Journal of Geoscience and Environment Protection, 2017, 5, 31-53
http://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Statistical Analysis for Assessing Randomness, Shift and Trend in Rainfall Time Series under Climate Variability and Change: Case of Senegal

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How to cite this paper: Ndione, D.M., Sambou, S., Sane, M.L., Kane, S., Leye, I., Tamba, S. and Cisse, M.T. (2017) Statistical Analysis for Assessing Randomness, Shift and Trend in Rainfall Time Series under Climate Variability and Change: Case of Senegal. *Journal of Geoscience and Environment Protection*, **5**, 31-53.
https://doi.org/10.4236/gep.2017.513003

Received: October 28, 2017
Accepted: December 26, 2017
Published: December 29, 2017

Abstract

The main purpose of this study is to assess the climate variability and change through statistical processing tools that able to highlight annual and monthly rainfall behavior between 1970 and 2010 in six strategical raingauges located in northern (Saint-Louis, Bakel), central (Dakar, Kaolack), and southern (Ziguinchor, Tambacounda) part of Senegal. Further, differences in sensitivity of statistical tests are also exhibited by applying several tests rather than a single one to check for one behavior. Dependency of results from statistical tests on studied sequence in time series is also shown comparing results of tests applied on two different periods (1970-2010 and 1960-2010). Therefore, between 1970 and 2010, exploratory data analysis is made to give in a visible manner a first idea on rainfall behavior. Then, Statistical characteristics such as the mean, variance, standard deviation, coefficient of variation, skewness and kurtosis are calculated. Subsequently, statistical tests are applied to all retained time series. Kendall and Spearman rank correlation tests allow verifying whether or not annual rainfall observations are independent. Hubert's procedures of segmentation, Pettitt, Lee Heghinian and Buishand tests allow checking rainfall homogeneity. Trend is undertaken by first employing the annual and seasonal Mann-Kendall trend test, and in case of significance, magnitude of trend is calculated by Sen's slope estimator tests. All statistical tests are applied in the period of 1960-2010. Explanatory analysis data indicates upwards trends for records in northern and central and trend free for southern records. Application of multiple tests shows that the Kendall and spearman ranks correlation tests lead to same conclusion. The difference in tests sensitivity was shown by outcomes of homogeneity tests giving different results either in dates of the shift occurrence or in the significance of an eventual shift. A synthesis analysis of results of tests was carried out to conclude about rainfall behaviors. Tests for homogeneity show that southern rainfall is homogeneous, while northern and central ones are not. According to trend test, upwards trends in Northern and central rainfall trend free in southern assumption in exploratory data analysis have been confirmed. The Sen's slop estimator shows that all retained trend can be assumed to linear type. The same test over the period 1960-2010 shows independence of observations in all raingauges and exhibits neither trends nor breaks. This seems to show a return to a wet period.

Keywords

Senegal, Rainfall, Time Series, Test, Independence, Homogeneity, Shift, Trend

1. Introduction

Trend and shift detection in observed hydroclimatic records are important themes in hydrological sciences particularly in the scope of natural climate variability and potential climate change [1]. Climate change and climate variability are one of the most important threats facing humanity and the environment. Many scientific studies in hydroclimatic field are oriented towards determining the states, the causes and consequences of climate variability and change [2] [3]. According to these studies, climate change is due to increased greenhouse gas concentrations, while trend and shift in runoff time series data are consequence of climate change effects, land use change (urbanization, clearing, deforestation and others) or change in management practice [4] [5] [6].

The concept of climate change is not simply an assumption: it has been well assessed by many reliable climate models [7]. Shifts in hydrological time series and warming trends detected in several regions throughout the world are climate change indicators. Climate change has repercussions on environment, hydrological data and human economic and social activities [8]. The Tropical North Africa monsoon has decreased considerably, and depth of many lakes has diminished up to 100 m [9]. In West Africa, shifts in time series of rainfall have been observed: a wet period occurred between 1930 and 1960, a drought from 1970 to 1980 and gradual return of normal rains in the period from 1990 to 2000. Change in precipitation frequency, intensity, duration and consequently on the hydrological cycle has then been notified by many authors [4] [10]. In Senegal, this style of agricultural practice employs 77% of working people and supplies 12.4% of the daily food [11].

Adaptation strategies to climate related consequences require financial means and a good scientific and technical development level. Many approaches can be used to assess climate change.

The first step is the exploratory analysis. Exploratory data analysis is a way to detect visually obvious trend; random behavior in hydrological time series by plotting data is plotted against time rather than testing them. This method allows selecting the appropriate hypothesis for statistical tests [12] [13] [14]. Statistic tests are performed to check the assumed time series behavior (randomness, trend and shifts) from exploratory data analysis. This approach has been used as guidance for the purpose of choosing appropriate model distribution to fit non stationary time series; results show that this approach gives in prior a good overview of the adequate model distribution for given observations [15]. The conclusion found on the basis of exploratory data analysis must be verified using statistical tests. The descriptive statistical tools such as mean, variance, and standard deviation, coefficient of variation, skewness and kurtosis may provide information regarding rainfall changes and variability [16]-[21].

The independence between observations in rainfall time series is verified using non-parametric tests. The most tests in use for this purpose are the Pearson's coefficient (r), Spearman's rho coefficient (ρ) or the Kendall's coefficient (τ). It has been noticed that the Kendall's tau can be an alternative to Spearman's rho for ranked data [22]. So, in some degrees, correlation between observations in Spearman's rho and Kendall's tau tests for independence assessment is associated to presence of trend in time series [23] [24] [25]. Hence, null hypothesis of randomness H_0 is tested against alternative hypothesis H_1.

Many scientific studies focused on checking for shifts in rainfall time series. For example, the climate variability and its impact on water resources in Grand-Lahou in Ivory Coast was analyzed using the Pettitt and Buishand tests; shifts in time series of precipitation, characterized by a diminishing of about 13% to 28% of precipitations and of about 58% of flow rates was detected around 1966 and 1981 [26]. Climate variability in western and central Africa has been also studied; a reduction of about 20% of rainfall and of about 45% of flow rates was diagnosed around the year 1970 [27]. Elsewhere, the effect of the rainfall regime in Northern Morocco and its influence on the drought extension have been studied; breaks in stationarity of rainfall records, characterized by a diminishing of about 15% to 30% according to the considered part of the study area were found in 1968 and 1984. This study reveals also that significant drought formally settled at this location beyond 1970 [28]. A study was also carried out on analysis of precipitations in sixteen stations distributed from the zone with a Sahelian climate to that with a Soudanian one of Niger; the Pettit test shows between 1965 and 1971 a break in 75% of the studied annual precipitations [29]. The behavior of annual, seasonal and monthly rainfall was studied in Southwestern China and results show a slight increasing trend and heterogeneity in space of annual and seasonal precipitation. In addition, no significant trend was found for months January and February of the winter season, while in autumn, significant downward trend and a shift were detected [30]. The quasi-decadal variability of the rainfall in the Sahel has been studied. Results show a zonal contrast in rainfall behavior, but also a downward trend between the wet period ranging from 1950 to 1960 and the dry ones from 1970 to 1980 [10]. The variation of the volume of the Lake

Naivasha, trend, flow rate and local rainfall variability has been studied. Results show a globally homogeneous situation with nevertheless abrupt changes as well as in precipitations than in flows. In addition to this, a net diminishing of about 9.35×10^6 m^3 per year of the volume has been noticed [6]. It has been proven that changes in rainfall characteristics are one of the most relevant signs showing current climate alterations [31]. As well as many countries in Western and Central Africa, the Senegal faces climate change and climate variability effects.

This study focuses on assessment of annual and monthly rainfall behavior through Senegal. For that, six rain gauges located in the North (Saint-Louis (SL) and Bakel (BK)), the central (Dakar (DK) and Kaolack (KL)) and the south (Ziguinchor (ZG) and Tambacounda (TC)) of Senegal have been selected. The used rainfall records cover the period from 1960 to 2010. First, the post-1970 rainfall series are analyzed in order to determine the behavior of corresponding states, and this is due to the fact that 1970 characterize the decline of precipitation in Senegal surrounding. In this period (1970-2010), exploratory data analysis involving analysis of histograms and moving average curves is made to detect obvious randomness, shift or trend in records. Furthermore, statistical characteristics such as the mean, the standard deviation, the coefficients skewness and kurtosis have been estimated. Taking into account the subjectivity of exploratory data analysis approach, statistical tests for randomness (Kendall and Spearman rank correlation tests), shift (Pettitt and Buishand tests; Lee-Heghinian and Hubert procedures) and trend (Mann-Kendall and Sen's tests) are applied to time series. Trend tests are also applied in monthly and seasonal scale. Indeed, application of multiple tests to check for a same behavior in a time series is done on one hand for exhibiting unlikeness of tests in term of sensitivity and on one other to confirm or to reject the hypothesis to test using conclusion on the basis of majority balance sheet. Then, the same statistical tests (randomness, shift and trend) will be applied to the period from 1960 to 2010 in order to highlight the dependency of results from statistical tests on interested interval of the time series.

2. Materials and Methods

2.1. Data and Study Area

Senegal is located in the most extreme part West Africa between latitudes of 12˚8N - 16˚41N and longitudes of 11˚21 - 17˚32O. Its area is estimated about 196,712 km^2. The climate in this country is constituted by two seasons: a rainy season from June to October and a dry one from November to May. The rainy season seldom exceeds four months. Data used in this study are obtained from the database of the National Civil Aviation and Meteorological Agency of Senegal (ANACIM) and are composed by annual and monthly rainfall depth gauged in following stations: Saint-Louis (SL), Bakel (KL), Dakar (DK), Kaolack (KL), Ziguinchor (ZG) and Tambacounda (TB) in the time interval of 1960-2010. Position of exploited raingauges through the area of Senegal is shown in **Figure 1**.

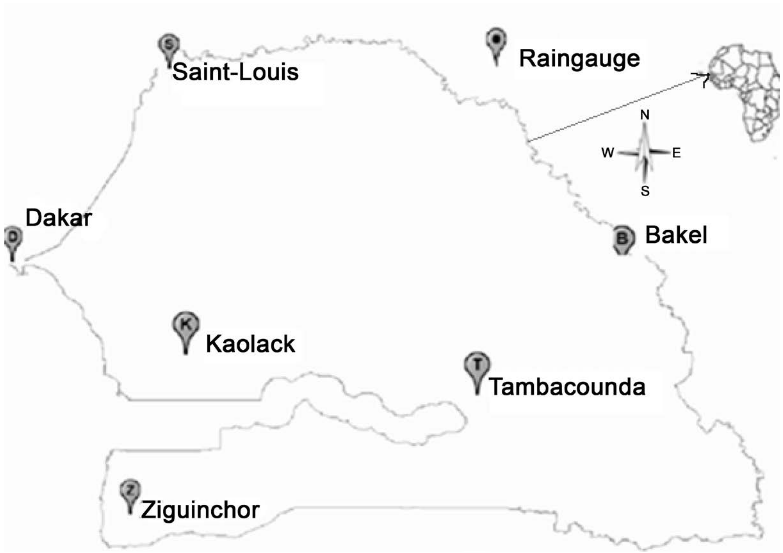

Figure 1. Position of raingauges through the study area.

Table 1. Information on the used raingauges and exploited data.

Station	*Station ID*	*Location* Longitude	Latitude	*Data (mm)*	*Period of record*
Saint-Louis	38004500	−16.05˚	16.05˚	Annual and monthly rainfall	1970-2010
Bakel	38007200	−12.45˚	14.90˚	Annual and monthly rainfall	1970-2010
Dakar	38008100	−17.5˚	14.73˚	Annual and monthly rainfall	1970-2010
Kaolack	38009700	−16.07˚	14.13˚	Annual and monthly rainfall	1970-2010
Ziguinchor	38013700	−16.27˚	12.55˚	Annual and monthly rainfall	1970-2010
Tambacounda	38011300	−13.68˚	13.77˚	Annual and monthly rainfall	1970-2010

Table 2. Climate characteristics in region surrounding raingauges.

Station \ *Characteristic*	$M_{max.}$ *TDS* (˚C)	$M_{max.}$ *TRS* (˚C)	$M_{min.}$ *TDS* (˚C)	$M_{min.}$ *TRS* (˚C)	*Max. TDS* (%)	*Max. TDS* (%)	*Min. TDS* (%)	*Min. TDS* (%)	*MMCEDS* (*mm*)	*MMCEDS* (*mm*)
Saint-Louis	31.8	31.9	17.7	24.2	81.9	92.7	34.0	61.3	5.2	2.9
Bakel	38.2	36.6	21.9	24.5	45.3	85.6	18.6	46.4	11.2	11.2
Dakar	26.1	29.9	19.3	24.6	90.6	89.9	55.5	67.7	3.0	2.5
Kaolack	37.7	34.9	19.7	24.2	67.6	93.1	22.5	50.3	6.8	2.9
Ziguinchor	36.3	32.8	20.2	21.5	88.8	97.1	30.1	62.1	3.9	1.6

In Table 1, raingauges characteristics, rainfall patterns and period of records are listed. In addition, for each station, mean of maximum temperature during the dry and the rainy season (M_{max} TDS and M_{max} TRS) is shown in Table 2 which mean of minimum temperature during the dry and the rainy season (M_{min} TDS and M_{min} TRS), maximum of the air moisture during the dry and the rainy season (Max. AMDS and Max. AMRS), minimum of the air moisture during the dry and the rainy season (Min. AMDS and Min. AMDS) and mean monthly of cumulative evaporation during the dry and the rainy season (MMCEDS and MMCERS).

2.2. Exploratory Data Analysis and Descriptive Statistic Tools

In this study, the first step in assessment of the rainfall behavior is exploratory data analysis. This is a graphical method in which data are plotted versus time. It allows visually checking out for randomness, shift or trend in time series observing histograms and moving average curves [12] [13]. The exploratory data analysis is a subjective method and is completed in this study by statistical tests. Descriptive statistic tools are used estimating statistic parameters of the time series (mean, standard deviation, coefficient of variation) and the probability distribution (kurtosis, skewness). The use of above statistical tools allows having an overview on variability of the data through the study area and their dispersion [19]. Indeed, the normal distribution is used as standard base for characterizing probability distribution of the data [19] [32].

2.3. Tests for Checking Independency of the Data in a Time Series

The Kendall and the Spearman rank correlation test ([33] [34] [35] [36] [37]) are applied in this paper to check for randomness of observations in time series. For both tests, the null hypothesis H_0 is the randomness of occurrences and significant level is fixed at 5%. We shortly describe the two tests below.

2.3.1. Kendall's Rank Correlation Test

The Kendall's rank correlation test is used to test the significance of random behavior or trend in hydroclimatic time series. It is an efficient tool for verifying linear behavior in time series, and is also referred as τ test. The Kendall's rank correlation test is based on determining a P number of the subsequent pairs (x_i, x_j) in the time series satisfying $x_i < x_j\ (i < j)$ [24] [25] [38]. For a given time series $X_i\ (i = 1, 2, 3, 4, \cdots, N)$, P is calculated using all (x_i, x_j) combinations, with: $i = 1, 2, \cdots, N-1$ and $j = i+1, \cdots, N$. The Kendall τ statistic to be tested is assumed to be of zero mean with its standard deviation are given by two following equations [24] [25]:

$$\tau = \frac{4P}{N(N-1)-1} \tag{1}$$

$$\sigma(\tau) = \left[\frac{2(2n+5)}{9n(n-1)}\right]^{1/2} \tag{2}$$

The corresponding standardized statistic Z is given by:

$$Z = \frac{\tau}{\sigma(\tau)} \tag{3}$$

The null hypothesis H_0 is accepted when Z belongs to the confident interval:

$$\left[Z_{1-\alpha/2}\sigma(\tau), -Z_{1-\alpha/2}\sigma(\tau)\right] \tag{4}$$

2.3.2. Spearman's Rank Correlation Test

The number of observations noticed by N in the time series is first classified in ascending order. Then, the rank of each observation corresponds to its position in the classification is considered [22] [38]. If R_{x_i} and R_{y_i} represent the observations of x_i and y_i respectively, the Spearman's ρ statistic is given by:

$$\rho = \frac{\left(\sum_1^N R_{x_i} R_{y_i} - \frac{\sum_1^N R_x \sum_1^N R_{y_i}}{N}\right)}{\left(\sqrt{\left(\sum_1^N R_{x_i}^2 - \frac{\left(\sum_1^N R_{x_i}\right)^2}{N}\right)\left(\sum_1^N R_{y_i}^2 - \frac{\left(\sum_1^N R_{y_i}\right)^2}{N}\right)}\right)} \tag{5}$$

If the number of the observations exceeds 10, the Student t-test can be used rather than the statistic table of Spearman. Then the statistic variable for the test is:

$$t = \rho \sqrt{\frac{(N-2)}{(1-\rho^2)}} \tag{6}$$

For $\alpha = 0.05$, the null hypothesis H_0 of randomness is accepted if $|t| \le 2.023$.

2.4. Tests for Shifts Detection

Observations in time series are assumed to be homogeneous if all data in the times series can be considered as belonging statistically to the same population, that is that they simply follow the same statistical distribution law [24] [39] [40]. In this study, we use Hubert procedure of segmentation of time series, Lee-Heghinian procedure, Pettitt and Buishand [24]. The null hypothesis H_0 is the homogeneity of the time series and the significance level is of $\alpha = 0.05$. These tests are briefly described below.

2.4.1. Hubert Procedure of Segmentation

In the Hubert's process, the time series is divided into consecutive segments m, with $m > 1$ and satisfying the Scheffe's test [24]. Means of different segments must be significantly different to the mean of the raw data. The tests in Hubert procedure of segmentation, involves the use of the quadratic deviation D_m between row observations and the means of all m retained segments, is estimated for the statistic test. Let's consider $i_k\ (k = 1, 2, \cdots, m)$ the rank of the last observation of a k^th^ validate segment in the raw time series X_t, the spread and the mean of corresponding segment shall be respectively:

$$n_k = i_k - i_{k-1} \tag{7}$$

$$\overline{x}_k = \frac{1}{n_k} \sum_{i=i_{k-1}+1}^{i_k} x_i \text{ whith } i_0 = 0 \tag{8}$$

For a considered series X_t, segmented into m sequences, the quadratic deviation, noticed by D_m, is given by the formula:

$$D_m = \sum_{k=1}^{m} d_k \tag{9}$$

$$d_k = \sum_{i=i_{k-1}+1}^{i_k} \left(x_i - \overline{x}_k\right)^2 \tag{10}$$

An acceptable segmentation must verify the Scheffe's test condition in which D_m is constrained to be minimal and the mean of the contiguous segments $\overline{x}_k \neq \overline{x}_{k+1}$ significantly different.

2.4.2. Procedure of Lee-Heghinian (L-H)

This is a procedure of Bayesian type that is based on an assumption of a single shift in the time series. Variables are supposed in prior independence and uniformly distributed. This model project requires a consideration of following characteristics of the times series: the timing of the shift occurrence noted $\tau_s \left(1 \le \tau_s \le N-1\right)$, the magnitude of the change in the mean noted δ, the mean of overall data noted by μ and the residual component ε_i that is a normal and random variable with zero mean and variance σ^2. In this study, the approach used is only based on posterior marginal distributions of the shift position in time τ_s [24] [41]. Then, the basic mathematical formulation of the Procedure is:

$$x_i = \begin{cases} \mu + \varepsilon_i & \text{if } i = 1, 2, \cdots, \tau_s \\ \mu + \varepsilon_i + \delta & \text{if } i = \tau_s + 1, \cdots, N \end{cases} \tag{11}$$

In Equation (11) ε_i are fluctuations around the mean that are assumed random and normal variables with zero mean and unknown variance σ^2. The variables μ, τ_s and δ are respectively the mean, the shift timing and the magnitude of the change. Considering that the prior probability density of τ_s is uniform, hence, its posterior probability will be:

$$P\left(\frac{\tau_s}{X}\right) \propto \left[\frac{N}{\tau_s\left(N-\tau_s\right)}\right]^{1/2} \left[R\left(\tau_s\right)\right]^{-(N-2)/2} \quad \text{for} \left(1 \le \tau_s \le N-1\right) \tag{12}$$

with

$$R\left(\tau_s\right) = \frac{\left[\sum_{i=1}^{\tau_s}\left(X_i - \overline{X}_{\tau_s}\right)^2 + \sum_{i=\tau_s+1}^{N}\left(X_i - \overline{X}_{N-\tau_s}\right)^2\right]}{\sum_{i=1}^{N}\left(X_i - \overline{X}_N\right)^2} \tag{13}$$

where: $\overline{X}_N = 1/N \sum_{i=1}^{N} X_i$ (Mean of the raw data); $\overline{X}_{\tau_s} = 1/\tau_s \sum_{i=1}^{\tau_s} X_i$ (Mean before date of the shift); $\overline{X}_{N-\tau_s} = 1/N - \tau_s \sum_{i=\tau_s+1}^{N} X_i$ (Mean after date of the shift).

In cases of unimodal distribution, the shift point is estimated by the mode of above marginal posterior distribution of τ_s.

2.4.3. Pettitt Test

The Pettitt test is a nonparametric test derived from the Mann-Whitney test. It has been formulated to test homogeneity against shift in a time series [24] [26]. In this approach, a shift point timing at τ_s indicates that the time series can be divided into two subsequences $x_t\left(t=1,2,3,\cdots,\tau_s\right)$ and $x_t\left(t=\tau_s+1,N\right)$. Thus, probability distribution functions $F_1\left(X\right)$ and $F_2\left(X\right)$ can be associated to the two subsequences respectively. In practice, the null hypothesis H_0 is $F_1\left(X\right)=F_2\left(X\right)$ and the alternative hypothesis H_1 is $F_1\left(X\right)\neq F_2\left(X\right)$ [24]. This method involves also a comparison of the observations so that:

$$D_{i,j}=\operatorname{sgn}\left(x_i-x_j\right)\begin{cases}1 & \text{if } \left(x_i-x_j\right)>0\\ 0 & \text{if } \left(x_i-x_j\right)=0\\ -1 & \text{if } \left(x_i-x_j\right)<0\end{cases} \tag{14}$$

Then for the implementation of the statistic variable to use for the test, a basic variable $U_{\tau_s,N}$ is defined as:

$$U_{\tau_s,N}=\sum_{t=1}^{\tau_s}\sum_{t=\tau_s+1}^{N}D_{i,j}, 1\leq\tau_s\leq N \tag{15}$$

Using the theory on statistic ranks, another K_N variable is derived from $U_{\tau_s,N}$. This new variable is defined as [42]:

$$K_N=\max\left|U_{\tau_s,N}\right|\ \left(\tau_s=1,2,\cdots,N-1\right) \tag{16}$$

For the test, a probability of exceedance is fixed for a threshold value k given by the formula:

$$P\left(K_N>k\right)\cong\frac{6\exp\left(-6k^2\right)}{\left(N^3+N^2\right)} \tag{17}$$

The null hypothesis, H_0 is rejected if the probability of exceedance given in equation 17 is less than the significant level α for a one-sided statistic test. Hence, the shift in the time series is observed at the time $\tau_s=t$ corresponding to the date of the occurrence of the retained K_N.

2.4.4. Buishand's U Statistic and Bois's Ellipse

The Buishand's U statistic is inferred from a formulation of shift point detecting in Gardne, 1969 [43]. This test is performed under assumption of a single shift in mean of the time series with unknown variance [24] [39]. The method requires normal distribution of the data, then, under the above single shift assumption, the time series is modeled as follow:

$$x_i=\begin{cases}\mu+\epsilon_i & \text{for } i\in 0,\tau_s\\ \mu+\epsilon_i+\delta & \text{for } i\in\tau_s+1,N\end{cases} \tag{18}$$

where ϵ_i are fluctuations around the mean that are assumed random and normal variables with zero mean and unknown variance σ^2. In Equation (18), μ,τ and δ are the same that of define in the Lee-Heghinian test (Equation (11)). The statistic test in this approach is performed on the basis of cumulative deviation from the mean given by:

$$S_k=\sum_{i=1}^{k}\left(x_i-\overline{x}\right)\text{ with } S_0=0; k=1,\cdots,N \tag{19}$$

S_k is assumed to be normally distributed with zero mean. The Buishand's U is then defined using S_k and replacing the unknown variance by that of the raw data noticed by D_x^2 (Equation (21)). The U is expressed as:

$$U = \left(N\left(N+1\right)\right)^{-1} \sum_{k=1}^{N-1} \left(S_k / D_x\right)^2 \tag{20}$$

$$D_x^2 = N^{-1} \sum\nolimits_{i=1}^{N} \left(X_i - \overline{X}\right)^2 \tag{21}$$

The test is made using an estimate of above unknown variance expressed in Equation (18). Estimate of the unknown is carried out to define the confident limit and is given by:

$$\hat{\sigma}^2 = k\left(N-k\right)\left(N-1\right)^{-1} D_x^2, k = 0, \cdots, N \tag{22}$$

The confidence interval that should contain the Buishand's U if the null hypothesis is accepted is given by an ellipse of control. The function defining the ellipse is implemented employing the estimate $\hat{\sigma}^2$ [39]:

$$\pm \left(U_{1-\frac{\alpha}{2}\sqrt{k(N-k)}} \right) \Big/ \sqrt{N-1}\, D_x \tag{23}$$

For a given significant level α, the null hypothesis H_0 is rejected if the Buishand's U goes out of the confidence area surrounded by the ellipse of control.

2.5. Tests for Trend Detection and Moving Average Curve

Trend tests are used in time series analysis to determine the direction of the data overall evolution in time. A declared trend indicates increasing or decreasing evolution in measured observations. It is important to highlight the fact that trend free in time series doesn't mean a case of equality in records. These tests are used in this study to supplement the graphical approach (Exploratory Data Analysis) in which histograms moving average curves was exploited. The moving average method filters the obvious irregularities in the time series [25]. The annual Mann-Kendall test is called upon for trend assessment in the annual rainfall depth. Then the Sen's slope estimator is used to estimate the linearity of the trend and its magnitude. The seasonal and monthly tests of Mann-Kendall are also carried out to complete the rainfall trend investigation.

2.5.1. Linear Moving Average Filtering Method

The moving average curve (MA) aims to filter short-term effects in time series. This approach of trend assessment involves weighting of a limited range of ($2k+1$) values of the raw time series X_t to transform it seems to be the most commonly used type [25]. Then, a new transformed series Y_t is obtained with substantial reduction of original short-term fluctuations:

$$Y_t = \frac{1}{\left(2k+1\right)^{-1}} \sum_{j=-k}^{k} X_{t+j} \tag{24}$$

2.5.2. The Man-Kendall Test

The Mann-Kendall (M-K) test is use in time series analysis to detect a trend and its direction without specifying whether the trend is linear or not [44]. The method is based on one statistic *S*. The statistic *S* is determined by result from a comparison between each pair of observations (x_i, x_j) with $i < j$, to find out, $x_i > x_j$, $x_i < x_j$ or $x_i = x_j$. A score of 1, −1 or 0 is associated for each case depending on the sign of the difference between pairs. Then explicitly, the M-K *S* statistic to be tested defined as [25] [45] [46] [47] [48] [49]:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \operatorname{sgn}(x_j - x_i) \tag{25}$$

With

$$\begin{cases} \operatorname{sgn}(x_j - x_i) = 1 & \text{if } (x_j - x_i) > 0 \\ \operatorname{sgn}(x_j - x_i) = 0 & \text{if } (x_j - x_i) = 0 \\ \operatorname{sgn}(x_j - x_i) = -1 & \text{if } (x_j - x_i) < 0 \end{cases} \tag{26}$$

A negative value of *S* indicates falling trend, while a positive value of the *S* indicates rising trend. Then, the *S* is assumed to be independent and normally distributed with zero mean and variance given by:

$$\operatorname{Var}(S) = \frac{N(N-1)(2N+5)}{18} \tag{27}$$

Hence, the *Z* normal standard distribution of the M-K *S* can be defined as:

$$\begin{cases} Z = \dfrac{(S-1)}{\sqrt{\operatorname{var}(S)}} & \text{if } S > 0 \\ Z = 0 & \text{if } S = 0 \\ Z = \dfrac{(S-1)}{\sqrt{\operatorname{var}(S)}} & \text{if } S < 0 \end{cases} \tag{28}$$

The null hypothesis H_0 is accepted if the *P* value exceeds 0.05.

2.5.3. Sen's Slope Estimator

In this method, for each pair of observations (x_i, x_j) an associated slope can naturally be given as:

$$S_{i,j} = \frac{x_j - x_i}{j - i} \tag{29}$$

where x_j and x_i are observations at time *j* and *i* $(i < j)$ respectively. In a sample of size *N*, the number of slopes one can obtained is given by $n = N(N-1)/2$. The Sen's slope estimator is given by the median slope estimated after ranking the n slopes in an increasing order. If n is odd number, the median slop (MS) is given by the formula: $Q_{[(n+1)/2]}$, while, if it is even by $\left\{Q_{n/2} + Q_{[(n+2)/2]}\right\}/2$. The null hypothesis is accepted if the estimated median slope is within the range of $\left[(n - C_\alpha)/2 \text{ and } (n + C_\alpha)/2\right]$, where $C_\alpha = Z_{1-\frac{\alpha}{2}} \sqrt{\operatorname{Var}(S)}$ is a standardized Gaussian statistic and α is the significance level. $\operatorname{Var}(S)$ is calculated using Equation (27), in the assumption of no tied value in the time series [35] [36] [47] [50] [51].

3. Results and Discussion

3.1. Exploratory Analysis of Data

Figure 2 presents the temporal variation of annual rainfall for all rain gauges by the mean of histograms and moving average curves of order 2 (MA.2). In exploratory analysis, shifts are not obvious, while random behavior for Ziguinchor (Figure 2(e)) and Tambacounda (Figure 2(f)) can be assumed. Furthermore, upwards trends seam to appear for Saint-Louis (Figure 2(a)), Dakar (Figure 2(c)), Bakel (Figure 2(b)) and Kaolack (Figure 2(d)) raingauges, while Tambacounda and Ziguinchor seem to be trend free.

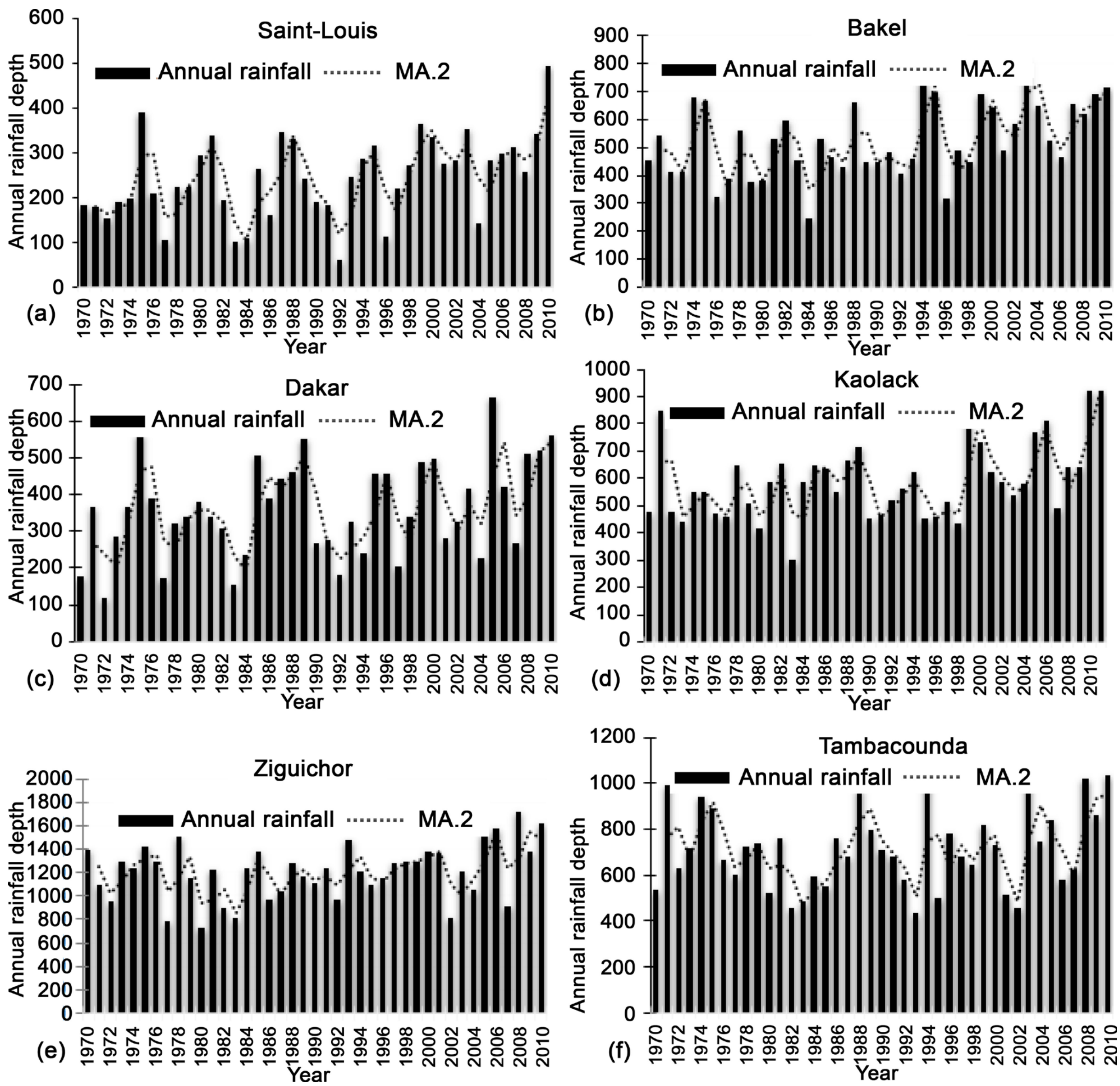

Figure 2. Evolution of annual rainfall between 1970 and 2010.

3.2. Statistical Characteristics of Annual Rainfall

The statistical characteristics of the annual rainfall are given in Table 3. The analysis of the means (Figure 3(a)) and the standard deviation over the period of 1970-2010 shows that the rainfall decreases from South to North and from East to West. The coefficient of variation decreases as the rainfall increases in magnitude (Figure 3(b)). So, the less the rainfall the unsteady they are. Distributions of annual rainfall are positively skewed for all rain gauges except that at Ziguinchor and are all platykurtic except that at Kaolack.

Table 3. Statistical characteristics of annual rainfall.

Station	*Mean* (*mm*)	*Standard deviation* (*mm*)	*Coefficient of variation*	*Skewness*	*Kurtosis*
Saint-Louis	243.91	90.68	0.37	0.19	−0.09
Bakel	526.96	129.63	0.25	0.14	−0.75
Dakar	360.86	128.58	0.36	0.16	−0.68
Kaolack	582.91	132.57	0.23	0.65	0.32
Ziguinchor	1208.93	233.89	0.19	−0.09	−0.47
Tambacounda	716.80	175.47	0.24	0.39	−0.74

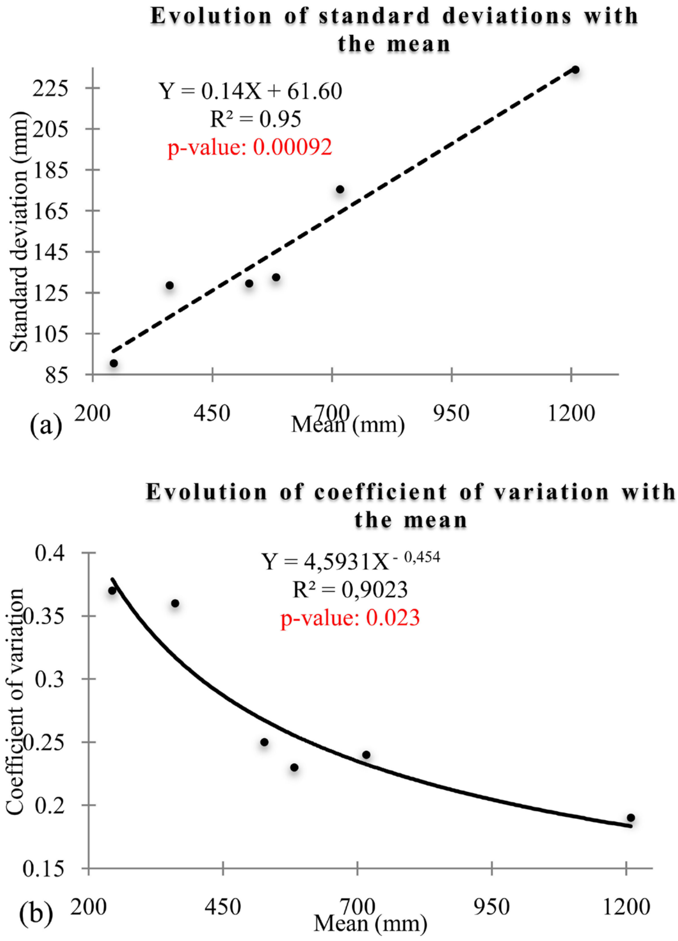

Figure 3. Evolution of standard deviations and coefficients of variation against the mean.

3.3. Synthesis of Tests for Independence

Results of independency test for all times series using Kendall tau and Spearman rho tests are presented in Table 4. It has been noticed that both above tests lead to same results: the null hypothesis of independence (I) is rejected for all rain gauges except for Ziguinchor and Tambacounda. For Saint-Louis, Bakel, Dakar and Kaolack, observations in time series are correlated (C). A special view of the results is given in Figure 4(a).

3.4. Synthesis of Tests for Homogeneity

The results of all homogeneity tests for annual rainfall between 1970 and 2010 are presented in Table 5. For raingauges at Saint-Louis and Bakel, the null hypothesis of homogeneity of rainfall time series is rejected for all tests. For Dakar and Kaolack, null hypothesis is rejected by three of the four tests, while for Ziguinchor and Tambacounda null hypothesis is rejected by two among the four tests. So, we finally consider that a rainfall time series is non-homogeneous when null hypothesis is rejected by at least three tests among the applied four. This is the case of Saint-Louis, Bakel, Dakar and Kaolack where rainfall time series are

Table 4. Results of tests for independence.

Test \ *Raingauge*		*Saint-Louis*	*Bakel*	*Dakar*	*Kaolack*	*Ziguinchor*	*Tambacounda*
Kendall	Kendall's τ	0.30	0.33	0.24	0.22	0.19	0.10
	Z Statistic	2.78	3.10	2.18	2.10	1.73	0.94
	H_0	Rejected	Rejected	Rejected	Rejected	Accepted	Accepted
	Conclusion	Correlated	Correlated	Correlated	Correlated	Independent	Independent
Spearman	Spearman's ρ	−0.436	−0.438	−0.323	−0.321	−0.239	−1.151
	Z Statistic	−3.027	−3.042	−2.135	−2.119	−1.540	−0.953
Spearman	H_0	Rejected	Rejected	Rejected	Rejected	Accepted	Accepted
	Conclusion	Correlated	Correlated	Correlated	Correlated	Independent	Independent

H_0: Null hypothesis.

Table 5. Results of tests for homogeneity of rainfall time series from 1970 and 2010.

Test \ *Raingauge*		*Saint-Louis*	*Bakel*	*Dakar*	*Kaolack*	*Ziguinchor*	*Tambacounda*
Hubert	H_0	Rejected	Rejected	Rejected	Rejected	Rejected	Rejected
	Date of shift	1997	1998	2004	1998	2004	2007
Pettitt	H_0	Rejected	Rejected	Accepted	Accepted	Accepted	Accepted
	Date of shift	1997	1993	Non shift	Non shift	Non shift	Non shift
Buishand	H_0	Rejected	Rejected	Rejected	Rejected	Accepted	Accepted
	Conclusion	Shift	Shift	Shift	Shift	Non shift	Non shift
L-H	Date of shift	2009	1998	2004	1998	2007	2007

L-H: Lee-Heghinian; H_0: Null hypothesis.

shifted. For Ziguinchor and Tambacounda, rainfall time series are assumed to be homogeneous. When H_0 is rejected, the dates of shift occurrence often vary from a raingauge to another and also from a test to another. So, we retain as date of shift occurrence in time series, the one indicated by the maximum of tests. Thus, shift occurred at 1997 at Saint-Louis, 1998 at Bakel, and 2004 at Dakar. Zones with and without shifts in rainfall time series through the study area are shown in Figure 4(b).

3.5. Synthesis of Results from Trend Assessment: M-K Test and Sen's Slope Estimator

Tests for trend (M-K and Sen) for all rain gauges are summarized in Table 6.

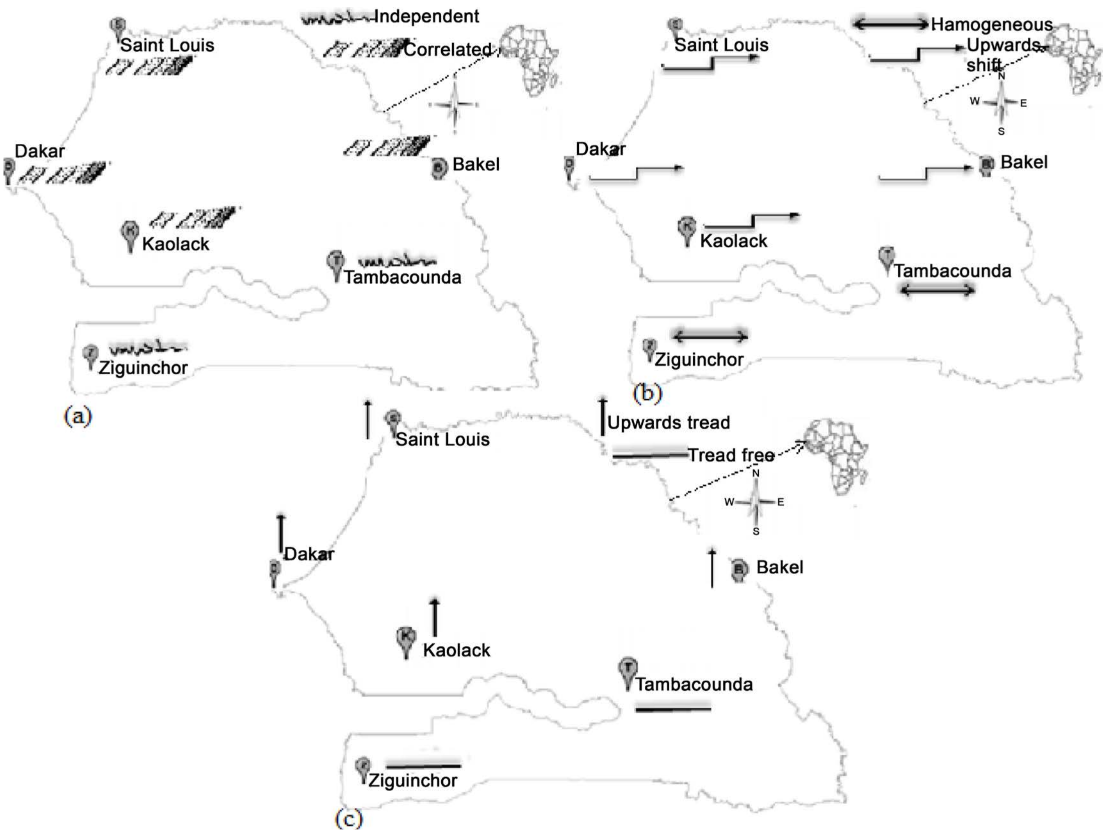

Figure 4. Results of tests for independency, shift and trend in the study area from 1970 to 2010.

Table 6. Results of trend tests for rainfall series from 1970 to 2010.

Test	Raingauge	*Saint. Louis*	*Bakel*	*Dakar*	*Kaolack*	*Ziguinchor*	*Tambacounda*
	Mann-Kendall Statistic (M-KS)	2.77	3.74	2.17	2.07	1.92	1.93
M-K	H_0	Rejected	Rejected	Rejected	Rejected	Accepted	Accepted
	conclusion	UT	UT	UT	UT	TF	TF
	Median Slope (MS)	3.21	4.71	4.27	7.35	6.48	2.64
Sen's	H_0	Accepted	Accepted	Accepted	Accepted	Accepted	Accepted
	conclusion	NLT	NLT	NLT	NLT	NLT	NLT

UT: Upwards trend; NLT: Nonlinear trend; H_0: Null hypothesis.

The M-K test is first applied to look for trend significance. Where trend exists, Sen's slope estimator is used to verify whether it can be considered as of a linear type, then its magnitude. The M-K test detects upwards trend (UT) for rainfall at Saint-Louis, Bakel, Dakar and Kaolack. According to the Sen's slope estimator, existing trends are of nonlinear type (NLT). In the study area, reparation in space of studied rainfall time series with and without trend are shown in **Figure 4(c)**.

3.6. Results of Tests for Trend at Monthly and Seasonal Scale

The seasonal and monthly M-K tests are applied from 1970 to 210. **Table 7** presents the results of the seasonal M-K test, while in **Table 8** are presented results in monthly scale. The seasonal M-K test accepts null hypothesis of no trend for all raingauges and for all seasonal time series except the months of June and September for the raingauge at Kaolack and the month of September for the raingauge at Ziguinchor. At monthly scale no trend has been detected by the M-K tests, although trends have been detected at annual scale.

3.7. Relativity of Results from Statistical Tests: Dependency of Statistical Tests Issues to Period of Study

In this part of the study, we try to know how the period of study impacts the results of the test. We consider two periods of study: 1960-2010 and 1970-2010. The same tests for independency, homogeneity and trend are applied on the two periods and for all raingauges. In this section, indices of (+) is used to define acceptation of the null hypothesis and (−) for its rejection.

3.7.1. Dependency of Results Independency Tests Issues to Period of Study

We compare in **Table 9** the results of tests for independence for the two periods

Table 7. Results of the M-K at seasonal scale between 1970 and 2010.

MONTH	OBSERVATION	STATISTIC	Z STATISTIC	P VALUE	NULLE HYPOTHESIS
		STATION OF KAOLACK			
JUN	41	222	2.493	0.012	Rejected
SEPTEMBER	41	194	2.179	0.029	Rejected
		STATION OF ZIGUINCHOR			
SEPTEMBER	41	183	2.055	0.040	Rejected

Table 8. Results of the M-K at monthly scale between 1970 and 2010.

VARIABLE \ STATION	SAINT-LOUIS	BAKEL	DAKAR	KAOLACK	ZIGUINCHOR	TAMBACOUNDA
LENGTH (MONTH)	492	492	492	492	492	492
Z STATISTIC	0.301	2.530	1.519	0.161	1.855	-0.049
P VALUE	1.193	0.011	0.129	0.031	0.063	0.961
H_0	Accepted	Accepted	Accepted	Accepted	Accepted	Accepted

H_0: Null hypothesis.

Table 9. Results of independence tests for the two periods in comparison.

PERIOD		1960-2010						1970-2010					
TEST	STATION	SL	BK	DK	KL	ZG	TB	SL	BK	DK	KL	ZG	TB
KENDALL RANK TEST	H_0	+	+	+	+	+	+	−	−	−	−	+	+
	conclusion	C	C	C	C	C	C	C	C	C	C	I	I
SPEARMAN RANK TEST	H_0	+	+	+	+	+	+	−	−	−	−	+	+
	conclusion	I	I	I	I	I	I	C	C	C	C	I	I

C: correlated; I: independent; H_0: Null hypothesis; +: H_0 accepted; −: H_0 rejected.

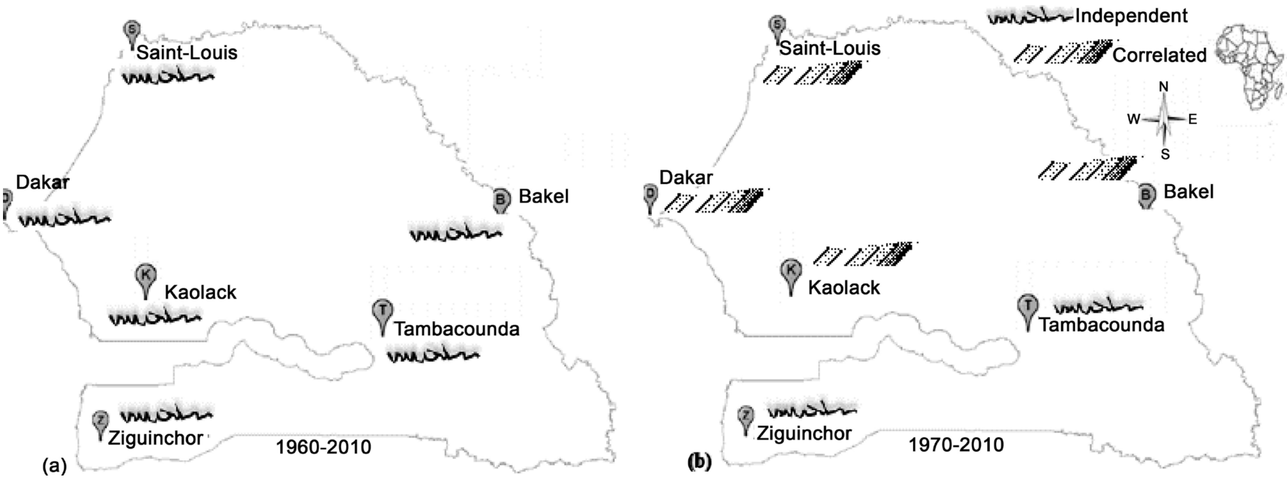

Figure 5. Effect of the period on tests for independence.

of study. The period of study does not impact the results of the test for Ziguinchor and Tambacounda raingauges. We note that annual rainfall is more important for these stations. Figure 5(a) & Figure 5(b) shows locations where outcomes of randomness tests were impacted or not by the variation in time series sequence.

3.7.2. Dependency of Homogeneity Tests Issues to Period of Study

Comparison of the test for homogeneity for the two is presented in Table 10. According to this table, the effect of the period is evident on the results of the tests for homogeneity (H). Over the period 1960-2010, most of these tests detected a shift around the 1970s in a sense of a decrease in rainfall. Over the period 1970-2010, the shifts generally appear later and indicate an increase in rainfall. This seems to confirm a return to rainfall observed in West Africa We focus on the Hubert procedure of segmentation. This method allows detecting many shifts (S) in a time series. In the period 1960-2010, only the first shift indicating a diminishing of rainfall is generally observed; the second shift indicating an increase in rainfall is not enough significant to appear. But in the period 1970-2010, the effect of rainfall of years 1960's disappears, and the shift in the sense of increasing of rainfall can now be notified. Figure 6(a) & Figure 6(b) shows locations where outcomes of shift detection tests were impacted or not by the variation in time series sequence.

Table 10. Results of homogeneity tests for the two periods in comparison.

PERIOD		1960-2010						1970-2010					
TEST	STATION	SL	BK	DK	KL	ZG	TB	SL	BK	DK	KL	ZG	TB
HUBERT	H_0	–	+	–	–	+	–	–	–	–	–	–	+
	Conclusion	1969	H	1969	1971	H	1966	1997	1998	2004	1998	2004	2007
PETTITT	H_0	+	+	+	+	–	–	–	+	+	+	+	+
	Conclusion	H	H	H	H	H	1975	1997	1993	H	H	H	H
BUISHAND	H_0	+	+	+	+	+	+	+	+	+	+	+	+
	Conclusion	H	H	H	H	H	S	S	S	S	S	H	H
L-H	Conclusion	1969	1998	1969	1967	1960	1966	2009	1998	2004	1998	2007	2007

h: Homogeneous; s: shift; L-H: Lee-Heghinian; H_0: Null hypothesis; +: H_0 accepted; –: H_0 rejected.

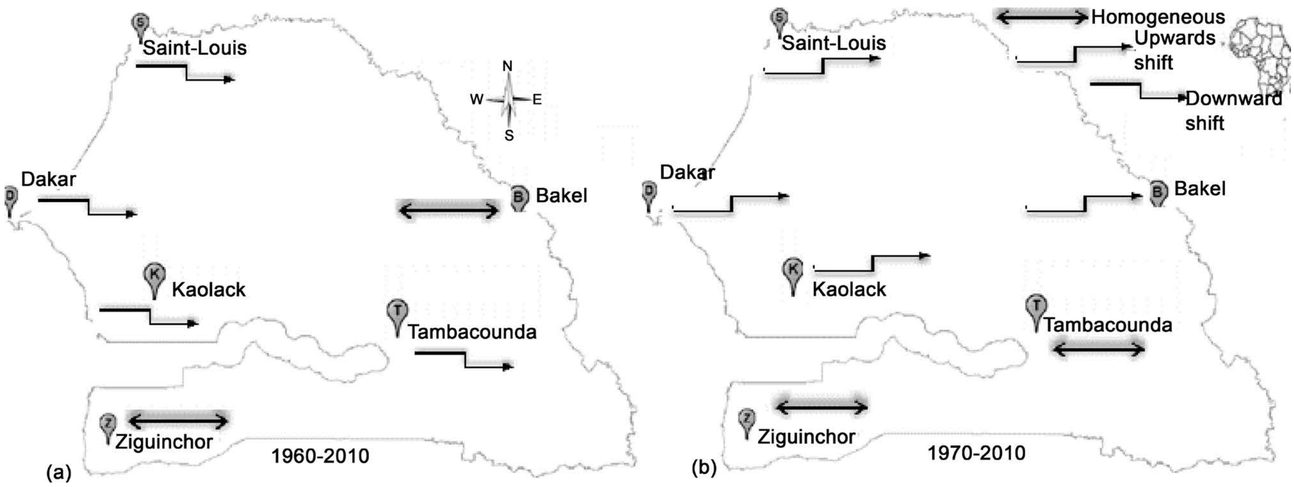

Figure 6. Effect of the period on tests for homogeneity.

3.7.3. Dependency of Trend Tests Issues to Period of Study

Results of tests for trend between the two periods are compared in Table 11. The application of the tests for trend between 1960 and 2010 does not detect any trend. For the period 1970 to 2010, we note upward trends (UT) in Central and Northern Senegal, while annual rainfall in Southern (Tambacounda and Ziguinchor) are trend free (TF). The period of study doesn't impact Ziguinchor and Tambacounda raingauges. For the other stations, upwards trend during the second period seems to indicate a come back to a rainy period. Locations where outcomes of trend tests were impacted or not by the variation in time series sequence are indicated in Figure 7(a) & Figure 7(b).

4. Conclusion

Through exploratory data analysis, an overview on distribution of rainfall depth in Senegal and an assumption about upward trend in rainfall in its northern and central parts are obtained. This approach shows that rainfall depth is more important in the south and has increasing evolution in central and northern part

Table 11. Results of trend tests for the two periods in comparison.

Tests \ Period / Station		1960-2010 SL	BK	DK	KL	ZG	TB	1970-2010 SL	BK	DK	KL	ZG	TB
M-K	H_0	+	+	+	+	+	+	−	−	−	−	+	+
	M-KZS	0.32	−0.50	1.04	0.28	−0.66	−0.82	2.77	3.74	2.17	2.07	1.92	1.93
	Conclusion	TF	TF	TF	TF	TF	TF	UT	UT	UT	UT	TF	TF
Sen's	H_0	+	+	+	+	+	+	+	+	+	+	+	+
	MS	0.31	1.44	−1.32	−1.42	−3.06	−3.06	3.21	4.71	4.27	7.35	6.48	2.64
	Conclusion	NLT	NLT	NLT	NLT	NLT	NLT	NLT	NLT	NLT	NLT	NLT	NLT

TF: Trend free; UT: Upwards trend; NLT: Nonlinear trend; H_0: Null hypothesis; M-KZS: The M-K Z Statistic; MS: Median Slope; H_0: Null Hypothesis; +: H_0 Accepted; −: H_0 Rejected.

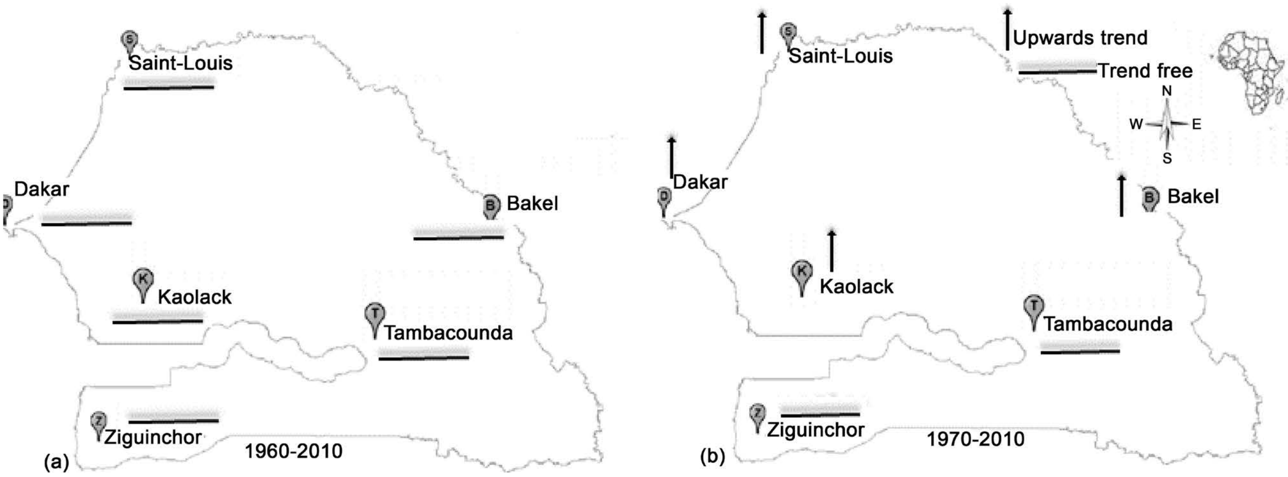

Figure 7. Effect of the time series sequences on tests for trend.

with reference to the period of 1970-2010. Descriptive statistics tools allow characterizing numerically rainfall distribution in time and space. Calculation of the means shows materialized the gradient of recorded rainfall depths in the area of Senegal. Between 1970 and 2010, rainfall gradient in space is coupled to high dispersion of observations around the means. Analysis of coefficients of variation exhibited the fact that the less the magnitudes of rainfall the higher their variability. Applied statistical tests show opposite features between rainfall in Northern and Central and those in southern, in term of independence, homogeneity and trend. They confirm that the assumed upward trends in exploratory data analysis were confirmed which randomness of rainfall was recorded in the southern part of Senegal. In addition to upward trends in northern and central, shifts were detected in related time series. Retained homogeneity hypothesis for series in southern can be considered as confirmation to their randomness feature. In monthly scale, the hypothesis of trend in the M-K test has been rejected for the same period. Therefore, results of statistical tests depend on the time series scale. Assessment of opportuneness of the time series sequence shows non-dependency of rainfall variability neither on the period nor on the geographical position. Relatively to this analysis, the high magnitude of rainfall depth from 1960 to 1970 included in the second involved period impacted the results. They have disturbed retained shift dates, inhibited confirmed upward rainfall trends and non-randomness of observations from the study focused on the period of 1970-2010. Hence, randomness tests (Kendall and Spearman ranks), if used as trend test lead to same results as the M-K one.

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