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Trend Analysis of Annual Rainfall Time Series in Northwest Libya

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Abstract

This study is based on historical total annual rainfall recorded at eleven meteorological stations located in the northwestern part of Libya. The data were analyzed to study long term temporal trends on annual scale. The rainfall time series data were tested for homogeneity and randomness in order to be confident that the measurements were taken at the time with the same instruments and location. After testing, Mann–Kendall test was applied to detect the trends in rainfall data. Theil-Sen's slope estimator test was used for finding the magnitude of change over a time period. The results of Mann–Kendall test detected statistically significant trends of increasing and decreasing rainfall in two out of eleven stations at 95% and 99% confidence levels, namely Sirt and Tripoli Airport stations. During the study period of observation, Sen's Slope and change percentage were estimated as 0.829 mm/year rainfall increase (36.88 %) in Sirt station and -0.686 mm/year (20.04 %) rainfall decrease in Tripoli Airport station.

Keywords: Annual rainfall: Time series; Homogeneity; Mann-Kendall test; Theil-Sen's slope.

المستخلص

تعتمد هذه الدراسة على السجلات التاريخية للمطر في إحدى عشرة محطة في شمال غرب ليبيا ، حيث تم تحليل البيانات لدراسة الانساق الوقتية على أساس سنوي. تم اختبار بيانات سلاسل الزمن المطرية من حيث التجانس والعشوائية للتأكد من أن القياسات قد تم أخذها في حينها بنفس الاجهزة والأماكن. بعد ذلك تم تطبيق اختبار مان–كيندال Mann-Kendall للحصول على أنساق البيانات كما تم استخدام اختبار ثايل – سن Theil-Sen لتقدير الانحدار لإيجاد شدة التغير عبر فترة من الزمن.

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كشف اختبار مان– كيندال عن وجود أنساق معتبرة من الزيادة والنقصان في محطتين من الاحدى عشرة محطة عند درجتي ثقة 95% و 99% وهما بالتحديد محطتي سرت ومطار طرابلس الغرب. قدر انحدار ثأيل – سن ونسبة التغير خلال مدة الدراسة بـ 0.829 مم/سنة من المطر ما يساوي زيادة 36.88% في محطة سرت و –0.686 مم/سنة (20.04%) انخفاض المطر في محطة مطار طرابلس.

Introduction

Libya is mostly located in the arid and semi-arid regions which cover more than 90% of the country. The majority of its people live in coastal zone threatened by fresh water scarcity where rain is highly variable in time, space, amount and duration. In recent decades, several parts of this zone have experienced intensive stress on their natural water resources. The irregularity of rainfall and over-extraction of groundwater have led to everlasting decline in groundwater levels and sea water encroachment in most of the coastal aquifers.

There is a common thought among people that the total annual rainfall quantities had decreased noticeably since the second half of the twentieth century. In this study, an attempt has been made to study the effect of the expected climate change on precipitation in the northwestern part of Libya. Trend analysis is a typical method to examine the temporal trend and variability of the total annual rainfall.

To be able to achieve such goal, annual rainfall data recorded at eleven meteorological stations operated by the Libyan National Meteorological Center (LNMC) were used. Accordingly, analysis of data quality as well as time series homogeneity and randomness were performed. Then, Mann–Kendall non-parametric statistical test was applied to all stations to confirm the existence of a possible trend(s). Theil-Sen’s slope estimator was also used in order to predict the magnitude of trends.

Study Area and Data Sources

The study area lies in northwestern part of Libya; approximately between Longitude 10° to 16° N and Latitude 30° to 33° E (Fig. 1). The monthly rainfall records from eleven LNMC stations were used (Table 1). The stations included in this study were selected on the basis of their latitudinal position, elevation from sea level, length of record, completeness and reliability of data.

Methodology

In this study, the annual precipitation totals were calculated first by summing the monthly precipitation for each stations. Before beginning trend analysis, exploratory data analysis often give preliminary indications of the suitability of the data steps to the non-parametric statistical trend analysis. Afterward, the following tests were applied for carrying out the rainfall trend analysis using Addinsoft's XLSTAT v. 2015 and ProUCL 5.0 softwaters:

- Homogeneity in annual series was tested by Pettitt's test, SNHT test and Buishand's test.

Table 1. Meteorological stations under study.

Station	Sample size (year)	Latitude (N)	Longitude (E)	Elevation a.m.s.l. (m)	Period of observation
Ghadames	86	30° 08′	09° 30′	357	1924-2009
Gharyan	86	32° 04′	13° 01′	741	1924-2009
Misurata	67	32° 19′	15° 03′	32	1943-2009
Nalut	79	31° 52′	10° 59′	621	1931-2009
Sirt	79	31° 12′	16° 35′	13	1931-2009
Tripoli Airport	81	32° 40′	13° 09′	81	1929-2009
Tripoli	79	32° 54′	13° 11′	25	1931-2009
Zwara	79	32° 53′	12° 05′	03	1931-2009
Az Zintan	42	31° 56′	12° 14′	713	1968-2009
Ghariat	42	30° 23′	13° 35′	497	1968-2009
Mizda	60	31° 27′	12° 59′	476	1925-2009

- Significance of randomness in data set was detected by using autocorrelation functions.
- Mann–Kendall (MK) test was applied to the non-autocorrelated series to detect the presence of trend in annual rainfall.
- Magnitude of a trend was estimated by Theil and Sen's slope estimator test.
- Changes were calculated as percentage change in rainfall trend over the observation period of rainfall series mean.

Homogeneity Test

Effective rainfall time-series trend analysis requires a fairly long sequence of data collected from observation stations at a fixed location, and by consistent methods. The data should be verified for reliability and homogeneity prior to their use in research. For that reason, homogeneous climate series may be defined as series only influenced by weather and climate variations (Peterson et al., 1998). In this study the homogeneity of the precipitation time series for all stations was assessed by applying three different tests at a 1% significance level: the Pettitt test (Pettitt, 1979), the standard normal homogeneity test (SNHT) (Alexandersson, 1986) and the Buishand range test (Buishand, 1982).

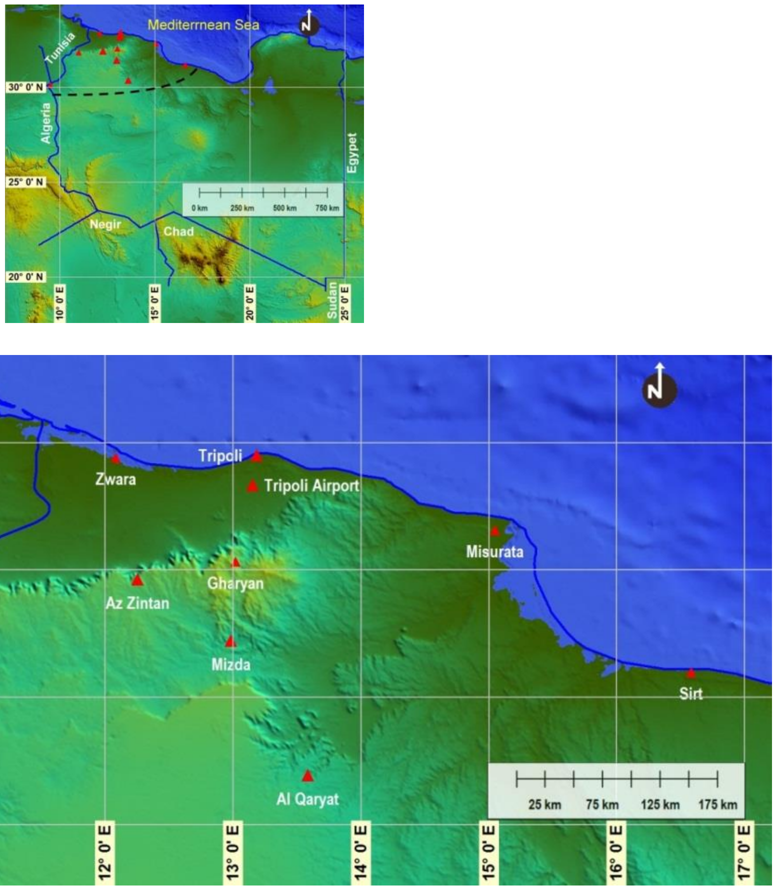

Figure 1. Location of meteorological stations under study.

The test results were classified according to the number of tests that reject the null hypothesis, using categories presented in Wijngaard et al. (2003) as follows:

- **Class 1: 'useful'** — one or zero tests reject the null hypothesis at the 1% level. Under this class, the series is grouped as homogeneous and can be used for trend analysis.
- **Class 2: 'doubtful'** — two tests reject the null hypothesis at the 1% level. In this class, the series have the inhomogeneous signal and the results of trend analysis should be regarded very critically.
- **Class 3: 'suspect'** — three or four tests reject the null hypothesis at the 1% level. In this category, the series are reliable but lack credibility; therefore, these series can be deleted or ignored and should not be used in further analysis.

Test of Randomness

The data analysis procedures used for trend detection require that the data should be random, that is, not influenced by rainfall in the previous time step. The autocorrelation function was used to test for such randomness and independence (Von Storch 1995). Conventionally the autocovariance is calculated for default length of n/4 for a time series with less than or equal to 240 observations (Davis 2002). If the sample autocorrelation coefficients (r_k) are close to zero, in this case, none of the autocorrelation coefficients are statistically significant at the 95.0% confidence level revealing that there is no significant correlation between neighboring data samples. Accordingly, the time series is completely random. If the absolute values of one or more non-zero autocorrelation coefficients exceed the confidence limits, plotted as horizontal dotted lines on the autocorrelograms (i.e., statistically significant at the 95.0% confidence level), the null hypothesis of no autocorrelation should not be rejected and the rainfall time series is not completely random.

Mann-Kendall (MK) Test

Mann–Kendall **(MK)** is a non-parametric test for linear trends, based on the idea that a lack of trend should correspond to a time series plot fluctuating randomly about a constant mean level, with no visually apparent upward or downward pattern (Gilbert, 1987; EPA 2009). The test has been widely used by several researchers to detect and evaluate a presence of a statistically significant trend in hydrological and climatological time-series. There are two advantages of using this test; first it is simple, robust, accommodates missing values, the data does not have to be normally distributed and it is less affected by extreme values and outliers as compared to the least squares method (Helsel and Hirsch, 1992 ; Birsan et al., 2005). Second, the test has low sensitivity to abrupt breaks due to inhomogeneous time series (Libisellere Grimvall, 2002; Gilbert, 1987). The test is based on the idea that a lack of trend should correspond to a time series plot and is computed by examining all possible pairs of measurements in the data set and scoring each pair.

For long term data (sample of sizes larger than 22) as in this study a normal approximation to ***S*** is used. In this case, a standardized ***S*** statistic, denoted by *Z* is computed by using the expected mean value and standard deviation of the test statistic *S*. The mathematical equations for calculating Mann-Kendall Statistics S, *sd*[*S*] and standardized test statistics Z are as follows:

$$S = \sum_{i=1}^{n} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right)$$

Where the x_j is the sequential data values, n is the length of the time-series and the *sign* of the difference, defined by

$$\operatorname{sgn}\left(x_j - x_i\right) = \begin{cases} 1 \;\; if \left(x_j - x_i\right) > 0 \\ 0 \;\; if \left(x_j - x_i\right) = 0 \\ -1 \;\; if \left(x_j - x_i\right) < 0 \end{cases}$$

The standard deviation of *S* can be computed using equation:

$$sd[S] = \sqrt{\frac{1}{18}\left[n(n-1)(2n+5) - \sum_{j=1}^{g} t_j\left(t_j - 1\right)\left(2t_j + 5\right)\right]},$$

where *n* is the sample size, *g* represents the number of groups of ties in the data set (if any), and t_j is the number of ties in the j^{th} group of ties.

Once the standard deviation of *S* has been derived, the standardized *Z*-statistic for an increasing (or decreasing) trend is formed using the equation:

$$Z = \frac{S-1}{sd[S]} \qquad if\ S>0$$

$$Z = 0 \qquad if\ S=0$$

$$Z = \frac{S+1}{sd[S]} \qquad\qquad S<0$$

Positive values of Z indicate increasing trends and vice versa. For a given significance level (α), the critical value Z_{cp} is determined from the standard normal distribution. If the p-value is larger than the specified α, the null hypothesis of no trend is not rejected. Specifically, by comparing Z against this critical point, if $Z>0$ and $Z>Z_{cp}$, conclude there is statistically significant evidence of an increasing trend. If $Z<0$ and $Z<Z_{cp}$, conclude there is statistically significant evidence of a decreasing trend. If neither exists, conclude that the sample evidence is insufficient to identify a trend. In this study, significance levels of $p = 0.01$ and 0.05 were applied.

Theil-Sen's Slope Estimator

The Mann-Kendall statistic identifies whether a trend exists or not, but it does not indicate the magnitude of the slope or estimate the trend line itself even when a trend is present. The Theil-Sen trend line is a nonparametric to alternative to linear regression which can be used in conjunction with the Mann-Kendall test to determine how steeply the significant rainfall trend is increasing or decreasing over time. If a linear trend is present in a time series, then the true slope can be estimated using a simple nonparametric procedure developed by Sen (1968). This implies that a linear model *f (t)* can be described as:

$$f(t) = Qt + B$$

where Q and B are the slope and the intercept of the trend line respectively.

To derive an estimate of the slope **Q**, the slopes of all data pairs are calculated as:

$$Q_i = \frac{x_i - x_j}{i-j}, \ i = 1, 2, \ldots\ldots N, \ j > k$$

where x_i and x_j are data points measured at times j and k respectively and $\boldsymbol{Q}$ is the Sen's estimator. Consider:

$$Q_i = \begin{cases} Q_{\frac{N+1}{2}} & if\ N\ is\ odd \\ \frac{1}{2}\left(Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}\right) & if\ N\ is\ even \end{cases}$$

A positive value of Q_i indicates an 'upward trend' (or increasing trend over time) and vice versa, in the time series.

Change of Magnitude as Percentage of Mean

The percentage change over the length of observation period have been estimated by following the assumption of linear trend, estimating magnitude by Theil - Sen's median slope and assessing the mean over the period;

$$\%\, change = \left\{\frac{median\ slope\ \times period\ length}{mean}\right\} \times 100$$

Results and Discussion

Preliminary Analysis

The common statistical parameters of the annual precipitation time series for the eleven meteorological stations under study were calculated. These include minimum **(R_m),** maximum **(R_x)**, mean **(R_e)**, standard deviation (SD), coefficient of skewness **(C_s)**, coefficient of kurtosis **(C_k)**, and coefficient of variation (**C_v)**. The maximum and minimum total annual rainfall of 783.90 mm and 0.40 mm were recorded at Gharyan in 1976 and Ghadames in 1947 respectively (Table 2). The mean annual rainfall of the study region is relatively low, ranging from 33.57 mm in the southwest part of the study area (Ghadames) to 341.06 mm in the central part of Jabel Nafusah (Gharyan). In general, the standard deviation is high, ranging from 28.69 mm in Ghadames to 152.82 mm in Gharyan.

For a time series data to be considered normally distributed, the coefficient of skewness and kurtosis must be equal to 0 and 3, respectively. The skewness varies between 2.85 and 0.23. Hovever, predominantly positive skewness was achieved, with an average around 1.1. This indicates that annual rainfall during the period of observation is asymmetric and lies to the right of the mean over all the stations. The coefficient of kurtosis varies between 0.14 and 13.98 for all stations.

To analyze the spatial variability of annual precipitation, the coefficient of variation (C_V) is a statistical measure of how the individual data points vary about the mean value, was also calculated. A greater value of C_V is an indicator of larger spatial variability, and vice versa. The coefficient of variation (C_V) varies between 85.0 % in the south western part (Ghadames station) and 30 % in Misurata. Generally a high variation in rainfall over the entire area is perceived with an average coefficient of variation of 46.5 %. Preliminary analysis of the rainfall indicates that the zones of usually moderately rainfall are the zones of least variability and zones of lower rainfall are the zone of highest variability.

Table 2. Summary of mean annual precipitation statistics.

Station	R_m (mm)	R_x (mm)	R_e (mm)	*SD* (mm)	C_s	C_k	C_v
Ghadames	00.40	204.80	33.57	28.69	**2.85**	**13.98**	**0.85**
Gharyan	63.50	783.90	341.06	152.82	0.59	-0.17	0.45
Misurata	77.10	461.90	276.91	82.53	0.23	-0.22	**0.30**
Nalut	37.00	568.80	143.13	77.84	2.39	10.73	0.54
Sirt	06.70	429.50	177.57	85.66	0.70	0.84	0.48
Tripoli Airport	49.10	581.90	277.29	100.07	0.72	0.75	0.36
Tripoli	98.40	654.50	338.76	112.40	0.59	0.03	0.33
Zwara	40.10	453.60	220.89	90.04	0.56	0.19	0.41
Az Zintan	69.00	492.10	223.33	89.97	0.61	0.71	0.40
Ghariat	8.40	150.70	56.70	38.18	0.87	-0.14	0.67
Mizda	11.00	295.50	74.99	45.88	2.01	7.72	0.61

Analysis of Homogeneity Tests

Results of the homogeneity tests across annual rainfall are given in Table 3. With critical value found to be 655, 12.03, 1.55 and 1.81 for Pettitt test, SNHT and BR test respectively (Wijngaard et al., 2003). At 1% significance level, null hypothesis of homogeneity of all series data are accepted. It means the, this implies that all stations exhibited homogeneity as all test statistics are marked as "useful".

Analysis of Randomness

Examination of the autocorrelograms (Fig. 2), indicates that rainfall time series data from the nine stations are completely random, with no significant correlation at all lags, thus, the Mann–Kendall test can be applied directly to the series. Time series data from Gharyan and Nalut stations show only one large positive significant autocorrelation coefficient at lag 12 and lag 4 respectively, implying that the two time series may not be completely random (Fig. 2). But since, no other autocorrelation coefficients exceeded the 95% confidence limit (dotted lines), Mann–Kendall trend test can also be performed.

Mann–Kendall Trend Analysis

Results of the Mann–Kendall (MK) test, for all stations are presented (Table 4 and Figure 3). The MK test failed to detect the significant trend neither at 5% nor at 1% significance level in most stations, which implies that, no major changes have occurred. Among the studied locations, only Sirt station exhibited positive significant trend in the annual rainfall with Z_{MK} value of 2.244 at 95% level of confidence. Tripoli Airport station showed the highest negative significant annual rainfall trend with Z_{MK} value of ***-1.546*** at 99 % confidence level.

Table 3. The results of the homogeneity tests for all rainfall time series.

Station	Pettitt's test (X_E)	SNHT (T_0)	Buishand's (BR) test		Classification
			$Q/\sqrt{n}$	$R/\sqrt{n}$	
Ghadames	391.00	4.776	0.642	0.673	Class 1
Gharyan	526.00	3.602	0.948	1.592	Class 1
Misurata	136.00	1.419	0.599	0.864	Class 1
Nalut	349.00	3.377	0.924	1.293	Class 1
Sirt	608.00	7.185	1.259	1.478	Class 1
Tripoli Airport	644.0	9.275	1.382	1.400	Class 1
Tripoli	260.00	3.809	0.582	1.143	Class 1
Zwara	345.00	3.634	0.912	1.345	Class 1
Az Zintan	110.00	4.760	0.648	0.874	Class 1
Ghariat	69.00	3.216	0.588	0.899	Class 1
Mizda	258.00	4.600	0.942	1.055	Class 1

For homogenous series, $X_E<655$, $T_0< 12.03$, $Q/\sqrt{n} < 1.55$ *and* $R/\sqrt{n} < 1.81$.

Magnitude of Trend (Sen's Slope)

Sen's slope estimator yielded only two significant values, positive trend at 95% confidence level with rainfall increasing rate of **0.829 mm/year** at Sirt station and negative trend at 99% confidence level with rainfall decreasing rate of **-0.686 mm/year** at Tripoli Airport (Table 4**).** These represent the maximum increasing and decreasing change in annual rainfall. The computed change percentage in rainfall trend for the two stations are **36.88** % in Sirt station and **20.04 %** for Tripoli Airport station, respectively.

Conclusion

Annual time series trends were analyzed with the Mann–Kendall test and the Sen's slope estimator for eleven meteorological stations located in the northwestern part of Libya. Results show that all analyzed time-series were homogeneous at 1% significance level. The majority of autocorrelation function plots for the annual rainfall time-series showed that the autocorrelation coefficients fall within the 95% confidence limits. Therefore, the time-series of most the stations are strongly random and only two stations may not be completely random. The Mann–Kendall test showed that most of the stations exhibited no widespread statistically significant trends throughout the region. On the other hand, only two stations, Sirt and Tripoli Airport, show considerable changes at significance at $p < 0.05$ or $p < 0.01$, respectively

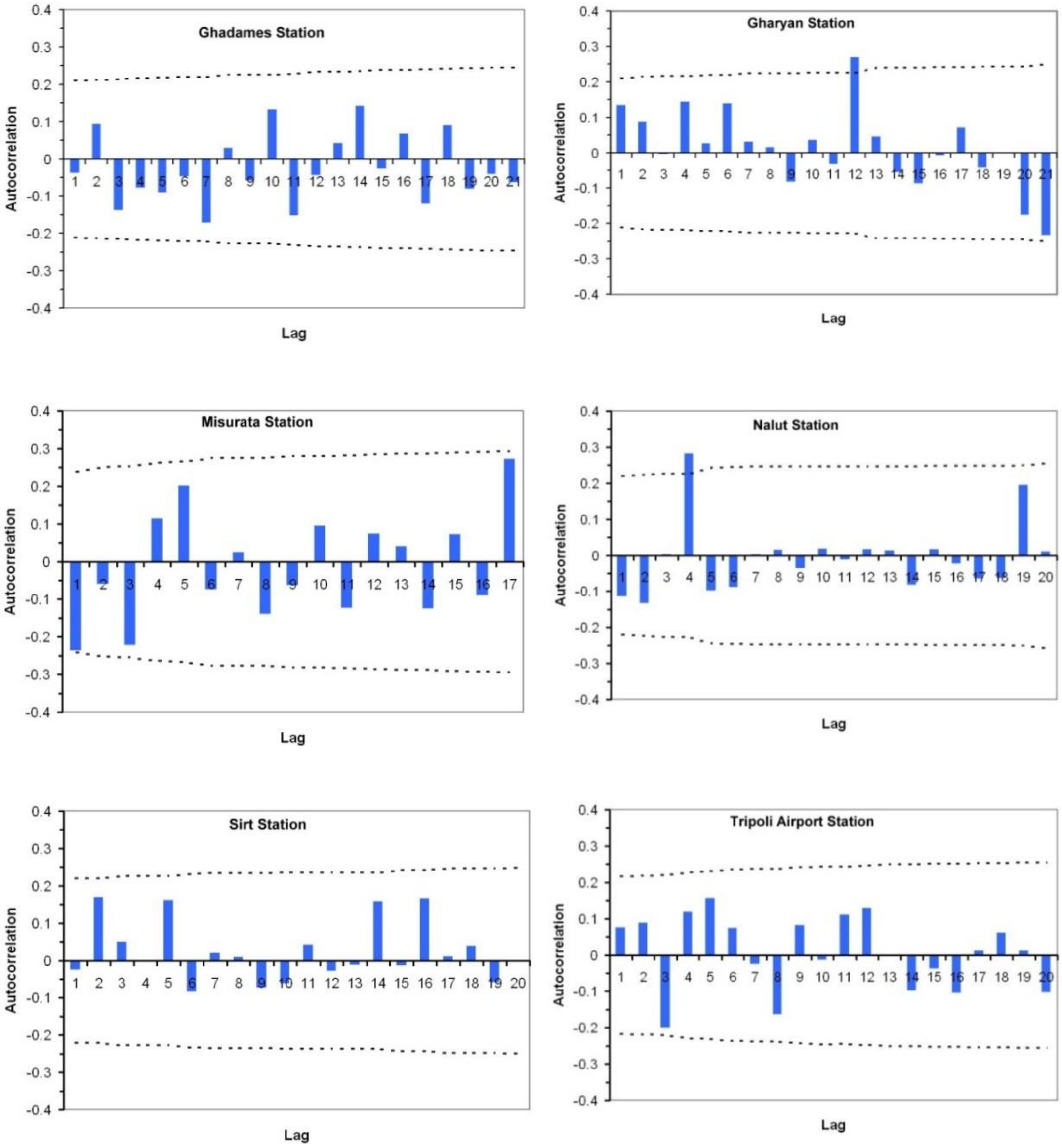

Figure 2. Autocorrelation plots for all stations, upper and lower dashed lines are 95% confidence bands.

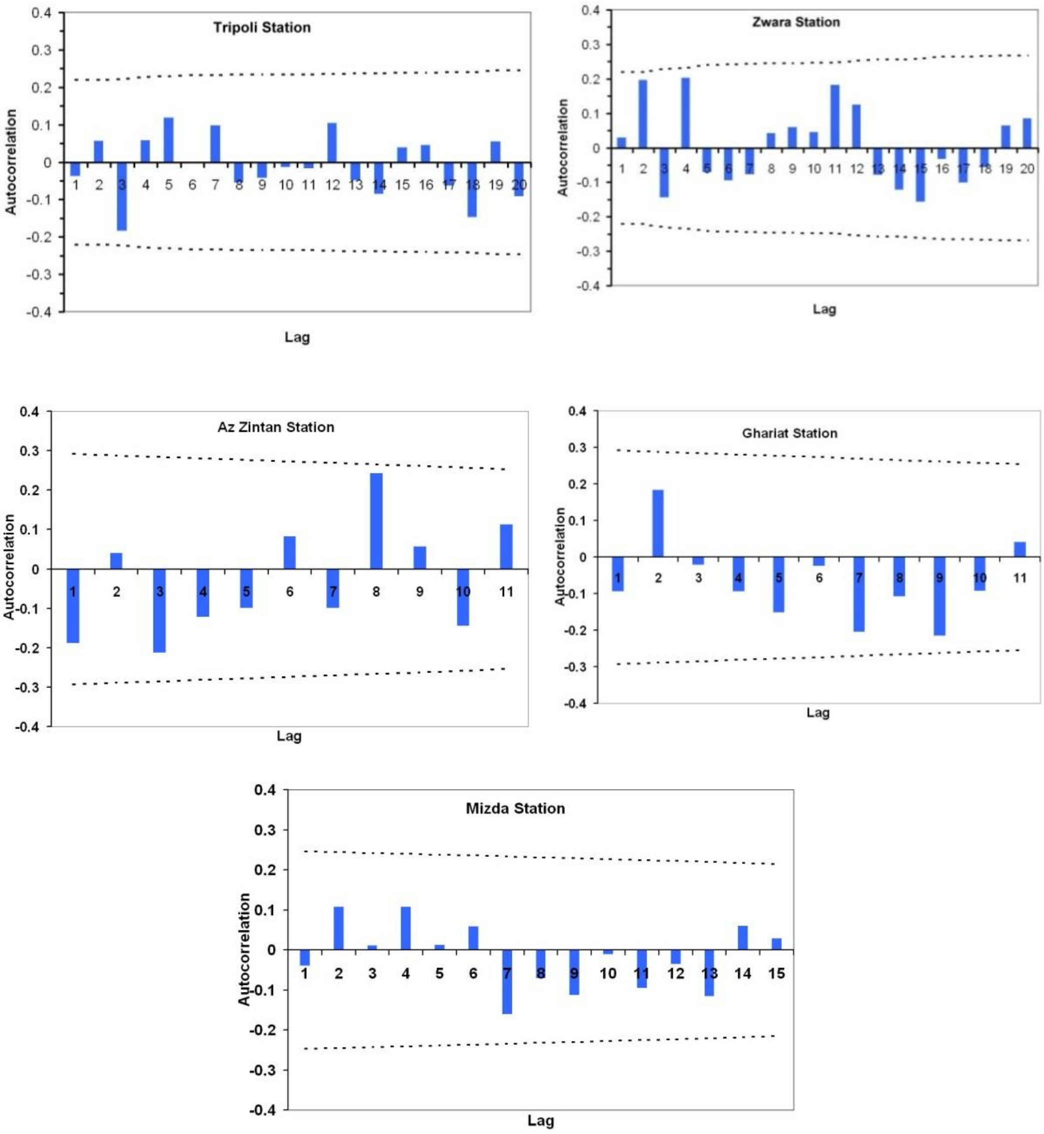

Figure 2. (Cont.).

. The magnitudes and percentage changes of these station are 0.829 mm/year (36.88 %) and -0.686 mm/year (-20.04 %). It can be concluded that there are no remarkable variations in total annual rainfall quantities were detected from the early time of recording until 2009.

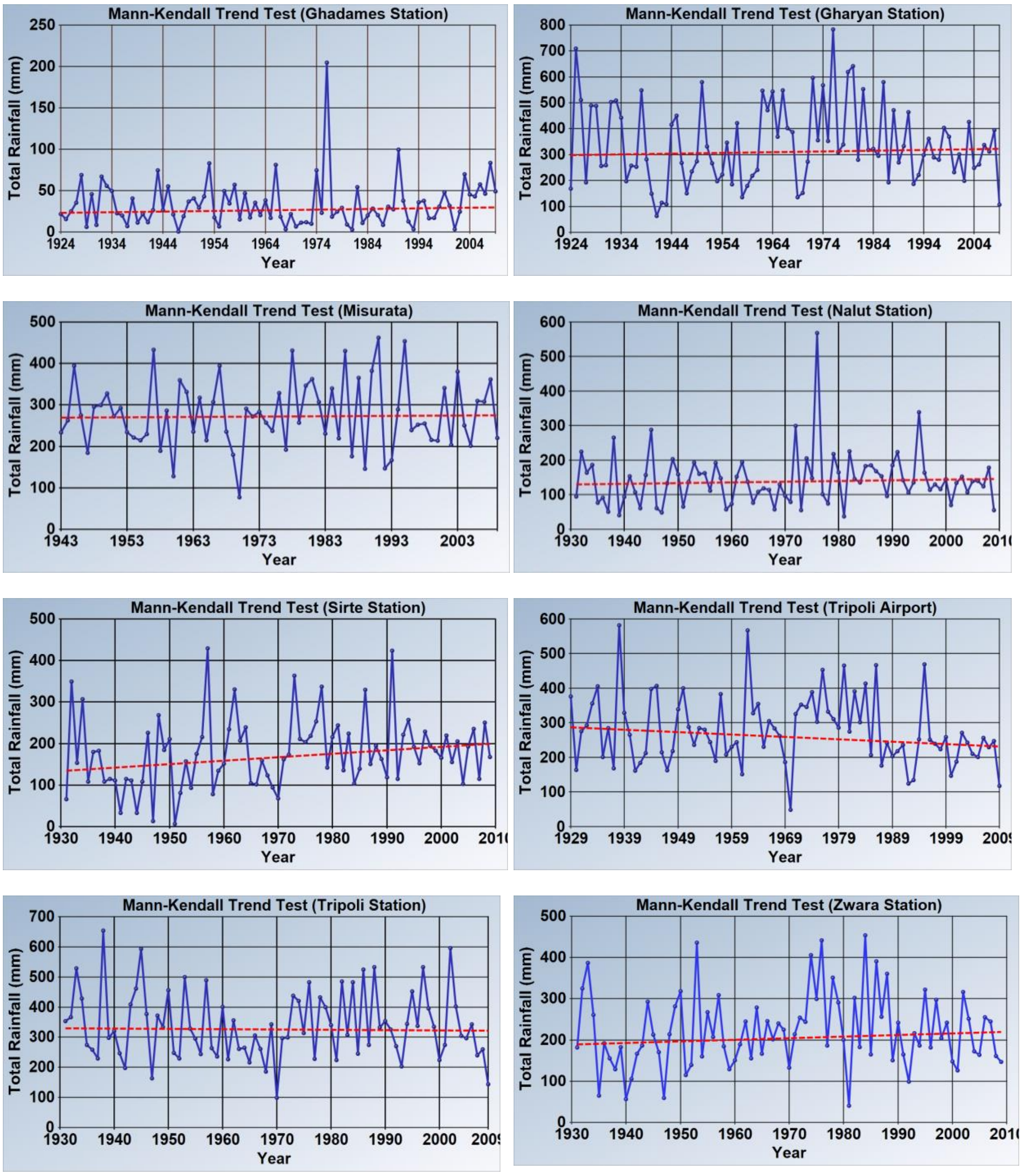

Figure 3. Annual rainfall fluctuations and straight line trends for stations.
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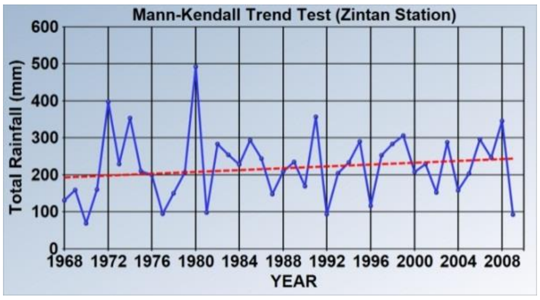

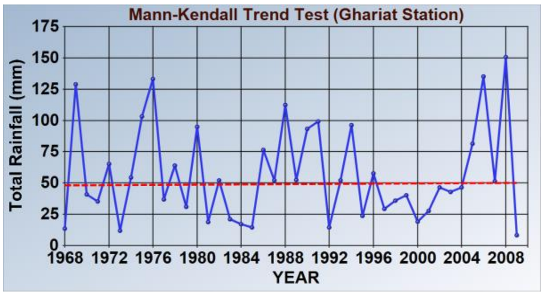

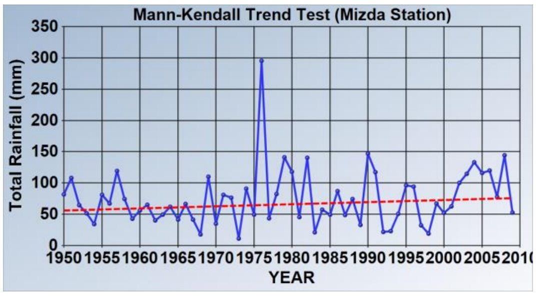

Figure 3. (Cont.).

Table 4. Results of Mann–Kendall trend test, Sen's slope and percentage change. The values in the column *p-value* refer to the significance level of the trends.

Station	*p-value*	Trend (MK)	Theil-Sen's slope	Significance	Change %
Ghadames	0.216	0.787	0.067	NS	17.16
Gharyan	0.0.374	0.321	0.274	NS	6.91
Misurata	0.423	0.195	0.081	NS	1.96
Nalut	0.277	0.593	0.200	NS	11.04
Sirt	**0.0124**	**2.244**	**0.829**[a]	**S**	**36.88**
Tripoli Airport	**0.0611**	**-1.546**	**-0.686**[b]	**S**	**-20.04**
Tripoli	0.396	-0.262	-0.111	NS	-2.59
Zwara	0.197	0.851	0.384	NS	13.73
Az Zintan	0.149	1.040	1.253	NS	23.56
Ghariat	0.444	0.141	0.050	NS	3.7
Mizda	0.102	1.269	0.328	NS	26.24

Note: Bold values indicate statistically positive significant trends in [a] at p<0.05 (CV=1.645) and italic bold shows negative statistically significant trend in [b] at p<0.1 (CV=-1.282).

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