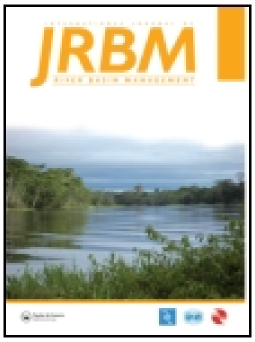

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# Detection of trends in extreme streamflow due to climate variability in the Lake Naivasha basin, Kenya

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Research paper

# Detection of trends in extreme streamflow due to climate variability in the Lake Naivasha basin, Kenya

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**ABSTRACT**
Variability of streamflow has far-reaching impacts especially in developing countries. This is aggravated by climate change which has adversely affected the water resources and food security. This paper presents the characterization trends in extreme streamflow regimes with a view to providing information for planning local coping mechanisms to climate variability and change using streamflow data recorded from 1959 to 2008 in the Lake Naivasha basin in Kenya. The maxima and percentiles of streamflow distributions were investigated to identify changes in extreme intensity and frequency, respectively, using the Mann–Kendall test. The results indicate significant increases in annual maxima at all gauging stations. The flows in the month of November increased significantly at gauging stations 2GB4 and 2GC4. Flow percentile exceedance revealed that the annual 95th percentile exceedance increased significantly at gauging stations 2GB1 and 2GB5 with a decrease in annual 90th and 97th percentile exceedance at gauging stations 2GB4 and 2GC4. The results presented in this paper are useful for climate change adaptation planning and management especially in water supply, hydropower generation and agriculture.

*Keywords:* Streamflow; Mann–Kendall trend test; extreme events; water resources; Lake Naivasha; climate change

## 1 Introduction

Variability in hydrological processes has over time been accompanied by changes which have altered the distribution of water resources. This has been characterized by a disproportionate increase in the intensity and frequency of extreme hydrological events (IPCC 2007). The climate change has not only adversely affected water availability but has also altered the streamflow regimes of many watersheds. This has led to changes in the temporal and spatial distribution of water resources, thereby threatening water and food security. Fluctuations of hydrological variables have affected the function and operation of existing water resources management practices. Adverse effects of hydrological variability have aggravated the impacts of other stresses, such as population growth, changing economic activities, land-use change and urbanization (Mogaka *et al*. 2006). The current water management practices within the Lake Naivasha basin are not adequate to cope with the impacts of hydrological variability on water resources reliability. Hence the characteristics of extreme weather events need to be studied so as to apply the appropriate mitigation measures.

The Lake Naivasha basin is a closed basin experiencing diverse climatic conditions ranging from semi-arid to humid. The water resources in this basin are under intensive use. The lake provides water for domestic and agricultural use as well as for livestock. For instance, 75% of Kenya's horticultural exports come from the flower industries established around this lake (Sharmo 2002). The flower industries alone consume approximately 60 MCM (Becht and Harper 2002) of water annually. The lake ecosystem is currently under constant anthropogenic pressure resulting from the quest for socioeconomic development. For instance, the adjacent area of the lake and its surrounding fragile ecosystems face increasing threats from irrigated agriculture, water abstraction, the fast-growing Naivasha Township and human population growth.

The per capita water availability within the Lake Naivasha basin is 647 $m^3$ as compared to 1000 $m^3$ recommended by the World Health Organization (WHO). This is expected to drop to 235 $m^3$ by the year 2025 due to effects of climate change,

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population growth and environmental degradation (WHO 2006). To minimize the adverse effect by these factors, it is therefore important to put in place water resources management measures to circumvent the fluctuations of extreme hydrological events.

Adaptation planning for hydrological regimes' variability depends on their intensity, frequency and persistence (Sharma 1997). For instance, extreme drought events require management practices which will retain adequate water in the catchment during the rainy season and thereafter (Onyando *et al*. 2004). Hence, to be able to adapt to future changes of extreme hydrological events, their temporal and spatial variability trends need to be determined. The aim of this study was to characterize trends in extreme streamflow regimes with a view to providing information for planning local coping mechanisms to climate variability and change. In addition, the study also established trends in intensity and frequency of streamflow extremes. Since the climate is changing, either naturally or due to human activities, there is need to account for these changes in the present times to prepare for the future. Successful management of current changes comes with successful mitigation strategies and ability to adapt to changing hydrological processes.

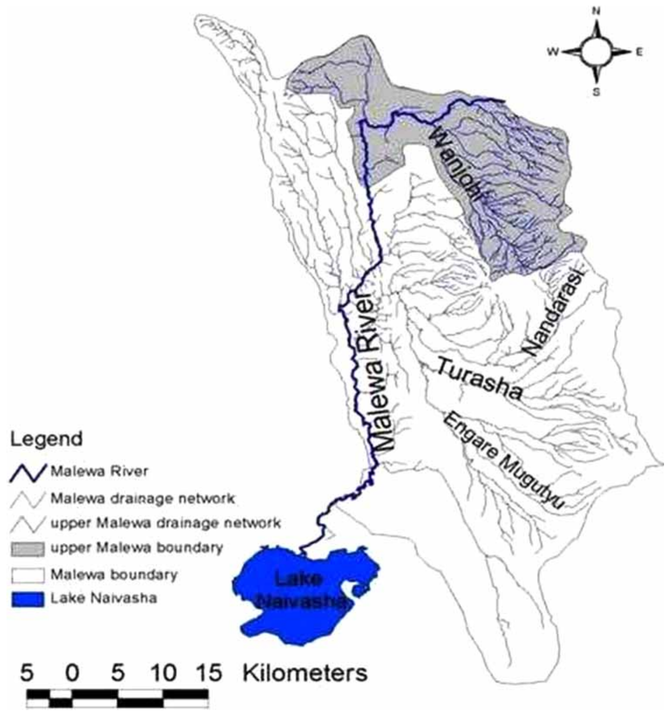


Figure 1 Map of study area showing Malewa River and its tributaries. Source: Generated by Authors from the digital elevation model (DEM) for the Lake Naivasha Basin.

## 2 Methods

### 2.1 *Study area*

The Lake Naivasha basin with an approximate area of 3376 km$^2$ is located in the Kenyan Rift Valley, approximately 70 km from the Kenyan capital city Nairobi. The maximum altitude is about 3990 m above mean sea level (a.m.s.l) on the eastern side of the Aberdare Ranges to a minimum altitude of about 1900 m (a.m.s.l). Malewa and Gilgil (Figure 1) are the two main perennial rivers flowing into this lake. River Malewa which has a catchment area of 1600 km$^2$ is the major river feeding the lake by contributing about 90% of the total discharge into Lake Naivasha (Lukman 2003). The Lake Naivasha basin experiences an average annual rainfall of 610 mm, with the wettest slopes of the Aberdare Ranges receiving as much as 1525 mm per annum. The long and short rains occur in March to May and October to November, respectively.

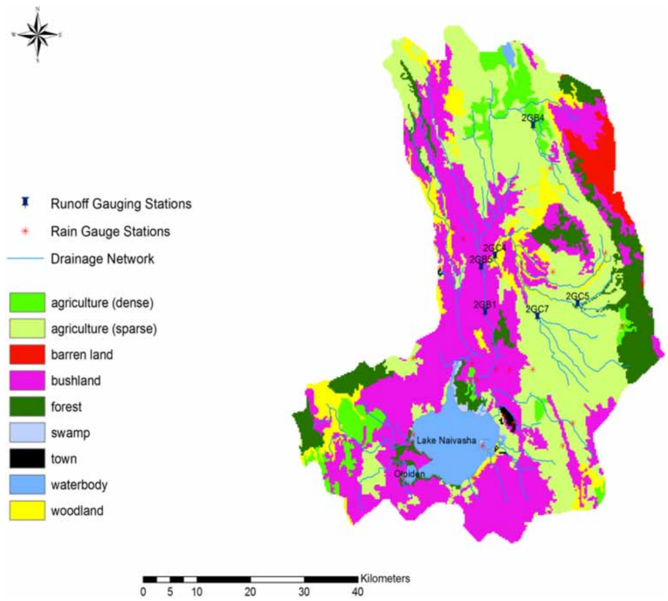


Figure 2 Map of study area showing the main gauging stations. Source: The Figure was generated by the authors from the digitised and developed DEM for the Lake Naivasha Basin.

### 2.2 *Data collection and selection*

Four streamflow gauging stations as given in Figure 2 and denoted as 2GB1, 2GB4, 2GB5 and 2GC4 were selected for analyses for time series trends. These gauges were selected since they have adequate data records for many years. The selection was done using the method developed by Haylock and Goodess (2004) as presented in Table 1. In their method, the authors investigated extreme rainfall across Europe and excluded stations with more than 10% missing values and included those with less than 10% missing data. Trend analysis requires river flows where artificial disturbances are minimal. In addition, there has to be an adequately long time series record of sufficient quality. Bower *et al*. (2004) stated that long-term records equate to a minimum of 25 years. All gauge records in the Lake Naivasha basin met this minimum requirement, having records of 50 years. In this study, the data were obtained from the Water

Table 1 Streamflow gauging stations

| Station Id. | Stn. Name | Elevation (m) | Latitude (m) | Longitude (m) | % Missing |
|---|---|---|---|---|---|
| 2GB1 | Malewa | 1950 | 209181 | 9926382 | 0.0 |
| 2GB5 | Malewa | 2323 | 212101 | 9964638 | 2.9 |
| 2GB4 | Wanjohi | 2438 | 220260 | 9969946 | 5.5 |
| 2GC4 | Turasha | 2005 | 210747 | 9945470 | 4.8 |

Resources Management Authority regional offices at Naivasha at a daily temporal resolution. All the gauge records were taken on 1 January of the specified year and were completed on 31 December 2008.

Prior to trend analysis, the hydrological records were tested for homogeneity and normality. Homogeneity of time series records is confirmed when observed variations result entirely from fluctuations in weather and climate. Testing for homogeneity enabled possible error sources resulting from gauge station and environmental changes to be identified. The non-parametric Pettit test was used to check the homogeneity of the time series records.

Data infilling was done using a procedure based on the premise of correlations between the gauging stations displaying hydrological homogeneity in terms of coefficient of variation ($C_v$), skewness ($C_s$) and serial correlation ($\rho$) as shown in Table 2 (Panu and Sharma 2002). The missing data were traced in the daily flow sequences, and infilling was accomplished in daily flows. In this procedure, the stations with missing data were paired with similar stations with observed data for the period in question. The pairing process explicitly considered values of the $C_v$, $C_s$ and $\rho$ to be in near equivalence. Only those stations meeting the requirement were paired. The infilling was then done using the linear regression equation between the data sets. At every stage of data infilling, it was ensured that the data so obtained yield the statistic within regional expectations.

## 2.3 *Trends in streamflow extremes*

Two data set types were subjected to the statistical Mann–Kendall (MK) test. To identify trends over a range of possible hydrological extremes, maximum values which represented the extreme intensity of various temporal data series and the number of events falling above long-term percentile values which represented extreme frequency were analysed. The non-parametric MK trend test is particularly suitable for censored, missing and non-Gaussian distributed variables. It searches for a trend in a time series without stipulating whether the trend is linear or non-linear (Maidment 1993). If the data consist of a uniformly sampled time series, the test indicates the direction and significance of any trend.

The time series were defined as $X_{1,}\ X_2, \ldots, X_n$, where the values of $X$ were treated as a random sample of $n$ independent, identically distributed variables and $F_i$ is the continuous cumulative distribution function of $X_i$ , where $i = 1,2,\ldots,n$. The MK test statistic, $S$, is defined as

$$S = \sum_{k=1}^{n-1}\left[\sum_{j=k+1}^{n}\operatorname{sgn}(x_i - x_k)\right], \tag{1}$$

where $x_j$ and $x_k$ are sequential data values for the data set record of length $n$. The test statistic represents the number of positive differences minus the number of negative differences between the adjacent points in the time series and equates to the sum of sgn series, which is defined as

$$\operatorname{sgn}(x_i - x_k) = \begin{cases} 1 & \text{if } x_i - x_k > 0, \\ 0 & \text{if } x_i - x_k = 0, \\ -1 & \text{if } x_i - x_k < 0. \end{cases} \tag{2}$$

Kendall (1975) determined the mean and the variance of $S$, $E(S)$ and $V(S)$, respectively, under the null hypothesis $H_o$ of randomness, given the possibility that there may be ties in the $x$ values, as

$E(S) = 0,$

$$V(S) = n(n-1)(2n+5) - \sum_t \frac{t(t-1)(2t+5)}{18}, \tag{3}$$

where $t$ is the extent of any given tie. denotes the summation over all ties and is only used if the data series contain tied values. The standard normal variate $Z$ is calculated as

Table 2 Descriptive statistics identifying the data set

| Station | $X_{min}$ | $X_{max}$ | $X_{med}$ | μ | $\sigma$ | $C_v$ | $C_s$ | $C_k$ | KS | $Z$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 2GB1 | 1.30 | 46.37 | 7.49 | 9.44 | 8.15 | 0.86 | 2.20 | 6.71 | 0.25 | 0.48 |
| 2GB4 | 0.37 | 9.41 | 2.10 | 2.33 | 1.60 | 0.68 | 1.79 | 5.67 | 0.24 | 0.02 |
| 2GB5 | 0.69 | 23.15 | 4.41 | 5.84 | 4.88 | 0.83 | 1.55 | 2.31 | 0.21 | 0.74 |
| 2GC4 | 0.05 | 15.43 | 1.87 | 3.11 | 2.91 | 0.93 | 2.10 | 5.15 | 0.26 | 0.37 |

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{[\mathrm{Var}(S)]}} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \dfrac{S+1}{\sqrt{[\mathrm{Var}(S)]}} & \text{if } S < 0. \end{cases} \quad (4)$$

Positive values of $Z$ indicate an upward trend and negative values indicate a downward trend, and the test statistic $Z$ is deemed significant at the $\alpha < 0.05$ confidence level.

### 2.4 *Trends in intensity of streamflow extremes*

The daily maxima time series records were analysed for trends in extreme flows. The yearly maxima of the daily maximum flow records were used to define the annual maxima (AM) series, which corresponds to the largest flow peak on record per year. In addition to trend analysis of the AM time series, exceedance of the discharge median threshold was considered for the flow records. The median annual maximum flow, QMED, is the middle-ranking value in an ordered AM series. It is commonly used as a flood index estimate that represents a discharge threshold exceeded on average once every two years (Reed and Robson 1999). Annual extreme event counts were calculated as the number of times the QMED was exceeded by the daily flow series. This gave an indication of the temporal frequency of extreme events and whether the two-year flood threshold was exceeded throughout the time series record above the average rate. Statistical trend analysis was performed on monthly and annual maximum values of flow time series.

### 2.5 *Trends in frequency of streamflow extremes*

Daily maximum flow magnitudes were categorized into several classes. The time series records were divided into frequency percentiles with the largest percentiles indicative of infrequent extreme events. As extreme events were of interest, only the extreme upper tail of the distributions was analysed. Above the 90th percentile is usually taken to signify very wet periods or periods of high flows, and above the 95th percentile is generally allocated as a threshold for extreme frequencies (Haylock and Nicholls 2000). Therefore, the data were analysed for counts of days that exceeded the long-term 90th, 95th and 97th percentiles (top 10%, 5% and 3%, respectively).

## 3 Results and discussion

### 3.1 *Flow annual maxima*

The MK test results indicated significant increases in AM at all gauging stations (Table 3). The trend at gauging station 2BG1 is even significant at $\alpha < 0.01$ which re-emphasizes the substantial increase in magnitude above the medium discharge (QMED) threshold. The flows in the month of November increased significantly at the gauging stations 2GB04 and 2GC04 with no other apparent trends noted at other gauges. The maximum flow value for the month of April increased significantly over the last 50 years at all gauges. No other monthly trends were detected.

The characteristics of flow magnitudes and frequencies are highly sensitive to climatic variations, in particular to changes in precipitation regimes as well as changes in physical catchment properties. The influence of precipitation on river flow regimes is

Table 3 Annual and monthly maxima analysis

| | 2GB1 | | 2GB5 | | 2GB4 | | 2GC4 | |
|---|---|---|---|---|---|---|---|---|
| | $Z$ | $\alpha$ | $Z$ | $\alpha$ | $Z$ | $\alpha$ | $Z$ | $x$ |
| *Annual* | | | | | | | | |
| Ann | **1.639** | **0.047** | **2.984** | **0.007** | **1.137** | **0.034** | **1.137** | **0.034** |
| *Monthly* | | | | | | | | |
| Jan | 0.719 | 0.036 | 0.160 | 0.138 | 0.365 | 0.629 | 0.071 | 0.472 |
| Feb | 0.913 | 0.011 | 0.000 | 0.500 | 0.573 | 0.208 | 0.500 | 0.390 |
| Mar | 0.633 | 0.047 | 0.206 | 0.418 | 0.216 | 0.481 | 0.268 | 0.377 |
| Apr | **1.820** | **0.034** | 0.169 | 0.433 | 1.499 | 0.607 | 1.230 | 0.093 |
| May | 0.670 | 0.043 | 1.519 | 0.064 | 1.231 | 0.131 | 0.856 | 0.196 |
| Jun | 1.000 | 0.001 | 0.657 | 0.226 | −1.106 | 0.143 | 1.214 | 0.113 |
| Jul | 0.315 | 0.099 | 0.430 | 0.074 | −0.171 | 0.473 | 0.143 | 0.443 |
| Aug | 0.731 | 0.032 | 0.657 | 0.256 | −0.607 | 0.272 | 0.928 | 0.177 |
| Sept | 0.547 | 0.060 | 0.582 | 0.280 | −0.428 | 0.334 | 1.213 | 0.113 |
| Oct | 1.000 | 0.001 | 0.807 | 0.210 | 1.477 | 0.142 | 1.089 | 0.138 |
| Nov | 0.828 | 0.022 | 0.582 | 0.280 | **1.713** | **0.043** | **1.891** | **0.029** |
| Dec | 1.000 | 0.001 | 0.094 | 0.463 | 0.431 | 0.333 | 0.821 | 0.206 |

Note: Z is the MK test statistic, $\alpha$ is the significance of the trend for flow discharge and boldface indicates significance at $\alpha < 0.05$.

complex with intricate interactions between evaporation losses, soil moisture conditions, catchment geology, land-use and artificial changes to watercourses. Changes in land cover and land use may also have direct implications on flow trends in the Lake Naivasha basin. The land cover change in the Lake Naivasha basin has been fairly high in the recent years. Deforestation may lead to decreased precipitation interception, transpiration and soil moisture deficits. This may lead to alterations in evapo-transpiration, soil stability and the timing and quantity of surface run-off.

Observed land-use changes are likely to have affected soil characteristics and subsequent susceptibility to climate-induced changes. Intense agricultural practices in the Lake Naivasha basin may be causing a reduction in soil water storage capacity and infiltration rate leading to overland flow and rapid run-off of water into rivers. Over the last years, there has been an increase in agricultural intensification due to economic pressures. This has affected the soil physical properties and hence enhancing run-off generation at least at the local level.

### 3.2 *Medium discharge exceedance (QMED)*

The results of daily flow values which exceeded the QMED threshold at individual gauging stations are given in Figure 3. The long-term threshold has evidently been exceeded more, both in frequency and magnitude in the latter part of the time series for all sites. Magnitude changes were greatest at gauging station 2GB5 with flows indicating a steady linear increase over time. The gauging station 2GC4 also exhibited a slight increase in QMED exceedance over the study period but there was a decrease in gauging station 2GB4 over the same period.

The gauging station 2GC4 is located on the upper catchment of the lake Naivasha basin meaning an environmental factor affecting run-off into this sub-catchment is likely to be influencing the flows. Annual frequency was high at all stations in 1998, reflecting the occurrence of the 1998 El-Nino floods. AM time series for 2GB1 and 2GB5 gauging stations indicated that in the last 10 years the QMED threshold was exceeded at least once a year by daily maxima events. Adaptation to climate change and variability requires the determination of how hydrological processes have altered over recent years. Prolonged flow over the Lake Naivasha basin from the year 1990 to 2008 as shown in all river gauging stations (Figure 3) may be due to the effects of precipitation changes on hydrological regimes and, in particular, the effect on flow intensity. The exceedance of QMED in the last 10 years has intensified in all gauging stations. This may have been caused by the dependence on the extent of change in climatic variables influencing the catchment, as well as basin morphology and the configuration of the drainage network and stream channel. Precipitation and evaporation are the most important drivers of the hydrological systems. Changes in these primary processes may be significantly influencing the timing and volume of streamflows. This may be occurring through changes in soil water storage, groundwater–surface water interactions and the variability of hydrological processes in the lake Naivasha basin.

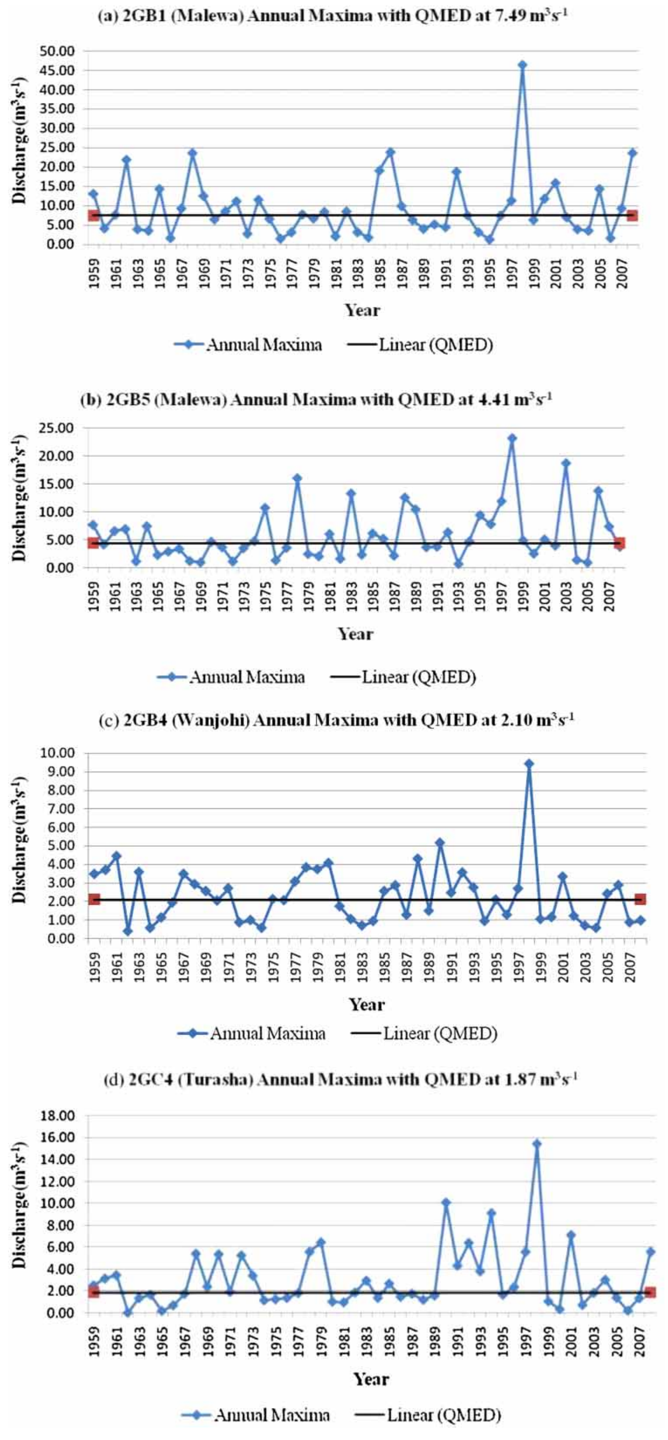


Figure 3 Daily maxima flows showing exceedance of the long-term QMED threshold at gauging stations 2GB1, 2GB5, 2GB4 and 2GC4.

### 3.3 *Streamflow percentiles*

Fitting of trends to the flow percentile exceedance data revealed that the annual 95th percentile exceedance increased significantly at 2GB1 and 2GB5 gauging stations (Table 4). The annual 90th and 97th percentiles exceedance at gauging stations

Table 4 Annual flow percentile analysis

| | 2GB1 | | 2GB5 | | 2GB4 | | 2GC4 | |
|---|---|---|---|---|---|---|---|---|
| | *Z* | $\alpha$ | *Z* | $\alpha$ | *Z* | $\alpha$ | *Z* | $\alpha$ |
| *Annual* | | | | | | | | |
| 90th | −0.492 | 0.334 | −0.732 | 0.322 | **0.172** | **0.016** | **0.198** | **0.023** |
| 95th | **1.827** | **0.034** | **1.789** | **0.043** | 1.312 | 0.095 | −0.769 | 0.221 |
| 97th | −0.521 | 0.301 | 0.789 | 0.190 | **1.896** | **0.015** | **1.842** | **0.033** |

Note: Z is the MK test statistic, $\alpha$ is the significance level and boldface indicates significance at $\alpha < 0.05$.

2GB4 and 2GC4 increased significantly. Overall, trends in the *Z*-values showed a general decrease in annual percentile exceedance for all gauges.

The increase in the wet season rainfall may result in a higher flow index value. During periods of excessive rainfall, high flow discharges increase when rainwater is not stored through infiltration and percolation processes in the unsaturated zone and this may have led to increase in wet periods in gauging stations 2GB1 and 2GB5. Increases in high flow discharges are expected in areas where agricultural land has largely increased by deforestation and in case of land degradation (Mati *et al*. 2008). This may be attributed to trends in gauging stations 2GB1 and 2GB5 which are in the lower parts of the Lake Naivasha basin.

## 4 Conclusions

The potential impacts of climate change can alter the risk to critical infrastructure resulting from changes to the intensity, frequency and magnitude of hydrological events. As well, the natural environment is affected by the hydrological regime, and changes in precipitation and flows can have negative impacts on ecosystems. In this study, the MK trend test method was applied to characterize trends in extreme streamflow regimes in the Lake Naivasha basin. The application of the MK trend test identified some significant trends in extremes flow time series data in the Lake Naivasha basin. In general, the flows increased annually although increased monthly flows were experienced in the months of April and November. Overall, trends are not particularly strong as there is little temporal consistency across the extremes for intensity and frequency.

Nonetheless, the trend test statistics show some significant results which provide an insight into the future water availability over the Lake Naivasha basin under a climate change scenario. Since the occurrence in intensity and frequency of extreme streamflow is increasing, different practices should be encouraged to harness the excess water for use during the time of water scarcity. These include efficient irrigation technologies, water harvesting and storage, increased sub-surface through increase in bund height to retain run-off within the fields, adoption of moisture-conserving management practices and increase in the groundwater table. These interventions are necessary but not sufficient. Adapting to climate change both needs to build on these water conservation interventions and requires a major shift in planning and designing water investments. New approaches in technology and management as well as the development of flexible systems that can anticipate and react to changing intensity and frequency of extreme streamflows are necessary. New design standards and criteria will also need to be developed for changed hydrological regimes in the Lake Naivasha basin. In all countries, social and physical adaptive measures will need to be developed to protect the most vulnerable populations and ecosystems from the effects of extreme weather associated with climate change.

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