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Analysis of streamflow and rainfall trends and variability over the Lake Kariba catchment, Upper Zambezi Basin

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ABSTRACT

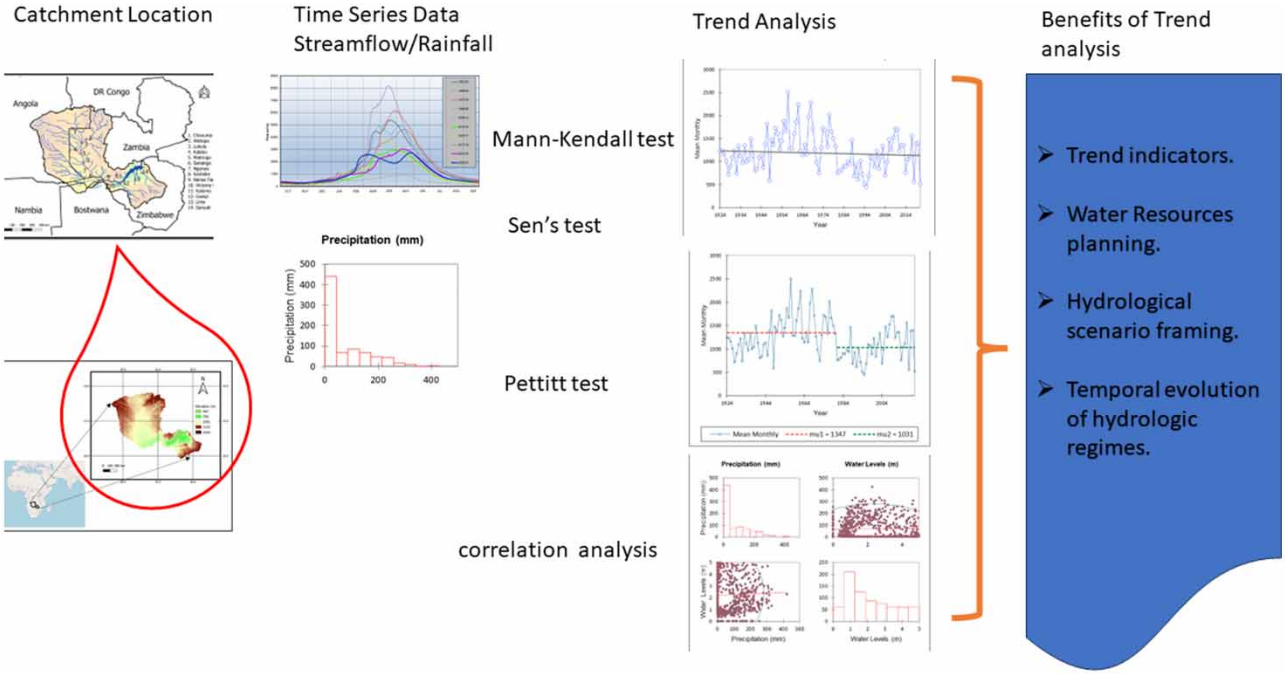
Hydro-meteorological trend analysis is critical for assessing climate change and variability at basin and regional levels. This study examined the long- and short-term trends from stream discharge and rainfall data in the Lake Kariba catchment. A trend and change point analysis was carried out on the mean, minimum and maximum monthly average time series for 14 gauging stations that are located within the Kariba catchment. The Mann–Kendall and the Pettitt tests were used to determine the trend and any changes in the long-term average of the time series. The magnitude of the trend was determined by Sen's slope method. The results indicate that generally there has been a decreasing trend in river and rainfall long-term mean values across the catchment. A statistically significant trend ($p \leq 0.05$) was observed at Zambezi River at Lukulu, Senanga and Victoria Falls, with a positive correlation in Pearsons's coefficient of water levels and rainfall at Lukulu (0.312) and Senanga (0.365). The decrease in the time series trend and the change point observed have been attributed to anthropogenic activities, climate change and variability impact on the catchment. The findings are critical for climate risk management and reduction decisions for near- and long-term timescales.

Key words: climate change and variability, Kariba catchment, Mann–Kendall test

HIGHLIGHTS

- Performed trend analysis of hydro-meteorological data to avoid erroneous conclusions.
- Fourteen gauging stations of river and rainfall data were analysed.
- Long-term data showed increasing and decreasing patterns in rainfall and discharge respectively, inconsistently.
- Correlation of rainfall to streamflow trends for selected stations.
- The findings improve the understanding of hydro-meteorological trend analysis.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water resources management and planning are wholly anchored on the past observation of hydro-meteorology data records that are projected in the future. The time series of the data collected determines the hydrological behaviour of the catchment or river system (Forootan 2019). To sustainably manage water resources requires an understanding of the hydrological regime of a river system that eventually affects the streamflow. Indeed, streamflow is variable and identification in the variability of streamflow data is vital in water resources planning as it moderates the consequences related to overestimation or underestimation of design parameters and water rights allocations way above the available water in the river system (Arrieta-Castro *et al.* 2020). Detecting any change in streamflow is one of the important parts of establishing hydrological variability. This stream flow variability with enough records establishes a trend of a river system at a point of monitoring (Burn & Hag Elnur 2002). Hence, trend analysis is dependent on the duration of the streamflow data being analysed (Dixon *et al.* 2006). Trend analysis has been used to determine any changes in streamflow or any climatic parameters. The assumption that records may repeat in the future is not valid anymore due to the trend (IPCC 2007). Various statistical methods are available now to determine the trend. These methods are distinguished based on the approach being used: parametric and non-parametric. A decline in streamflow has generally been established in southern Africa, with concerns about its availability to various competing needs of hydropower production, irrigation and water supply among others. The decline in streamflow has been attributed to insufficient rainfall, an increase in population, land cover changes and hydrological regulation (Banze *et al.* 2018; Winton *et al.* 2021; Ndhlovu & Woyessa 2022).

Several studies have been done on trend analysis in streamflow and rainfall. Elouissi *et al.* (2017) and Benzater *et al.* (2019) analysed the impact of climate change on the rainfall pattern of not less than 41 stations within the Macta watershed in Algeria, with a downward trend being established together with the corresponding deficit within the time series. Şen (2017) employed statistical procedures to determine trend constituents in any hydro-meteorological time series. Ndhlovu & Woyessa (2021) assessed the impact of various climate change prediction scenarios on stream flow data. It was determined that the climatic component of temperature showed an upward trend with considerable ambiguities in precipitation. Other studies have found no pattern of change in streamflow as rainfall varies spatially and temporally (Hannaford 2015). Gebremicael *et al.* (2013) analysed the temporal and spatial changes in rainfall and streamflow in the Upper Tekeze Atbara River Basin in Ethiopia using the Mann–Kendall and Pettitt test. The result indicated that rainfall did not exhibit statistically significant changes; however, streamflow patterns exhibited a statistically significant increasing and decreasing trend.

Similarly, Tigabu *et al.* (2020) and Hassaballah *et al.* (2019) revealed that streamflow was increasing without a significant increase in rainfall change patterns. On the other hand, Orke & Li (2021) showed an increasing rainfall has resulted in decreasing streamflow and a shortage of water resources in the watershed in the same basin. The lack of agreement on trends in the same catchment was probably due to differences in timescales as Orke & Li (2021) used a long-term record (more than 30 years). More than 30 years of recorded rainfall and streamflow data are reasonable for applying trend statistical analysis as demonstrated by other studies such as Love *et al.* (2010) and Gebremicael *et al.* (2013).

One of the major basins in southern Africa is the Zambezi, of which the Kariba catchment is part. The hydrology of the basin has existing and potential hydropower development, water supply, irrigation and other ecological processes (Beilfuss 2012). The Intergovernmental Panel on Climate Change (IPCC) has categorised the Zambezi as a river basin displaying more dire potential effects of climate change among 11 major African basins as it has been established that a minimal change in rainfall has a bigger change in runoff over the basin, hence being classified as highly sensitive to any changes in climate (Pachauri & Meyer 2014; Chisanga *et al.* 2022).

Lake Kariba, whose catchment this research is studying, was principally built for hydropower generation, with time, the catchment now serves multiple uses that include tangible fisheries, agriculture, urban water supplies, transportation, energy and intangible influence derived from tourism (Tumbare 2008). Each use requires a certain quantity and quality of water. Nonetheless, there is no information regarding a systematic trend valuation and analysis of streamflow over the catchment regarding water requirements for each of these uses. This has led to sustainability threats ranging from reduced water availability for hydropower generation to water pollution from aquaculture, agrochemicals as well as urban and industrial activities, invasive weeds and oil leaks from boats (Tumbare 2008).

The effects of the various types of water for power generation and other uses have become a source of concern based on recent trends of low flows that the Kariba catchment has been experiencing (ERB 2019). The causes of these low water levels have been attributed to anthropogenic activities, natural causes, climate change and mismanagement (Fathian *et al.* 2015). We hypothesize that the data length (both stream flow and rainfall) will impact the trend detection analysis. Therefore, the objective of this paper was to carry out trend analysis on 14 gauging stations located in the Kariba catchment using the entire set of records with varying data length and identify change points, if any, from 1924 to 2022. The results of this study will be of use in the planning and operation of Kariba Reservoir and any future hydraulic infrastructure development in Kariba catchment.

2. MATERIALS

2.1. Study area

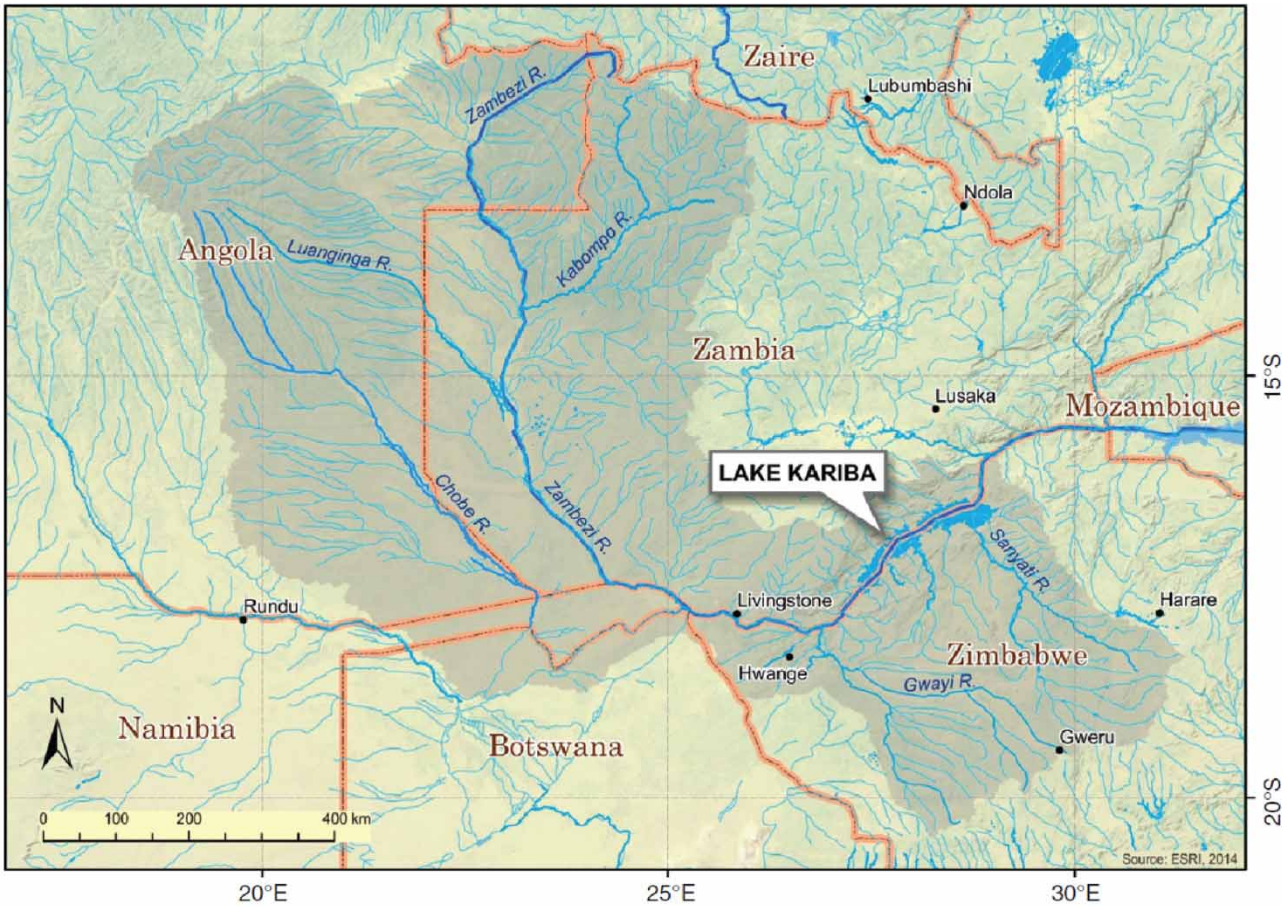
Kariba catchment is located between longitudes of 11 °S and 21 °S and latitudes of 18 °E and 32 ° E, spread across Angola, Botswana, the Democratic Republic of Congo, Namibia, Zimbabwe and Zambia (Figure 1). The Kariba catchment has a drainage area of 663,840 km^2 or approximately 47% of the total Zambezi drainage. The catchment hosts Lake Kariba, built in the late 1950s, mainly for hydropower production. The lake boasts a reservoir surface area of 5,580 km^2, a reservoir length of 280 km and a width of 32 km at its widest point. The catchment lies between 400 and 1,600 m above sea level.

2.2. Gauging stations and data pre-processing

For more than half a century, the Kariba catchment has been gauged and runoff records have been kept at various stations, as shown in Figure 2. The stream flow and water levels data were obtained from the Zambezi River Authority, a statutory body jointly owned by the Governments of Zambia and Zimbabwe whose mission is to effectively utilise the water and other resources of the Zambezi River common to the borders of the two countries (ZRA 2018). The data obtained were pre-processed for quality and consistency by missing data filling, outliers' identifications (Adeloye & Montaseri 2002).

2.3. Meteorology and climate data

The Kariba catchment lies within the tropical African region south of the equator. It has three distinct seasons with small onset variations. These are the cool and dry season (April to August), warm and dry season (September to October) and warm and wet season (November to March) (SADC 2018). Intensive solar radiation provides the energy source for evaporation and for heating the Earth's surface. A temperature gradient, which builds up between the equator and the poles, drives the general circulation of the atmosphere. The average annual rainfall for the whole catchment is approximately 970 mm, with variations ranging from 1,200 mm in the northern part of the catchment to about 500 mm in the southern part



Source: ESRI, 2014

Figure 1 | Lake Kariba catchment in southern Africa.

(SADC 1998). Table 1 shows the location of gauging stations, the type of data collected, the duration of the datasets and the type of gauge used to collect the data. It should be noted that different entities collect the data on the Zambian side, the Water Resources Management Authority (WARMA) is mandated to manage the country's water resources, whereas, in Zimbabwe, the Zimbabwe Water Authority (ZINWA) has a similar mandate. However, the duration of rainfall data is less than 25% of the duration of river records.

Due to a lack of consistency in meteorology and climate data in the Lake Kariba catchment that corresponds to the records of stream data under consideration with most gauging stations with less than 15 years of data, while underscoring the importance of surface measurements, which many times are just point measurements, have non-uniform coverage and often have data void regions (Beven 2012). To overcome this challenge of field measurements, Earth Observation System (EOS) techniques, such as the use of reanalysis products, become useful (Schultz 1996; Farr & Kobrick 2000). Reanalysis can be defined as a scientific procedure of mounting a complete record of weather and climate variables and their variations over time (Wang-Erlandsson *et al.* 2016). The ability of the reanalysis products to simulate close-to-reality situations has been well documented in the literature though appropriate consideration must be undertaken when using the reanalysis datasets (Wang-Erlandsson *et al.* 2016; Muñoz-Sabater *et al.* 2021). The major advantage of this dataset is that it covers the entire globe and encompasses a longer period. For this present study, the TerraClimate and ERA5-Land precipitation dataset was used on selected stations to validate the trends that will be observed in the stream or river data. TerraClimate is a dataset of monthly climate and climatic water balance for global terrestrial surfaces from 1958 to 2022 with a temporal resolution of 4 km (1/24th degree) (Abatzoglou *et al.* 2018), while the land component of the fifth generation of European ReAnalysis referred to as ERA5-Land has the spatial resolution of 11.1 km at the time scale of daily spanning a period of 1963 to 2023. The dataset was obtained from the Climate Engine website (https://climateengine.com/).

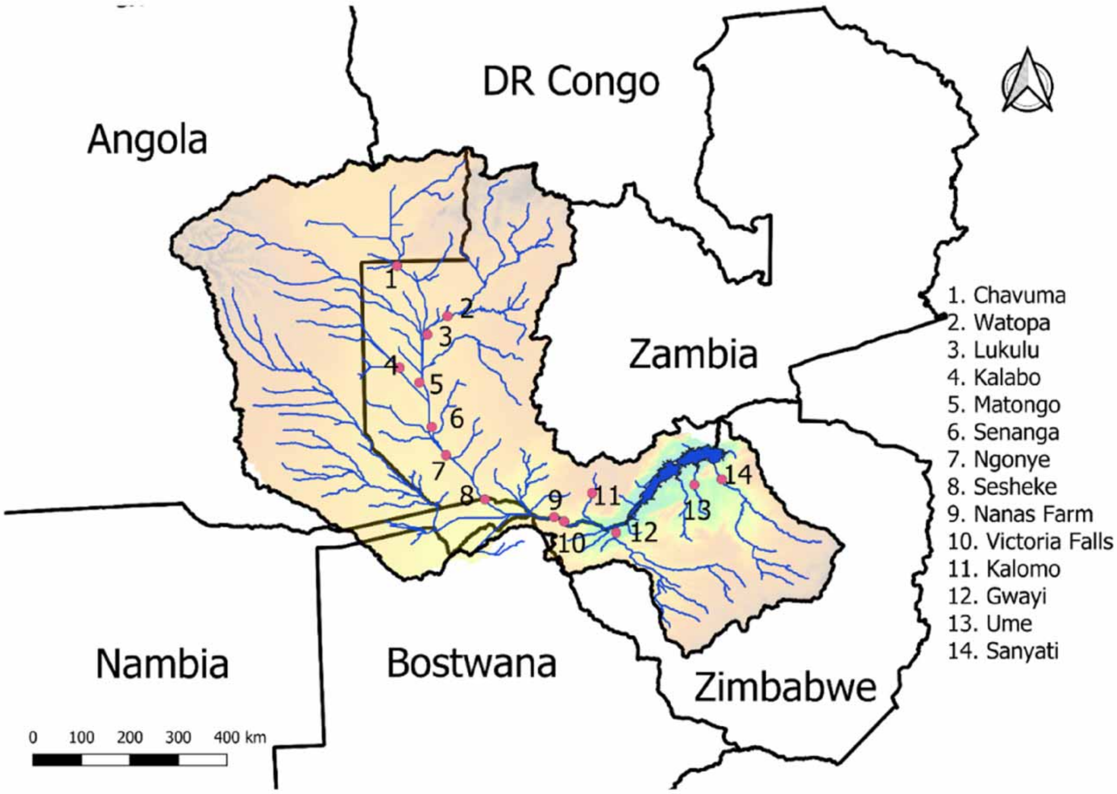


Figure 2 | Location of gauging stations in the Kariba catchment.

3. METHODOLOGY

Non-parametric statistical methods were used in the study to determine the trend in streamflow data, the magnitude of the trend and change point detection of the time series with the determined confidence level. The methods chosen for this study are the Mann–Kendall test for trend analysis, Sen's test method for the magnitude of trend determination and Pettitt test method for determining abrupt changes in streamflow data records. All these methods have been used in hydro-meteorology data analysis and have shown impressive results (Sen 1968; Harrigan *et al.* 2014; Pohlert 2016; Sidibe *et al.* 2018; Arrieta-Castro *et al.* 2020; Wang *et al.* 2020; Cooley & Chang 2021; Das & Banerjee 2021; Ekolu *et al.* 2022; Panditharathne *et al.* 2022). The Mann–Kendall test statistics (S) is computed using the following equation:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} Sgn(x_j - x_K) \tag{1}$$

where n is the number of observations, x_j is the jth observation and Sgn(.) is the sign function, which can be calculated as:

$$Sgn(x_j - x_k) = \begin{cases} +1 \quad if \ (x_j - x_k) \ > \ 0 \\ \ 0 \quad if \ \ (x_j - x_k) \ = \ 0 \\ -1 \quad if \ \ (x_j - x_k) \ < \ 0 \end{cases} \tag{2}$$

The variance of S is computed (Helsel *et al.* 2020) as:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i+1}^{m} t(t-1)(2t+5)}{18} \tag{3}$$

Table 1 | List of gauging stations on the Kariba catchment with type and duration of records

		Location			Rainfall				
No.	**Station name**	**Latitude**	**Longitude**	**River and period of records**	**and period of records**	**Country**	**Data collected**	**Type of gauge**	**Comment**
1	Chavuma	−13.08	22.68	Zambezi – 1959 to date	2011 to Date	Zambia	Water level, discharge, rainfall	Manual + SADC HYCOS Telemetry	Good continuous records on flows only
2	Watopa Pontoon	−14.04	23.63	Kabompo – 1958 to date	2005 to date	Zambia	Water level, discharge, rainfall	Manual + WARMA GSM Telemetry	Good continuous records on flows only
3	Lukulu	−14.38	23.24	Zambezi – 1950 to date	2015 to date	Zambia	Water level, rainfall	Manual + WARMA GSM Telemetry	Good continuous records on water level only
4	Kalabo	−14.99	22.70	Luanginga – 1957 to date	2015 to date	Zambia	Water level, discharge, rainfall	Manual + WARMA GSM Telemetry	Good continuous records on flows only
5	Matongo Platform	−15.26	23.07	Little Zambezi – 1958 to date	2015 to date	Zambia	Water level	Manual + ZRA + WARMA GSM Telemetry	Good continuous records on water levels only
6	Senanga	−16.12	23.29	Zambezi – 1948 to date	2015 to date	Zambia	Water level, rainfall	Manual + WARMA GSM Telemetry	Good continuous records on water levels only
7	Ngonye	−16.64	23.56	Zambezi – 2005 to date	2010 to date	Zambia	Water level, discharge, rainfall	Manual + WARMA GSM Telemetry	Good continuous records on flows only
8	Sesheke	−17.49	24.30	Zambezi – 1997 to date	2015 to date	Zambia	Water level, rainfall	Manual + WARMA GSM Telemetry Underway	Good continuous records on water level only
9	Nana's Farm	−17.83	25.65	Zambezi – 1994 to date	2011 to date	Zambia	Water level, discharge, rainfall	Manual + SADC HYCOS Telemetry	Good continuous records on flows only
10	Victoria Falls – Big Tree	−17.91	25.85	Zambezi – 1924 to date	–	Zimbabwe (ZINWA)	Water level, discharge	Manual	Good continuous records
11	Kalomo	−17.38	26.40	Kalomo – 2008 to Date	2010 to date	Zambia	Water level, discharge, rainfall	Manual	Good continuous records on flows only
12	Gwayi	−18.13	26.86	Gwayi1993 to Date	2010 to date	Zimbabwe	Water level, discharge, rainfall	Manual + ZRA Telemetry	Good continuous records on flows only
13	Ume	−17.22	28.39	Ume River – 2006 to date	2010 to date	Zimbabwe	Water level, discharge, rainfall	Manual	Good continuous records on flows only
14	Sanyati	−17.12	28.93	Sanyati 1993 – Date	2010 to date	Zimbabwe	Water level, discharge, rainfall	Manual + ZRA Telemetry	Good continuous records on flows only

where m is the number of tied ranks. Each with t_i tied observations. The Mann–Kendall is represented by Z and is calculated as in Equation (4):

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S-1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \tag{4}$$

whereas the positive value of Z denotes an increasing trend and the negative value is associated with a decreasing trend. The magnitude of the trend is calculated based on the method of (Sen 1968), Equation (5), which is known as the Sens Slope method (SS):

$$\text{SS} = \text{median}\left[\frac{x_j - x_i}{j - i}\right] \text{for all } i \ < j \tag{5}$$

where x_i is the data value at time step i and x_j at time j.

A Pettitt's test was done on the monthly time series values with the following assumptions, H_0: Data are homogeneous and H_a: There is a date at which there is a change in the data. If the computed p-value is greater than the significance level $\alpha = 0.05$, one cannot reject the null hypothesis H_0. The change point detection method is important in recognising jumps in the time series that can be attributed to climate change (Palaniswami & Muthiah 2018)

The Pettitt method (Pettit 1979) for change detection assumes that when a sample is split into two segments, the mean of both samples does not change. The non-parametric statistics U_t is expressed as follows:

$$U_t = \sum_{i=1}^{t} \sum_{j=t+1}^{n} \text{sign } (x_t - x_j) \tag{6}$$

where:

$$Sgn(x_t - x_j) = \begin{cases} +1 & \text{if } (x_i - x_j) \ > \ 0 \\ 0 & \text{if } (x_i - x_j) \ = \ 0 \\ -1 & \text{if } (x_i - x_j) \ < \ 0 \end{cases} \tag{7}$$

The test statistic K and the corresponding confidence level (P) of length (n) of a sample are defined by:

$$K = Max|U_t| \tag{8}$$

$$p = \exp\left(\frac{-K}{n^2 + n^3}\right) \tag{9}$$

If the p is smaller than the specified confidence level, the null hypothesis should not be accepted. Hence the significance probability (P) for a change point is expressed as follows:

$$p = 1 - p \tag{10}$$

The statistics analysis was performed with a confidence level of 0.05 using an add-in software XLSTAT in Microsoft Excel. A Mann–Kendall trend test was carried out on the monthly average, minimum and maximum values for the 14 gauging stations in the Kariba catchment for various durations based on two hypotheses (two-tailed test): one is null (H_0) and the other is the alternative hypothesis (H_a). The H_0 elucidates that there is no trend in the time series while the H_a denotes the presence of a trend in the time series. Therefore, the trend identification in the time series will be based on the condition of a 5% significance level, with p-value being $\leq \alpha = 0.05$, which translates to the acceptance of the H_a, which signifies the presence of a trend in the time series and with p-value being $\geq \alpha = 0.05$, signifying the absence of a trend. Further analysis of point and areal rainfall reanalysis data obtained over the Kariba catchment was subjected to similar statistical analysis using the Pearson correlation coefficient on selected gauging stations that had statistically significant trends in stream time series. The Pearson correlation coefficient indicates the strength of the relationship between two values, either positive or negative, in this case, the stream measurements and rainfall data. The theory and application of this method has well been documented in the literature and statistical textbooks (Kothyari & Singh, 1996; Sahat *et al.* 2020)

4. RESULTS

This section outlines the results of various analyses of mean, minimum and maximum monthly stream flow for all 14 gauging stations and selected stations for rainfall reanalysed dataset. The results presented are from the Mann–Kendall test for trend analysis, Sen's test method for the magnitude of trend determination and the Pettitt test method for determining abrupt changes in data records. A further result of the correlation between the stream flow/water level and rainfall on the three stations that had statistically significant trends are presented, these are the Zambezi River at Lukulu, Senanga and Victoria Falls.

4.1. Trend analysis results for the average monthly values

Table 2 shows the results of the trend analysis for monthly mean values for all the 14 gauging stations. In general, all the 14 gauging stations exhibited some trends with four stations exhibiting statistically significant trends whose p-values have been highlighted in Table 2. Nine stations showed decreasing trends, while five showed upward trends with Nanas Farm gauging station being the only one presenting a significant upward trend.

Figure 3 shows the spatial variation of mean monthly trends for streamflow with a statistically decreasing trend (down-pointing triangles in red), statistically increasing trend (up-pointing triangles in blue) and no significant trend, either general increasing or decreasing trends (circles) in green and red, respectively.

The graphical representation of the magnitude of the trend in mean values at all the 14 gauging stations based on the Sen's slope developed by Sen (1968) is shown in Figure 4. The Sen's slope graphs indicate that only 35% of the total gauging stations under consideration in Lake Kariba catchment exhibit an increasing trend while 65% indicate a decreasing trend. The magnitude of Sen's slope denotes generally that there is a decreasing trend in Lake Kariba catchment mean values. On the monthly timescale, all the stations exhibited one or more statistically significant trends in the monthly mean time series except for Watopa and Ngonye gauging stations whose monthly p-values were more than the α value of 0.05. Nanas Farm had the maximum number of months seven that had a statistically significant trend: October, November, January,

Table 2 | Results of the Mann–Kendall trend test on mean monthly values

	Gauging station name	Period of analysis	Kendall's tau	S	Var (S)	p-value (two-tailed)	α
1	Zambezi River at Chavuma	1959–2022	−0.042	−83	28,427	0.63	0.05
2	Kabompo River at Watopa	1958–2022	0.010	20	29,792	0.91	0.05
3	Zambezi River at Lukulu	1950–2022	−0.112	−286	42,316	0.17	0.05
4	Little Zambezi at Matongo	1958–2022	0.061	131	32,650	0.47	0.05
5	Luanginga River at Kalabo	1957–2022	−0.104	−217	31,199	0.22	0.05
6	Zambezi River at Senanga	1948–2022	−0.161	−435	45,917	**0.04**	0.05
7	Zambezi River at Ngonye	2005–2022	0.015	2	589	0.97	0.05
8	Zambezi River at Sesheke	1997–2022	0.231	75	2,058	0.10	0.05
9	Zambezi River at Nanas Farm	1994–2022	0.302	114	2,560	**0.03**	0.05
10	Zambezi River at Victoria Falls	1924–2022	−0.047	−222	106,149	0.50	0.05
11	Kalomo River at Luezhi Ranch	2008–2022	−0.495	−45	334	**0.02**	0.05
12	Gwayi River at Deka Road Bridge	1993–2022	−0.062	−17	1,624	0.69	0.05
13	Ume River at Binga Road Bridge	2006–2022	−0.450	−54	493	**0.02**	0.05
14	Sanyati River at Binga Road Bridge	1993–2022	−0.042	−16	2,562	0.77	0.05

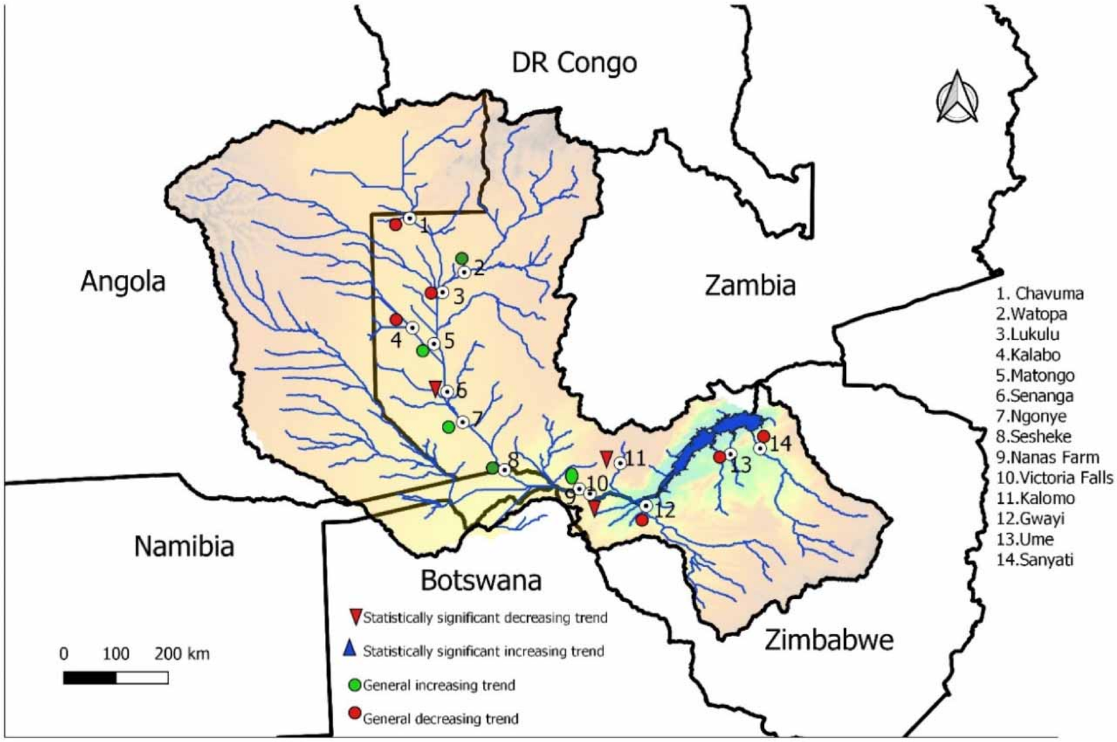


Figure 3 | Spatial variation of mean monthly trends for streamflow over the Lake Kariba catchment.

February, July, August and September. While Lukulu and Senanga had the second highest number of months with a statistically significant trend with five each, Luanginga River at Kalabo and Zambezi River at Sesheke recorded four months each of statistically significant trend. The rest of the stations had either one, two or three months of statistically significant trend. Figure 5 shows the monthly mean values with those months exhibiting statistically significant trends being shown with bar charts in green not exceeding the α horizontal line value of 0.05.

Table 3 shows the results of the Pettitt test that was done on all 14 gauging stations to determine abrupt changes in the long-time mean values and what time the change occurred. Statistically significant changes in the time series were observed at Lukulu, Senanga, Nanas Farm, Victoria Falls, Kalomo and Ume gauging stations.

Figure 6 shows the graphs of all the 14 gauging stations showing abrupt changes that have occurred in the long-term mean values for the whole period of record. Zambezi River at Lukulu had its long-term water mean value change from 2.580 to 2.081 m with the change being observed in 1980, Zambezi River at Senanga changed from 2.580 to 2.182 m in 1978, Zambezi River at Nana's Farm increased its mean value from 905 to 1,256 m^3/s in 2005. Zambezi River at Victoria Falls reduced its annual mean flow from 1,347 to 1,031 m^3/s in 1980. The Kalomo River at Luezhi Ranch and Ume River at Binga Road Bridge reduced their mean water level from 2.897 to 1.596 m and 2.030 to 0.929 m, respectively in 2012.

4.2. Trend analysis results for minimum monthly values

A trend test on monthly minimum values was done as shown in Table 3 giving summary results for all 14 gauging stations. Ten gauging stations indicated a decreasing trend while four showed an increasing trend. Table 4 indicates that seven stations indicated a statistically significant trend at a 95% confidence level, of which five stations showed a decreasing trend and two increasing trends. The station with a statistically significant trend has *p*-values less than 0.05 and are in bold.

Figure 7 shows spatial variation of mean monthly trends for streamflow with a statistically decreasing trend (down-pointing triangles in red), statistically an increasing trend (up-pointing triangles in blue) and no significant trend, either general increasing or decreasing trends (circles) in green and red, respectively.

The graphical representation of the magnitude of the trend in mean values at all the 14 gauging stations based on the Sen's slope developed by Sen (1968) is shown in Figure 8. The Sen's slope graphs indicate that only 71% of the total gauging

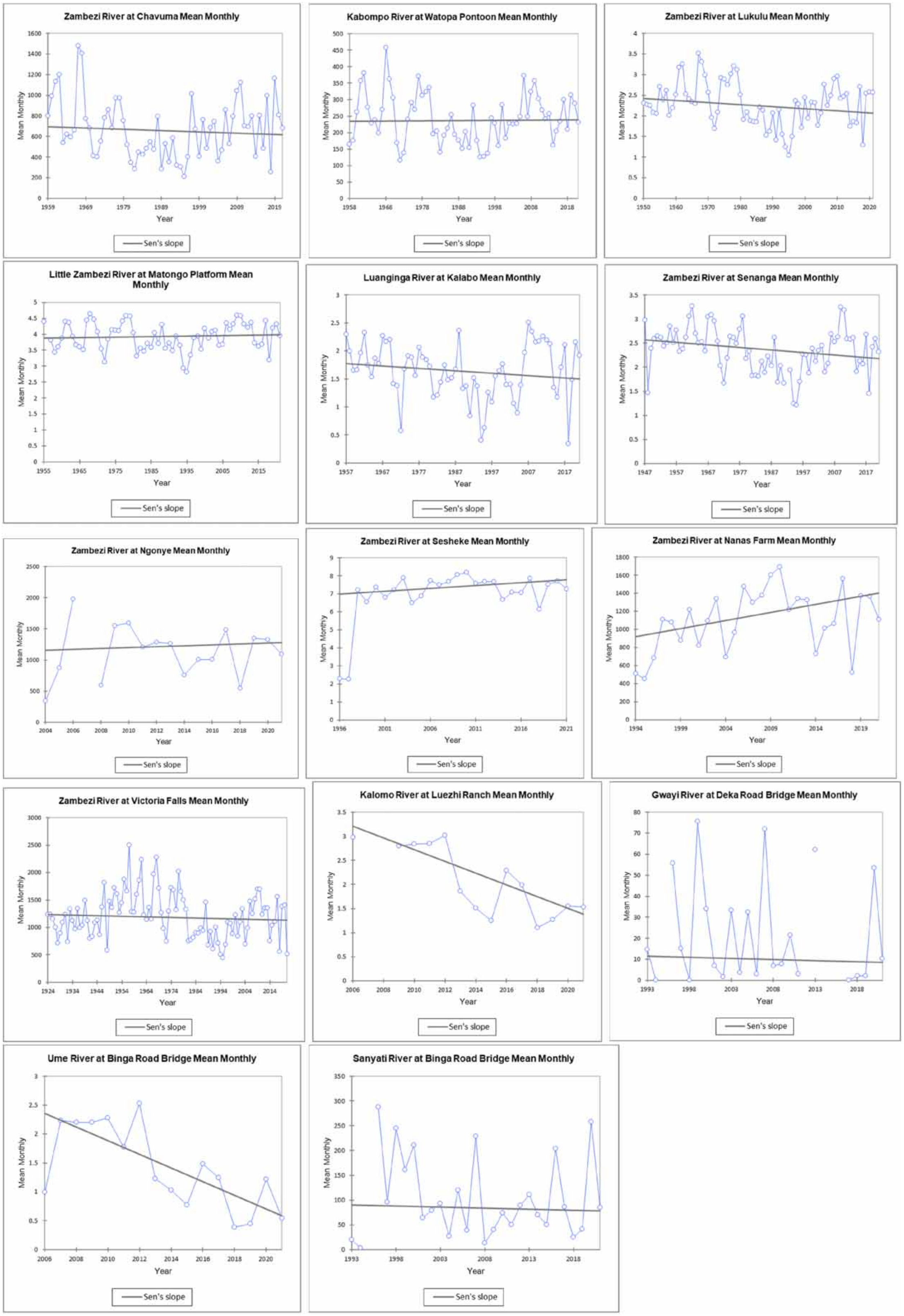


Figure 4 | Sen's slope trend analysis for mean values of stream flow.

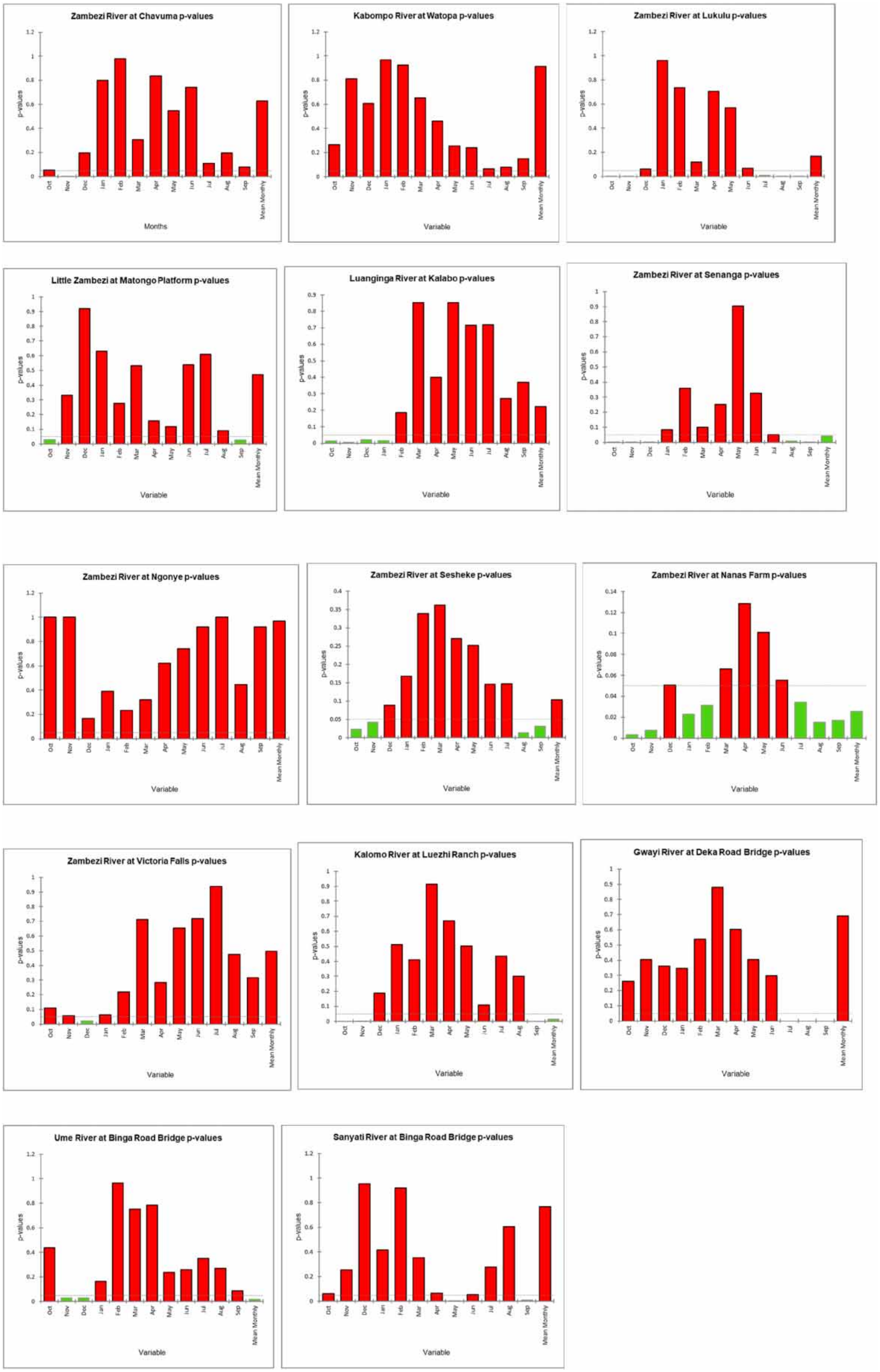


Figure 5 | Mean monthly *p*-values from selected 14 gauging stations in the Kariba catchment.

Table 3 | Pettitt's test on change point detection on mean values

	Gauging station name	Period of analysis	*K*	*t*	*p*-value (two-tailed)	*α*
1	Zambezi River at Chavuma	1959–2022	378	1979	0.09	0.05
2	Kabompo River at Watopa	1958–2022	311	1980	0.34	0.05
3	Zambezi River at Lukulu	1950–2022	665	1980	**0.00**	0.05
4	Little Zambezi at Matongo	1958–2022	320	1999	0.36	0.05
5	Luanginga River at Kalabo	1957–2022	344	1969	0.22	0.05
6	Zambezi River at Senanga	1948–2022	722	1978	**0.00**	0.05
7	Zambezi River at Ngonye	2005–2022	24	2005	0.61	0.05
8	Zambezi River at Sesheke	1997–2022	94	2005	0.11	0.05
9	Zambezi River at Nanas Farm	1994–2022	124	2005	**0.03**	0.05
10	Zambezi River at Victoria Falls	1924–2022	1005	1980	**0.00**	0.05
11	Kalomo River at Luezhi Ranch	2008–2022	45	2012	**0.01**	0.05
12	Gwayi River at Deka Road Bridge	1993–2022	34	2013	0.24	0.05
13	Ume River at Binga Road Bridge	2006–2022	53	2012	**0.02**	0.05
14	Sanyati River at Binga Road Bridge	1993–2022	50	1994	0.47	0.05

stations under consideration in Lake Kariba catchment exhibit a decreasing trend while 29% indicate an increasing trend in minimum monthly values. The magnitude of Sen's slope denotes generally that there is a decreasing trend in Lake Kariba catchment in the minimum values.

The variations on monthly trends were observed in all the 14 gauging stations except at Kabompo River at Water and the Zambezi River at Ngonye in minimum values. Zambezi River at Nana's farm had the highest number of months that had a statistically significant trend of eight months, with Zambezi River at Lukulu and Senanga exhibiting seven months with a statistically significant trend, as shown in Figure 9. A Pettitt's test was done to determine any change in the long-term minimum values with possible time of change, the results are shown in Table 5. The stations that exhibited a significant trend ($p \leq 0.05$) have their *p*-values in bold. Nine gauging stations exhibited statistically significant shifts in the long-term minimum values.

The following changes were observed in long-term minimum values for the nine stations that exhibited a significant shift, as shown in Figure 10.

- The Zambezi River at change had its long-term minimum value change from 69.58 to 45.95 m^3/s, with the change point being in 1981.
- Zambezi River at Lukulu had its value change from 0.679 to 0.374 m in year 1982.
- The little Zambezi River at Matongo increased its minimum long-term value from 1.803 to 2.033 m in 1975.
- Luanginga River at Kalabo's minimum long-term value changed from 0.398 to 0.165 m in 1993.
- Zambezi River at Senanga changed from 0.810 to 0.594 m in 1980.
- Zambezi River at Nana's Farm minimum flow increased from 175.69 to 244.97 m^3/s in 2000.
- Zambezi River at Victoria Falls' long-term minimum flow decreased from 273.44 to 176.66 m^3/s in 1989.
- Kalomo River at Luezhi Ranch values shifted from 2.084 to 0 m in 2012.
- Sanyati River at Binga Road Bridge's flows decreased from 2.084 to 0 m^3/s.

4.3. Trend analysis results for maximum monthly values

Table 6 gives a summary of the results of tests using the Mann–Kendall trend test on maximum monthly values. Eight gauging stations exhibited a decreasing trend, while six showed an increasing trend with one station (Zambezi River at Senanga) showing a statistically significant decreasing trend in maximum values.

Figure 11 shows spatial variation of maximum monthly trends for streamflow with a statistically decreasing trend (down-pointing triangles in red), statistically an increasing trend (up-pointing triangles in blue) and no significant trend, either general increasing or decreasing trends (circles) in green and red, respectively

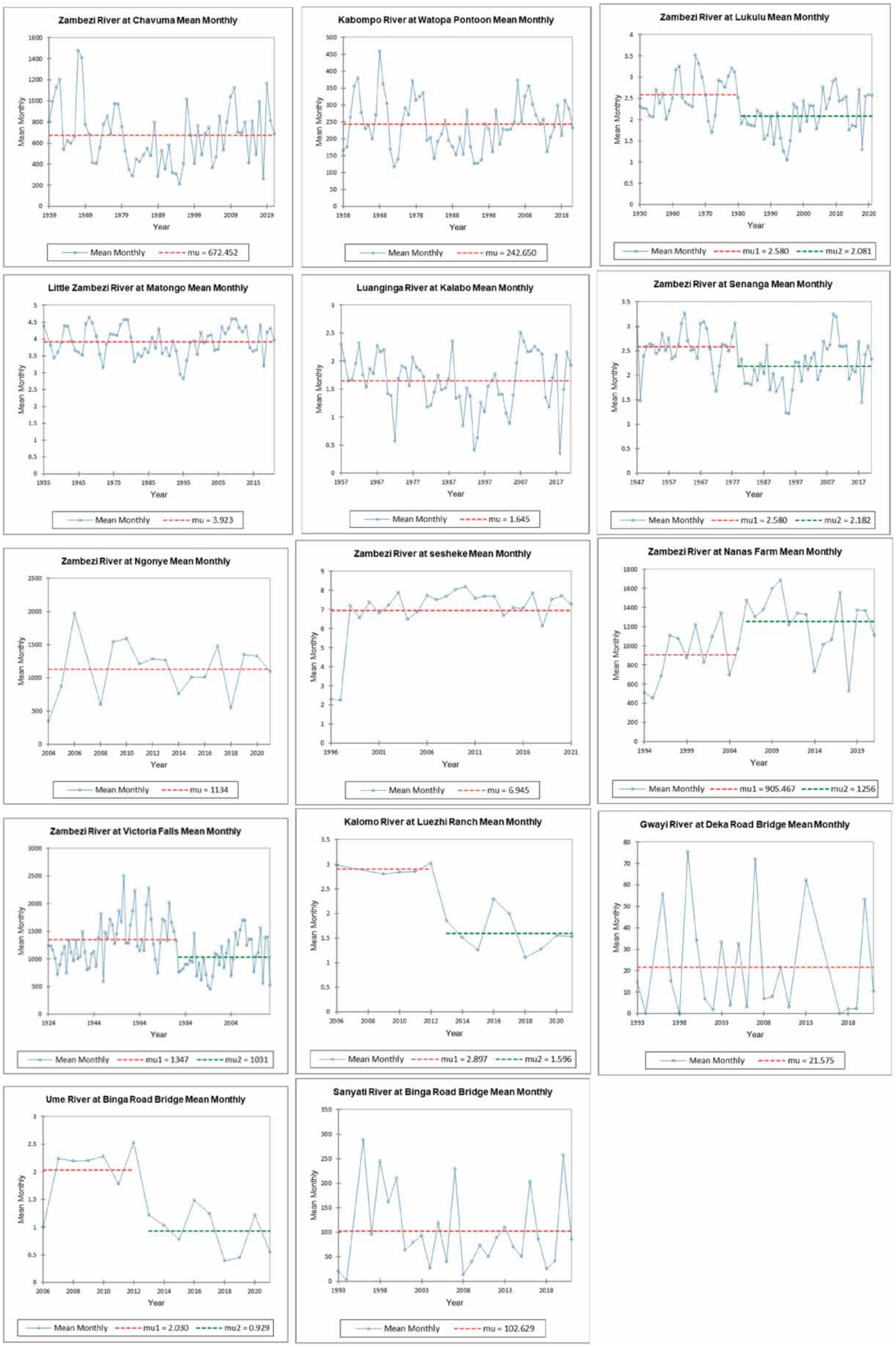


Figure 6 | Changepoint detection in mean values.

Table 4 | Results of the Mann–Kendall trend test on minimum monthly values

	Gauging station name	**Period of analysis**	**Kendall's tau**	***S***	**Var (S)**	***p*-value (Two-tailed)**	***α***
1	Zambezi River at Chavuma	1959–2022	−0.24	−419	24,540	**0.01**	0.05
2	Kabompo River at Watopa	1958–2022	0.01	22	29,761	0.90	0.05
3	Zambezi River at Lukulu	1950–2022	−0.21	−462	34,124	**0.01**	0.05
4	Little Zambezi at Matongo	1958–2022	0.28	530	27,093	**0.00**	0.05
5	Luanginga River at Kalabo	1957–2022	−0.31	−587	27,054	**0.00**	0.05
6	Zambezi River at Senanga	1948–2022	−0.27	−602	34,103	**0.00**	0.05
7	Zambezi River at Ngonye	2005–2022	−0.12	−16	589	0.54	0.05
8	Zambezi River at Sesheke	1997–2022	0.19	62	2,057	0.18	0.05
9	Zambezi River at Nanas Farm	1994–2022	0.47	130	1,625	**0.00**	0.05
10	Zambezi River at Victoria Falls	1924–2022	−0.12	−578	105,999	0.08	0.05
11	Kalomo River at Luezhi Ranch	2008–2022	−0.68	−48	241	**0.00**	0.05
12	Gwayi River at Deka Road Bridge	1993–2022	−0.24	−19	192	0.19	0.05
13	Ume River at Binga Road Bridge	2006–2022	−0.35	−27	277	0.12	0.05
14	Sanyati River at Binga Road Bridge	1993–2022	−0.28	−90	2,211	0.06	0.05

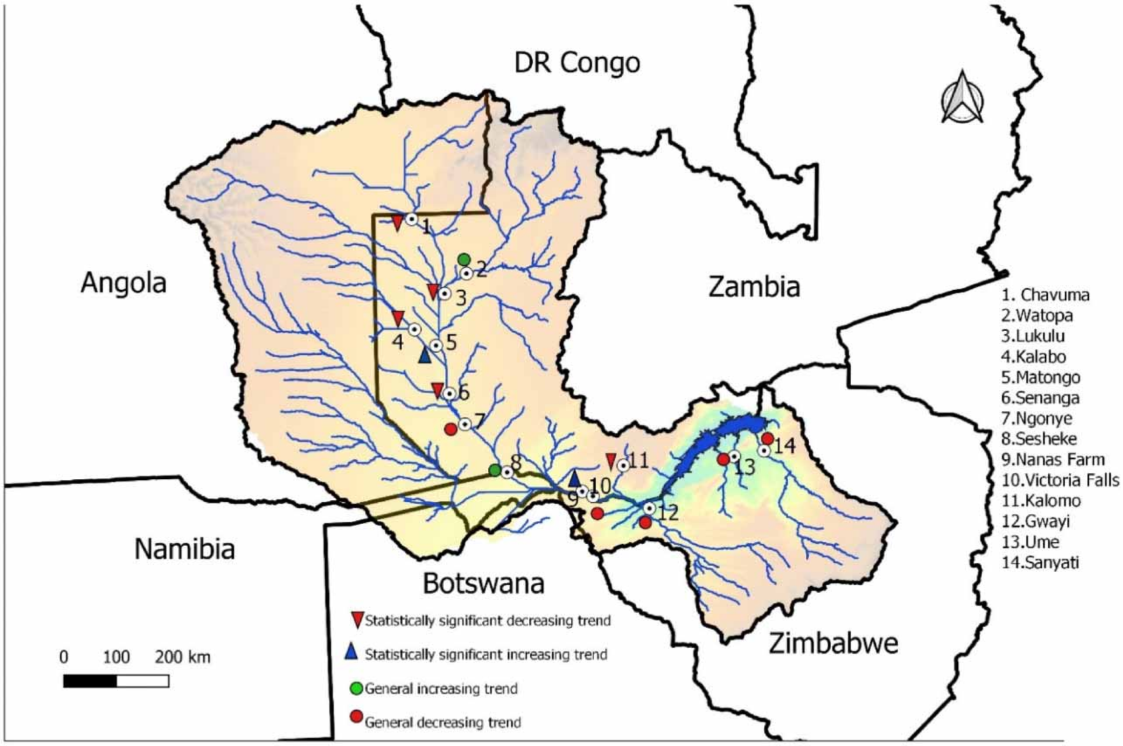
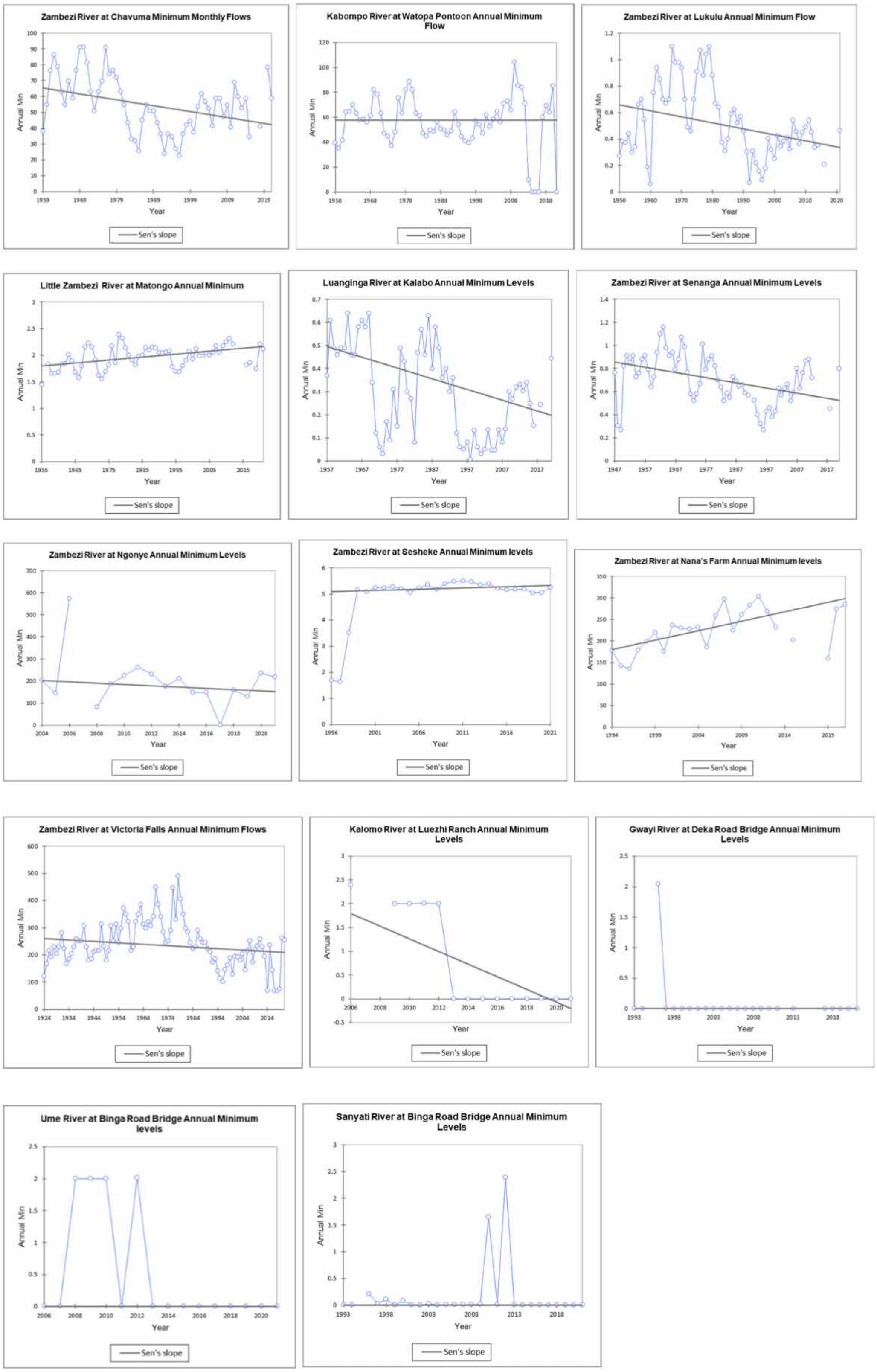


Figure 7 | Spatial variation of minimum monthly trends for streamflow over Lake Kariba catchment values.

The graphical representation of the magnitude of the trend in mean values at all the 14 gauging stations based on the Sen's slope developed by Sen (1968) is shown in Figure 12. The Sen's slope graphs indicate that only 57% of the total gauging stations under consideration in Lake Kariba catchment exhibit a decreasing trend while 43% indicate an increasing trend in maximum monthly values. The magnitude of Sen's slope denotes generally that there is a decreasing trend in Lake


Zambezi River at Chavuma Minimum Monthly Flows

Kabompo River at Watopa Pontoon Annual Minimum Flow

Zambezi River at Lukulu Annual Minimum Flow

Little Zambezi River at Matongo Annual Minimum

Luanginga River at Kalabo Annual Minimum Levels

Zambezi River at Senanga Annual Minimum Levels

Zambezi River at Ngonye Annual Minimum Levels

Zambezi River at Sesheke Annual Minimum levels

Zambezi River at Nana's Farm Annual Minimum levels

Zambezi River at Victoria Falls Annual Minimum Flows

Kalomo River at Luezhi Ranch Annual Minimum Levels

Gwayi River at Deka Road Bridge Annual Minimum Levels

Ume River at Binga Road Bridge Annual Minimum levels

Sanyati River at Binga Road Bridge Annual Minimum Levels

Figure 8 | Sen's slope trend analysis for minimum values of streamflow.

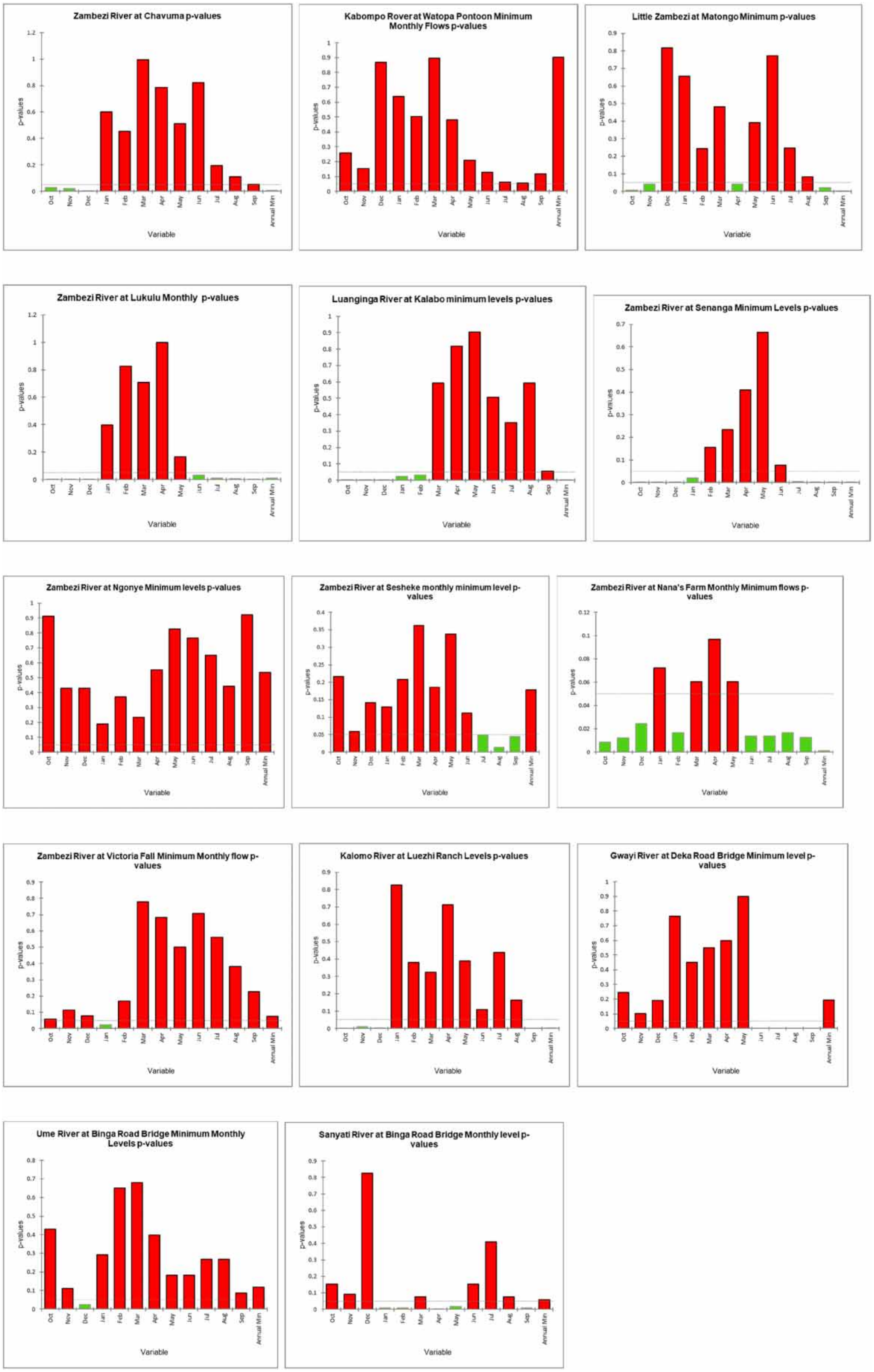


Figure 9 | Minimum monthly *p*-values from the selected gauge stations in the Kariba catchment.

Table 5 | Pettitt's test on change point detection on minimum values

	Gauging station name	Period of analysis	*K*	*t*	*p*-value (two-tailed)	*α*
1	Zambezi River at Chavuma	1959–2022	673	1981	**< 0.0001**	0.05
2	Kabompo River at Watopa	1958–2022	372	2003	0.06	0.05
3	Zambezi River at Lukulu	1950–2022	713	1982	**< 0.0001**	0.05
4	Little Zambezi at Matongo	1958–2022	489	1975	**0.01**	0.05
5	Luanginga River at Kalabo	1957–2022	656	1993	**< 0.0001**	0.05
6	Zambezi River at Senanga	1948–2022	741	1980	**< 0.0001**	0.05
7	Zambezi River at Ngonye	2005–2022	28	2014	0.96	0.05
8	Zambezi River at Sesheke	1997–2022	91	2000	0.13	0.05
9	Zambezi River at Nanas Farm	1994–2022	103	2000	**0.01**	0.05
10	Zambezi River at Victoria Falls	1924–2022	1457	1989	**< 0.0001**	0.05
11	Kalomo River at Luezhi Ranch	2008–2022	45	2012	**< 0.0001**	0.05
12	Gwayi River at Deka Road Bridge	1993–2022	21	1996	0.34	0.05
13	Ume River at Binga Road Bridge	2006–2022	36	2012	0.05	0.05
14	Sanyati River at Binga Road Bridge	1993–2022	126	2012	**0.01**	0.05

Kariba catchment in the maximum values. The trends in monthly values for all 14 gauging stations are presented in Figure 13. The Zambezi River at Lukulu, Senanga and Nana's Farm had five, six, and seven months each respectively that had a statistically significant trend.

The results of Pettitt's test done on the maximum monthly time series values are shown in Table 7. Four gauging stations showed abrupt changes in the long-term maximum values: the Zambezi River at Lukulu, Senanga, Victoria Falls and the Gwayi River at Deka Road Bridge.

Figure 14 shows the graphs of all the 14 gauging stations showing any abrupt changes that occurred in the long-term maximum values for the whole period of record. Zambezi River at Lukulu had its long-term water maximum value change from 6.281 to 5.484 m with the change observed in 1980. Zambezi River at Senanga changed from 5.245 to 4.568 m in 1978, Zambezi River at Victoria Falls decreased from 4,206 to 2,924 m^3/s in its maximum average value and the change happened in 1978. The Gwayi River at Deka Bridge had its long-term value increase from 573.53 to 1,899 m^3/s in 2019.

4.4. Trend analysis results for rainfall values

Table 8 gives a summary of results of the Mann–Kendall trend test on the TerraClimate monthly and ERA5-Land daily precipitation data for Kariba catchment and selected point gauging stations. The results show intense rainfall variability across the catchment, with a decreasing trend on the Kendall's tau negative values, with Chavuma and Lukulu gauging stations showing a statistically significant decreasing trend in rainfall under the ERA5_Land dataset although, overall, the catchment received a minimal increase in rainfall for TerraClimate and ERA5_Land datasets.

The results of Pettitt's test done on the ERA5_land and TerraClimate rainfall dataset time series values are shown in Table 9. ERA5_land dataset showed a consistence abrupt change in the rainfall values for all the stations under consideration, as shown in the *p*-value that is less than 0.05. The TerraClimate dataset showed either constant or reduced long-term mean values for all sampled stations while the ERA5_Land dataset showed fluctuations in the long-term mean values. These fluctuations in the rainfall pattern across the catchment can be well correlated with the corresponding fluctuations being observed in river and stream levels.

4.5. Correlation of stream flow/water level to rainfall for stations with a statistically significant trend

A correlation analysis of the stream flow/water level and rainfall was done on the three stations that had a statistically significant trend: Zambezi River at Lukulu, Senanga and Victoria Falls. The Pearson correlation coefficient was used to determine the linear relationship between the two variables. The results showed that there was a positive correlation between rainfall and water levels at the Zambezi River Station at Lukulu and Senanga, while the Zambezi River at Victoria Falls showed a negative correlation, as shown in Table 10.

Figure 10 | Change point detection in minimum values of streamflow.

Table 6 | Results of the Mann–Kendall trend test on maximum monthly values

	Gauging station name	**Period of analysis**	**Kendall's tau**	***S***	**Var (S)**	***p*-value (two-tailed)**	α
1	Zambezi River at Chavuma	1959–2022	−0.12	−234	28,426	0.17	0.05
2	Kabompo River at Watopa	1958–2022	−0.07	−133	29,789	0.44	0.05
3	Zambezi River at Lukulu	1950–2022	−0.13	−327	42,311	0.11	0.05
4	Little Zambezi at Matongo	1958–2022	0.07	157	32,646	0.39	0.05
5	Luanginga River at Kalabo	1957–2022	0.06	128	31,194	0.47	0.05
6	Zambezi River at Senanga	1948–2022	−0.17	−446	45,905	**0.04**	0.05
7	Zambezi River at Ngonye	2005–2022	0.09	12	589	0.65	0.05
8	Zambezi River at Sesheke	1997–2022	0.25	80	2,057	0.08	0.05
9	Zambezi River at Nanas Farm	1994–2022	0.20	74	2,562	0.15	0.05
10	Zambezi River at Victoria Falls	1924–2022	−0.09	−442	106,124	0.18	0.05
11	Kalomo River at Luezhi Ranch	2008–2022	0.12	11	334	0.58	0.05
12	Gwayi River at Deka Road Bridge	1993–2022	−0.01	−2	1,623	0.98	0.05
13	Ume River at Binga Road Bridge	2006–2022	−0.29	−34	485	0.13	0.05
14	Sanyati River at Binga Road Bridge	1993–2022	−0.05	−20	2562	0.71	0.05

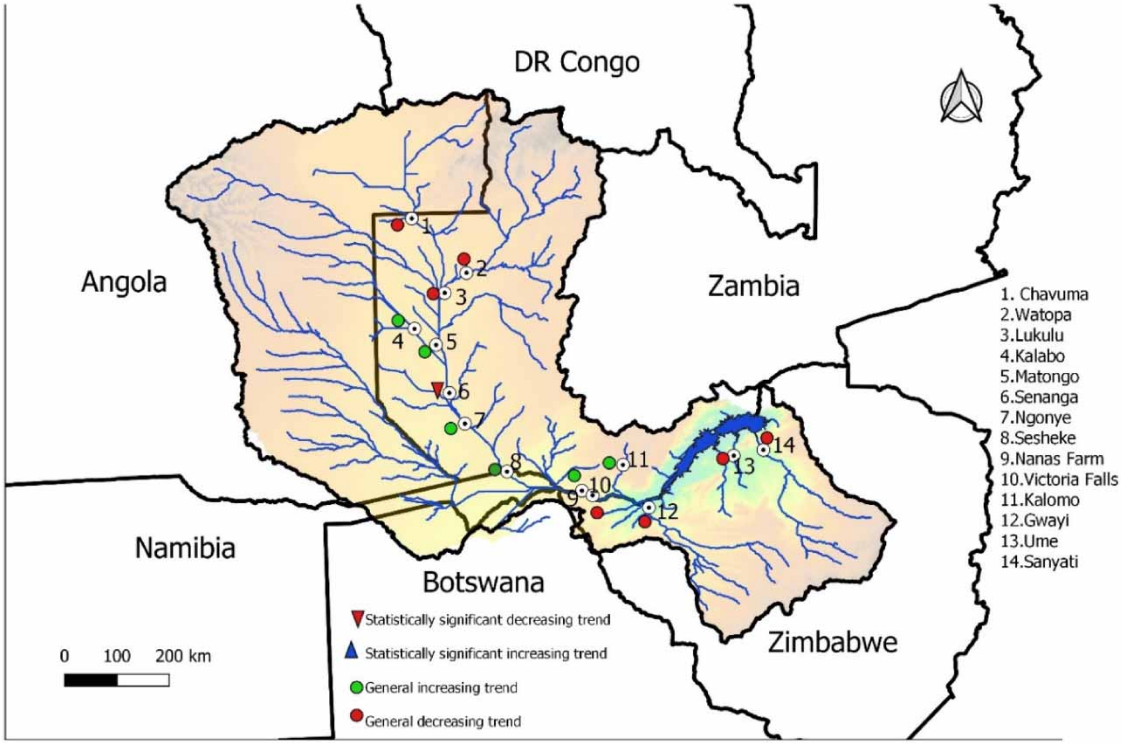


Figure 11 | Spatial variation of maximum monthly trends for streamflow over the Lake Kariba catchment.

A matrix plot of histogram and scatter plots is shown in Figure 15 for the three stations that had a statistically significant trend on the two variables. Data points in the scatter plots indicate whether there is a positive (coloured in red) or negative (coloured in blue) correlation. The arrangement of scatter plots signifies the type and the potency of the relationship between the variables.

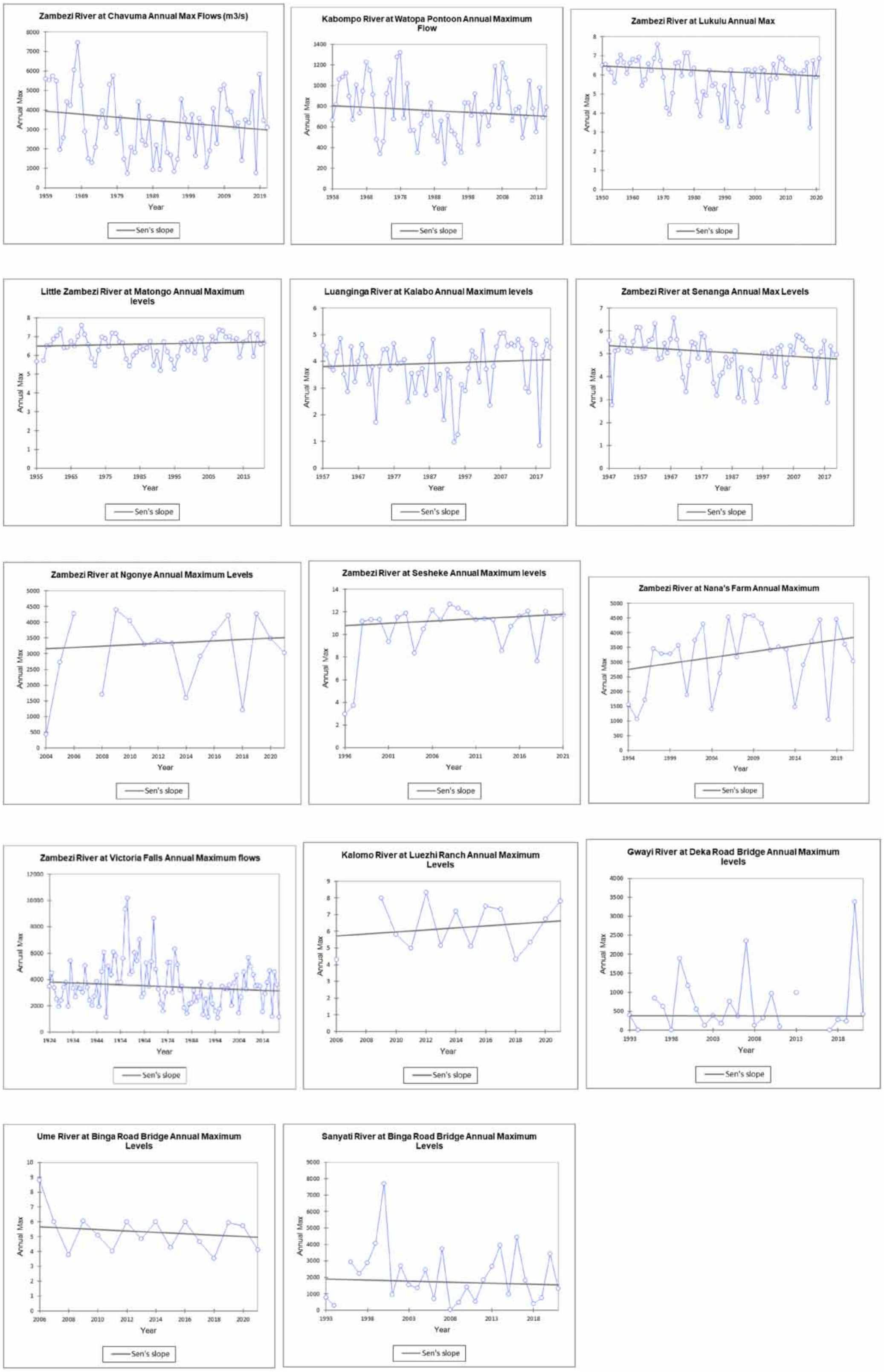
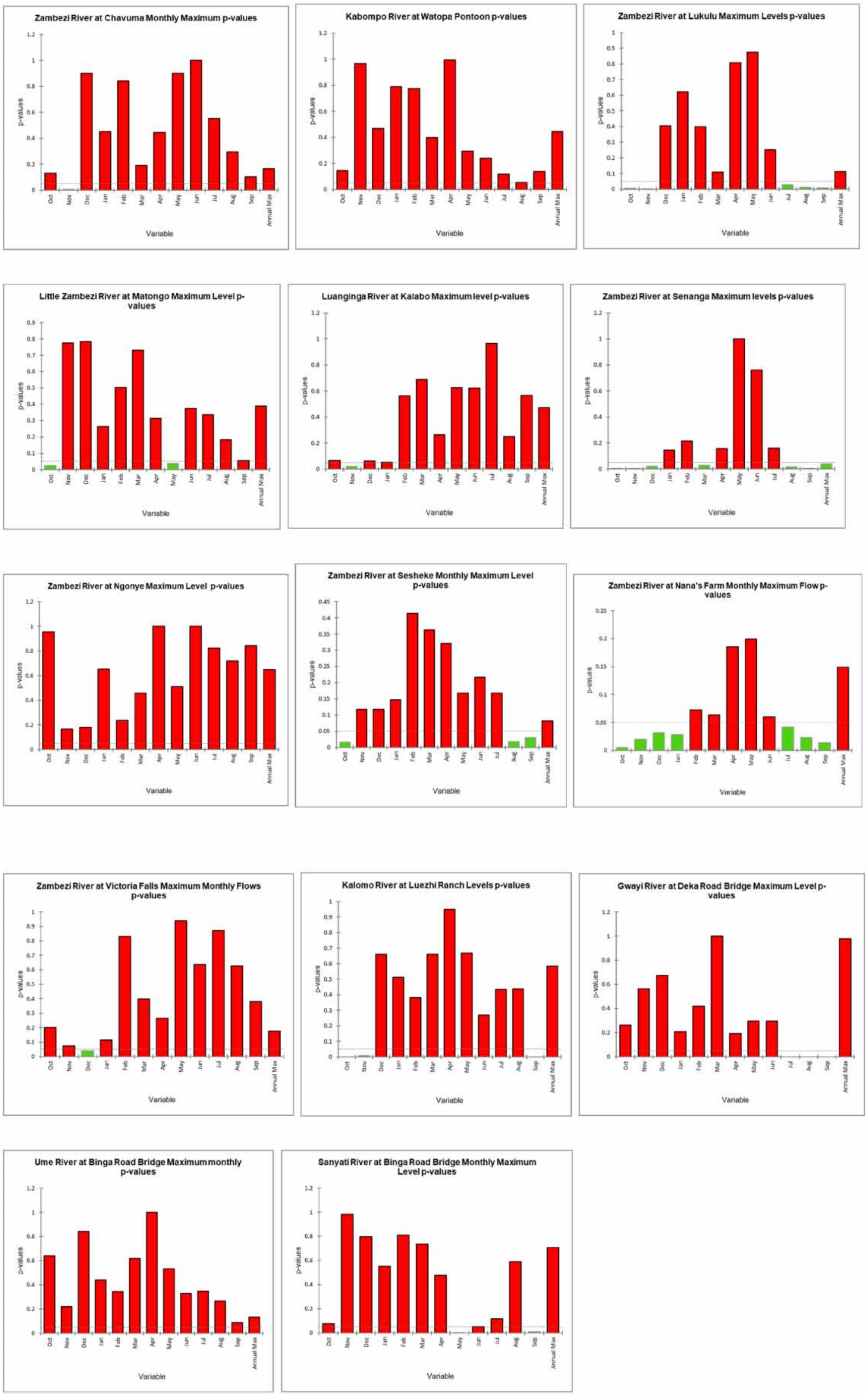


Figure 12 | Sen's trend analysis for maximum values of streamflow.



Zambezi River at Chavuma Monthly Maximum p-values

Kabompo River at Watopa Pontoon p-values

Zambezi River at Lukulu Maximum Levels p-values

Little Zambezi River at Matongo Maximum Level p-values

Luanginga River at Kalabo Maximum level p-values

Zambezi River at Senanga Maximum levels p-values

Zambezi River at Ngonye Maximum Level p-values

Zambezi River at Sesheke Monthly Maximum Level p-values

Zambezi River at Nana's Farm Monthly Maximum Flow p-values

Zambezi River at Victoria Falls Maximum Monthly Flows p-values

Kalomo River at Luezhi Ranch Levels p-values

Gwayi River at Deka Road Bridge Maximum Level p-values

Ume River at Binga Road Bridge Maximum monthly p-values

Sanyati River at Binga Road Bridge Monthly Maximum Level p-values

Figure 13 | Maximum monthly *p*-values of streamflow.

Table 7 | Results of Pettitt's test on change point detection on maximum values

	Gauging station name	Period of analysis	K	t	p-value (two-tailed)	α
1	Zambezi River at Chavuma	1959–2022	397	1980	0.06	0.05
2	Kabompo River at Watopa	1958–2022	382	1980	0.10	0.05
3	Zambezi River at Lukulu	1950–2022	588	1980	**0.01**	0.05
4	Little Zambezi at Matongo	1958–2022	369	2005	0.16	0.05
5	Luanginga River at Kalabo	1957–2022	399	2005	0.09	0.05
6	Zambezi River at Senanga	1948–2022	665	1978	**0.00**	0.05
7	Zambezi River at Ngonye	2005–2022	24	2005	0.61	0.05
8	Zambezi River at Sesheke	1997–2022	85	2005	0.21	0.05
9	Zambezi River at Nanas Farm	1994–2022	82	2005	0.45	0.05
10	Zambezi River at Victoria Falls	1924–2022	967	1978	**0.01**	0.05
11	Kalomo River at Luezhi Ranch	2008–2022	13	2006	0.15	0.05
12	Gwayi River at Deka Road Bridge	1993–2022	26	2019	**0.04**	0.05
13	Ume River at Binga Road Bridge	2006–2022	25	2016	0.89	0.05
14	Sanyati River at Binga Road Bridge	1993–2022	48	2007	0.41	0.05

5. DISCUSSION

The amount of water available at any point in the stream, tributary or river is vital in supporting the social and economic development of a nation (Ndebele-Murisa *et al.* 2021). Its availability is usually affected by many factors such as land cover changes, amount of rainfall received and climate change. Hence these factors are crucial in determining the variation and establishment of trends in streamflow (Roudier *et al.* 2014). The results obtained from this analysis for average, minimum and maximum values for all the 14 gauging stations in the Kariba catchment indicate general declining water levels with a few exceptional increasing trends. The observed increasing trends are attributed to the length of records as established already on two stations that are fairly adjacent but indicating a different trend and also the variability of rainfall across the catchment has a significant influence on the phenomenon. The change points of these time series have been observed in the 1980s for the dataset with more than 50 years of records.

The change in mean average values for stations with a statistically significant change point ($p \leq 0.05$) indicates that Zambezi River at Lukulu had its mean value reduced by 20%, at Senanga a reduction of 15% was observed. The Zambezi River at Victoria Falls had its mean value reduced by 23%. Ironically, Nana's Farm located some 33 km upstream of Victoria Falls (typically the same reach) had its mean value increase by 28%. The difference in trend indicators at Victoria Falls and Nana's Farm gauging station can be attributed to the length of records that were at the two stations. Zambezi River at Nana's Farm was opened in 1994 and the analysis is for 28 years of the record while Zambezi River at Victoria Falls has recorded as far back as 1907, with the analysis for this present study restricted from 1924 to 2022. Dixon *et al.* (2006) established the relationship between the length of record of analysis of streamflow data and the trend of the streamflow as a cause-and-effect kind of relationship. Furthermore, Ekolu *et al.* (2022) indicated that studies with a span of less than 30 years of streamflow analysis in southern Africa tend to show an increasing trend while those with more than 30 years of data analysis have a decreasing trend. This agrees with the findings of this present study where change points in the long-term mean were observed in the 1980s. The lower catchment of Kariba gauging stations had exceptional shifts in mean values as they have less than 30 years of dataset records. Kalomo River at Luezhi Ranch with 14 years of records had its mean value reduced by 55% and Ume River at Binga Road Bridge with 16 years of records had its mean value reduced by 46%. Coincidentally, the changepoint year for the two gauging stations in the lower catchment of Kariba happened in 2012.

The minimum average values had substantial changes observed in statistically significant change points ($p \leq 0.05$). Zambezi River at Chavuma had its minimum average flow reduced by 34%, Lukulu by 45%, Senanga by 27%, Victoria Falls by 35% and the Luanginga River at Kalabo reduced as high as 59%. A rise in minimum average values was observed at Little Zambezi River at Matongo (11%) and Zambezi River at Nana's Farm recorded an increase of 28%. The lower catchment

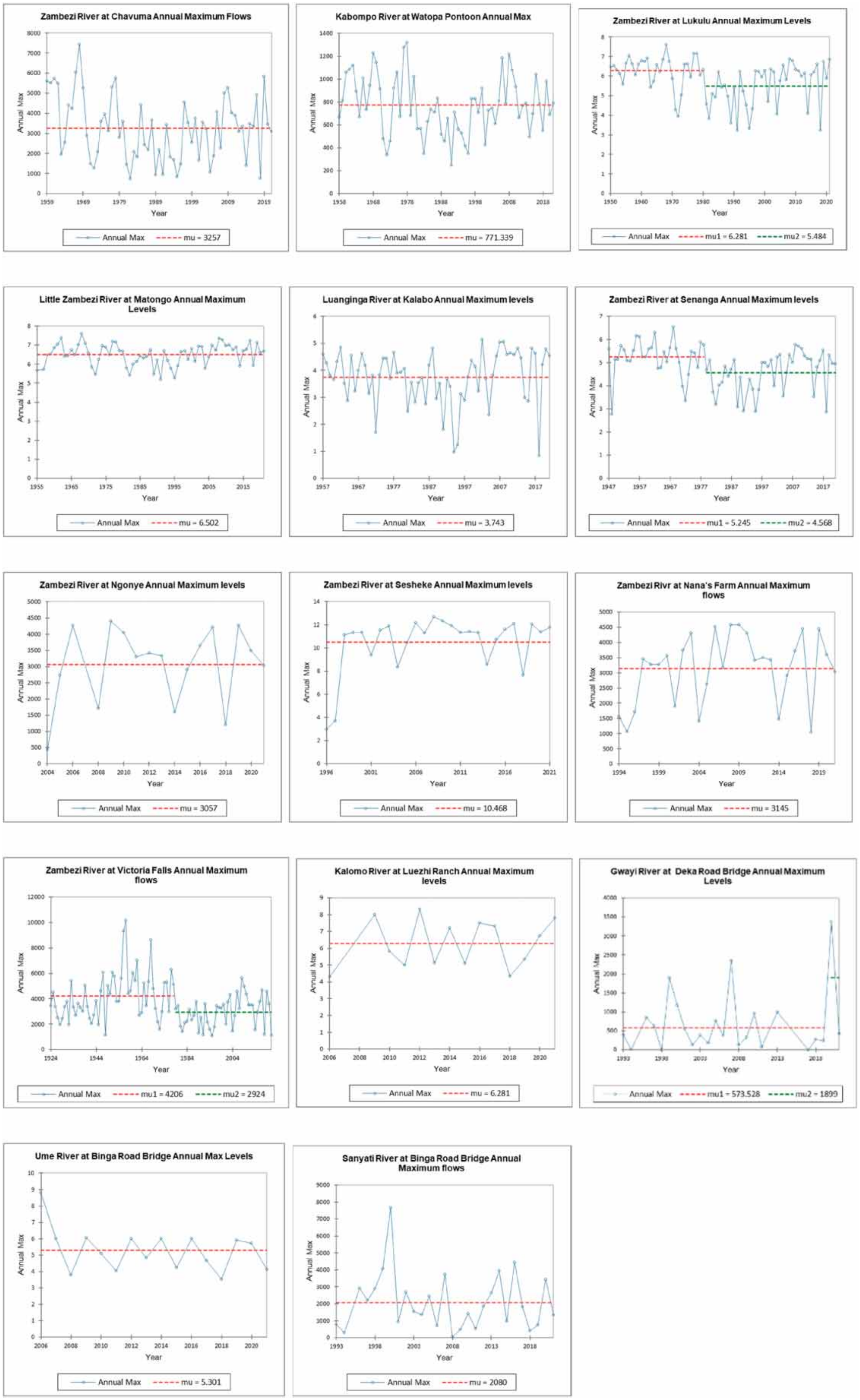


Figure 14 | Change point detection in maximum values of streamflow.

Table 8 | Results of the Mann–Kendall trend test on TerraClimate and ERA5_Land precipitation

Station	Dataset	Kendall's tau	S	Var (S)	*p*-value (two-tailed)	α
Kariba	TerraClimate	0.016	4,812	52,827,342	0.508	0.05
	ERA5_Land	0.000	−84,887	1,152,997,825,209	0.937	0.05
Victoria Falls	TerraClimate	−0.012	−3,353	50,674,052	0.638	0.05
	ERA5_Land	0.001	346,668	1,149,324,200,078	0.746	0.05
Chavuma	TerraClimate	0.024	6,946	51,619,913	0.334	0.05
	ERA5_Land	−0.011	−2,638,565	1,150,079,539,015	**0.014**	0.05
Lukulu	TerraClimate	0.013	3,818	51,534,390	0.595	0.05
	ERA5_Land	−0.011	−2,575,529	1,148,991,277,446	**0.016**	0.05
Kalabo	TerraClimate	0.014	3,934	51,477,595	0.584	0.05
	ERA5_Land	−0.009	−2,036,073	1,148,720,685,151	0.057	0.05
Senanga	TerraClimate	−0.001	−384	50,603,357	0.957	0.05
	ERA5_Land	−0.006	−1,430,458	1,148,396,237,850	0.182	0.05
Gwayi	TerraClimate	−0.007	−2,095	50,602,173	0.768	0.05
	ERA5_Land	−0.004	−998,776	1,148,994,531,999	0.351	0.05
Sanyati	TerraClimate	−0.014	−3,941	50,948,278	0.581	0.05
	ERA5_Land	0.000	−46,975	1,150,953,322,572	0.965	0.05

Table 9 | R.esults of Pettitt's test on change point detection on ERA5_Land and TerraClimate datasets

Station	Dataset	*K*	*t*	*p*-value (two-tailed)	α
Kariba	TerraClimate	9926.000	1/10/2005	0.927	0.05
	ERA5_Land	3176990.000	18/10/1968	**0.010**	0.05
Victoria Falls	TerraClimate	5142.000	1/4/1981	**0.017**	0.05
	ERA5_Land	3981919.000	27/10/1968	**0.000**	0.05
Chavuma	TerraClimate	13844.000	1/10/2005	0.311	0.05
	ERA5_Land	4180963.000	2/5/1993	**0.000**	0.05
Lukulu	TerraClimate	9920.000	1/10/2005	0.964	0.05
	ERA5_Land	4502909.000	28/4/1993	< **0.0001**	0.05
Kalabo	TerraClimate	9659.000	1/10/2005	0.881	0.05
	ERA5_Land	4146790.000	2/5/1993	**0.000**	0.05
Senanga	TerraClimate	4509.000	1/3/1981	**0.003**	0.05
	ERA5_Land	3599106.000	1/5/1989	**0.002**	0.05
Gwayi	TerraClimate	5817.000	1/4/1981	0.054	0.05
	ERA5_Land	3988110.000	9/11/1968	**0.000**	0.05
Sanyati	TerraClimate	5932.000	1/4/1981	0.067	0.05
	ERA5_Land	4686925.000	27/10/1973	< **0.0001**	0.05

Table 10 | Pearson correlation coefficient between rainfall and stream water levels

Station/variable	Pearson correlation to rainfall
Lukulu (water level, m)	0.312
Senanga (water level, m)	0.365
Victoria Falls (flow, m^3/s)	−0.102

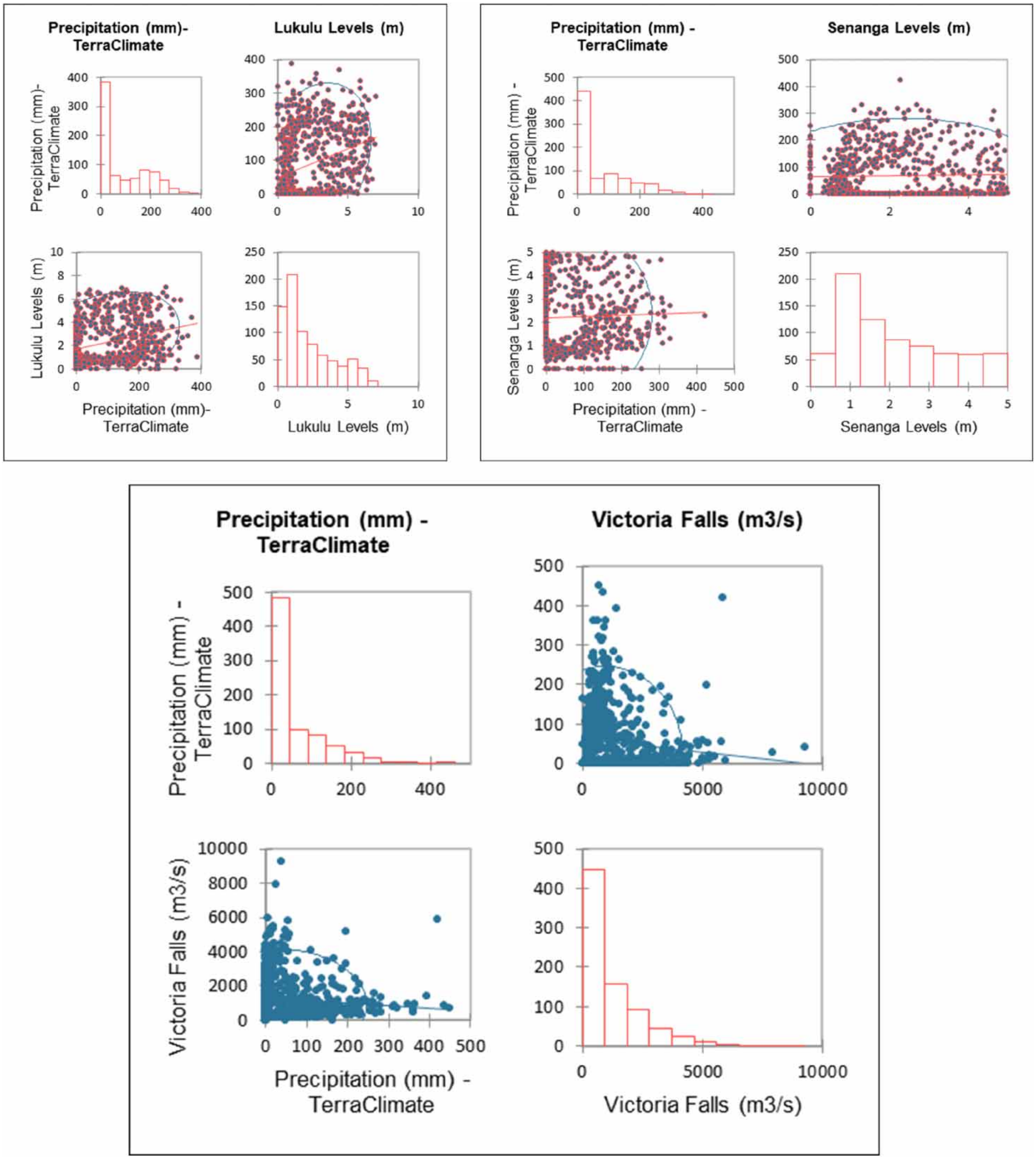


Figure 15 | Matrix of histogram and scatter plots.

gauging stations, by nature or regime of the flow of being annual streams with a minimum value of zero were difficult to determine the change; however, they all showed a statistically decreasing trend.

In terms of the maximum average values, the entire catchment had a generally decreased trend too, with significant changes in maximum values being observed at Zambezi River at Lukulu (13%), at Senanga (13%) and Victoria Falls reduced by 30%. Exceptionally, the Gwayi River at Deka Road Bridge had its annual maximum average increase of 70%, with the year of change being 2019.

The results obtained are close to what Zimba *et al.* (2018) obtained when a Pettit homogeneity test was done on Lukulu and Senanga mean values where at both stations, changes were observed in 1981. Furthermore, a 19 and 25% reduction in mean values was observed at Senanga and Lukulu, respectively for the period of analysis, while for the present study, a 15 and 20% reduction has been observed for Senanga and Lukulu, respectively.

The trend and changes in long-term mean, minimum and maximum values can be attributed to changes in land cover and land use to a certain extent. However, climate change contribution cannot be ruled out as Beilfuss (2012) and Ndhlovu (2013) suggested that the Zambezi River basin whose total area is 47% Kariba catchment is at risk of the effects of climate change. Temperature rises and variations in precipitation have been noted in the Zambezi basin since 1980 (Kling *et al.* 2014), this has also been demonstrated in the results obtained from the analysis of ERA5_Land and TerraClimate precipitation dataset over the Lake Kariba catchment and point gauging stations. The fluctuations in the rainfall pattern being observed across the catchment can be well correlated with the corresponding fluctuations being observed in river and stream levels. For example, the statistically significant shift in the trend of water levels can be well correlated with the rainfall obtained at stations, such as Lukulu and Senanga, as shown in the positive Pearsons correlation coefficient, while Victoria Falls station showed an inverse correlation, which can be attributed to the length of the rainfall dataset that was used in determining the correlation. Further studies on the effects of climate change on the Zambezi basin indicated that a 20% decrease in precipitation and a corresponding increase of about 25% in evaporation coupled with the planned abstractions in the Zambezi basin would translate into reduced runoff and streamflow from as low as 5% to as higher as 40% (Chenje 2000; Desanker & Magadza 2001; Kling *et al.* 2014). This agrees with the findings of the present study as highlighted in the changes in the time series obtained on most of the gauging stations and those that Beilfuss (2012) obtained in the Zambezi basin.

6. CONCLUSION

The Kariba catchment is an important catchment to Zimbabwe, Zambia and the entire southern Africa region as it houses the two hydropower stations which are integral parts of the Southern African Power Pool (SAPP). The availability of water in the catchment for hydropower production has been of concern in the recent past. A trend analysis of stream time series at a 95% confidence level was conducted in the present study at all the 14 gauging stations to establish if there are any changes in the time series in the water level, discharges and precipitation over the Lake Kariba catchment, the trend and change points can be observed.

The results indicate a general decreasing trend in the water level and precipitation, with statistically significant trends and change points in time being observed at some of the gauging stations. Various factors that influence streamflow have been explored in the literature review such as land cover changes, rainfall and climate change, a thorough examination of long-term trends, change points and variations in streamflow at multiple gauging stations has been done, with a consideration to results and outcomes of similar previous studies conducted. The findings of the present study indicate that stream flow has been impacted by both land use and climate change.

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AUTHOR CONTRIBUTIONS

B.M. contributed to conceptualisation, data analysis, writing draft paper, and editing. K.B. contributed to conceptualisation, reviewing, editing, supervision, funding, and resource management. L.C. contributed to reviewing, supervision, funding and resource management. Y.U. contributed to reviewing, funding and resource management. I.N. contributed to conceptualisation, review, supervision, funding and resource management. The authors discussed the analysed data and the results of the final paper.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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