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Rainfall trends analysis of Iran in the last half of the twentieth century

Reza Modarres[1] and Ali Sarhadi[1]

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[1] The present study performs the spatial and temporal trend analysis of the annual and 24-hr maximum rainfall of a set of 145 precipitation gauging stations of Iran. The study shows that the annual rainfall is decreasing at 67% of the stations while the 24-hr maximum rainfall is increasing at 50% of the stations. The negative trends of annual rainfall are mostly observed in northern and northwestern regions, whereas positive trends of 24-hr maximum rainfall are mostly located in arid and semiarid regions of Iran. However, the Kolmogorov-Smirnov test for Mann-Kendall (MK) statistics show that the regional trend of annual rainfall is significant, but it is not significant for 24-hr maximum rainfall. On the other hand, the sequential MK test reveals that the trends of annual rainfall and 24-hr maximum rainfall began since 1970s for most of the stations. The negative trend of the rainfall for most of the country may show the initial stages of climate change in Iran, but further information and analysis is required for future studies.

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1. Introduction

[2] In recent years, a number of studies have focused on trend assessment of hydroclimatic variables worldwide and its possible effects on variability in water resources, desertification, loss of biodiversity and agricultural productivity [e.g., *Delitala et al.*, 2000; *Lazaro et al.*, 2001; *Burlando and Rosso*, 2002].

[3] The trends and changes in both the long-term climatic mean and the intensity and frequency of climatic extremes, such as floods, droughts, storms, heat waves and high wind, have been reported by many investigators around the world [e.g., *Wang et al.*, 2006; *Dixon et al.*, 2006; *Andreadis and Lettenmaier*, 2006; *Wang and Zhou*, 2005].

[4] Precipitation, as the major variable in the assessment of water balance over space and time, has received considerable attention through the detection of long-term trend over various geographic areas. For example, *Wang and Zhou* [2005] found a significantly increasing trend in southwest, northwest and east China and significant decreasing trend in central, north and northeast regions of China. *Xu et al.* [2007] found a decreasing trend for the summer and early autumn months and an increasing trend for the spring month in China. *Wang et al.* [2006] found a remarkable increasing trend in summer precipitation, number of rainy days and extreme rainfall events in Seoul, South Korea. *Nandintsetseg et al.* [2007] detected that the number of days with precipitation has increased slightly while the annual total precipitation has not significantly increased in northern Mongolia.

[5] There is growing evidence that the total precipitation has increased across the United States over the last several decades [e.g., *Kunkel et al.*, 2002; *Small et al.*, 2006].

[6] Precipitation trends found by *Keim and Fischer* [2005] in the United States Climate Division database (CDD) were mostly increasing through time.

[7] In this study, we extend the previous analysis of precipitation trends in arid and semiarid region of Iran by *Modarres and da Silva* [2007] for both total annual precipitation and extreme 24-hr precipitation events over the entire country.

2. Data and Study Area

[8] Iran is located between 45°E and 64°E in longitude and 25°N and 40°N in latitude. The average precipitation of Iran is 260 mm [*Modarres*, 2006] and the coefficient of variation (CV) varies from 18% in north to 75% in southeast of the country [*Dinpashoh et al.*, 2004]. The climate of Iran can be divided into eight groups governed by different factors such as proximity to the sea, elevation and the presence or absence of large atmospheric phenomenon such as subtropical high pressure [*Modarres*, 2006; *Soltani et al.*, 2007]. These groups have been illustrated in Figure 1. The distribution of monthly rainfall for one representative station in each group is also given in Figure 2. Group 1 dominates the arid and semiarid regions of Iran which receives the lowest annual rainfall comparing with other groups and no rainfall in summer months. Groups 2, 5 and 7 receive winter and spring rainfall but the annual rainfall of group 7 is higher than two other groups due to the higher elevation. The group 4 covers the margins of Persian Gulf which receives winter rainfall. The groups 6 and 8 cover the margins of the Caspian Sea which receives summer rainfall. However, the rainfall decreases from the western to the eastern region. The group 3 covers northwestern region of

[1]Faculty of Natural Resources, Isfahan University of Technology, Isfahan, Iran.

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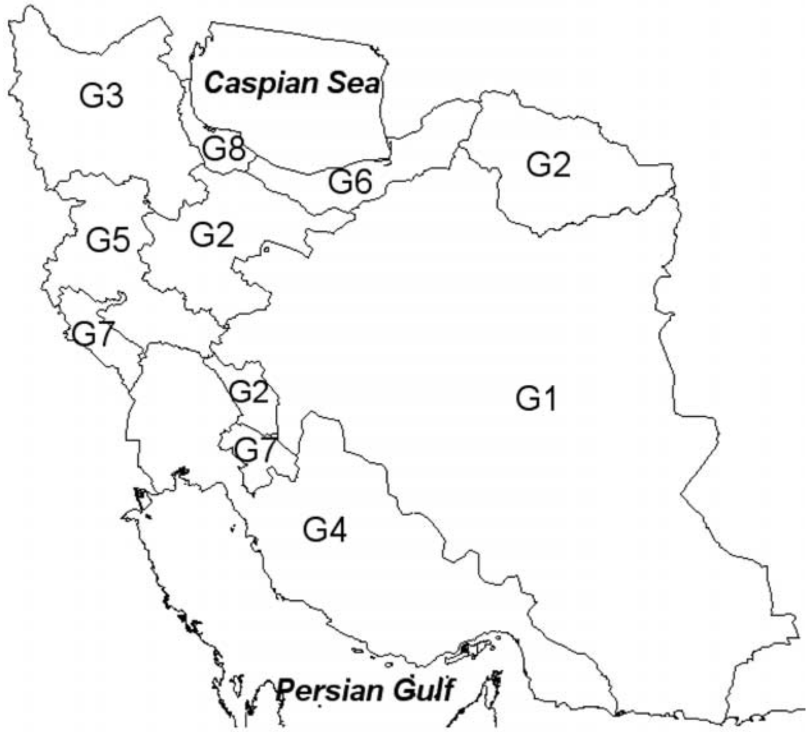

Figure 1. Rainfall groups of Iran.

Iran which receives spring rainfall and a small amount of summer rainfall.

[9] In this study, the observed annual total and 24-hr maximum precipitation data for 145 stations in Iran were obtained from the Iran Meteorological Organization for the period of 1951–2000.

3. Methods

3.1. At-Site Trend Assessment

[10] To examine the linear trend of the selected variables we apply the popular Mann-Kendall (MK) test. The advantages of the MK test are that (1) it can be used for nonnormal data such as seasonal data or for censoring and missing values and (2) it has an asymptotic efficiency [*Fu et al.*, 2004].

[11] For any sample of n variables, $x_1, \ldots, x_n$, the null hypothesis states that the sample is independent and identically distributed. The alternative hypothesis of a two-sided test is that the distributions of x_i and x_j are not identical for all k, $j \leq n$ with $i \neq j$.

[12] The MK test is based on test statistic S defined as follows.

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

where the x_j are the sequential data values, n is the length of the time series and sign $(x_i - x_j)$ is -1 for $(x_i - x_j) < 0$; 0 for $(x_i - x_j) = 0$ and 1 for $(x_i - x_j) > 0$.

[13] The mean E[S] and variance V[S] of the statistic S may be given as

$$E[S] = 0, \tag{2}$$

$$Var[S] = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)}{18} \tag{3}$$

where t_p is the number of ties for the *p*th value and q is the number of tied values. The second term represents an adjustment for tied or censored data. The standardized test statistic (Z_{MK}) is computed by

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \tag{4}$$

A positive Z_{MK} indicates an increasing trend while a negative Z_{MK} indicates a decreasing trend. To test for either an increasing or decreasing monotonic trend at p significance level, the null hypothesis is rejected if the absolute value of Z is greater than $Z_{1-p/2}$, where $Z_{1-p/2}$ is obtained from the standard normal cumulative distribution tables. In this work, the significance level of p = 0.01 and 0.05 are applied.

[14] In order to see any changes of trend over time and to detect the beginning time of any trend we apply sequential MK (SQMK) test [*Sneyers*, 1990].

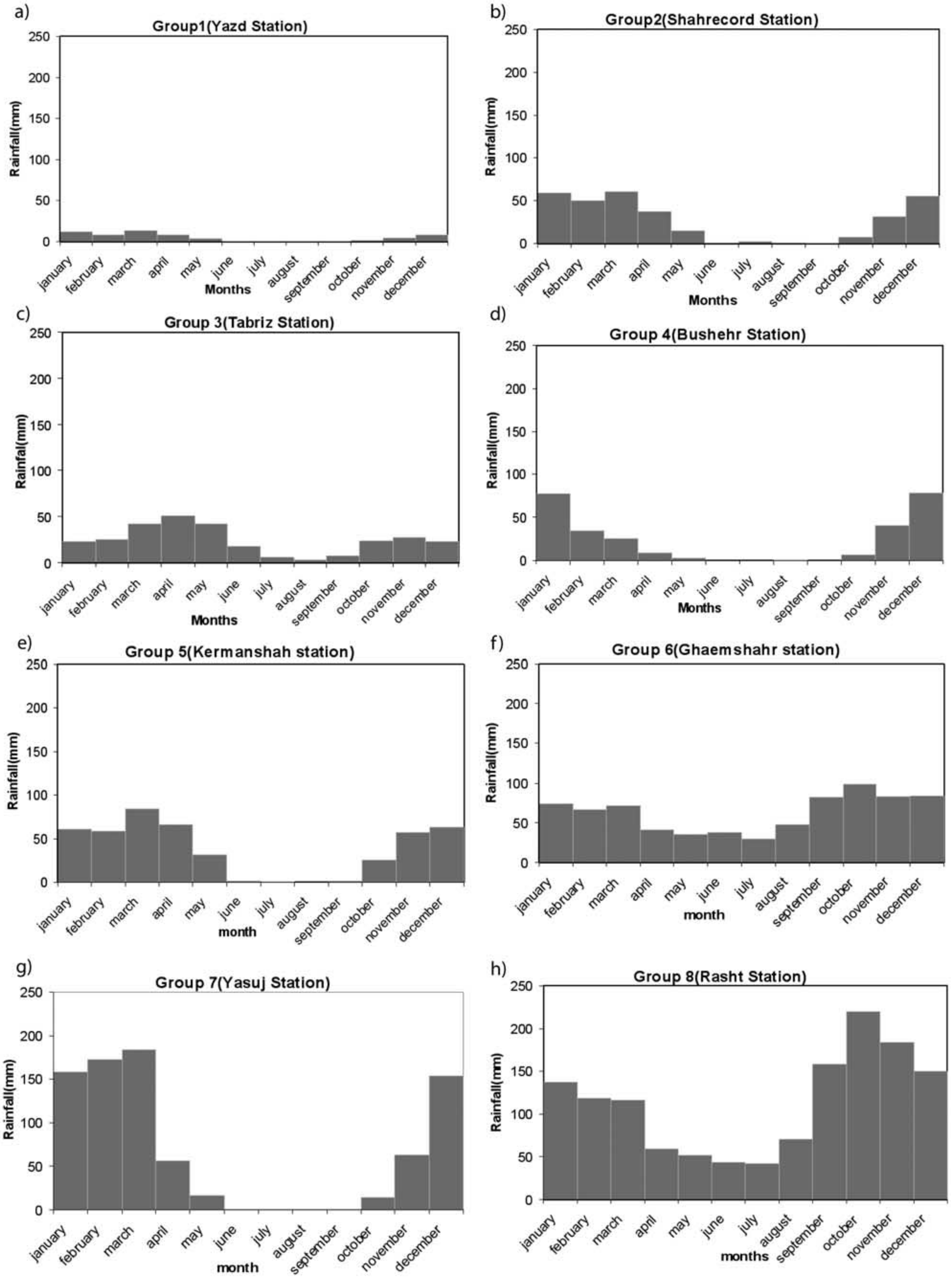

Figure 2. Monthly rainfall distribution for one station in each rainfall group. (a) Yazd station, (b) Shahrecord station, (c) Tabriz station, (d) Bushehr station, (e) Kermanshah station, (f) Ghaemshahr station, (g) Yasuj station, and (h) Rasht station.

[15] The sequential values, $u(t)$ and $u'(t)$, from the progressive analysis of the Mann-Kendall test are calculated. Herein, $u(t)$ is a standardized variable that has zero mean and unit standard deviation. Therefore its sequential behavior fluctuates around the zero level. The following steps are applied to calculate $u(t)$ and $u'(t)$.

[16] 1. The values of x_j annual mean time series ($j = 1, \ldots, n$) are compared with x_i ($i = 1, \ldots, j - 1$). At each comparison, the number of cases $x_j > x_i$ is counted and denoted by n_j.

[17] 2. The test statistic t is then calculated by equation

$$t_j = \sum_{1}^{j} n_j \tag{5}$$

[18] 3. The mean and variance of the test statistic are

$$E(t) = \frac{n(n-1)}{4} \quad \text{and} \quad \mathrm{Var}(t_j) = [j(j-1)(2j+5)]/72 \tag{6}$$

[19] 4. The sequential values of the statistic $u(t)$ are then calculated as

$$u(t) = \frac{t_j - E(t)}{\sqrt{\mathrm{Var}(t_j)}} \tag{7}$$

The values of $u'(t)$ are computed similarly backward, starting from the end of the series.

3.2. Regional Trend Assessment

[20] In addition to at-site trend assessment, the regional rainfall trends are also investigated. The regional trend assessment can be done by averaging the stations within each region and then any trends in regional rainfall can be checked using the Mann-Kendall test. In order to evaluate if the significance levels follow a uniform distribution the Kolmogorov-Smirnov (K-S) test and the quantile-quantile (q-q) plot of the estimated p values of the MK statistics are employed. Departure from a uniform distribution would indicate that (1) the null hypothesis of no apparent trend must be rejected or (2) the hypothesis tests are not independent of each other because annual rainfall and maximum 24-hr rainfall sequences exhibit spatial correlation.

4. Results

4.1. Trends in Annual Rainfall at Various Stations

[21] The annual rainfall shows a decreasing trend in precipitation over the study area for the majority of the stations (100 of 145 stations or 67%) and increasing trend for the remaining minority of the stations (45 of 145 stations or 23%). In order to examine the spatial distribution of precipitation trends, a map is created to display the location of gauges with decreasing and increasing trends. Figure 3 shows the location of gauging stations with both downward and upward trends in annual rainfall within different rainfall groups.

[22] Although a decreasing trend is observed for entire country the most significant trends are observed in the western and northern regions. On the other hand, only 24 stations (17%) exhibit significantly negative trend at the 95% confidence level and are mostly located in west and north of the country. For example, the variation in annual rainfall for the Zahedan (Group 1) and Tabriz (Group 3) stations and their associated trends have been given in Figure 4.

[23] The sequential MK test reveals that the significant downward trend began in the 1970s. Sequential values, $u(t)$ and $u'(t)$, for two typical stations, Tabriz station in the northwest and Zahedan station in the southeast, are given in Figure 5. By inspecting the plot of $u(t)$, an apparent decreasing trend is identified and the two functions begin to diverge in 1975 for Zahedan station and in 1970 for Tabriz station. The similar behavior in sequential values are observed for other stations demonstrating the 1970s to be the beginning time of decrease in rainfall trend across Iran.

4.2. Trends in Station 24-hr Maximum Rainfall

[24] In this section, the MK trend test is performed for 24-hr maximum rainfall across Iran.

[25] Dissimilar to the annual rainfall, the number of stations with negative MK statistics is approximately equal to those with positive MK statistics. There are 20 (14%) stations with significant trend at the 5% significant level among which 10 stations show positive trends.

[26] The average values of positive and negative MK statistics are also equal to each other indicating that 24-hr maximum rainfall has changed uniformly across the country. However, the positive values are mostly distributed in central regions of Iran including arid and semiarid regions of the country. Although we need more rainfall intensity-duration data for more reliable conclusions, the increasing trend in 24-hr rainfall could indicate higher soil erosion vulnerability in these regions. Figure 6 shows the location of gauging stations with notable trends in 24-hr maximum rainfall within different rainfall groups. Time series of 24-hr maximum rainfall for two typical stations, Shahrood and Arak have been given in Figure 7 with trend lines.

[27] The sequential test for 24-hr maximum rainfall also indicates 1970s as the beginning of decreasing or increasing trend of the stations. The sequential values of Sharood station in semiarid region of Iran and Arak station in the west are illustrated in Figure 8 for example.

4.3. Regional Trends

[28] Regional trends in annual and 24-hr maximum rainfall are examined by the use of MK test on the average rainfall over each region for each year. The MK statistics and their significance level are given in Table 1. Table 1 illustrates that the subregional trend of the annual rainfall is not significant for most of the climate zones of Iran, except for G2 and G8. On the other hand, the regional trend for the 24-hr rainfall shows similar results except for G1, G6 and G8 zones. The G1 zone covers arid and semiarid reigns of Iran where water erosion is one of the most vital problems. The increasing trend in heavy rainfall may accelerate soil erosion through flash floods resulting in soil loss in particularly sensitive region.

[29] The MK statistics of the annual and 24-hr maximum rainfall for the entire country is also given in Table 1. The rainfall series covering the entire country have been calculated in the same way as the zonal rainfall. The results show that previously identified regional trend is not significant for the entire country. In order to check the above results, the Kolmogorov-Smirnov test is also applied. The K-S test of uniform distribution shows that we cannot reject the null

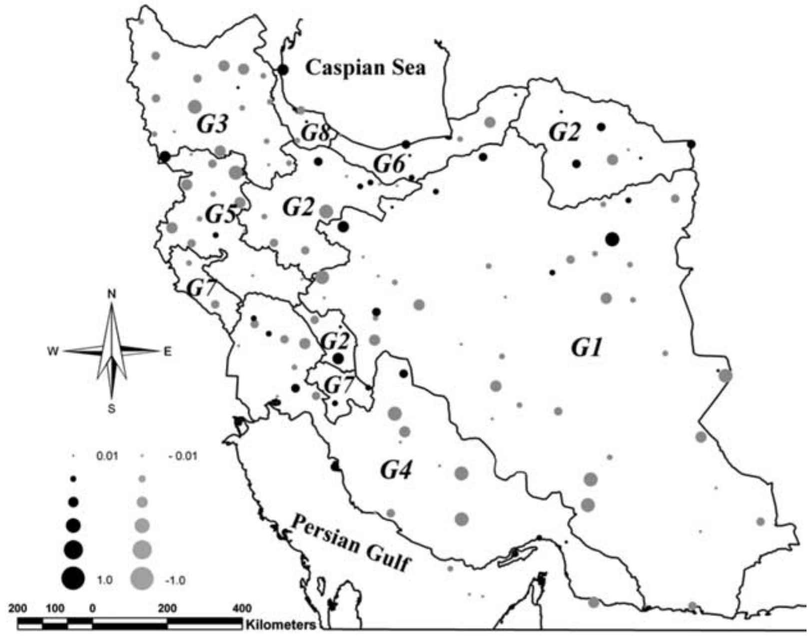

Figure 3. Spatial distribution of MK statistics of annual rainfall of Iran (black and gray circles show positive and negative trend, respectively).

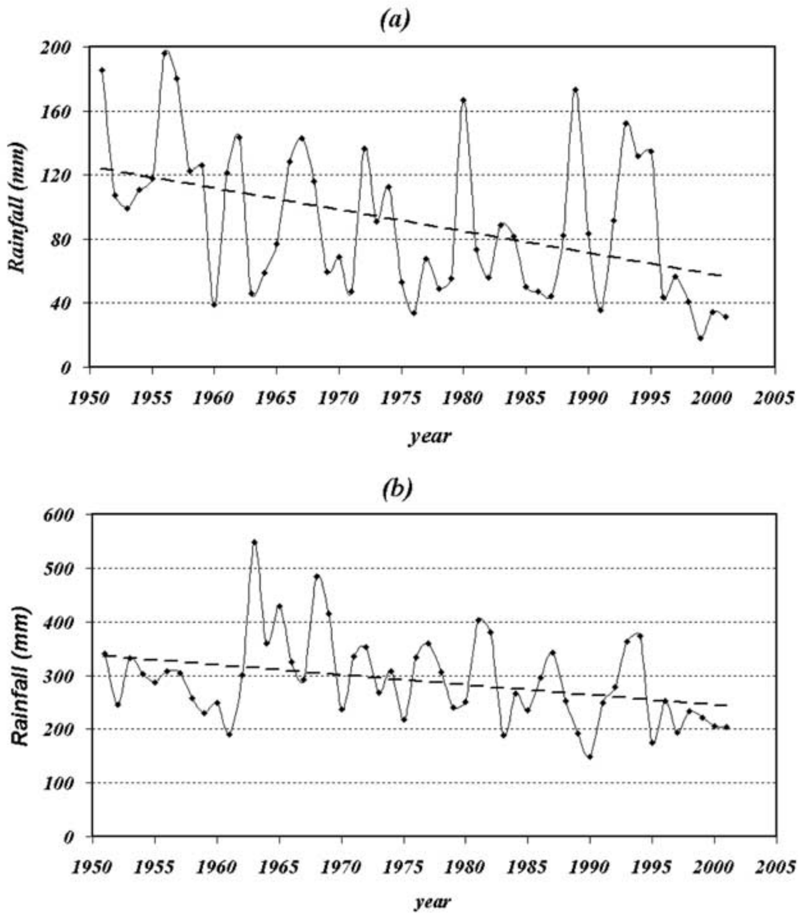

Figure 4. Time series of the annual rainfall for (a) Zahedan and (b) Tabriz stations. Dashed lines are linear trends estimated using ordinary least squares technique.

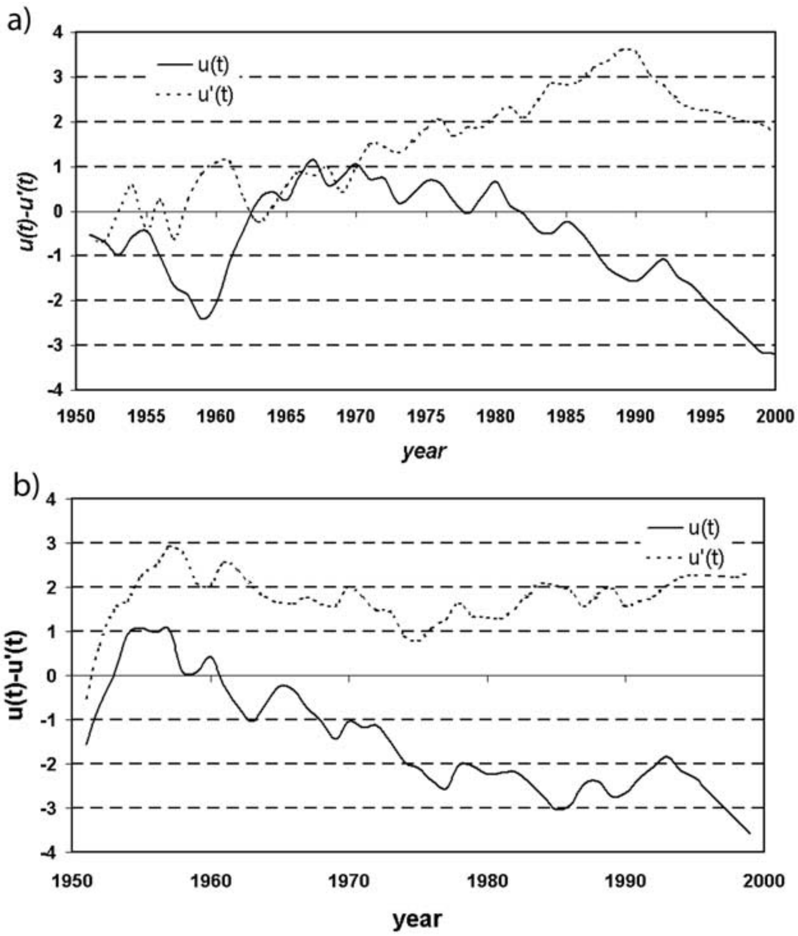

Figure 5. Sequential values of the statistics $u(t)$ (solid line) and $u'(t)$ (dashed line) from the Mann-Kendall test for annual rainfall for (a) Tabriz station and (b) Zahedan station.

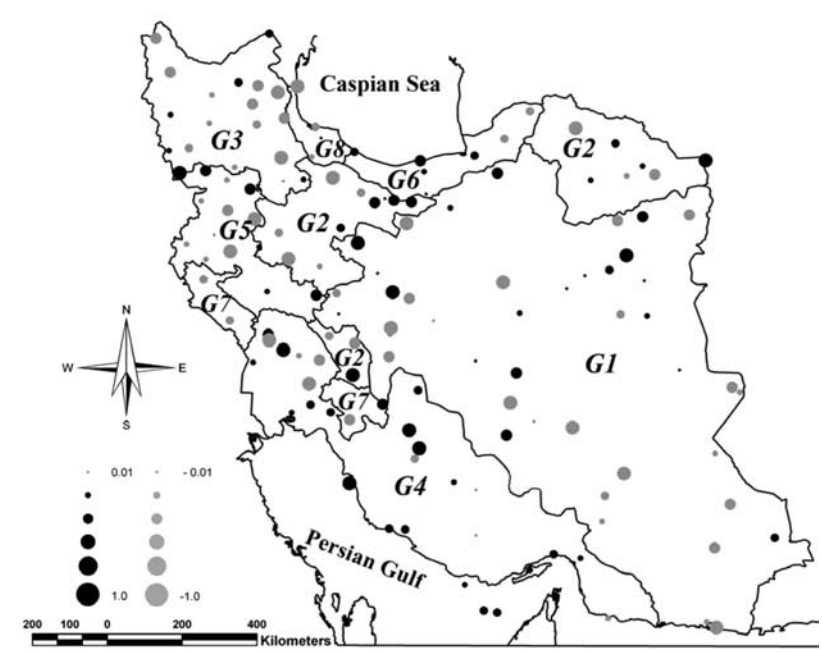

Figure 6. Spatial distribution of MK statistics of 24-hr maximum rainfall of Iran (black and gray circles show positive and negative trend, respectively).

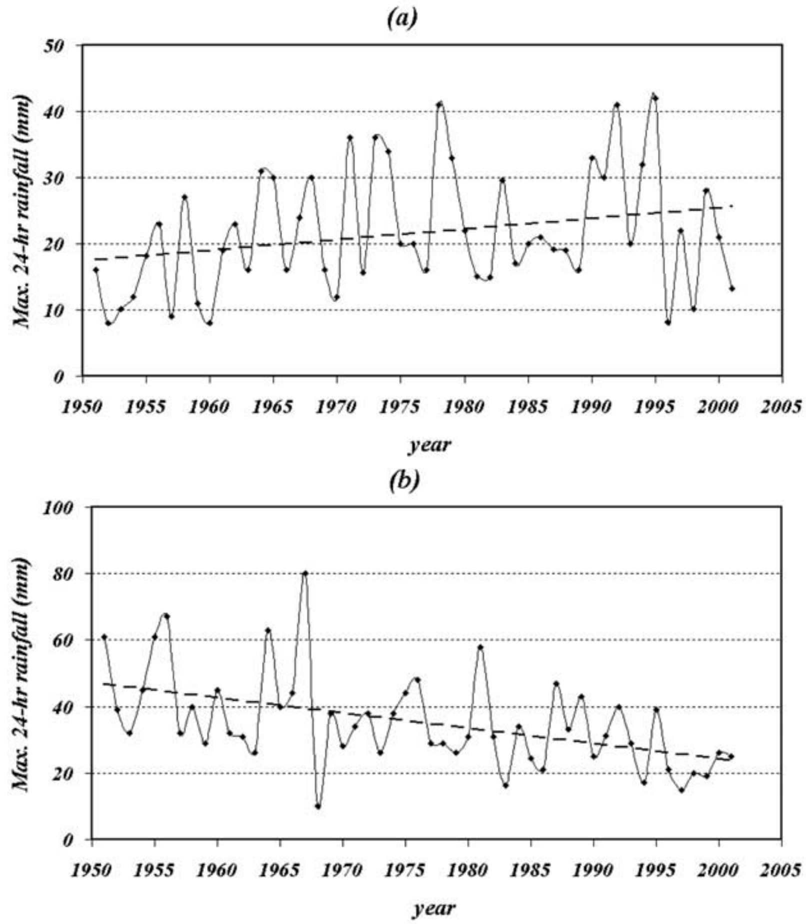

Figure 7. Time series of the 24-hr maximum rainfall for (a) Shahrood and (b) Arak stations. Dashed lines are linear trends estimated using ordinary least squares technique.

hypothesis of no trend in annual rainfall of the entire country at 5% significant level (p = <0.048). The (q-q) plot of the annual rainfall is given in Figure 9.

[30] In the last, the K-S test reveals that the null hypothesis of no trend cannot be rejected at 5% significant level (p = >0.145). The (q-q) plot of the MK statistics of 24-hr maximum rainfall is shown in Figure 10. This plot of *p*-values does not deviate from linearity and we cannot conclude that the 24-hr maximum rainfall shows significant trend across the country. In other words, 24-hr maximum rainfall show local changes rather than clearly identifiable regional trends.

5. Summary and Conclusion

[31] A set of 145 rainfall stations in Iran was used to detect trends in annual and 24-hr maximum rainfall. A consistent decreasing trend in annual rainfall amount was detected for most of the stations over the country during the last half century. These decreasing trends are particularly significant in western and northwestern Iran. However, the q-q plot and K-S test demonstrate that no significant regional trend in annual rainfall exists.

[32] The MK test for 24-hr maximum rainfall shows an equal number of stations with increasing and decreasing trend. However, the increasing trends are mostly observed in the central arid and semiarid region of Iran where soil erosion is prevalent which may be influenced and accelerated by the increasing trend in 24-hr maximum rainfall during the last half century. The q-q plot and K-S test show that the regional trend is not significant for 24-hr maximum rainfall as the K-S test does not reject the null hypothesis of no trend.

[33] Although the results of this study demonstrate a negative trend in annual rainfall for most the country and a negative trend of 24-hr maximum rainfall for some parts of the country, it is difficult to determine whether or not climate change is occurring across the country. However, the information provided by this study on trend detection may provide a useful resource for water planning and management activities in Iran. The decreasing trend in annual rainfall may lead to significant change in water supply and demand for agriculture and urban drinking water in the arid and semiarid belt of Iran. Nevertheless, the increasing trend of 24-hr maximum rainfall may accelerate soil degradation and desertification in arid regions of Iran.

[34] On the other hand, the sequential MK test reveals that the significant positive or negative trends may have begun in the 1970s when it is largely agreed modernization of the country began. The decreasing or increasing trend of rainfall may be the result of rapid civilization in the last

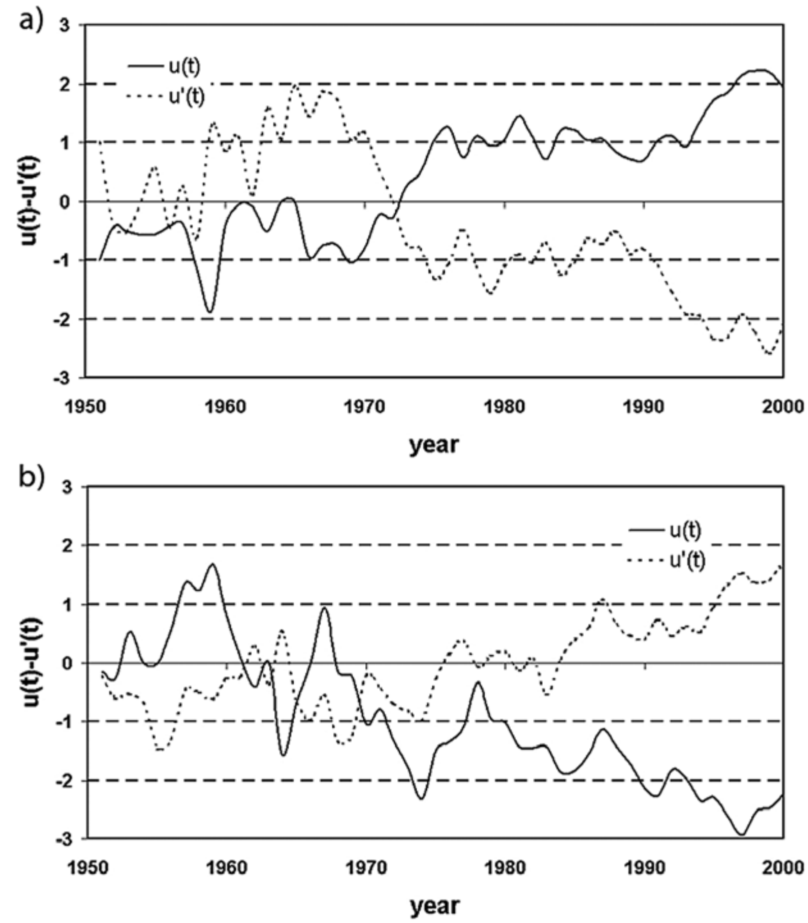

Figure 8. Sequential values of the statistics $u(t)$ (solid line) and $u'(t)$ (dashed line) from the Mann-Kendall test for 24-hr maximum rainfall for (a) Shahrood station and (b) Arak station.

30 years. However, from this data, it is difficult to find the above relationship and we need a longer record of data and other data such as streamflow data to find the relationship between civilization and climate change in Iran.

[35] In general, as climate change and its effects have not been fully investigated in Iran yet, this paper develops, for the first time, a full picture of recent rainfall trends over Iran which should be of interest to future soil and water resources management personnel and to find the potential

Table 1. MK Statistics (Z-Value) and Their Corresponding Significant Level (p-Value) for Regional Rainfall of Different Rainfall Groups of Iran

	Annual Rainfall		24-Hour Maximum Rainfall	
Climate Zone	Z-Value	p-Value	Z-Value	p-Value
G1	0.055	0.561	0.225	0.018[a]
G2	0.270	0.004[b]	0.142	0.133
G3	−0.078	0.407	−0.021	0.824
G4	0.055	0.560	−0.024	0.800
G5	0.123	0.195	0.055	0.560
G6	0.062	0.509	0.233	0.014[a]
G7	−0.006	0.970	−0.029	0.821
G8	−0.430	0.001[b]	−0.331	0.001[b]
Entire Country	0.042	0.656	0.036	0.701

[a]Significant at 5% level.
[b]Significant at 1% level.

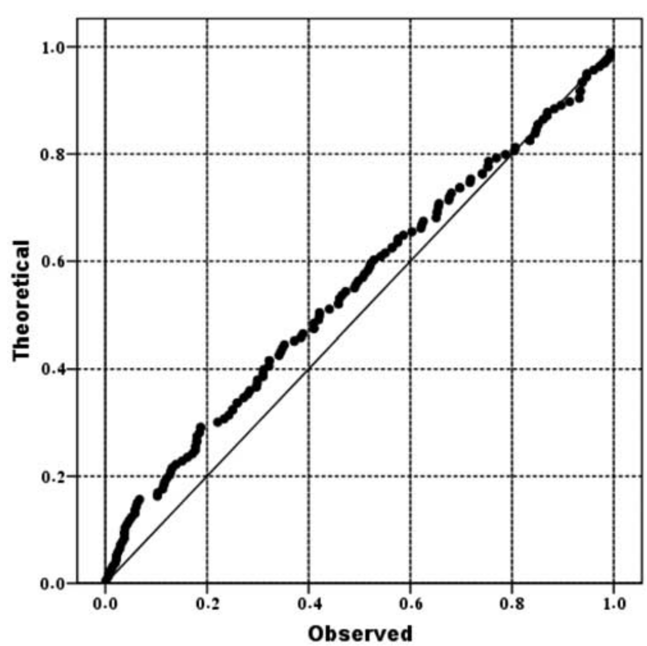

Figure 9. Quantile-Quantile plot for the trend test of the annual rainfall across the entire Iran.

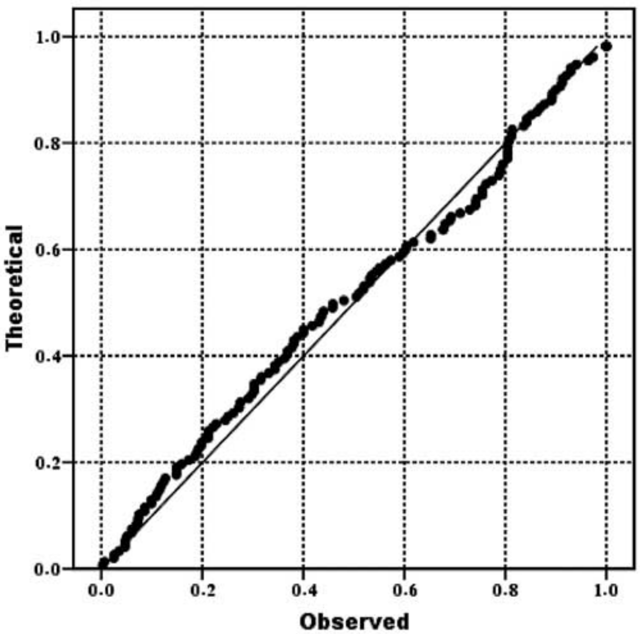

Figure 10. Quantile-Quantile plot for the trend test of the 24-hr maximum rainfall across the entire Iran.

influence of climate change on natural and environmental resources of the country.

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R. Modarres and A. Sarhadi, Faculty of Natural Resources, Isfahan University of Technology, P.O. Box 8415683111, Isfahan, Iran. (modarres2005@gmail.com)