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Spatial and temporal Trend Analysis of Long Term rainfall records in data-poor catchments with missing data, a case study of Lower Shire floodplain in Malawi for the Period 1953-2010

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Abstract. This paper investigated the long-term trends in precipitation from 16 stations located in the lower Shire catchment in Malawi over the period 1953-2010. Annual trend analysis was first considered, and in order to take into account seasonality and serial correlation, the different months of the year are considered. Trend significance was determined using the nonparametric Mann-Kendall (MK) test statistic while the determination of the trends magnitudes was achieved using Sen's slope method. The homogeneity of trends was examined using the Van Belle and Hughes method. The results indicate that annual precipitation has increased, whereas, monthly precipitation revealed an upward trend in wet seasons (November to April) and a downward trend in dry seasons (May to October). The monthly peak trend analysis has shown upward trend in rainy months at all stations.

Keywords: Climate change; Watershed hydrology; statistical trend analysis; Mann–Kendall test; Sen's slope estimator; Van Belle and Hughes.

1 Introduction

The impact of climate change on water resources is felt worldwide but its effects are more overwhelming in places where flooding or drought takes place (Howard et al. 2016; Arnell et al. 2016; IPCC 2014; Bhave et al. 2016). However, the foremost influences are witnessed on the water cycle and its effect on domestic use, flood control, irrigation, etc (Daccache et al. 2017; Simonovic 2017; Makwiza et al. 2015). Changes in rainfall patterns might affect future planning in terms of housing and other urban facilities, proposed irrigation projects, land use, insurance and other activities that assume the climate will not change over project life. In addition, intensification in rainfall may lead to increased frequency of floods, landslides, soil loss, sediment

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transport, and would have consequences for aquifer recharge and the general water quality situation (Khan et al. 2016; Pina, Amaury, and Francois 2016; Hattermann et al. 2017; Scherler et al. 2016).

Therefore, to protect water resources availability and assess future land use, efforts have been devoted to study climate change, especially as it affects rainfall. These studies aim to understand the trend of change in rainfall patterns by analysing long term historical rainfall and runoff data, which then forms the basis of forecasting future scenarios.

For example, Jana et al. (2017) analysed spatio-temporal rainfall change scenarios in the 20th century (1901–2000) over Bundelkhand, India. They found that decreasing rainfall trends during monsoon seasons and increasing trends during pre and post-monsoon seasons are an indication of shifting rainfall patterns away from a typical seasons.

Furthermore, Engström and Waylen (2017) analysed historical (1952–2014) precipitation and streamflow data from 18 basins in southeast United States for long-term changes in the hydroclimatology. They found that there is a change in the precipitation-runoff relationship in the late 1990s where there is a decreased precipitation storage and consequently increased streamflow.

Buendia et al. (2016) analysed the hydro-climatic trends at the annual and monthly scales in three nested sub-catchments in a central Pyrenean basin, Spain, using the Non-parametric Mann–Kendall statistic for data from 1965 to 2009. The results demonstrate that upward trends were detected for temperature and potential evapotranspiration, particularly during summer months (June to August) and winter months (December to February). Precipitation trends indicated a decrease, particularly for February and July. Results also indicated that a change in annual runoff took place in the 1980s.

Paul et al. (2017) used both parametric and non-parametric approaches to identify the trends at different temporal scales of the Rajahmundry city rainfall, lower Godavari basin, India, during the period 1960–2013. They witnessed a negative trend at a weekly scale during the monsoon months. For example, the magnitude of Sen's slope was observed to be negative during the months of April–September.

Therefore, trend analysis can be used to examine if there is any significant change in climatological parameters and several statistical techniques now exist to detect trends in hydro-meteorological data. These techniques can be classified into parametric and non-parametric approaches. Parametric methods make assumptions about the form of probability distribution of the variable, i.e. principally that the variable has a Gaussian distribution, which often invalidates their applications to non-Gaussian distributed variables. Additionally, even where it can be established that the variable does follow the normal distribution, the estimation of the parameters of the distribution can be hampered, i.e. subject to large biases and variability, due to the typically short data records that are available.

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This work aims to find the trends in precipitation in the Shire Basin, Malawi, not only in the annual total precipitation but also in the total monthly precipitation, in addition to the trends of monthly peaks. The study utilised a record of daily data that spanned 58 years (1953-2010). The daily records from which the monthly and annual records were generated contain numerous gaps and missing values which require a scientific infilling before performing any trend analysis. This infilling exercise has been performed and reported elsewhere (Mwale, Adeloye, and Rustum 2012); hence only a brief mention of this will be made here.

The procedures implemented in this paper are based on the non-parametric Mann-Kendall test to detect a monotonic trend of a time series. The magnitude of the trend, and the slope of the linear trend, were estimated with the nonparametric Sen's method, which is not significantly affected by single data errors or outliers (Thenmozhi and Kottiswaran 2016; Bouza-Deaño, Ternero-Rodríguez, and Fernández-Espinosa 2008). The spatial and temporal homogeneity of trends were examined using Van Belle and Hughes (Kahya and Kalayci 2004). The following sections discuss these methods in detail.

2 Statistical Trend analysis techniques

2.1 Mann-Kendall Test

The Mann–Kendall (MK), commonly known as the Kendall's tau statistic, is a non-parametric test used for trend analysis. Mann (1945) first used this test and Kendall (1975) derived the test statistic distribution. The test has been suggested by the World Meteorological Organisation (WMO) to assess trends in environmental data time series (WMO 2014) as the test is suitable for cases where the trend may be assumed monotonic and therefore no seasonal aspects are presented in the data. The method is simple, does not require assuming normality, robust against outliers and can handle missing values (Hess, Iyer, and Malm 2001). Accordingly, when compared to parametric test like t-test, the Mann-Kendall test has a higher power for non-normally distributed data, which are normally presented in hydrological data (Yue and Pilon 2004). It is worth to mention that some researchers (e.g. Sang et al., 2014) highlighted the need for pre-whitening of the time series data before conducting any trend analysis test, however, if the sample size is more than 70 then serial correlation does not affect the MK test (Basistha, Arya, and Goel 2009)

The Mann–Kendall test calculates the slope of the line formed by plotting the variable of interest against time, but only considers the sign and not the magnitude of this slope. Hence, the MK test statistic is calculated from the sum of the signs of the slopes. The statistic S is:

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

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Where, n is the number of data point, x_j is the j[th] observation and x_i is the i[th] observation where $j>i$. The *sgn(.)* can be estimated as:

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} 1 & if \quad (x_j - x_i) > 0 \\ 0 & if \quad (x_j - x_i) = 0 \\ -1 & if \quad (x_j - x_i) < 0 \end{cases} \tag{2}$$

The Mann-Kendall test is based on the null hypothesis that a sample data is independent and identically distributed, which means there is no trend in the data points. Thus, if the null hypothesis H_o is accepted at the significant level α, then the mean and variance of the S statistics are given by Kendall (1975) as it is approximately normally distributed, mean (S) is zero.

$$mean(S) = 0 \tag{3}$$

In the case where there are no ties in either ranking, the distribution of S may be well approximated by a normal distribution with mean zero and variance as stated in Equation 4.

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{4}$$

And in the case of ties, the variance of S is more complicated as in Equation 5.

$$\begin{aligned} Var(S) = & \left\{\frac{n(n-1)(2n+5)}{18} - \sum t_i(t_i-1)(2t_i+5) - \sum u_i(u_i-1)(2u_i+5)\right\} \\ & + \frac{1}{9n(n-1)(n-2)}\left\{\sum t_i(t_i-1)(t_i-2)\right\}\left\{\sum u_i(u_i-1)(u_i-2)\right\} \\ & + \frac{1}{2n(n-1)}\left\{\sum t_i(t_i-1)\right\}\left\{\sum u_i(u_i-1)\right\} \end{aligned} \tag{5}$$

Where t_i is the number of data point for i[th] tie.

The normal approximation, Z statistics, is stated in Equation 6.

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if \quad S < 0 \end{cases} \tag{6}$$

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A positive value of S indicates that there is an increasing trend and vice versa. However, the absolute value of Z is compared with the standard normal cumulative distribution to detect if there is any trend at the selected level of significance (α). The trend is said to be decreasing if Z is negative and increasing if Z is positive. H_0, the null hypothesis of no trend, is rejected if the absolute value of Z is greater than $Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables.

2.2 Sen's slope estimator

As stated previously, the Mann–Kendall test only indicates the direction but not the magnitude of significant trends. Thus, the magnitude is usually determined by Sen's test (Sen 1968) which is also a nonparametric technique. The method uses a linear model to calculate the change of slope and the variance of the residuals should be constant in time. The function of Sen's model is:

$$f(t) = Qt + B \tag{7}$$

Where Q is the slope and B is constant

To calculate the model parameters, B and Q, the slope between any two observations is calculated as in Equation 8.

$$Q_i = \frac{x_j - x_k}{j - k} ;\text{where } j > k \tag{8}$$

Therefore, the total number of slopes, N, is estimated as:

$$N = \frac{n(n-1)}{2}$$

The slope of Sen's test Q is the median of these Q_i slopes.

$$Q = median[Q_i]_{i=1}^{N} \tag{9}$$

The intersect B is the median of n values of difference x_i-Qt_i

$$B = median[x_i - Qt_i]_{i=1}^{n} \tag{10}$$

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2.3 Test of Homogeneity of trends

Trend results should be consistent between stations, seasons and stations-seasons. For example, by applying the MK test, each month or each station is dealt with separately, thus the results of trend analysis may not be significant, but when the catchment is considered as a whole, the trend might be highly significant. Therefore, one figure should represent all stations at a particular month, and another figure to represent the trend of all months in a particular station, and a third figure to represent the catchment wise. These figures can be generated by analysing the trend statistics, Z statistics in case of MK test, to get a single trend figure. The most widely used homogeneity test of trend is the Van Belle and Hughes (van Belle and Hughes 1984). This test has been widely applied in Hydrology (Dabanlı et al. 2016; Akinsanola and Ogunjobi 2017; Kahya and Kalayci 2004).

The van Belle and Hughes (1984) procedures are based on dividing the sum of the squares using the Chi-square tests to get the trend homogeneity between months, between stations and station–month interactions.

$$\chi^2_{\mathrm{hom}ogeneous} = \chi^2_{total} - \chi^2_{trend} \Rightarrow \chi^2_{\mathrm{hom}ogeneous} = \sum_{i=1}^{m} (Z_i)^2 - m(\check{Z})^2 \tag{11}$$

$$\check{Z} = \frac{1}{\mathrm{m}} \sum_{i=1}^{m} Z_i \tag{12}$$

(m=12 for homogeneity between months, m= number of stations for homogeneity between stations, and m=m* number of stations for station-month interaction).

According to Kahya and Kalayci (2004), if the Chi-square (homogenous) exceeds the predefined α level critical value for the Chi-square distribution with (m-1) degrees of freedom, the null hypothesis of homogeneous trend must be rejected and in this case, different seasons or stations show dissimilar trends, otherwise, the Chi-square (trend) is referred to the chi-square distribution with 1 degree of freedom to test a common trend.

However, this is a complex procedure and may not be understood by ordinary readers; instead, homogeneity is tested graphically by plotting the Z values over all stations and all months. This provides an overview if the stations or the months are homogeneous, or heterogeneous.

3 Materials and Methods

3.1 Study Area

The Shire Basin is located in the southern region of Malawi (Figure 1). The Lower Shire floodplain is the most vulnerable area to flooding and thus the most affected in Malawi. Its biophysical vulnerability arises from heavy rainfall in the upper and

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middle catchments of the Shire River and from the Ruo catchment on its main tributary. Although the floodplain rainfall is only around 600 mm annually, the upper and middle Shire River catchments receive annual rainfall of around 900 mm and the Ruo catchment has average annual rainfall in excess of 2,000 mm. The population is predominantly rural and has the highest levels of poverty in the country. Livelihoods are intricately linked to natural resources, especially water, which is why most of the settlements are along river courses. Due to resource constraints, the catchment has very limited investment in structural measures for flood control (Mwale, Adeloye, and Rustum 2014) .

3.2 Data collection and handling

Daily rainfall Data from 16 rain gauges, collected by the Department of Climate Change and Meteorological Services (DCCMS), were used in this study. The DCCMS collects rainfall data using manual rainfall gauges. The historical periods of data provided for this study are presented in Table 1, from which it is clear that the periods are non-uniform. Several of the records are missing and, although this is not evident in Table 1, some of the missing periods do overlap thus, making the use of traditional infilling approaches such as regression impossible. Therefore, the self-Organizing map (SOM) was first used to infill the missing data in order to generate a complete record. This task has been published in (Mwale, Adeloye, and Rustum 2012) . Therefore, 16 stations with sufficient length of records during the period of Jan. 1953– Dec.2010 were selected for the present analysis. The 58 – year record for the 16 stations meets minimum conditions of 25 years set by (Burn and Hag Elnur 2002) that ensures validity of the trend results statistically. Annual data statistical description is presented in Table 2 from which it is clear that the highest rainfall occurs over Momosa and Thyolo of about 1425 mm and 1110 mm respectively. The peak value of 2485 mm occurs over Mwanza. . The coefficient of variation varies from 23.4% in Bvumbwe to 36.1 in Balaka; thus, the variability in the dataset does not change more than 12% from one station to the other. The mean monthly rainfall data is presented in Table 3. From this table, it can be seen that the wet season is from October to March and the highest precipitation occurs over Mimosa during January that is 57.5 mm. Although May, Jun and July are considered dry seasons, they often experience some precipitation, for example, averaging about 10 mm in Mimosa.

4 Result and discussion

4.2 Annual trend

The results of the trend analysis of annual precipitation using Mann-Kendall and Sen's slope estimate are shown in Table 4. Trend analysis revealed a significant increasing trend of at least 0.001 confidence. The slope of the increase Q ranges from 3.30mm/year at Mwanza to 10.27 mm/year at Mimoza. Trend analysis using linear regression is also presented in Table 5 from which it is clear that the Sen's test results are almost consistent with the linear regression results and reveal the same conclusion. The spatial distribution of the Z values, shown from Table 4 and Fig. 2, highlight that the highest trend increase was witnessed in Mimosa (Z=3.8) and the lowest in Mwanza (Z=1.69). Time series plots of annual data are presented in

Figure 3, from which it is clear that the trend line moves upward at all stations and hence there is an increase in annual rainfall depth. This is also reviled from Table 5, where we can see the slope of the linear regression ranging from 3.4 mm/year at Mwanza to 10.07 mm/year at Mimosa. Additionally, Table 4 highlights the smallest significant level α with which the test demonstrates that the null hypothesis of no trend should be rejected. For example, in case of Nsanje, the results of the test is returned as H=1, hence the null hypothesis at the significant level of 5% is rejected, whereas in case of Makhanga, the H is zero, thus, the null hypothesis cannot be rejected at the significant level of 5%. The general overview of the table exhibits that the catchment varies in both Z and Q, however, the general observation is that there are significant rising trends at all stations.

4.3 Monthly trend

The MK test was applied to different months and hence every time series for 58 years is considered as uncorrelated and thus meet the test assumptions. Additionally, since the time lag between any two consecutive data points are virtually one year, then the monthly time series is assumed to be independent.

Table 6 presents the precipitation trend results in terms of the Z statistic for all stations for monthly precipitation. The slope and the intersect of Sen's slope are also presented in Table 7. The test is calculated based on the smallest significant level α in which the trend is considered statistically significant at the α confidence level. The results determine that most stations exhibit positive trends during wet months (November - March) and negative trends during dry months. Furthermore, it is evident from the graphical illustrations of the Z values in Fig 5. Additionally, the values of z are illustrated using contour lines as seen from figure 6, from which it is clear that the highest values of z are in Monkey Bay during January. The magnitude of the trend is shown from Sen's slope estimate in Table 7. Moreover, it is also clear that the highest magnitude of Sen's slop is in Monkey Bay (B=3.67) during January. The numerical results of Z from Table 6, are illustrated using contour lines as in Fig 6, demonstrating that the highest values are around Monkey Bay in the north of the catchment.

The results of homogeneity of trends between stations based on van Belle and Hughes (1984) at different months are presented in Table 8 and the results of homogeneity of trends between months at different stations are presented in Table 9. The results of the homogeneity of month-station interactions are presented in Table 10. The values of homogeneity Chi-squares for stations, months and station-month interactions were compared with the significant level α=5%. By comparing the results, it is clear that Chi-squares exceeds the critical value of α for all cases, thus, the trend results are homogenous between months, stations and between month stations interaction. The homogeneity is also clear from Figure 5, where all stations follow the same trend when Z values move from one month to the other. Therefore, it is clear that there is a positive trend during wet seasons and a negative trend during dry seasons.

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4.4 Peak monthly trend analysis of precipitation

The results of monthly peak trend analysis are presented in Tables 11 and 12. The statistical test Z indicate the there is a positive trend of the peak precipitation during wet months and negative trend during dry months. The highest z value was witnessed in Monkey Bay in the north of about 5.06 during January while the highest negative value is in the same station during Jun of about -5.76. The magnitude of trends is shown from Table 12 from which we can see the Sens' slope ranges from - 0.17 in Chingale to 0.8 in Monkey Bay during the months of January. The general view of the peak monthly tends analysis results show that there is an upward trend on wet seasons in all stations in general and in the northeast part in particular as illustrated in Figure 6. Therefore, the northeast regions may expect more heavy rainfall in the future and hence the area is subject to a more flood.

5 Conclusion

This paper studies the trends in annual, monthly-total and monthly peaks of 16 rainfall stations in the Shire Basin, Malawi, during a period of 58 years, 1953-2010. The techniques applied were based on a nonparametric Mann-Kendall test to detect a monotonic trend of a time series. The magnitude of the trends were estimated with the nonparametric Sen's method. A linear regression model was used to validate the MK significance test and to determine the magnitude of the trend. The spatial and temporal homogeneity of trends were examined using Van Belle and Hughes and ISO-MK-Z plots, demonstrating the trend results were homogeneous.

The results highlight that there is an upward trend in annual precipitation. This increase is due to a positive significant trend during wet seasons, (November, December, January and February), in contrast to a down trend during dry seasons. The spatial distribution of trends increase from south to the north and from east to west. The results also reveal an increase in peak values year over year, which may explain an increase in flood events in recent years. Almost similar trends were observed using Sen's method and linear regression method. Thus, coherent and significant increases in rainfall was observed over wet seasons with obvious decreases found over dry seasons. The cause of these changes, requires further investigation to establish a linkage between climate variability and observed trends.

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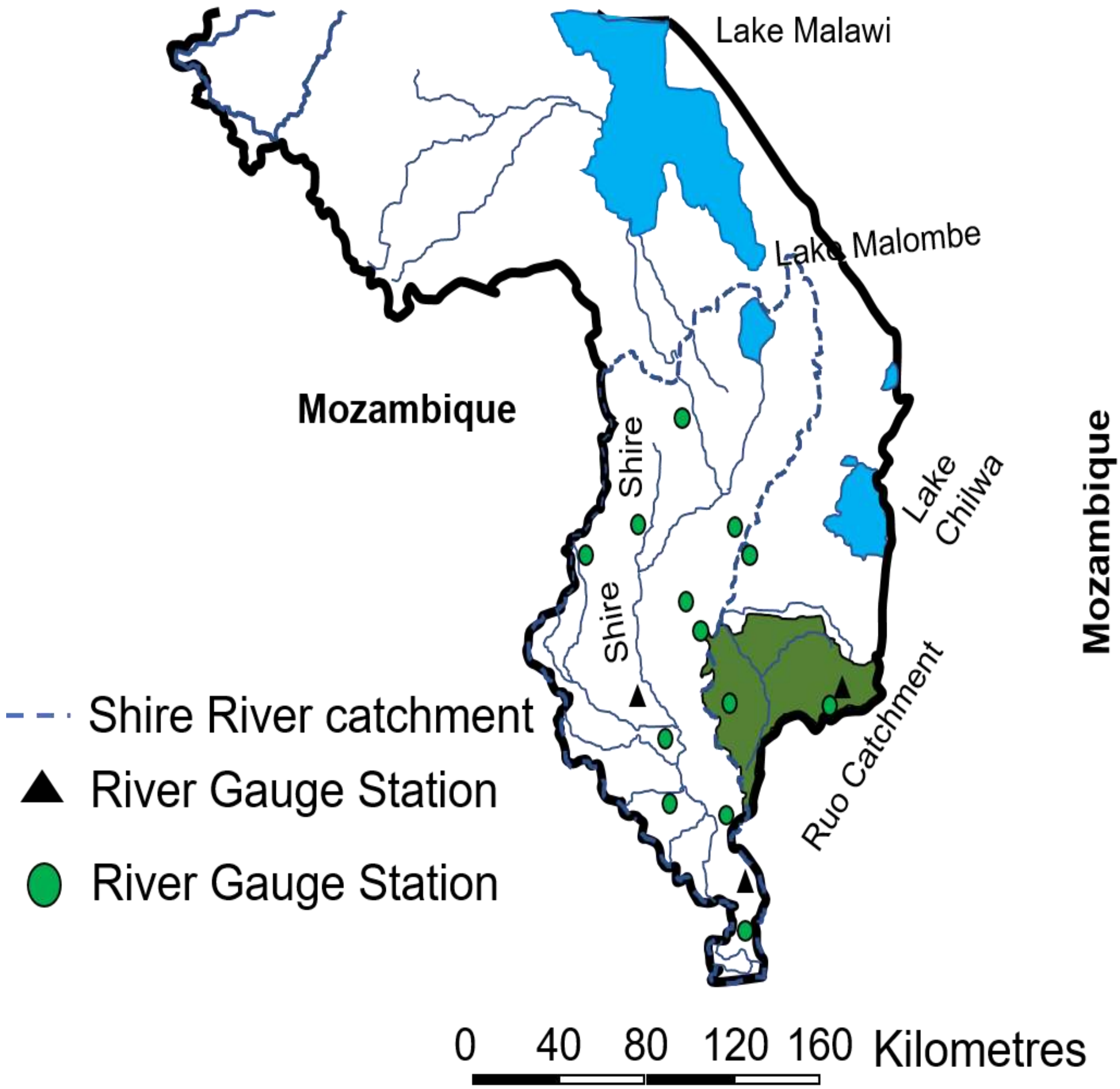

5 **Figure 1 The study area with main gauge and rainfall station locations.**

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Station No. N	Station Name
1	Nsanje
2	Makhanga
3	Ngabu
4	Chikwawa
5	Nchalo
6	Neno
7	Mwanza
8	Mimosa
9	Thyolo
10	Bvumbwe
11	Chileka
12	Chichiri
13	Makoka
14	Chingale
15	Balaka
16	MonkeyBay

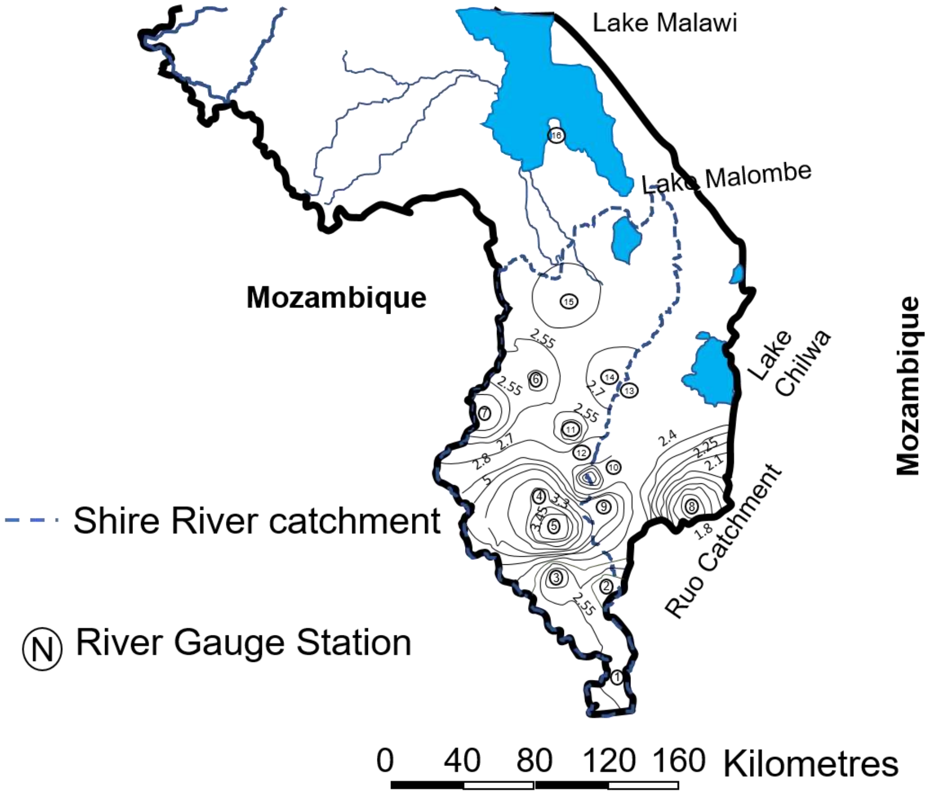

Figure 2. Spatial distribution of MK Z statistics for annual rainfall trend analysis.

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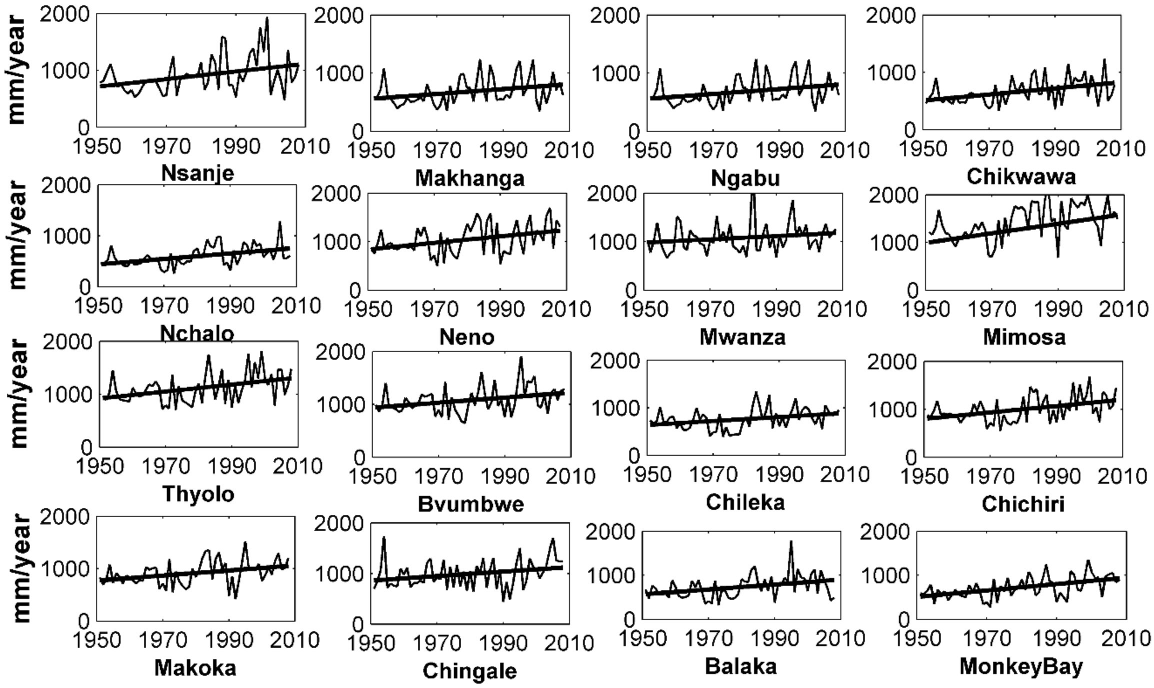

Figure 3 Time series of annual rainfall data together with the linear trend line.

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Station No. N	Station Name
1	Nsanje
2	Makhanga
3	Ngabu
4	Chikwawa
5	Nchalo
6	Neno
7	Mwanza
8	Mimosa
9	Thyolo
10	Bvumbwe
11	Chileka
12	Chichiri
13	Makoka
14	Chingale
15	Balaka
16	MonkeyBay

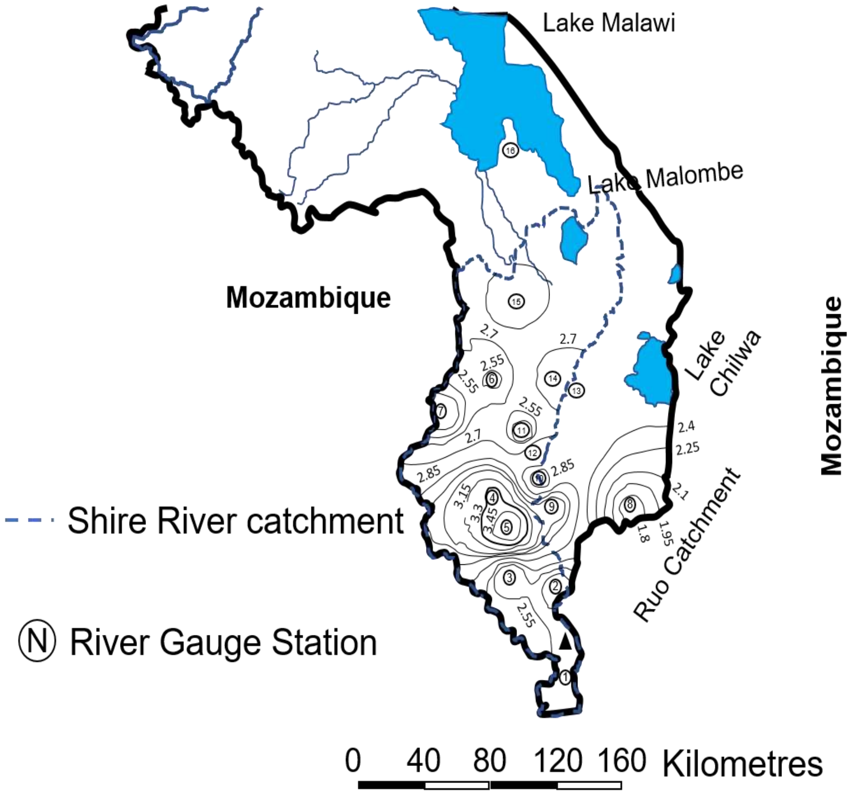

Figure 4 spatial distribution of January Z trend statistics over the 16 stations for 58 years.

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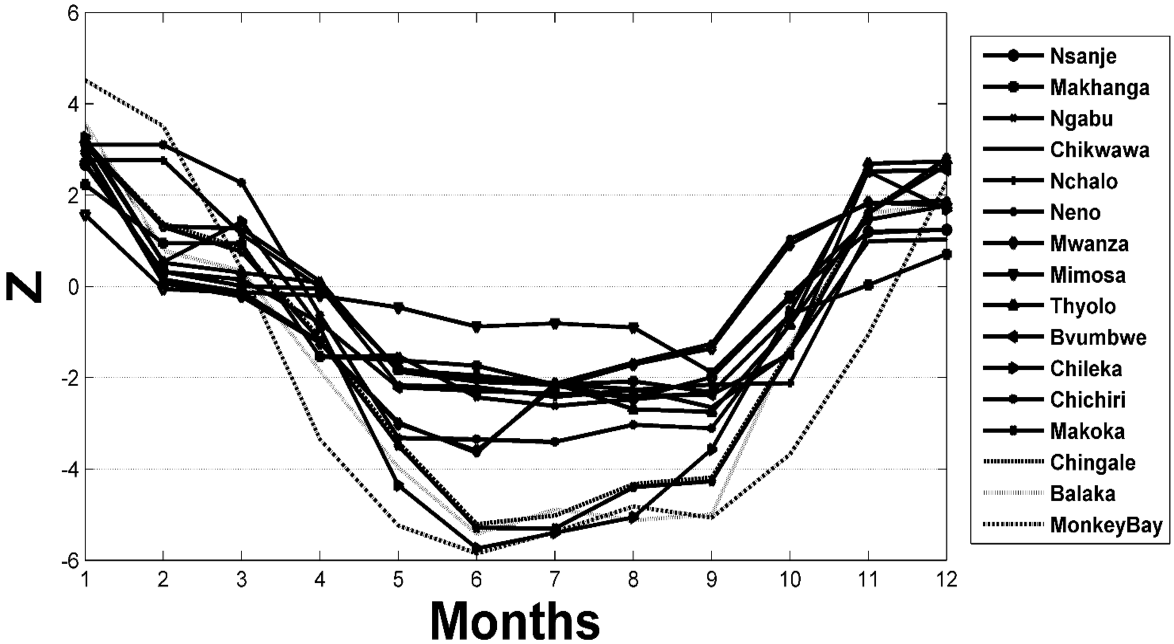

Figure 5 temporal distribution of Z values over 16 stations for 12 months

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Station No. N	Station Name
1	Nsanje
2	Makhanga
3	Ngabu
4	Chikwawa
5	Nchalo
6	Neno
7	Mwanza
8	Mimosa
9	Thyolo
10	Bvumbwe
11	Chileka
12	Chichiri
13	Makoka
14	Chingale
15	Balaka
16	MonkeyBay

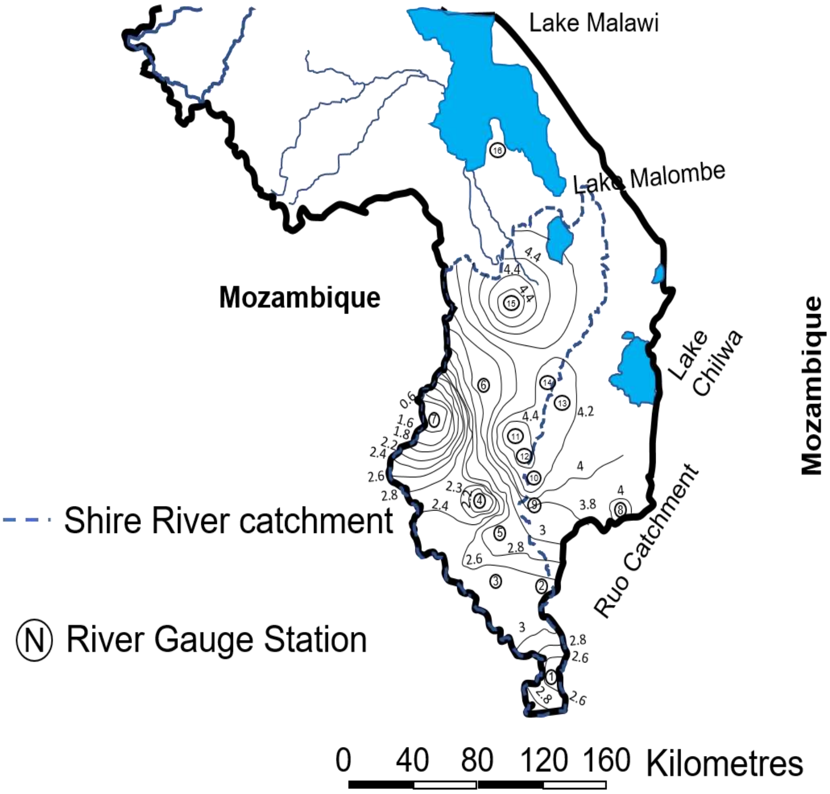

Figure 6. Spatial distribution of January (peaks) Z trend statistics over the 16 stations for 58 years.

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Table 1 Details of selected stations

Station	Location	Elevation (m)	Record Length (year)	Proportion of missing data (10%)
Nsanje	16°55'26.7"S 35°15'54.3"E	51	1973-2009	8.4
Makhanga	16°30'51.9"S 35°10'20.8"E	76	1953-2010	3.2
Ngabu	16°27'08.0"S 34°53'36.1"E	102	1981-2010	0
Chikwawa	16°01'00.6"S 34°47'31.8"E	107	1979-2010	10.7
Nchalo	16°11'04.8"S 34°52'50.4"E	52	1981-2010	1.6
Neno	15°24'04.1"S 34°46'46.4"E	899	1980-2009	14.0
Mwanza	15°34'44.5"S 34°29'10.6"E	1260	1935-2006	17.1
Mimosa	16°04'16.6"S 35°36'33.1"E	652	1958-2010	2.5
Thyolo	16°04'07.7"S 35°08'40.5"E	820	1962-2010	0.2
Bvumbwe	15°55'08.9"S 35°03'59.5"E	1146	1953-2010	0.6
Chileka	15°40'30.0"S 34°58'04.0"E	767	1961-2010	0.7
Chichiri	15°47'52.3"S 35°02'37.8"E	1132	1981-2010	0
Makoka	15°29'08.6"S 35°14'03.5"E	1029	1981-2010	0.7
Chingale	15°23'33.3"S 35°10'49.4"E	610	1952-2010	15.1
Balaka	14°58'51.7"S 34°57'21.4"E	625	1981-2010	1.4
MonkeyBay	14°04'58.8"S 34°55'00.0"E	482	1961-2010	0.02

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Table 2 Statistical description of yearly data

	Minimum (mm)	Maximum (mm)	Mean (mm)	Median (mm)	CV, coefficient of variation (%)
Nsanje	479	1946	912	823	34.6
Makhanga	345	1240	681	623	33.9
Ngabu	345	1240	681	623	33.9
Chikwawa	326	1238	663	619	32.0
Nchalo	260	1282	597	558	33.2
Neno	493	1697	1041	972	29.3
Mwanza	665	2485	1077	1022	29.1
Mimosa	681	2196	1425	1430	25.3
Thyolo	701	1808	1110	1099	25.0
Bvumbwe	647	1909	1077	1039	23.4
Chileka	392	1339	762	749	28.9
Chichiri	546	1678	1001	940	26.5
Makoka	417	1516	914	897	25.2
Chingale	442	1735	991	997	28.0
Balaka	325	1789	731	685	36.1
MonkeyBay	274	1359	722	670	33.4

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Table 3. Mean monthly rainfall data (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Nsanje	53.4	44.4	42.1	19.2	7.8	6.7	6.6	3.5	4.9	20.1	30.9	40.6
Makhanga	38.6	37.6	29.8	10.4	6.3	4.0	6.0	2.8	3.6	10.3	20.6	33.5
Ngabu	38.6	37.6	29.8	10.4	6.3	4.0	6.0	2.8	3.6	10.3	20.6	33.5
Chikwawa	46.5	33.4	32.4	13.9	5.1	4.1	5.0	3.5	1.9	8.5	21.6	32.4
Nchalo	37.8	34.2	27.0	16.0	4.8	4.1	6.1	2.8	3.1	6.8	19.4	31.1
Neno	50.4	39.1	42.5	21.5	7.1	5.6	5.2	3.9	5.4	13.7	25.3	41.2
Mwanza	51.9	53.1	40.9	22.4	9.5	7.3	6.8	4.8	5.7	20.5	30.0	48.2
Mimosa	57.5	44.0	45.9	31.4	15.5	11.5	10.6	9.6	8.8	21.1	37.1	53.0
Thyolo	50.1	49.6	39.5	20.7	9.0	6.3	6.2	4.7	4.6	16.0	31.8	48.1
Bvumbwe	48.5	47.4	36.7	19.4	8.7	6.4	6.2	4.6	4.5	13.2	29.5	44.7
Chileka	40.4	40.1	33.2	16.1	5.6	2.9	1.9	2.3	3.2	11.6	27.9	34.1
Chichiri	43.2	44.5	38.2	18.2	6.7	5.6	4.0	3.1	3.9	14.6	25.9	37.5
Makoka	42.6	41.7	30.2	20.0	5.7	3.2	2.2	2.4	2.4	9.8	20.9	41.7
Chingale	53.5	53.1	39.2	19.2	5.5	2.4	3.1	1.3	3.1	9.4	32.0	46.2
Balaka	41.8	36.3	27.3	14.7	4.6	1.7	1.4	0.8	1.7	10.0	24.8	31.6
MonkeyBay	43.2	44.0	28.9	11.9	3.3	2.0	1.8	1.3	1.0	4.1	13.6	38.7

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Table 4 Trend tests of yearly precipitation of Low Shire catchment obtained through the MK method and Sen's slope estimate during 1953-2010.

	Mann-Kendall trend					Sen's Slope estimate	
Station	H	p_value	Test S	Test Z	Significant α	Q	B
Nsanje	1	0.0117	377	2.52	0.05	5.45	721.79
Makhanga	1	0.0146	365	2.44	0.05	3.92	530.94
Ngabu	0	0.0146	365	2.44	0.05	3.92	530.94
Chikwawa	1	0.0018	467	3.13	0.01	5.43	507.90
Nchalo	1	0.0003	535	3.58	0.001	4.90	447.02
Neno	0	0.0112	379	2.54	0.05	6.76	856.78
Mwanza	0	0.0909	362	1.69	0.1	3.30	936.78
Mimosa	1	0.0001	253	3.80	0.001	10.27	1127.89
Thyolo	0	0.0034	437	2.92	0.01	6.55	928.46
Bvumbwe	0	0.0152	363	2.43	0.05	4.25	936.16
Chileka	0	0.0131	371	2.48	0.05	4.01	656.62
Chichiri	0	0.0039	431	2.88	0.01	5.85	818.55
Makoka	0	0.0067	405	2.71	0.01	4.65	790.79
Chingale	0	0.0196	416	2.33	0.05	5.51	824.07
Balaka	0	0.0104	383	2.56	0.05	5.05	563.15
MonkeyBay	0	0.0002	557	3.73	0.001	7.13	544.54

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Table 5 Trend tests of yearly precipitation of Low Shire catchment obtained through linear regression method during 1953-2010.

Station	Linear model Poly1: Y= p1*x + p2
Nsanje	Y=6.721*x-12410
Makhanga	Y=4.225*x-7691
Ngabu	Y=4.225*x-7691
Chikwawa	Y=5.348*x-9934
Nchalo	Y=5.397*x-10100
Neno	Y=6.706*x-12250
Mwanza	Y=3.405*x-5669
Mimosa	Y=10.0*x-18530
Thyolo	Y=6.582*x-11930
Bvumbwe	Y=4.793*x-8420
Chileka	Y=4.229*x-7618
Chichiri	Y=6.686*x-12250
Makoka	Y=4.829*x-8656
Chingale	Y=4.427*x-7781
Balaka	Y=5.607*x-10380
MonkeyBay	Y=7.239*x-13620

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Table 6 Trend tests of monthly total precipitation of Low Shire catchment obtained through the MK method during 1953-2010.

ST.		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Test S	533	117	51	-277	-593	-809	-730	-764	-747	-194	242	263
Balaka	Test Z	3.57	0.78	0.34	-1.85	-3.97	-5.42	-4.89	-5.12	-5.00	-1.29	1.62	1.76
	Signifi	***			+	***							+
	Test S	405	49	23	-121	-330	-342	-352	-359	-354	-222	376	381
Bvumbwe	Test Z	2.71	0.32	0.15	-0.80	-2.21	-2.29	-2.35	-2.40	-2.37	-1.48	2.52	2.55
	Signifi	**				*	*	*	*	*		*	**
	Test S	463	463	340	-95	-496	-501	-510	-452	-464	-125	240	421
Chichiri	Test Z	3.10	3.10	2.27	-0.63	-3.32	-3.35	-3.41	-3.03	-3.11	-0.83	1.60	2.82
	Signifi	**	+	*		***	**	*	**	**			**
	Test S	477	198	191	17	-280	-312	-321	-336	-396	-215	148	155
Chikwawa	Test Z	3.19	1.32	1.27	0.11	-1.87	-2.09	-2.15	-2.25	-2.65	-1.44	0.99	1.03
	Signifi	**				+	*	*		**			
	Test S	488	81	213	-137	-651	-857	-806	-756	-533	-83	375	253
Chileka	Test Z	3.27	0.54	1.42	-0.91	-4.36	-5.74	-5.40	-5.06	-3.57	-0.55	2.51	1.69
	Signifi	**				***	***	***	***	***		*	+
	Test S	472	206	126	-168	-510	-778	-750	-646	-626	-206	250	408
Chingale	Test Z	3.16	1.38	0.84	-1.12	-3.41	-5.21	-5.02	-4.33	-4.19	-1.38	1.67	2.73
	Signifi	***		+				***			*		**
	Test S	333	141	141	-231	-242	-260	-321	-311	-347	-94	6	107
Makhanga	Test Z	2.23	0.94	0.94	-1.54	-1.62	-1.74	-2.15	-2.08	-2.32	-0.62	0.03	0.71
	Signifi	*								*			
	Test S	461	195	115	-179	-521	-789	-791	-657	-637	-217	239	397
Makoka	Test Z	3.09	1.30	0.76	-1.19	-3.49	-5.29	-5.30	-4.40	-4.27	-1.45	1.60	2.66
	Signifi	**				***	***	***	***	***			**
	Test S	241	-10	-21	-32	-71	-136	-125	-139	-289	-32	225	271
Mimosa	Test Z	1.57	-0.06	-0.13	-0.20	-0.46	-0.88	-0.81	-0.90	-1.88	-0.20	1.46	1.77
	Signifi	*		*						+		+	*
	Test S	675	525	57	-500	-782	-873	-803	-719	-757	-550	-159	344
onkeyBay	Test Z	4.52	3.51	0.38	-3.35	-5.24	-5.85	-5.38	-4.82	-5.07	-3.68	-1.06	2.30
	Signifi	***	***		***	***	***	***	***	***	***		*
	Test S	438	10	-33	-190	-461	-551	-336	-261	-208	140	282	270
Mwanza	Test Z	2.94	0.07	-0.22	-1.24	-3.01	-3.60	-2.20	-1.71	-1.36	0.92	1.84	1.77
	Signifi	+						+	**	**		*	
	Test S	413	413	171	-4	-324	-329	-362	-339	-322	-317	176	187
Nchalo	Test Z	2.76	2.76	1.14	-0.02	-2.17	-2.20	-2.42	-2.27	-2.15	-2.12	1.17	1.25
	Signifi	**				*		*			*	**	
	Test S	449	23	-19	-181	-445	-545	-319	-250	-189	156	271	281
Neno	Test Z	3.01	0.15	-0.12	-1.21	-2.98	-3.65	-2.13	-1.67	-1.26	1.04	1.81	1.88
	Signifi	**				**	***		+			+	+
	Test S	333	141	141	-231	-227	-363	-391	-369	-347	-94	6	107
Ngabu	Test Z	2.23	0.94	0.94	-1.54	-1.52	-2.43	-2.62	-2.47	-2.32	-0.62	0.03	0.71
	Signifi	*								*			
	Test S	399	49	3	-9	-271	-300	-325	-366	-298	-39	180	186
Nsanje	Test Z	2.67	0.32	0.01	-0.05	-1.81	-2.01	-2.17	-2.45	-1.99	-0.25	1.20	1.24
	Signifi	**				+			*	*			
	Test S	429	79	46	13	-274	-291	-319	-402	-411	-128	402	410
Thyolo	Test Z	3.19	0.52	0.30	0.08	-1.83	-1.95	-2.13	-2.69	-2.75	-0.85	2.69	2.74
	Signifi	**				+				**		**	

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Table 7 Trend tests of monthly total precipitation of Low Shire catchment obtained through Sen's slope estimate during 1953-2010.

ST		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Balaka	Q	3.11	0.54	0.23	-0.43	-0.19	-0.14	-0.25	-0.19	-0.27	-0.04	-0.04	1.00
	B	95.43	112.06	80.49	45.69	10.44	7.05	13.85	12.51	14.85	11.01	11.01	90.31
Bvumbwe	Q	2.06	0.35	0.52	-0.16	-0.24	-0.10	0.10	-0.07	-0.16	-0.25	1.05	1.20
	B	189.52	192.85	125.30	50.26	25.85	18.38	15.20	14.27	13.37	32.04	42.06	160.66
Chichiri	Q	1.91	1.51	1.13	-0.15	-0.34	-0.21	-0.17	-0.18	-0.19	-0.10	0.61	1.84
	B	171.34	143.41	114.97	44.12	23.39	17.68	19.22	12.94	12.51	25.62	44.94	144.18
Chikwawa	Q	2.04	0.60	0.55	0.01	-0.13	-0.08	0.10	-0.02	-0.06	-0.10	0.62	0.56
	B	105.83	94.05	63.21	26.43	14.92	9.69	8.50	6.22	4.82	12.34	23.22	98.71
Chileka	Q	2.20	0.46	0.73	-0.22	-0.30	-0.25	-0.18	-0.14	-0.16	-0.06	1.01	1.00
	B	123.00	127.82	73.65	36.73	16.98	13.22	9.37	7.05	10.33	19.82	32.03	108.65
Chingale	Q	1.14	0.70	1.34	-0.14	0.02	-0.14	0.15	-0.25	-0.14	0.24	-0.18	0.02
	B	221.32	185.44	86.72	42.93	5.55	7.05	-0.07	13.85	7.05	3.93	68.94	194.97
Makhanga	Q	1.59	0.63	0.42	-0.22	-0.07	-0.04	0.04	-0.04	-0.05	-0.02	0.01	0.45
	B	97.57	89.86	67.48	29.19	11.13	7.86	8.59	6.04	5.41	9.74	37.95	101.22
Makoka	Q	2.40	0.94	0.45	-0.33	-0.26	-0.29	-0.25	-0.15	-0.17	-0.15	0.35	1.95
	B	152.80	162.36	114.23	51.94	16.54	15.27	13.85	8.32	8.72	19.63	39.95	138.33
Mimosa	Q	2.45	0.20	1.81	0.76	-0.09	-0.11	0.29	-0.05	-0.23	-0.02	0.76	2.16
	B	215.18	211.39	162.94	61.96	44.31	36.05	24.72	27.55	25.56	44.03	65.90	181.38
MonkeyBay	Q	3.67	2.81	0.24	-0.48	-0.26	-0.25	-0.13	-0.25	-0.07	-0.08	-0.17	1.83
	B	85.02	95.41	77.19	33.29	13.36	13.85	6.57	13.85	3.44	4.61	25.29	81.13
Mwanza	Q	1.25	-0.26	0.15	0.16	0.11	0.03	0.19	0.23	0.18	0.15	0.82	0.50
	B	191.86	201.43	134.38	48.26	16.32	15.07	8.96	2.04	2.84	23.02	50.75	176.00
Nchalo	Q	1.56	0.70	0.43	0.00	-0.12	-0.01	0.19	-0.03	-0.02	-0.10	0.61	0.71
	B	90.15	82.50	66.34	25.43	13.83	9.91	7.21	5.64	4.76	10.53	19.70	82.62
Neno	Q	3.14	0.22	0.59	-0.35	-0.36	-0.40	-0.10	-0.12	-0.08	0.18	0.62	1.62
	B	164.88	187.83	126.69	58.74	28.87	27.05	16.49	12.28	11.62	16.57	33.67	135.65
Ngabu	Q	1.59	0.63	0.42	-0.22	-0.07	-0.04	0.04	-0.04	-0.05	-0.02	0.01	0.45
	B	97.57	89.86	67.48	29.19	11.13	7.86	8.59	6.04	5.41	9.74	37.95	101.22
Nsanje	Q	2.17	0.23	0.96	-0.02	-0.15	-0.10	-0.02	-0.16	-0.16	-0.03	0.44	0.79
	B	143.72	130.94	90.17	32.40	16.57	18.08	14.95	12.83	11.92	24.92	52.56	142.63
Thyolo	Q	2.41	0.45	0.94	0.04	-0.22	-0.12	0.12	-0.09	-0.20	-0.16	0.86	1.16
	B	177.36	184.99	114.15	46.23	28.39	18.67	16.53	15.36	14.91	28.91	37.90	161.18

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Table 8. Results of homogeneity of trends between stations based on the Van Belle and Hughes' Homogeneity of Trend test

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ž	2.95	1.12	0.64	-0.97	-2.70	-3.36	-3.16	-2.98	-2.89	-0.93	1.36	1.85
$\chi2$ trend	139.22	20.01	6.62	14.99	116.99	180.16	159.65	141.81	133.80	13.73	29.40	54.75
$\chi2$ total	145.50	38.10	13.62	27.02	139.86	221.15	193.78	168.40	155.48	32.50	44.12	62.65
$\chi2$ homogeneous	6.28	18.09	7.00	12.03	22.87	40.99	34.13	26.59	21.68	18.77	14.72	7.90

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Table 9 Results of homogeneity of trends between months based on the Van Belle and Hughes' Homogeneity of Trend test

	Ž	χ2 total	χ2 trend	χ2 homogeneous
Nsanje	-0.44	32.27	2.334302	29.94
Makhanga	-0.60	29.95	4.341378	25.61
Ngabu	-0.72	36.52	6.259333	30.26
Chikwawa	-0.38	42.21	1.703424	40.51
Nchalo	-0.35	49.18	1.511995	47.67
Neno	-0.43	49.53	2.200192	47.33
Mwanza	-0.48	49.25	2.818445	46.43
Mimosa	-0.06	13.84	0.044704	13.79
Thyolo	-0.22	52.54	0.593954	51.95
Bvumbwe	-0.47	50.16	2.671086	47.49
Chileka	-1.35	142.79	21.79704	121.00
Chichiri	-0.40	88.71	1.911611	86.80
Makoka	-1.33	130.69	21.27583	109.41
Chingale	-1.24	126.33	18.4803	107.85
Balaka	-1.62	144.56	31.66608	112.89
MonkeyBay	-1.98	203.64	46.93736	156.70

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Table 10 Results of homogeneity of trends between months based on the Van Belle and Hughes' Homogeneity of Trend test

Zba	χ^2 trend	χ^2 total	χ^2 homogeneous
-0.76	109.56	1242.17	1132.61

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Table 11 Trend tests of monthly peaks precipitation of Low Shire catchment obtained through the MK method during 1953-2010.

ST		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Test S	736	508	325	-42	-547	-800	-698	-722	-726	-6	504	685
Balaka	Test Z	4.93	3.40	2.17	-0.28	-3.66	-5.36	-4.68	-4.84	-4.86	-0.03	3.37	4.59
	Signifi	***	***	*		***		+		+		***	***
	Test S	651	591	314	39	9	27	21	117	40	-34	442	519
Bvumbwe	Test Z	4.36	3.96	2.10	0.25	0.05	0.17	0.13	0.78	0.26	-0.22	2.96	3.47
	Signifi	***	***	*				***	*			**	***
	Test S	667	658	603	75	-204	-64	-153	26	-56	163	312	631
Chichiri	Test Z	4.47	4.41	4.04	0.50	-1.36	-0.42	-1.02	0.17	-0.37	1.09	2.09	4.23
	Signifi	***	***	***				+				*	***
	Test S	312	321	396	195	6	-51	-112	69	-310	-111	471	302
Chikwawa	Test Z	2.09	2.15	2.65	1.30	0.03	-0.34	-0.74	0.46	-2.07	-0.74	3.15	2.02
	Signifi	*	*	**						*		**	*
	Test S	708	303	280	-6	-419	-571	-573	-500	-166	108	530	534
Chileka	Test Z	4.74	2.03	1.87	-0.03	-2.80	-3.82	-3.84	-3.35	-1.11	0.72	3.55	3.58
	Signifi	***	*	**		**	***	*	***			***	***
	Test S	638	501	390	3	-317	-399	-241	-262	-317	55	466	541
Chingale	Test Z	4.27	3.35	2.61	0.01	-2.12	-2.67	-1.61	-1.75	-2.12	0.36	3.12	3.62
	Signifi			+				*	***		+		+
	Test S	451	347	375	94	57	13	18	-57	-116	117	126	483
Makhanga	Test Z	3.02	2.32	2.51	0.62	0.38	0.08	0.11	-0.38	-0.77	0.78	0.84	3.23
	Signifi	**	*	*			*	**	+				**
Makoka	Test S	640	506	398	14	-303	-382	-221	-239	-291	84	498	576
	Test Z	4.29	3.39	2.66	0.09	-2.03	-2.56	-1.48	-1.60	-1.95	0.56	3.33	3.86
	Signifi	***	***	**		*	*			+		***	***
Mimosa	Test S	601	402	453	383	249	181	220	161	121	349	480	697
	Test Z	4.02	2.69	3.03	2.56	1.66	1.21	1.47	1.07	0.80	2.33	3.21	4.67
	Signifi	***	**	***	*	+	+	***	**		*	**	***
	Test S	755	720	450	-200	-595	-860	-696	-661	-649	-355	81	586
MonkeyBay	Test Z	5.06	4.82	3.01	-1.33	-3.98	-5.76	-4.66	-4.43	-4.35	-2.37	0.54	3.92
	Signifi	***	***	**		***		*	***		*		***
	Test S	-251	-252	-133	-119	-251	-378	-112	28	83	-74	181	-214
Mwanza	Test Z	-1.69	-1.69	-0.89	-0.80	-1.68	-2.54	-0.75	0.19	0.56	-0.50	1.21	-1.44
	Signifi	+	+			+	*						
	Test S	547	301	432	162	123	28	-14	73	-47	-112	505	385
Nchalo	Test Z	3.66	2.01	2.89	1.08	0.82	0.18	-0.09	0.48	-0.31	-0.74	3.38	2.58
	Signifi	***	*	**			*	***				***	**
	Test S	553	285	113	-45	-152	-89	17	108	119	290	276	427
Neno	Test Z	3.70	1.91	0.75	-0.30	-1.01	-0.59	0.11	0.72	0.79	1.94	1.84	2.86
	Signifi	***	+	**				*			+	+	**
	Test S	451	347	375	94	109	78	67	-18	-116	117	126	483
Ngabu	Test Z	3.02	2.32	2.51	0.62	0.72	0.52	0.44	-0.11	-0.77	0.78	0.84	3.23
	Signifi	**	*	*			*	**	+				**
	Test S	373	233	207	157	67	47	113	124	118	212	295	288
Nsanje	Test Z	2.50	1.56	1.38	1.05	0.44	0.31	0.75	0.83	0.78	1.42	1.97	1.93
	Signifi	*		*	+			**				*	+
	Test S	549	494	342	173	61	147	13	69	45	92	563	514
Thyolo	Test Z	3.68	3.31	2.29	1.15	0.40	0.98	0.08	0.46	0.30	0.61	3.77	3.44
	Signifi	***	***	*				***	*			***	+

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Table 12 Trend tests of monthly peaks precipitation of Low Shire catchment obtained through Sen's slope estimate between 1953 and 2010.

ST		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Balaka	Q	0.90	0.40	0.25	-0.02	-0.04	-0.01	-0.01	-0.01	-0.01	0.00	0.31	0.49
	B	12.86	17.85	14.36	10.38	2.48	2.11	0.82	0.56	0.44	3.45	10.81	13.19
Bvumbwe	Q	0.47	0.22	0.26	0.02	0.00	0.06	0.15	0.06	0.04	0.00	0.41	0.46
	B	34.92	36.21	29.80	15.30	5.94	3.38	0.60	0.82	0.66	10.78	17.22	33.03
Chichiri	Q	0.36	0.62	0.53	0.04	-0.05	0.00	0.04	0.00	0.00	0.08	0.21	0.48
	B	28.68	23.29	20.15	13.24	5.81	4.02	1.25	1.37	1.11	8.78	16.34	22.26
Chikwawa	Q	0.33	0.26	0.43	0.11	0.00	0.01	0.05	0.00	0.00	0.00	0.33	0.27
	B	30.84	26.27	13.10	6.96	3.36	2.47	0.77	0.68	0.27	3.56	6.79	22.81
Chileka	Q	0.57	0.30	0.43	0.00	-0.05	-0.04	-0.01	-0.01	0.00	0.03	0.53	0.46
	B	23.74	26.57	15.72	10.25	4.53	2.24	0.78	0.56	0.62	9.14	11.27	19.94
Chingale	Q	-0.17	-0.17	0.20	-0.12	0.00	0.00	0.01	0.03	0.00	0.08	-0.19	-0.30
	B	51.23	52.36	28.90	17.16	1.82	1.33	0.51	-0.03	0.48	3.72	29.46	53.75
Makhanga	Q	0.44	0.28	0.34	0.03	0.02	0.05	0.09	0.03	0.00	0.04	0.07	0.38
	B	21.09	22.16	15.64	7.91	2.20	1.02	0.33	0.27	0.47	3.43	14.97	23.85
Makoka	Q	0.61	0.58	0.34	0.00	-0.05	-0.04	-0.01	-0.01	-0.01	0.02	0.26	0.61
	B	22.48	23.17	20.21	15.27	4.05	2.66	1.26	0.74	0.73	6.88	9.56	21.44
Mimosa	Q	0.74	0.39	0.66	0.38	0.11	0.11	0.22	0.17	0.03	0.25	0.44	0.67
	B	27.39	30.66	21.09	15.40	9.53	6.18	1.50	1.35	1.74	10.47	15.23	25.52
MonkeyBay	Q	0.82	0.94	0.35	-0.08	-0.05	-0.06	-0.02	0.00	0.00	-0.01	0.05	0.66
	B	13.83	13.66	15.70	9.82	2.68	3.77	1.00	0.25	0.60	0.80	8.81	15.25
Mwanza	Q	-0.19	-0.30	-0.13	-0.10	-0.09	-0.10	-0.03	0.00	0.00	-0.03	0.14	-0.25
	B	52.52	58.28	44.81	20.32	9.96	9.28	7.03	3.95	1.91	12.78	18.09	51.84
Nchalo	Q	0.51	0.27	0.36	0.08	0.02	0.05	0.12	0.01	0.01	0.00	0.36	0.37
	B	23.96	22.35	12.35	7.62	3.01	1.71	-0.09	0.62	0.48	3.18	4.56	17.95
Neno	Q	0.70	0.16	0.45	-0.01	-0.03	-0.01	0.07	0.01	0.01	0.13	0.17	0.49
	B	27.17	28.55	20.18	17.96	6.91	5.40	1.13	1.46	1.66	5.90	16.34	25.70
Ngabu	Q	0.44	0.28	0.34	0.03	0.02	0.05	0.09	0.03	0.00	0.04	0.07	0.38
	B	21.09	22.16	15.64	7.91	2.20	1.02	0.33	0.27	0.47	3.43	14.97	23.85
Nsanje	Q	0.65	0.25	0.53	0.11	0.02	0.02	0.07	0.02	0.01	0.11	0.24	0.25
	B	30.71	30.53	26.25	8.14	3.93	3.12	2.09	2.06	0.81	6.73	13.88	31.22
Thyolo	Q	0.37	0.22	0.29	0.10	0.02	0.04	0.15	0.07	0.04	0.06	0.47	0.24
	B	38.04	38.96	32.19	13.20	6.13	3.84	0.80	0.84	1.17	9.11	13.67	38.66

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