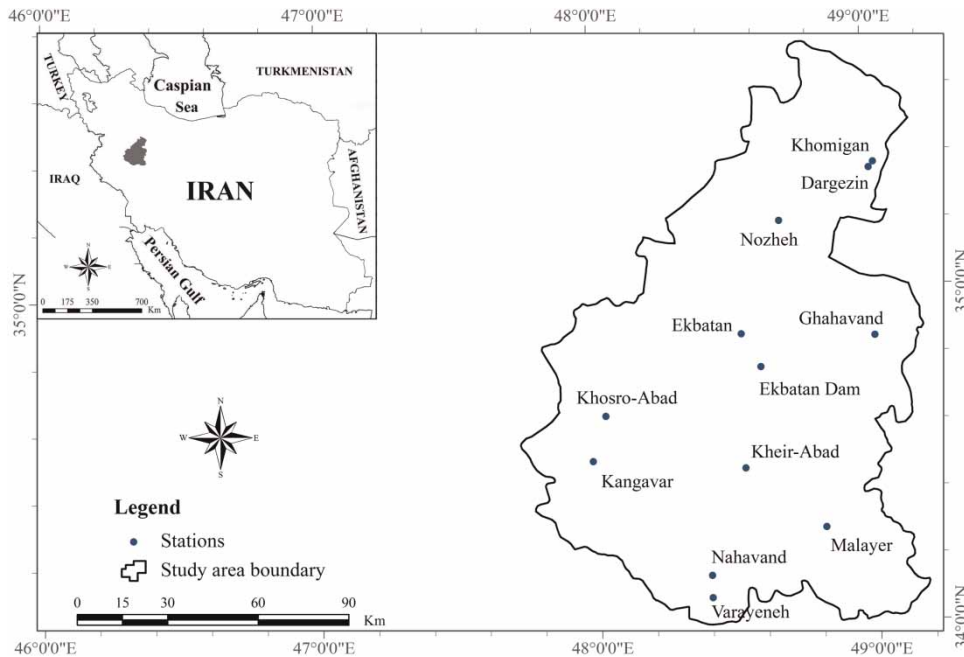


Figure 1 | Geographic location of the study region and the stations.

## 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:

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

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

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

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

This is calculated using a table of reduced normal distribution. If  $\alpha < \alpha_0$ , the null hypothesis is rejected for a significance level of  $\alpha_0$ . 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  $\tau$  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  $x_1, x_2, \dots, x_n$ , 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 ( $i = 1, j = 2, 3, \dots, n$ ), ( $i = 2, j = 3, 4, \dots, n$ ),  $\dots$ , ( $i = n - 1, j = n$ ),  $n$  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  $(n - 1) + (n - 2) + \dots + 1$  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,

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

The test is based on the statistic  $\tau$ ,

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

A positive  $\tau$  indicates an increasing trend in the time series, and a negative  $\tau$  indicates a decreasing trend (Ma et al. 2008). Under the null hypothesis, the test statistic  $\tau$  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:

$$d_i = \sum_i m_i \quad (8)$$

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

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

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

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

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

The sequential Mann–Kendall test, consisting of the application of the test to all series starting with the first term and ending with the  $i$ th, and to those starting with the  $i$ th 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 ( $x_1, x_2, \dots, x_n$ ). 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:

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

in which  $1 < j < i < n$ . The estimator  $\beta$  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:

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

where  $n$  is the data set record length,  $\beta$  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  $K_{\text{pan}}$  and  $E_{\text{pan}}$ .

### 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 Talaei 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):

$$Y_t = X_t - r_1 X_{t-1} \quad (14)$$

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

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

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

## 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  $K_{\text{pan}}$  values were obtained as the ratio of the estimated  $ET_o$  values to the observed  $E_{\text{pan}}$  values (Equation (2)). An average  $K_{\text{pan}}$  of 0.81 was found for the whole study area. The inter-annual variations of the areal means of the  $ET_o$ ,  $E_{\text{pan}}$  and  $K_{\text{pan}}$  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  $ET_o$ ,  $E_{\text{pan}}$  and  $K_{\text{pan}}$  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  $E_{\text{pan}}$  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  $K_{\text{pan}}$  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

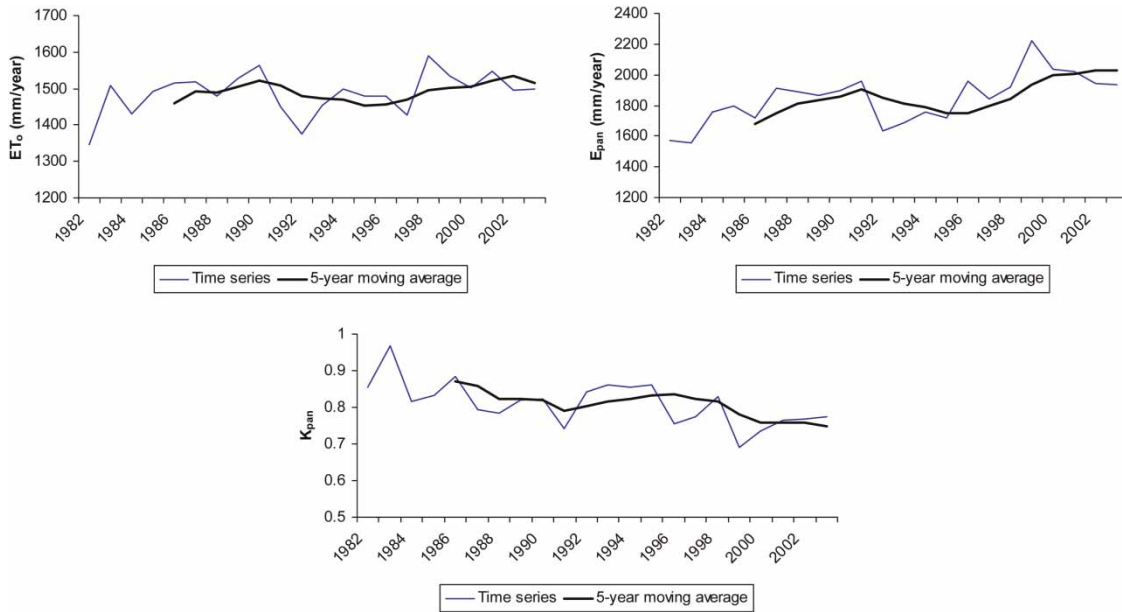


Figure 2 | Observed and 5-year moving average of annual  $ET_o$ ,  $E_{pan}$  and  $K_{pan}$  series for the period 1982–2003.

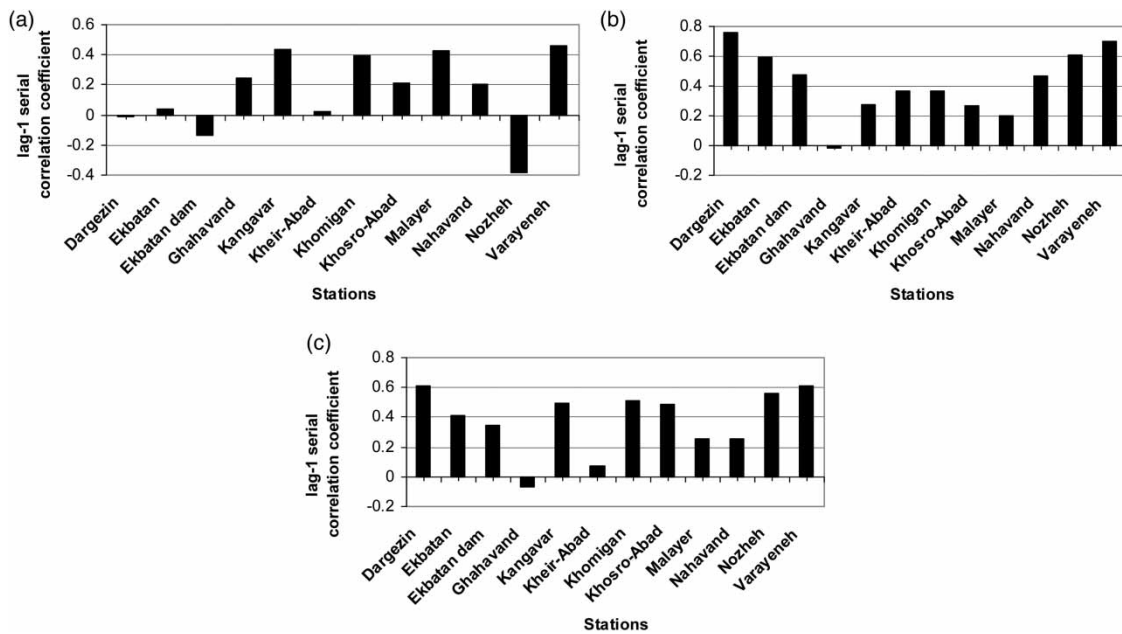


Figure 3 | Lag-1 serial correlation coefficient for the considered parameters at the stations: (a)  $ET_o$ ; (b)  $E_{pan}$ ; and (c)  $K_{pan}$ .

serial correlation will decrease the possibility of rejecting the null hypothesis (Tabari & Aghajano 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

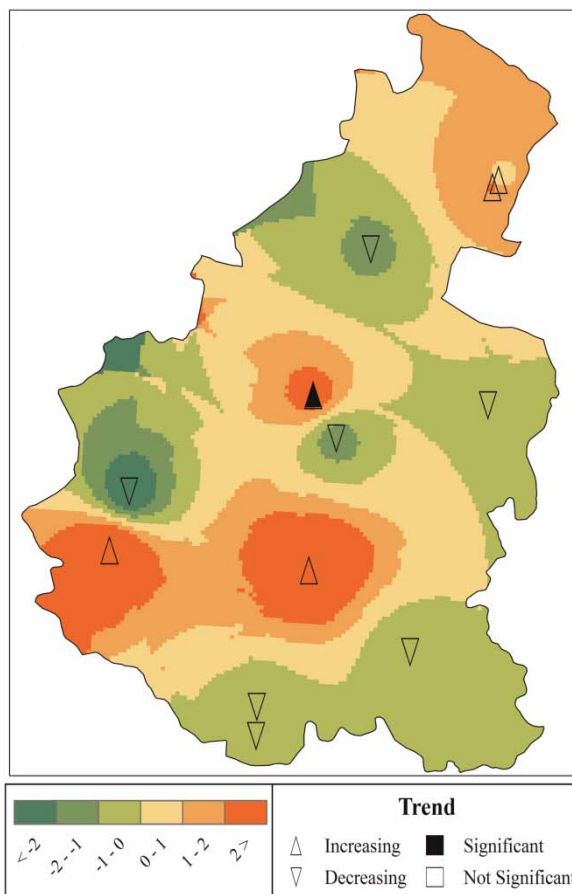
test on the  $ET_o$  time series are presented in Figure 4. In this study, the trends are considered statistically significant at the 95% confidence level when identified by the two Kendall and Spearman trend tests. According to the results, five out of the 12 stations exhibited an upward  $ET_o$  trend. 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  $ET_o$ ,

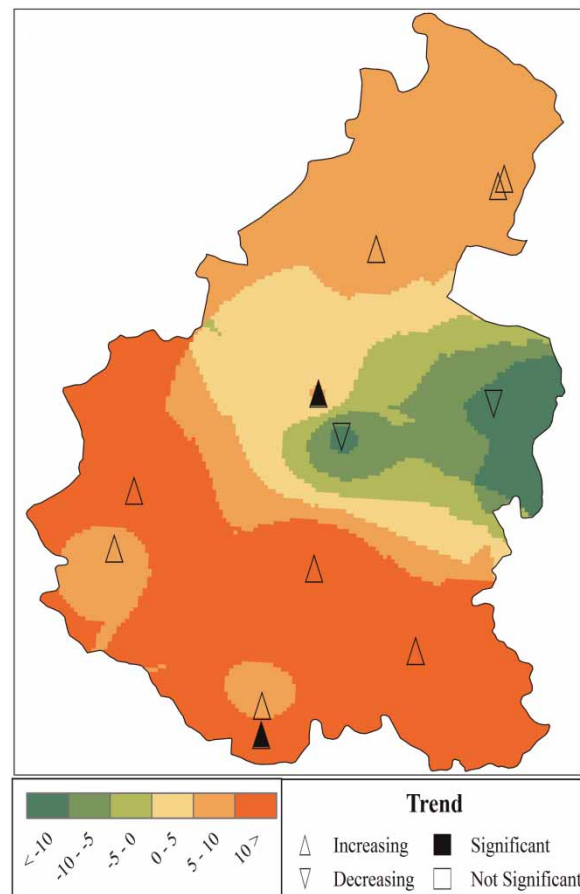
magnitudes, and the positive and negative changes can be observed in different parts of the study area.

$ET$  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 Talaei 2010c) 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).

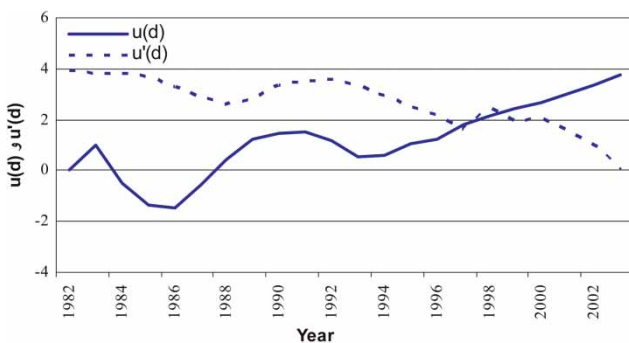


12 stations for the period 1982–2003 was (+)6.73 mm/year or (+)7%.

The spatial distribution of the trend magnitude (mm/year) obtained by the Theil-Sen's estimator of annual  $E_{\text{pan}}$  for the period 1982–2003 are plotted in Figure 5. As can be seen from Figure 5, the trend magnitude of annual  $E_{\text{pan}}$  was positive for the whole study area, except a small part in the eastern region. Generally speaking, the positive changes of annual  $E_{\text{pan}}$  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  $E_{\text{pan}}$  series at Varayeneh station. As the plots indicate, the  $E_{\text{pan}}$  trend at Varayeneh station began around 1998.

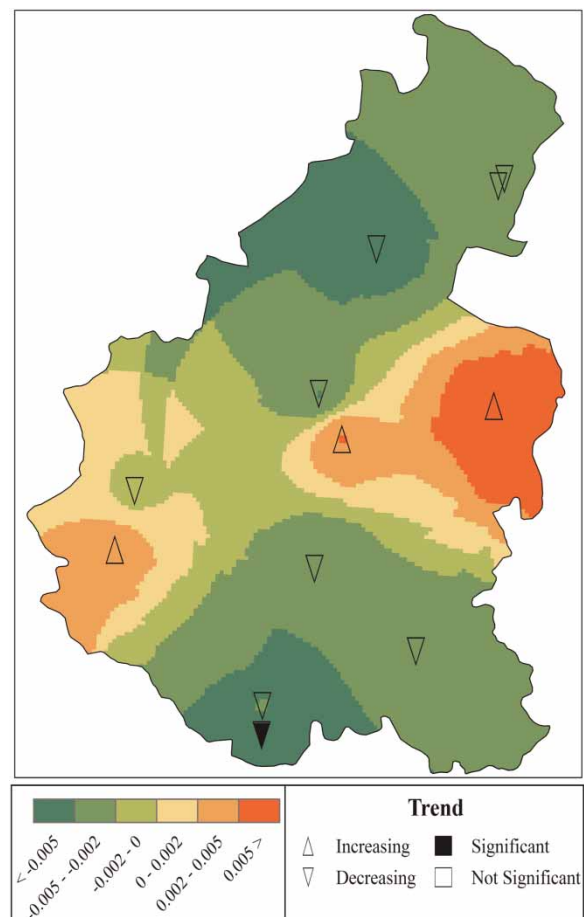
Evaporation has great effect on the water balance of the earth surface (Ogolo 2011). The positive trends of  $E_{\text{pan}}$  observed in the study area imply that the evaporation component of the hydrological cycle has been increasing which has great effect on the water balance of the study area (Fang & Imura 2005; Ogolo 2011). The  $E_{\text{pan}}$  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  $E_{\text{pan}}$  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



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

earth surface than were replenished through rainfall from the atmosphere.

The results of the Spearman trend test on the  $K_{\text{pan}}$  series are shown in Figure 7. As expected, the majority of the  $K_{\text{pan}}$  trends at the study stations were downward. Only the downward  $K_{\text{pan}}$  trend of Varayeneh station was statistically significant. The annual  $K_{\text{pan}}$  of Varayeneh station decreased at the rate of 20% during the study period. The  $K_{\text{pan}}$  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 7** | Spatial distribution of the trend magnitude (dimensionless) of annual  $K_{\text{pan}}$  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  $K_{\text{pan}}$  for the period 1982–2003. A negative change of annual  $K_{\text{pan}}$  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  $K_{\text{pan}}$  series at Varayeneh station. The  $u(d)$  and  $u'(d)$  curves intersected at about 1994 when  $K_{\text{pan}}$  begins to decrease. So, the decreasing  $K_{\text{pan}}$  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  $ET_o$ ,  $E_{\text{pan}}$  and  $K_{\text{pan}}$  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  $E_{\text{pan}}$  series; from 5 to 1 in the  $K_{\text{pan}}$  series. Furthermore, the sign of the  $ET_o$  trend changed at Malayer and Varayeneh stations after the pre-whitening of

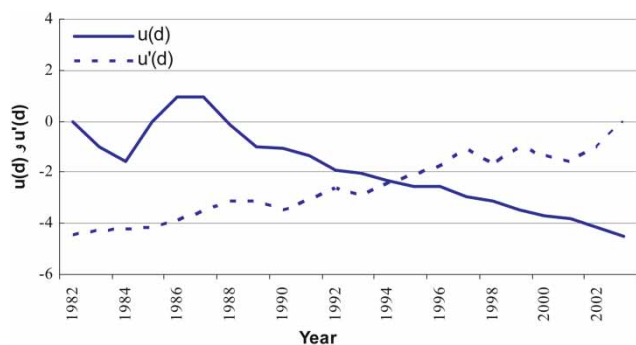


Figure 8 | Progressive values of  $u(d)$  and  $u'(d)$  for annual  $K_{\text{pan}}$  at Varayeneh station for the period 1982–2003.

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
$E_{\text{pan}}$	8	7	1	2
$K_{\text{pan}}$	5	5	1	1

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  $E_{\text{pan}}$  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  $ET_o$ ,  $E_{\text{pan}}$  and  $K_{\text{pan}}$  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 ( $E_{\text{pan}}$ ) and pan coefficient ( $K_{\text{pan}}$ ), i.e., the ratio of  $ET_o$  to  $E_{\text{pan}}$ , 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  $ET_o$ ,  $E_{\text{pan}}$  and  $K_{\text{pan}}$  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  $E_{\text{pan}}$  and  $K_{\text{pan}}$  series of Varayeneh station. The significant upward  $E_{\text{pan}}$  trend of 16 mm/year at Varayeneh station began in 1998. Furthermore, the significant downward  $K_{\text{pan}}$  trend of Varayeneh station, with the relative change of  $-20\%$ , started in 1994. Generally, the relative changes of the  $E_{\text{pan}}$  (average increment of 7.03%) and  $K_{\text{pan}}$  (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  $ET_o$ ,  $E_{\text{pan}}$  and  $K_{\text{pan}}$  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).

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.

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