Homogeneity Analysis of Rainfall Series in the Upper Blue Nile River Basin, Ethiopia

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Abstract **Reliability and quality Assessment of historical rainfall records are required in the hydrological modelling, water resource processes and for climatic studies. The homogeneity of the annual rainfall data sets throughout the Upper Blue Nile River Basin (UBNRB) was examined using four absolute homogeneity tests namely; Standard Normal Homogeneity Test (SNHT), Buishand Range (BR), Pettitt test and Von Neumann ratio tests (VNR). The rainfall records from 30 meteorological stations during the period between 1901 and 2013 were considered. Results of SNH and BR tests showed that the annual series of the considered stations are homogeneous and classified as "useful"at 95% significance level. However, the Von Neumann ratio test detected inhomogeneity at six stations. Moreover, only 16 out of 30 stations were classified as homogenous based on the Pettitt test which confirmed that Pettitt test is more sensitive to detect the non-homogeneity for the time series. On the basis of results of the performed tests, SNHT and BRT were able to detect breaks at the series' end. Overall, the data set is representing a reliable climatic series to be considered in the subsequent trend analysis.**

Keywords: **Standard Normal Homogeneity test; Buishand Range test; Pettitt test; Von Neumann Ratio test; Upper Blue Nile.**

I. INTRODUCTION

Long-term rainfall series comprise a great importance in the study of natural variability of climate and hydrology. Nevertheless, the historical rainfall records may be suffered from non-climatic factors that cause inhomogeneity of such records. Conard and Pollak, (1950) defined the homogeneous time series as one in which variations are caused only by the weather and the climate. Homogenization procedures are essential for confirming the accuracy and adequacy of long-term time series in examining of climatic changes and variations**.** There are many non-climatic factors affecting the quality of the climate data and these factors should be understood and considered both for scientific and climatic analyses. The non-climatic factors that may cause variations in long-term time records are the location of the stations, instruments; and method used, and the station environment (Peterson et al., 1998).

Although there are universally accepted standards and recommendations for instrument installation and observations, the instruments and measurement practices may vary from station to station and/or they might be changed in the same station temporally (Sahin and Cigizoglu, 2010). Homogeneity of collected data may avert the series analysis from demonstrating the actual causes of climate change which is resulting in biases in the results of climate and hydrological studies (Costa and Soares, 2009). The use of non-homogeneous climatological time series can lead to inconsistent conclusions (Tuomenvirta, 2002). So, both the reliability and homogeneity of the rainfall that are recorded at meteorological stations should be examined before any statistical analysis.

There are two main types of homogeneity tests, namely the absolute homogeneity tests and relative homogeneity tests. The absolute tests depend on the use of a single station's records, whereas relative tests depend on the use of neighboring stations' data that are possibly homogeneous (Karabo et al., 2007). (Wijngaard et al., 2003) applied the SNHT, BR, Pettitt, and VNR tests to investigate the reliability and homogeneity of daily rainfall and temperature of 20th Century European data series. The results were categorized into three classes, namely useful, doubtful and suspect according to the number of tests that are rejecting the null hypothesis (*Ho*). In the study period, about 94% of the temperature series and 25% of the rainfall series are labeled 'doubtful' or 'suspect'.

(Karabo et al., 2007) investigate the homogeneity of rainfall records for the period 1973–2002 from 212 metrological stations in Turkey by applying the SNHT and the Pettit test. (Turkes et al., 1996) checked the homogeneity of maximum and minimum temperature records in Turkey by applying the non-parametric Kruskal–Wallis (K–W) test for homogeneity of means to annual and seasonal series. (Kang and Yusof, (2012) applied Buishand range (BR) test and Pettitt test to detect the inhomogeneity of the rainfall time series on the peninsula of Malaysia. (Al-Lami et al., 2014) checked the homogeneity of 36 gauging stations in Iraq over the periods 1981–2010 using the Von Neumann ratio test, Pettitt test, SNHT, and Buishand range test. (Mahmood Agha et al., 2017) used the SNH and Pettit tests to check the homogeneity of rainfall and temperature data series in Iraq.

(Kahya et al., 2016) investigated the homogeneity of the monthly rainfall records at 160 meteorological stations in Turkey. Using the SNH, Pettitt and BR tests, they found some of the stations non-homogenous due to the wet responses of Turkish rainfalls to El Nino events, whereas those for La Nina events seem like to be masked by sampling variations during the study period. (Mostafa et al., 2016) used four statistical absolute homogeneity tests; SNHT, Pettitt, BR and the VNR tests to evaluate the homogeneity of the rainfall data for the period (1901-2002) over the Blue Nile Basin. They reported that the investigated time series was categorized as a homogeneous series and was classified as "useful" series.

The main objective of this study is to examine the homogeneity characteristics of annual rainfall series collected at 30 meteorological stations. We are using four common absolute homogeneity tests of the SNHT, Buishand Range test, Pettitt test, and Von Neumann ratio test. This research has inspired by the importance of having suitable climatic data to study climate and hydrological changes so that we can conduct statistical studies.

II. Materials and Methods

A. Study Area and Data Set

The Upper Blue Nile River Basin (UBNRB) starts at Lake Tana and ends at the Ethiopia–Sudan border. The (UBNRB) is the part of the watershed of the Blue Nile River Basin which is the source of water for major irrigation schemes in Sudan and contributes about 60–69% of the Nile's annual flow (Conway, 2000; Tabari et al. , 2015). The area of the basin is represented 199,812 km^2 and lies in three national regional states where 46% of the basin area is Amhara, 32% in Oromia and 22% in Binishangul-Gumuz (Assefa and

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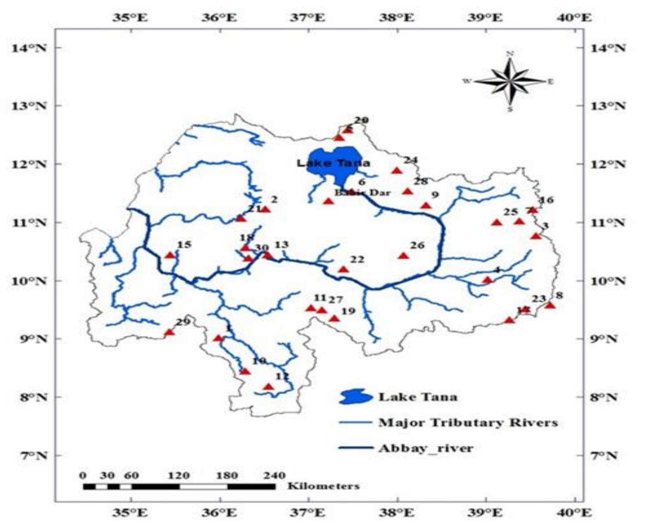


Figure 1.Locations of the rainfall meteorological stations in the Upper Blue Nile River Basin.

Moges, 2018). The UBNRB represents an essential water resource for Ethiopia and for the downstream countries Sudan and Egypt as well.

The Lake Tana, which is the largest lake in Ethiopia and the third largest lake in the Nile Basin, is located in this basin (Gebre and Ludwig, 2015). The upper Blue Nile basin is located in the northwest of Ethiopia, between latitudes of 7˚45 'N and 12˚46 'N and longitudes of 34˚05'E and 39˚45'E. Locally called Abbay is the largest river basin in terms of the volume of discharge, and the second largest in terms of watershed area in Ethiopia (Gebre and Ludwig, 2015). The rivers flow in the basin was related to the rainfall variability (Conway, 2005). The basin is characterized by high annual rainfall which varies from 800 to 2200 mm (Tabari et al., 2015). According to (Tesemma et al., 2010) The average rainfall over the Blue Nile sub-basin is about 1394 mm and is higher than the other Sub-basins of the Nile basin. The rainfall over the Blue Nile basin varies from 1000 mm in the northeast part to 1450-2100 mm over the southwest part of the sub-basin.

The data set includes long time series of annual rainfall totals (mm) covered the period 1901–2013. The data from 30 stations were provided by, Environment and Climate Research Institute (ECRI), National Water Research Centre. At each station, annual total rainfall data were computed by summing up monthly rainfall data. The data belong to 41 gauging stations distributed all over the study area. The geographical locations of the stations are shown in (Figure 1).The UBNRB has an average rainfall of 1320 mm/year as shown in (Figure 2). Rainfall in the Ethiopia has a high spatial and temporal variability.

There are regions in the south of the UBNRB which receive up to 1500 mm of annual rainfall, whereas the segment of the country gets less than 1200 mm. A statistical summary of UBNRB rainfall is present in

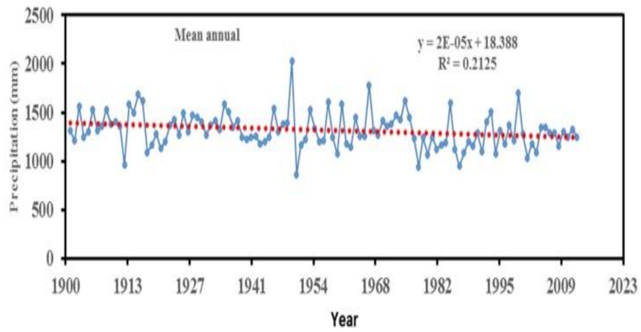


Figure 2. Mean annual rainfall distribution in the Upper Blue Nile Basin over the period (1901-2013).

B. Methodology

- *Homogeneity tests*

The absolute homogeneity test is widely used to assess the continuous of the time series. Four homogeneity tests namely (SNHT), (BR) test, Pettitt test, and (VNR) test were used. Under the null hypothesis, the annual data records are independent and identically distributed and the series is considered as homogeneous except for VNR test. Meanwhile, under the alternative hypothesis, SNHT, Pettitt test and BR test consider that the series contains a break in the mean and classified as inhomogeneous one. The main advantage of the three tests is that each test is capable to detect exactly the year where the break occurs. Contrariwise, VNR test cannot detect the year break because it assumes that series is not randomly distributed under the alternative hypothesis.

TABLE 1
STATISTICAL SUMMARY OF ANNUAL RAINFALL AT THE CONSIDERED STATIONS FOR 1901–2013.

Rainfall Stations	Annual rainfall (mm)					
	Minimum (mm)	Maximum (mm)	Mean (mm)	Standard deviation (mm)	Skewness	Kurtosis
1	995.8	1987.4	1376.9	179.1	0.48	0.48
2	780.8	2614.2	1450.6	347.7	0.61	1.02
3	711.5	2426.1	1173.7	235.6	1.27	6.30
4	407.1	2669.1	1092.7	328.6	1.71	6.43
5	573.1	2182.9	1206.6	241.2	.69	2.01
6	516.7	2671.5	1346.8	249.6	1.16	6.92
7	580.1	2757.8	1254.8	302.3	1.65	6.18
8	667.7	1695.1	1158.7	206.8	0.14	0.11
9	352.4	2874.2	1207.8	387.8	1.76	5.59
10	1256.0	2064.0	1612.9	173.8	0.21	-0.20
11	892.8	2356.0	1529.8	209.9	0.79	2.29
12	1064.3	1796.0	1412.5	151.3	0.26	-0.34
13	768.7	2402.7	1362.3	295.6	0.87	1.37
14	829.4	2722.5	1528.9	271.5	0.82	2.82
15	324.1	2338.5	1192.9	337.5	0.43	1.97
16	579.2	2414.5	1034.9	225.7	2.01	11.71
17	844.1	1639.5	1222.2	179.0	0.30	-0.43
18	435.3	3259.3	1342.4	472.3	1.06	3.43
19	1116.9	2287.0	1665.8	216.3	0.54	0.69
20	633.6	1814.6	1118.3	212.2	0.53	0.77
21	370.7	2996.5	1285.0	436.9	0.85	2.86
22	745.5	2241.7	1335.3	213.4	0.96	2.55
23	696.4	2126.1	1176.9	240.6	0.93	2.55
24	584.4	2619.7	1313.3	250.4	1.23	6.12
25	956.6	1967.5	1421.7	197.5	0.48	0.36
26	424.6	2610.0	1231.7	325.8	1.47	4.98
27	641.2	2035.5	1235.2	209.5	.82	2.02
28	640.8	2444.5	1334.9	248.1	.77	3.06
29	995.8	2238.0	1492.2	222.6	.50	.81
30	563.0	3007.2	1389.44	412.83	1.01	3.12

- *The Standard Normal homogeneity test*

This test was suggested by (Alexandersson,1986) to detect a variation in a time series of rainfall data by comparing the mean of the first *k* years of the record with the last *n-k* years as follows:-

$$T(k) = K\bar{z}^{-2}{}_1 + (n-k)\bar{z}^{-2}{}_2 \quad , k = 1,2,3,\ldots,n \qquad (1)$$

where:-

$$\bar{z}_1 = \frac{1}{k}\sum_{i=1}^{k}\frac{(y_i - \bar{y})}{s} \qquad (2)$$

$$\bar{z}_2 = \frac{1}{n-k}\sum_{i=k+1}^{n}\frac{(y_i - \bar{y})}{s} \qquad (3)$$

$$s = \frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2 \qquad (4)$$

The null and alternative hypotheses are the same as in the Buishand range test. If a break occurs in the records at any year *K*, then *T(k)* reaches a maximum value near the year *k* = *K*. The test statistic *To* is defined as:

$$T_0 = \max_{1\le k\le n} T(k) \qquad (6)$$

The null hypothesis is rejected if *To* is above a critical level, which is dependent on the sample size. The standard Normal Homogeneity test identifies breaks near the beginnings and ends of time-series.

- *Buishand test*

The Buishand range test is a parametric test that assumes that test values are independent and identically normally distributed (null hypothesis). The alternative hypothesis assumes that the series contains a jump-like shift (break). The Buishand test can be applied to variables following any type of distribution. The test statistics are the adjusted partial sum of the first year or cumulative deviations from the mean (Buishand, 1982), and k until n years, which are defined as:

$$s_0^* = 0 \quad (7)$$

$$s_k^* = \sum_{i=1}^{k}(Y_i - \bar{Y}) \quad , k = 1,2,3, \ldots \ldots, n \quad (8)$$

where, $\boldsymbol{Y_i}$ is the element of the times-series and $\bar{\boldsymbol{Y}}$ is the mean value of the times-series. When a time-series is homogenous, the values of $\boldsymbol{S_k^*}$ fluctuates around zero because there are no systematic deviations of the $\boldsymbol{Y_i}$ values with respect to their mean. If a break is present in year *K*, then $\boldsymbol{S_k^*}$ reaches a maximum (negative shift) or minimum (positive shift) near the year $k = K$. *The* $(\frac{S_k^*/s}{\sqrt{n}})$ is depicted in the graphs representing the results of this test. The significance of the shift can be tested with the rescaled adjusted range statistics (R), which is the difference between the maximum and the minimum of the $\boldsymbol{S_k^*}$ values scaled by the sample standard deviation:

$$\mathbf{R} = \frac{(\max_{0<k<n} s_k^* - \min_{0<k<n} s_k^*)}{s} \quad (9)$$

- *Pettitt's test*

The Pettitt's test is an adaptation of the rank-based Mann-Whitney test that allows identifying the time at which the break occurs. The test is a nonparametric rank test and requires no assumption about the data distribution. The null hypothesis is the same as in the Buishand range test. The ranks r1,...., rn of the Yi, ..., Yn are used to calculate the statistics (Pettitt, 1979).

$$\boldsymbol{X_k = 2\sum_{i=1}^{k} r_i - k(n+1)} \quad , \boldsymbol{k = 1, 2, 3, \ldots n} \quad (10)$$

If a break occurs in year K, then the statistic is the maximal or minimal near the year k = Ki.

$$\boldsymbol{X_k = \max_{1 \le k \le n} |X_k|} \quad (11)$$

- *Von Neumann ratio tests*

The Von Neumann ratio test (Neumann, 1941) is a nonparametric test with the null hypothesis that the data are independent and identically distributed random values. The von Neumann ratio (N) is calculated as follows:

$$\mathbf{N} = \frac{\sum_{i=1}^{n-1}(y_i - y_{i+1})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (12)$$

If the investigated time-series contains a break, the value of *N* tends to be lower than the critical value. If the sample contains rapid variations in the mean, then the value of N may rise above 2 (Bingham and Nelson, 1981; Faizah et al., 2016). Only this test does not detect the year of break. The von Neumann ratio test is very powerful at all times but does not allow detecting the time of the change.

- *Homogeneity test classification*

In 2003, Wijngaard et al. classified the test results as three classes "useful", "doubtful" and "suspect" based on the number of tests rejected the null hypothesis. The results were classified as useful if it rejected one or none null hypothesis under the four tests, it was then considered as homogeneous and can be used for further analysis. If the series rejects the two null hypotheses of the four tests, it was considered doubtful and was inspected before further analysis. A data series was considered suspect if it rejects three or the four null hypotheses and therefore was not considered for further analysis.

III. Results and Discussion

The homogeneity of the annual total rainfall time-series at the 30 rainfall stations located in the Upper Blue Nile River Basin was tested by using four tests (i.e. SNHT, Buishand range test, Pettitt test, and the von Neumann ratio test). The results of each test were evaluated at the 95% significance level. Data series was considered inhomogeneous when the p-values were lower than 5% significance level. TABLE 2 shows the results of the homogeneity tests for 30 stations based on annual total rainfall.

The result indicates that there are three inhomogeneous stations with p-value lower than the significance level of 0.05. BR test illustrated that 5 out of 30 stations were nonhomogeneous. According to the results of the Pettitt test, 16 out of 30 stations have homogenous records. The VNR test identified inhomogeneity at six stations. As presented in table 2, the station no.1 and st.2 were non- homogeneous according to the four absolute homogeneity tests. In general, the annual rainfall time series at stations (1, 14, 28 and 29) were found to be inhomogeneous by applying the both SNHT and Buishand test.

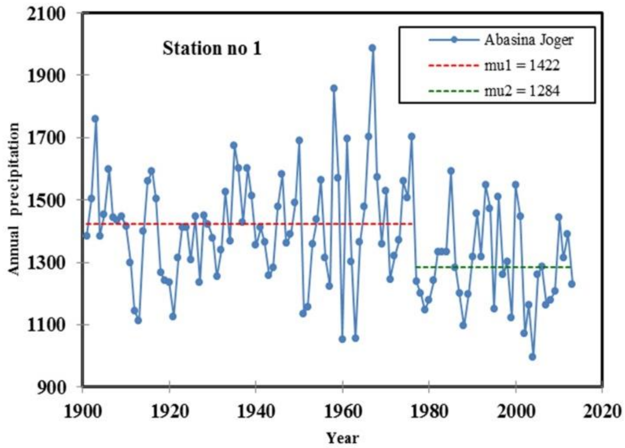


Figure **4**.Testing of homogeneity for station No 1 by SNHT, Buishand and by Pettitt.

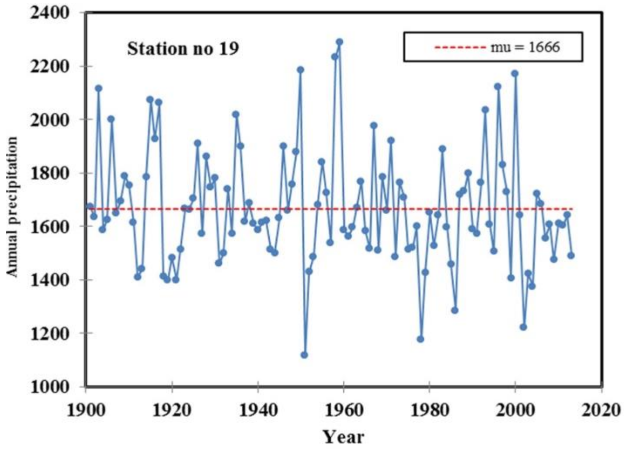


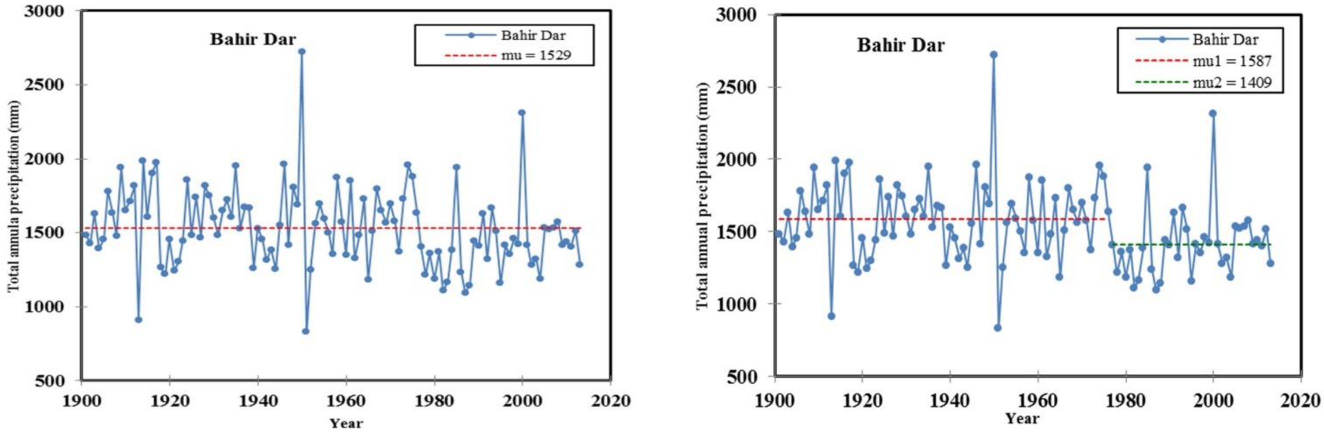
Figure 5.Testing of homogeneity for station No 19 by SNHT, Buishand and by Pettitt.

TABLE 3 presents the breaking points at inhomogeneous stations and corresponding classification .the breakpoint years for the annual rainfall series at seven stations (1, 2, 14, 15, 16, 28, and 29) were found in 1976. In station (9, 13,18,21,22, and 30), the break year was found in 1950 by Pettitt test. The Standard Normal Homogeneity test and Buishand Range test detected breaks near the end of the data series. Whereas, the von Neumann ratio test did not give information about the break year.

Furthermore, it is noticeable that the inhomogeneous structure was detected at five and seven out of 30 stations in 1950 and 1976, respectively by Pettitt test.

The overall results many ‘useful’ station series (23), five series are assigned to the ‘doubtful’ class. Only two stations (1 and 29) assigned to the suspect class.

Figure **3** shows the break in the rainfall time series of Bahir Dar station for SNH, BR, and Pettitt tests. Figure 4 and Figure 5 illustrate the homogeneity analysis for station no 1 and station no 19 respectively. The statistical results according to the classification system are shown in Figure 6.



(a) SNHT (b) Buishand and Pettitt test

Figure 3.Tests of homogeneity for Bahir Dar station (a) Homogeneity test results by SNHT (b) Homogeneity test results by Buishand and by Pettitt.

TABLE 2

THE TEST RESULTS FOR THE ANNUAL RAINFALL SERIES. NOTE: RED CELL REFERS TO NON-HOMOGENOUS STATIONS AT THE 5% SIGNIFICANT LEVEL

Stations	SNHT		BR test		Pettitt's test		VNR test	
	To	p-value	R/√n	p-value	K	p-value	N	p-value
1	14.643	0.004	0.000	0.012	1272	0.003	1.394	0.001
2	10.506	0.046	0.004	0.080	1298	0.002	1.730	0.074
3	3.485	0.610	0.057	0.605	682	0.480	2.230	0.895
4	5.397	0.328	0.031	0.251	870	0.138	1.791	0.128
5	7.229	0.164	0.015	0.105	1137	0.012	1.932	0.349
6	7.142	0.187	0.018	0.098	1092	0.019	2.123	0.745
7	1.940	0.916	0.086	0.831	602	0.742	2.207	0.876
8	6.947	0.153	0.014	0.260	615	0.679	2.002	0.505
9	7.151	0.199	0.019	0.132	1010	0.042	1.829	0.175
10	9.048	0.058	0.005	0.035	729	0.348	1.401	0.001
11	6.523	0.167	1.232	0.167	1055	0.02	1.994	0.467

12	4.031	0.550	0.052	0.753	400	0.337	1.636	0.028
13	7.316	0.166	0.016	0.277	1320	0.002	1.728	0.069
14 (Bahir Dar)	10.719	0.0509	0.005	0.040	1344	0.0012	1.919	0.3238
15	9.444	0.082	0.008	0.094	1342	0.002	1.665	0.037
16	1.855	0.918	0.086	0.926	579	0.848	2.313	0.960
17	8.423	0.067	0.006	0.186	596	0.764	1.802	0.146
18	5.907	0.304	0.029	0.443	1348	0.002	1.716	0.061
19	4.965	0.389	0.037	0.800	632	0.628	1.678	0.044
20	5.180	0.351	0.033	0.185	942	0.070	1.716	0.067
21	5.771	0.303	0.029	0.454	1338	0.002	1.750	0.097
22	8.151	0.106	0.010	0.136	1155	0.012	1.871	0.242
23	5.744	0.287	0.027	0.266	780	0.255	1.780	0.119
24	4.826	0.404	0.038	0.238	808	0.210	2.161	0.813
25	7.551	0.126	0.012	0.500	554	0.952	1.792	0.126
26	8.220	0.159	0.015	0.112	966	0.070	1.808	0.152
27	7.126	0.189	0.018	0.181	860	0.138	1.816	0.158
28	10.442	0.054	0.005	0.038	1258	0.002	1.946	0.383
29	21.804	0.000	0.000	0.000	1684	0.000	1.422	0.001
30	6.289	0.241	0.023	0.388	1292	0.002	1.7175	0.068

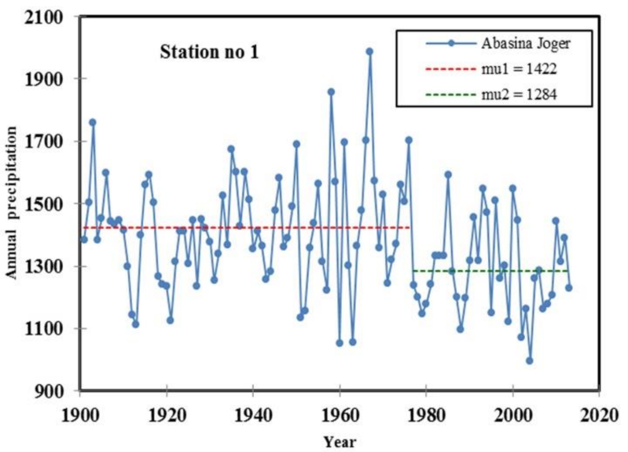


Figure 4.Testing of homogeneity for station No 1 by SNHT, Buishand and by Pettitt.

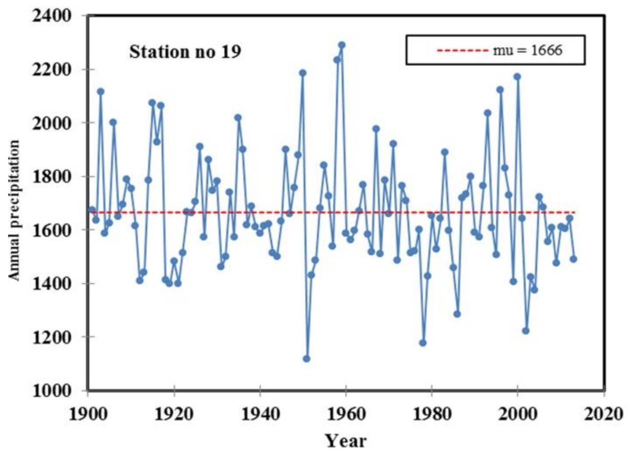


Figure 5.Testing of homogeneity for station No 19 by SNHT, Buishand and by Pettitt.

TABLE 3
THE BROKEN YEAR NON-HOMOGENOUS STATIONS AND THEIR CLASSIFICATION

stations number	Latitude	Longitude	Break year				Classification
			SNHT	BR test	Pettitt's test	VNR test	
1	9.02	36.00	1976	1976	1976	×	suspect
2	11.23	36.52	1976	—	1976	—	doubtful
3	10.77	39.57	—	—	—	—	useful
4	10.02	39.02	—	—	—	—	useful
5	12.46	37.36	—	—	1959	—	useful
6	11.53	37.50	—	—	1976	—	useful
7	11.03	39.38	—	—	—	—	useful
8	9.58	39.73	—	—	—	—	useful
9	11.30	38.33	—	—	1950	—	useful
10	8.45	36.30	—	1976	—	×	doubtful

11	9.54	37.04	—	—	—	—	useful
12	8.19	36.56	—	—	—	×	useful
13	10.45	36.55	—	—	1950	—	useful
14 (Bahir Dar)	11.37	37.23	1976	1976	1976	—	doubtful
15	10.45	35.45	1976		1976	×	doubtful
16	11.22	39.53	—	—	—	—	useful
17	9.33	39.27	—	—	—	—	useful
18	10.57	36.30	—	—	1950	—	useful
19	9.36	37.30	—	—	—	—	useful
20	12.59	37.45	—	—	—	—	useful
21	11.07	36.25	—	—	1950	—	useful
22	10.20	37.40	—	—	1950	—	useful
23	9.52	39.45	—	—	—	—	useful
24	11.90	38.00	—	—	—	—	useful
25	9.38	38.49	—	—	—	—	useful
26	10.44	38.08	—	—	—	—	useful
27	9.50	38.40	—	—	—	—	useful
28	11.54	37.16	1976	1976	1976	—	Doubtful
29	9.12	35.44	1976	1976	1976	×	Suspect
30	10.39	36.33	—	—	1950	—	Useful

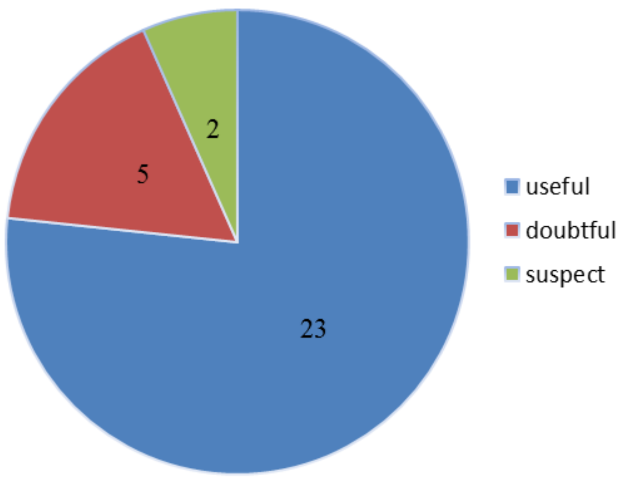


Figure 6. Classification of stations by homogeneity status using total annual rainfall as testing variable

IV. CONCLUSION

This study examined the homogeneity in annual rainfall in UBNRB in, Ethiopia for the period 1901-2013. Homogeneity analysis was conducted by using (SNH), (BR), (Pettitt) and (VNR) tests. The inhomogeneous rainfall time series and their break years were identified at a significance level of 95%. Based on the results of (SNHT), (BRT), and (VNR) tests, the annual rainfall time series are homogeneous at most stations. The results of the BR and VNR tests showed that 5 and 6 out of 30 stations are inhomogeneous, respectively. According to the Pettitt test, 14 out of 30 stations are inhomogeneous. Only two stations showed inhomogeneity according to the four tests. The highest numbers of the inhomogeneous rainfall data series were gained from the Pettitt test. Interestingly, The SNH and BR tests detected breaks near the end of the data series at the 1976 year. While the (VNR) test did not give information about the year of break. The breaks captured by the Pettitt test tend to appear in the middle of the period 1901-2013. Generally, it can be concluded that the Pettitt test is more sensitive to detect the non-homogeneity for the time series. In addition, the results were evaluated by classifying the 30 stations into three categories, 23 stations are useful, 5 stations are doubtful and 2 stations are suspect.

Most of the inhomogeneity that was detected in rainfall variables are in the south and west region. A non-climatological jump in the total of these rainfall series may be attributed to an abrupt change associated with the relocation of a station or from a rapid increase or decreasing trend in rainfall values. The detected breaks were near the beginning and the end of the data series, however the Pettit test indicated a single breakpoint in a time series. The breaks captured by the Pettitt test were in the middle of the 1901-2013 period. The results confirmed that using of several homogeneity tests is beneficial in testing the homogeneity of rainfall series before studies of climatic changes and variations.

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