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Trends in Rainfall and Discharge over Zaaba Sub Catchment, Vihiga County, Kenya

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Abstract

Temporal variation of rainfall has a direct influence on discharge of a river; however, considerable land cover changes through conversion of natural vegetation to agricultural land, settlement and commercial usage like urbanization have led to encroachment into forested, river riparian and other wetland areas therefore altering runoff generation through variation of rates of vegetal interception, infiltration, evapotranspiration and surface detention. This study determined rainfall trends and discharge from 1991 to 2020 and factors determining response of streamflow to rainfall variability in Zaaba river sub catchment in Vihiga County, Western Kenya. Rainfall data was sourced from Kenya Meteorological Department, discharge data was sourced from Water Resources Authority and land cover data was downloaded from USGS website http://www.earthexplorer.usgs.gov/. Trend analysis was determined by Z-Test, p-value and Sen's slope estimator. Regression analysis determined the correlation between rainfall and discharge. Data from Key informant interviews, questionnaires and Focus Group Discussions was analysed through SPSS by computing totals and percentages and drawing charts. Rainfall trend analysis at $\alpha = 0.05$ revealed rainfall was variable at monthly (p-value = 0.037 and Sen's slope = 0.182), seasonal (Sen's slope = −0.030 and p-value = 0.043 for MAM and Sen's slope = 0.136 and p-value = 0.046 for OND) and annual (Sen's slope = 1.081 and p-value = 0.010) time steps. Discharge trend analysis at $\alpha = 0.05$ revealed existence of trend on seasonal (Sen's slope = 0.51 and p-value = 0.009 for MAM and Sen's slope = 0.521 and p-value = 0.008 for OND) and annual (Sen's slope = 0.085 and p-value = 0.001). Regression analysis revealed insignificant seasonal correlation (MAM and OND with $r = −0.124$ and 0.067) and annual correlation ($r = 0.051$). Statistical analysis revealed that major land cover changes were agricultural area that decreased from 50.05% (2001) to 41.07% (2011) and 32.8% (2020) and increased buildup areas from 5.06% (2001) to 9.29% (2011) to 17.68% (2020) attributed to increased population, expansion of urban areas and encroachment into river riparian that decreased from 5.18%

(2001) to 1.18% (2011) and 0.87% (2020). These findings would encourage capacity building on increasing rainfall trends and take measures to control floods.

Subject Areas

Hydrology

Keywords

Land Cover Changes, Mann Kendall, Rainfall Variability, Sen's Slope, Streamflow, Zaaba River

1. Introduction

Examining temporal variation in rainfall and land cover is key to sustainable management and conservation of water resources at basin level. Land cover changes, brought about by socio-economic activities and increasing population, mainly involve destruction of natural vegetation through anthropogenic activities [1]-[3]. The reduced extend of vegetation cover, which occurs as a result of encroachment into forested, riparian and wetland areas, has influenced hydrological processes like precipitation, evapotranspiration, interception, infiltration, surface detention and generation of runoff at a basin.

Variability in rainfall, which is a global concern brought about by climate change and socio-economic activities, occurs in form of fluctuations in amounts, intensity, distribution, season's onset and cessation dates which influence water levels of streams and rivers and the frequency of occurrence of extreme events by determining magnitude of runoff and quantity of water resources at a watershed [4]-[6]. In East Africa, variability in rainfall is highly attributed to Indian Ocean Dipole, El Nino Southern Oscillations and jet streams that result in increased frequency of floods and droughts witnessed annually in the region since 2000 [7] [8]. Analysis of rainfall trends is therefore vital in determining rainfall-runoff relations and performance of sectors that like agriculture, livestock, energy, manufacturing and environment which depend on water security.

Streamflow at a catchment primarily depends on rainfall; however, other hydrological and physical factors like land cover changes and water abstractions and diversions affect the volume of streamflow [9]-[11]. Rapid human induced land cover changes in sub-Saharan Africa have enhanced or depleted extend of vegetal cover by encroaching forested, riparian and wetland areas for agricultural activities, infrastructural development and urbanization which vary hydrological processes like precipitation, evapotranspiration, infiltration and absorption that influence generation of runoff at a basin.

High population growth rate at the study area led to increased demand for land and anthropogenic activities that interfere with natural vegetation cover through conversion and modification of land cover types like bare surfaces, forests, grasslands and water bodies. Expansion of urban areas, diversion and abstraction of water and set up of settlements on fragile ecosystems like steep slopes, wetlands and riparian areas have impacted on streamflow, which represents the runoff phase of a hydrological cycle [11] [12].

Several studies have been conducted on rainfall trends in arid and semi-arid areas, land cover changes and their influence on hydrology of a river basin. This study, however, focused on a catchment that traditionally receives high rainfall that is distributed in two seasons, that is high rain season in MAM and low rain season in OND and the basin land cover changes over three decades and their influence on discharge of the river. The objective of the study was to determine rainfall and discharge trends and factors determining response of streamflow to rainfall variability.

2. Materials and Methods

2.1. Study Area

Figure 1 depicts the study area which lies in Yala River basin within Lake Victoria North Catchment in Western region of Kenya near Kisumu City. The area is in the coordinate 0˚0' latitude and 34˚40'E longitude covering an area of 79.51 km^2 with an altitude that ranges between 1320 m and 1839 m above mean sea level.

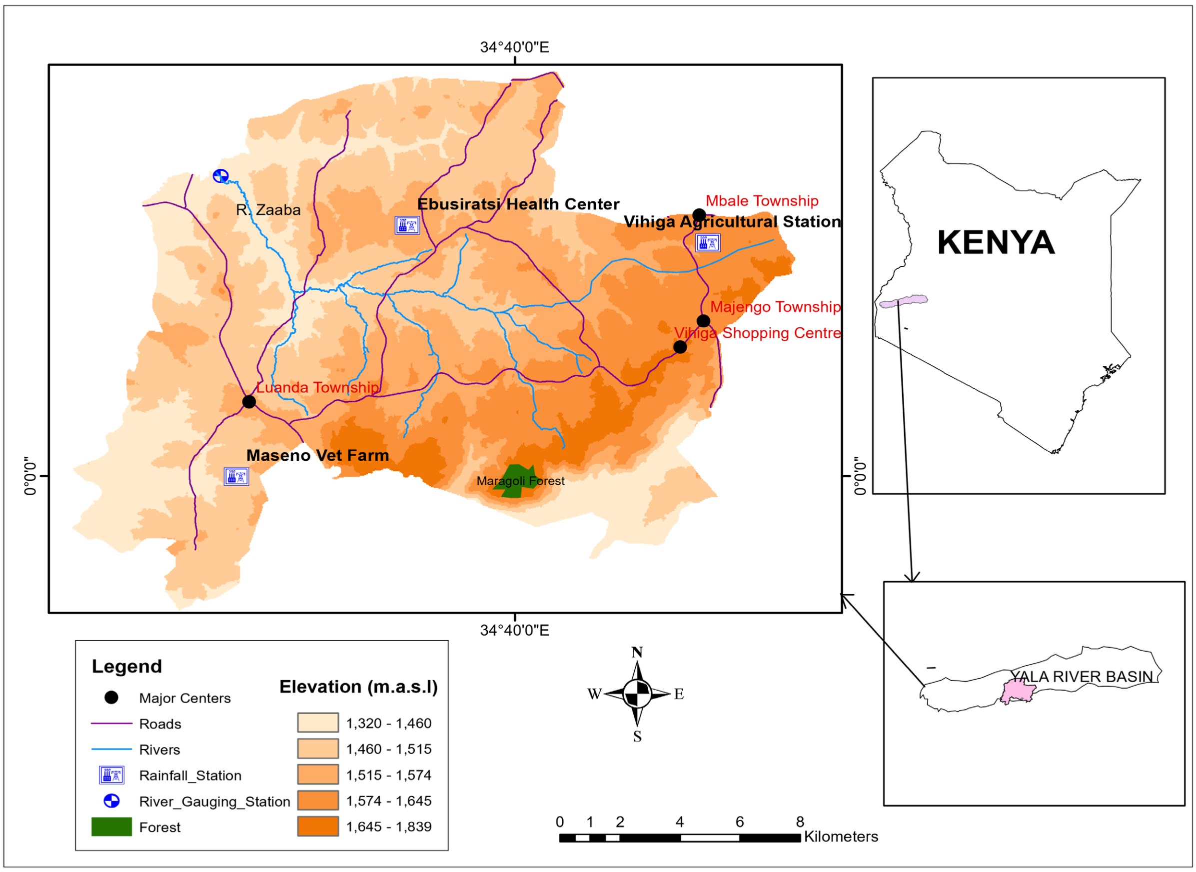

Figure 1. Zaaba River Sub catchment.

The area experiences equatorial climate with bimodal rainfall pattern. Long rains occur in MAM while short rains occur in OND and the mean annual precipitation is 1900 mm. December, January and February experience the highest temperatures, lowest precipitation and with an average atmospheric moisture of 41.75%.

Zaaba river, which drains the area, is a tributary of Yala river flowing in a westward direction covering 17 km. There are seasonal streams that include Ematenje, Ebutanyi and Itumbu which flow in a South West direction into Zaaba River. The other water resources within the sub catchment are springs, hand dug and drilled wells, rain water harvesting and small streams that include Ejorodani, Nasibi, Emukhalia and Mukhalakhala [12]-[14].

Kavirondian and Nyanzian are the dominant geological formations Nyanzian rocks consist of rhyolites, basalts and andesites while Kavirondian rocks are compost of grits, conglomerates and mudstones which are sedimentary derivatives of Nyanzian system rocks that form the dystric acrisols and humic nitisols [12].

Luanda Municipality, Majengo and Mbale Municipality are the major urban centres in the study area. Most people live in rural set ups where farming is a dominant economic activity where crops are grown mainly for subsistence and include maize, potatoes, groundnuts, sugarcane, bananas, arrowroots, cassava, sweet potatoes, millet, sorghum, vegetables, fruit trees and beans. Tea is the cash crop grown in the area. There is livestock farming, poultry farming, quarrying for building stones and extraction of sand from the river bed. The livestock bred include Zebu cattle, dairy cattle, sheep, goats, pigs and rabbits. A few farmers practice fish farming with main fish species being tilapia and catfish. Napier grass is grown on farms, road reserves and along river banks. The farmers practice agroforestry with eucalyptus trees forming about 70% of the tree species grown on farms [12].

2.2. Data Sources

Daily historical record for the rainfall stations for 1991 to 2020 was sourced from Kenya Meteorological Department whereas daily historical record of discharge data for Zaaba River Gauging station was sourced from Water Resources Authority. Normal Ration Method [15] in "Equation (1)" was used to fill gaps in rainfall data.

$$P_4 = \frac{1}{3}\left[\frac{N_4}{N_1}P_1 + \frac{N_4}{N_2}P_2 + \frac{N_4}{N_3}P_3\right] \quad (1)$$

Data on land cover types was downloaded from USGS website http://www.earthexplorer/ in form of_Landsat 7 for 2001 and Landsat 8 for 2011 and 2020. The major land cover types considered in this study were tree cover, agricultural area, grasslands, buildup areas, bare surfaces and river riparian.

2.3. Data Analysis

2.3.1. Trends in Rainfall

Daily rainfall data was converted to monthly, seasonal and annual time steps before analysis was done to detect trend. The MK test and Sen's slope were used to detect any significant statistical trend and its nature using the mathematical relation by Bluman (2009) [16] shown in "Equation (2)".

$$s = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\left(x_j - x_k\right) \tag{2}$$

where:

x_j and x_k = time series observation;

n = length of time series.

sgn (x) defined by function expressed in "Equation (3)":

$$\operatorname{sgn}(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases} \tag{3}$$

The variance (VAR) and S were used to estimate the value of standardized test statistics (Z) as shown in "Equation (4)" and "Equation (5)" respectively.

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right] \tag{4}$$

where t_p is the number of ties at p^{th} value and q is the number of tied groups.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & \text{if } S < 0 \end{cases} \tag{5}$$

The values of Z indicate the presence of statistical significance in the time series.

The Z positive value indicates an upward trend in the time series. The Z negative value indicates a downward trend in the time series.

2.3.2. Discharge Variations

Z test, p-value and Se's slope estimator were used to determine existence of significant trend in seasonal and annual time steps and infer variations in discharge.

2.3.3. Discharge Response to Rainfall Variability

Regression analysis for seasonal and annual data determined correlation between variability in rainfall and discharge using the mathematical relation by [16] shown in "Equation (6)".

$$y = a + bX \tag{6}$$

where:

y is river discharge

X is rainfall

b is slope

a is intercept.

2.3.4. Factors Determining Streamflow Response to Rainfall Variability

1) Land Cover Changes

ArcGIS 10.3.1 and ERDAS Imagine 2013 software were used to derive catchment topography and generate land cover maps that were processed and analysed for extraction of statistical change in cover given as percentages and presented by drawing charts.

2) Other Factors

Qualitative data was analyzed by computing totals, percentages and drawing charts from which inference was made on their influence on streamflow variation.

3. Results and Discussions

3.1. Monthly, Seasonal and Annual Trends in Rainfall

Monthly rainfall variation over Zaaba sub catchment is shown in Figure 2. April month had the highest average rainfall while February had the lowest average rainfall. Rainfall trend analysis at $\alpha = 0.05$ revealed average monthly rainfall was variable with an increasing trend with p-value = 0.037 and Sen's slope of 125.455 as indicated in Table 1.

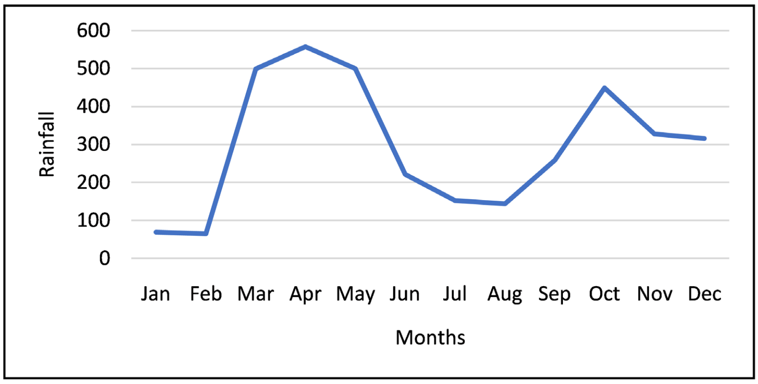

Figure 2. Monthly Rainfall over Zaaba sub catchment during the period 1991 to 2020.

Table 1. Monthly rainfall statistics.

Kendall's tau	0.182
P-value	0.037
Sen's slope	125.455

The study area has two rainy seasons: long rains in MAM (March April May) with highest rainfall recorded in 2018 and lowest in 2014 as shown in Figure 3 and short rains in OND (October November December) whose highest rainfall was recorded in 2019 and lowest recorded in 2016 as shown in Figure 4. For the MAM season rainfall peaked in April-May while for OND rainfall peaked in October-November.

The examination of seasonal trends revealed that at $\alpha = 0.05$ MAM season had decreasing trend with p-value = 0.043 and Sen's slope of −0.030 while OND season had increasing trend with p-value = 0.046 and Sen's slope of 0.136 as shown in Table 2.

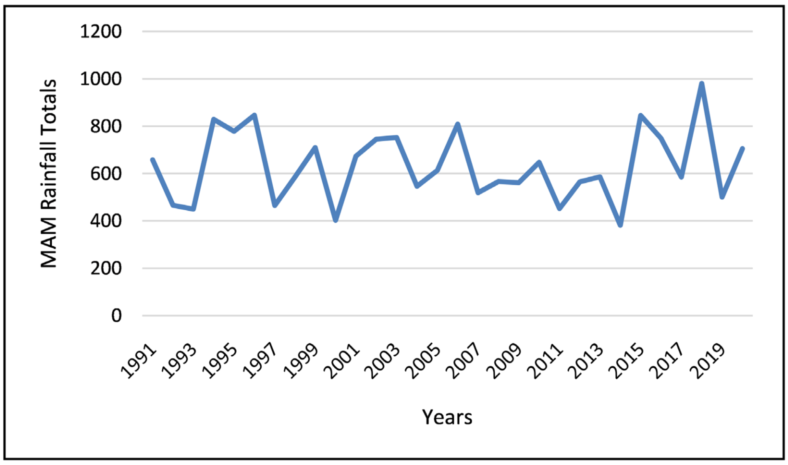

Figure 3. MAM rainfall variation during the period 1991 to 2020.

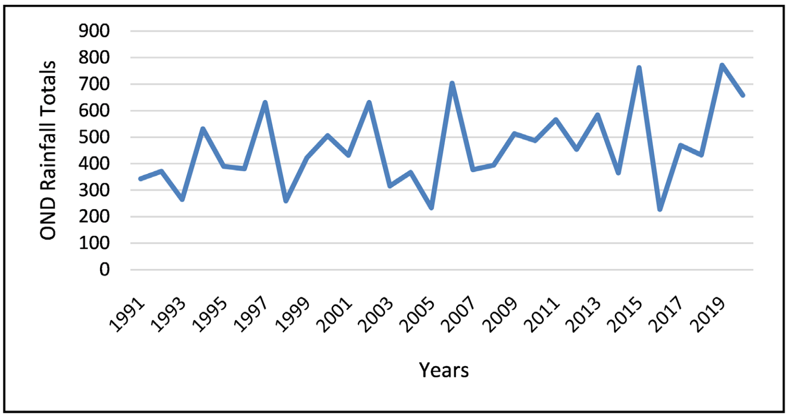

Figure 4. OND rainfall variation during the period 1991 to 2020.

Table 2. MAM and OND season statistics.

STATISTIC	MAM SEASON	OND SEASON
p-value	0.043	0.046
Z test	1.407	3.83
Kendall slope	-0.030	0.136

Annual rainfall variations are shown in Figure 5. Highest annual rainfall was recorded in 2020 while lowest rainfall total was recorded in 2015. Annual rainfall trend analysis revealed existence of trend with p-value = 0.010 and Sen's slope of 1.081. The high rainfall received in 1996 up to early 2020 was registered in rainfall stations in most parts of Kenya whereas the low rainfall registered in 1992 and 1993 was due to the drought that occurred in the country in 1992/93 [17].

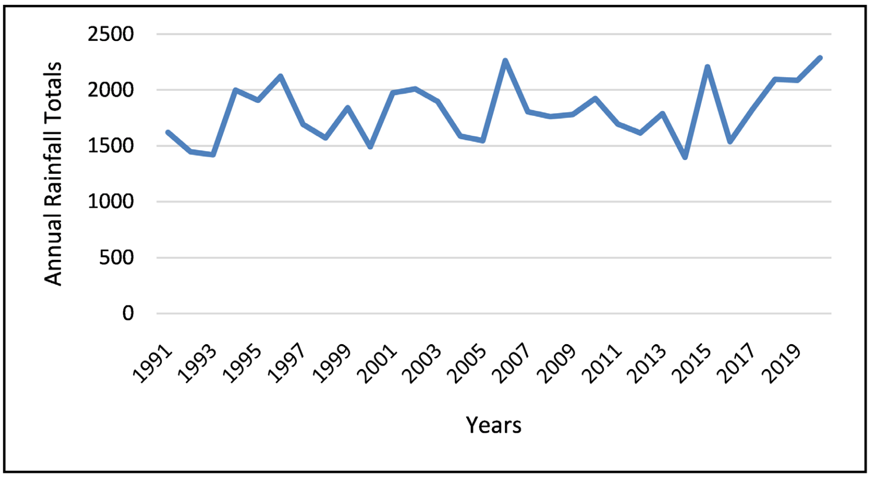

Figure 5. Annual Rainfall Variations for Zaaba sub catchment.

3.2. Discharge Variations

3.2.1. Discharge Variations for MAM and OND Season

MAM season variations in discharge are shown in Figure 6. Highest season discharge was 386.55 m^3/s in 2012 while lowest season discharge was 36.9 m^3/s in 1999. High rainfall was received in Kenya in 2012 which led to the high discharge while the droughts experienced in 1998 and low rainfall in 1999 led to the low discharge [18].

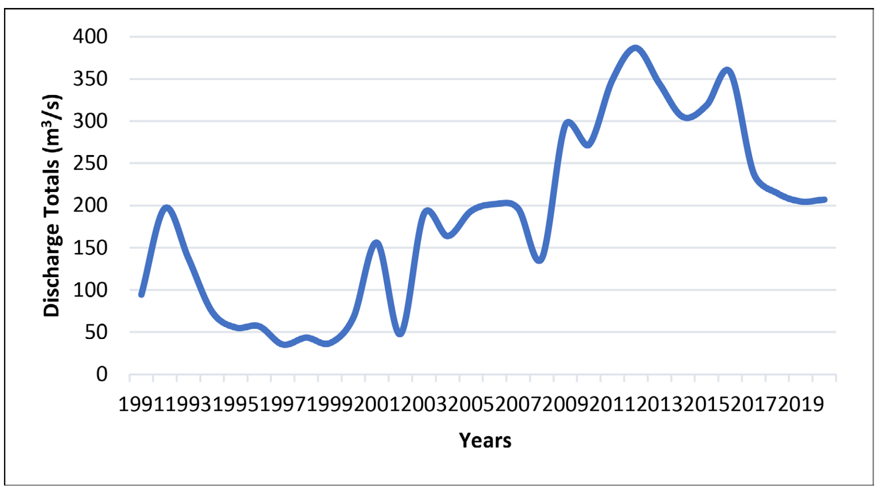

Figure 6. MAM season flow hydrograph for Zaaba.

OND season variation is shown in Figure 7. 1996 had highest discharge of 167.1 m^3/s while 1993 had lowest discharge of 56.6 m^3/s.

There existed increasing trend in season discharge time series during the study period. Table 3 summarizes the discharge statistics for MAM and OND seasons. For MAM season, Kendall statistic was 0.51, Z-test = 53 and p-value = 0.009 at α = 0.05. For OND season, Kendall statistic was 0.521, Z-test = 3.67 while p-value = 0.008 at $\alpha = 0.05$.

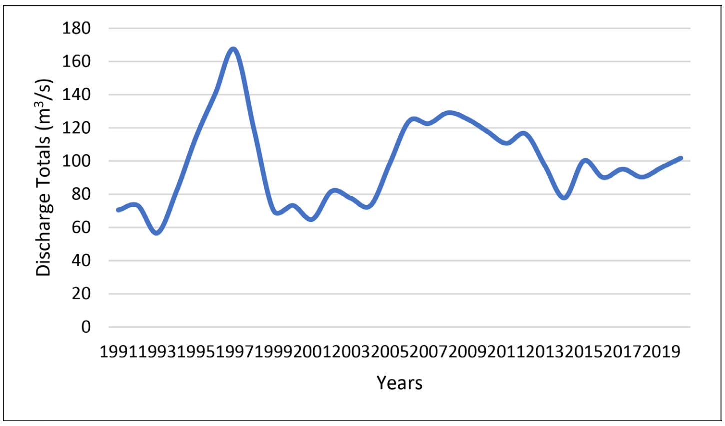

Figure 7. OND season flow hydrograph for Zaaba River.

Table 3. Summary Statistics for Discharge trends for MAM and OND season.

STATISTIC	MAM SEASON	OND SEASON
Kendall's	0.510	0.521
Z-test	53.0	3.67
P-value	0.009	0.008

3.2.2. Annual Variations in River Discharge

Variations in annual discharge are shown in Figure 8. Highest discharge of 892.4 m^3/s was in 2012 while 2002 registered lowest discharge of 239.6 m^3/s. An increasing trend existed in annual discharge time series with Kendall's statistic = 0.003 with a slope of 0.085, Z-test = 2.001 and p-value = 0.009 at $\alpha = 0.05$ as indicated in Table 4.

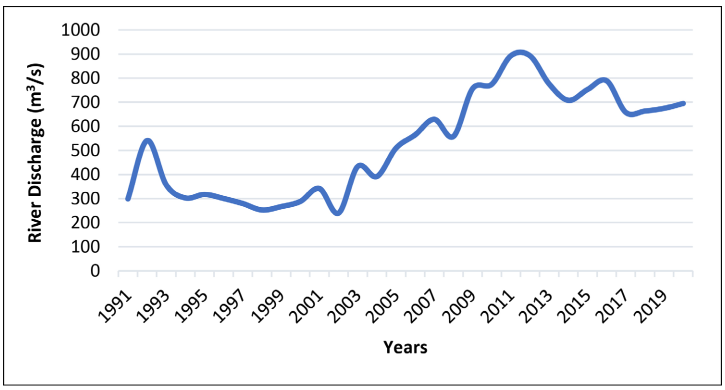

Figure 8. Annual flow hydrograph for Zaaba River.

Table 4. Descriptive Statistics for Annual River Discharge.

STATISTIC	ANNUAL DISCHARGE
Kendall's	0.003
Z-stat	2.001
p-value	0.009
Slope	0.085

3.3. Discharge Response to Rainfall Variability

In the MAM season, highest discharge was 386.55 m^3/s in 2012 while lowest discharge was 36.9 m^3/s in 1997 as depicted in Figure 9. Regression analysis at 95% confidence interval revealed the existence of negative correlation of 0.124 between rainfall and discharge with $r = -0.124$. Figure 10 depicts rainfall and discharge for OND season in which highest discharge was 167.1 m^3/s in 1997 due to the effects of El Nino phenomenon while lowest discharge was 56.6 m^3/s in 1993 due to the 1992/93 droughts in the country [18]. Regression analysis at 95% confidence interval revealed positive correlation with $r = 0.067$ which is statistically insignificant. These results conform with the findings by [19] where a negative correlation existed between rainfall and discharge for the MAM season and an insignificant correlation for the OND season.

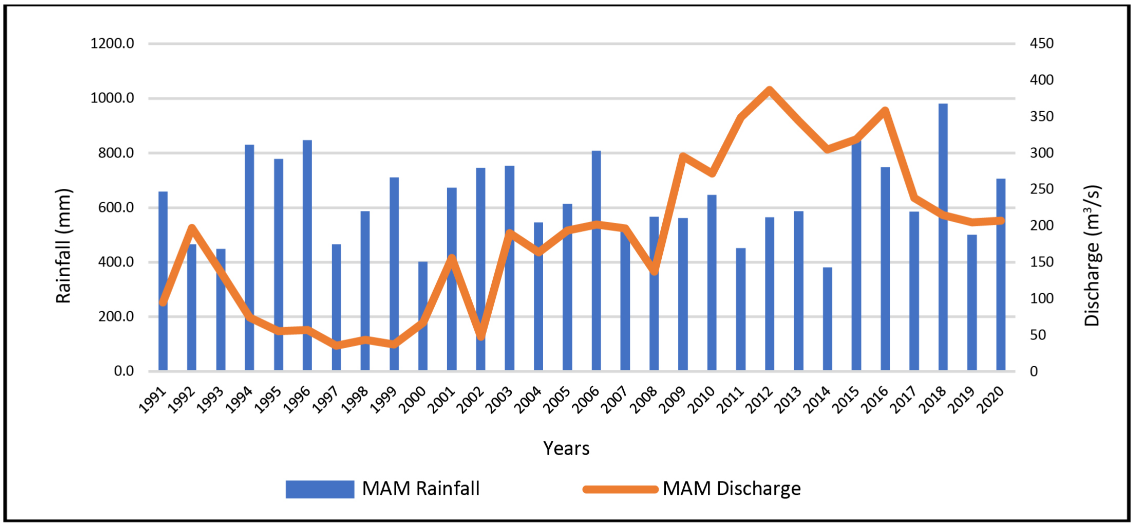

Figure 9. Discharge and Rainfall for MAM season.

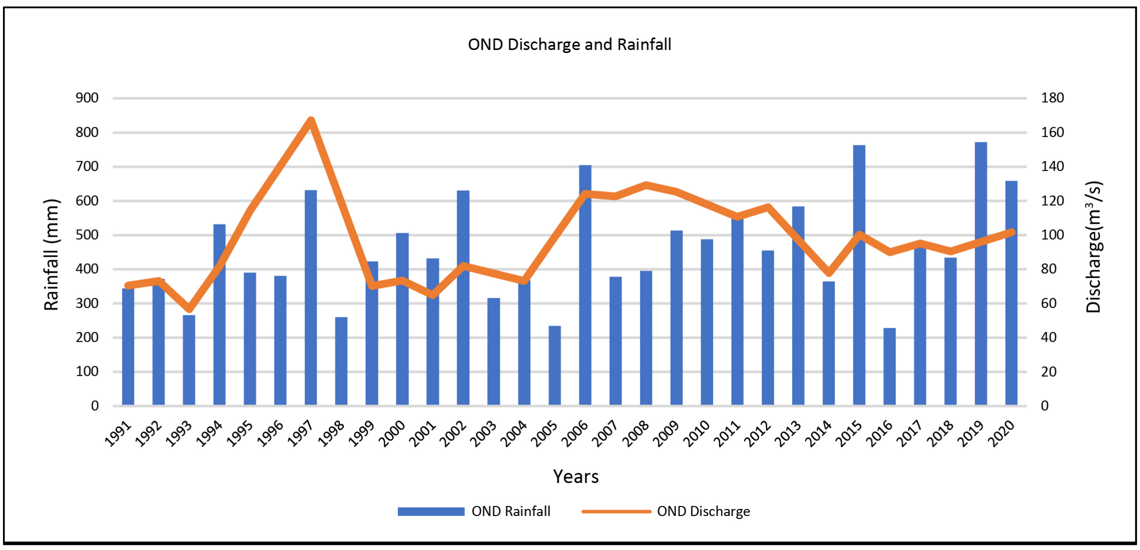

Figure 10. Discharge and Rainfall for OND season.

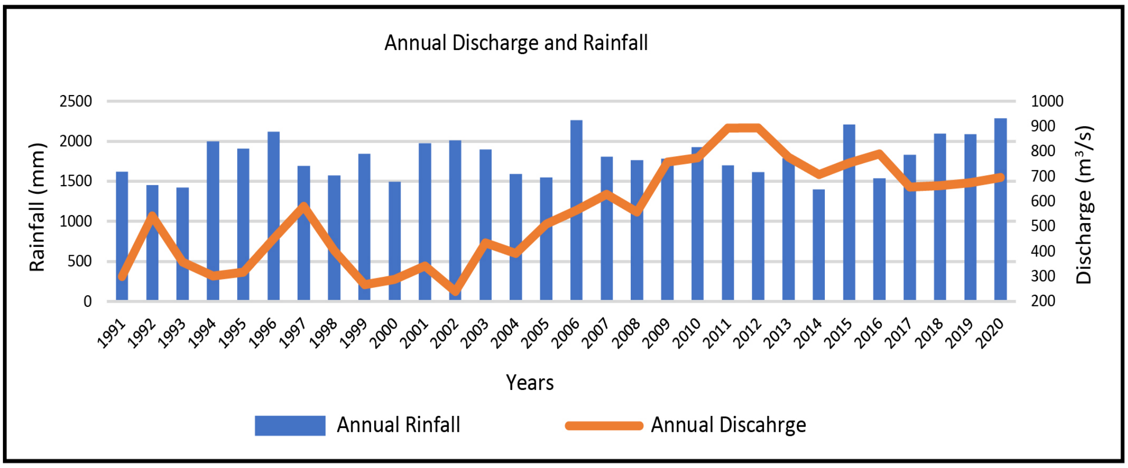

Figure 11. Annual Discharge and Rainfall.

A statistically insignificant correlation exists between annual rainfall and discharge with $r = 0.051$ at 95% confidence interval. There was an increase in annual discharge between 2003 and 2012 is shown in Figure 11 which may be attributed to increasing rainfall trends in the years.

3.4. Factors Determining Streamflow Response to Rainfall Variability

3.4.1. Land Cover Changes

Classified land cover maps for 2001 in Figure 12, 2011 in Figure 13 and 2020 in Figure 14 were generated and compared statistically to detect change in cover. Variations in land cover for 2001, 2011 and 2020 indicated that agricultural land declined from 50.05% to 41.07% to 32.8%. There was an increase in tree cover from 6.71% in 2001 to 10.19% in 2011 to 12.42% in 2020. Grasslands decreased from 2.29% in 2001 to 1.92% in 2011 and then increased to 12.36% in 2020. River riparian declined from 5.18% in 2001 to 1.18% in 2011 to 0.87% in 2020. There was an increase in buildup areas from 5.06% in 2001 to 9.29% in 2011 to 17.68% in 2020. Bare surfaces increased between 2001 and 2011 from 30.72% to 36.8% and then declined to 23.87% in 2020.The land cover changes were caused by anthropogenic activities due to the increased population that triggered off growth and expansion of buildup areas and encroachment into forested, riparian and wetland areas [20].

Changes in land cover affect components of hydrology like runoff generation, rate of infiltration, evapotranspiration and surface flow [21]. In 2001, the annual discharge was 341.4 m^3/s which increased to 892.68 m^3/s in 2011 and then decreased to 694.62 m^3/s in 2020. Table 5 summarizes variations in discharge for MAM and OND season in which in both seasons, there was an increase in discharge between 2001 and 2011 and a decrease in discharge in 2020. The increase in discharge for 2001 and 2011 may be attributed to the decline in grasslands from 2.29% to 1.92% and river riparian vegetation from 5.18% to 1.18%. Similarly, an increase in tree cover from 10.19% to 12.42% and grasslands from 1.92% to 12.36% may have led to the decline in discharge in 2020.

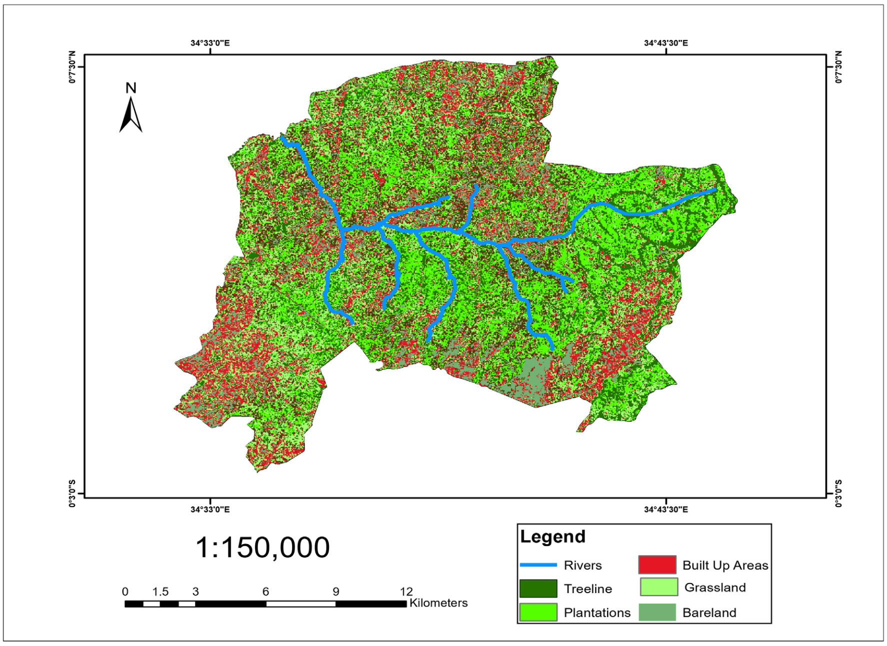

Figure 12. Land cover map for 2001.

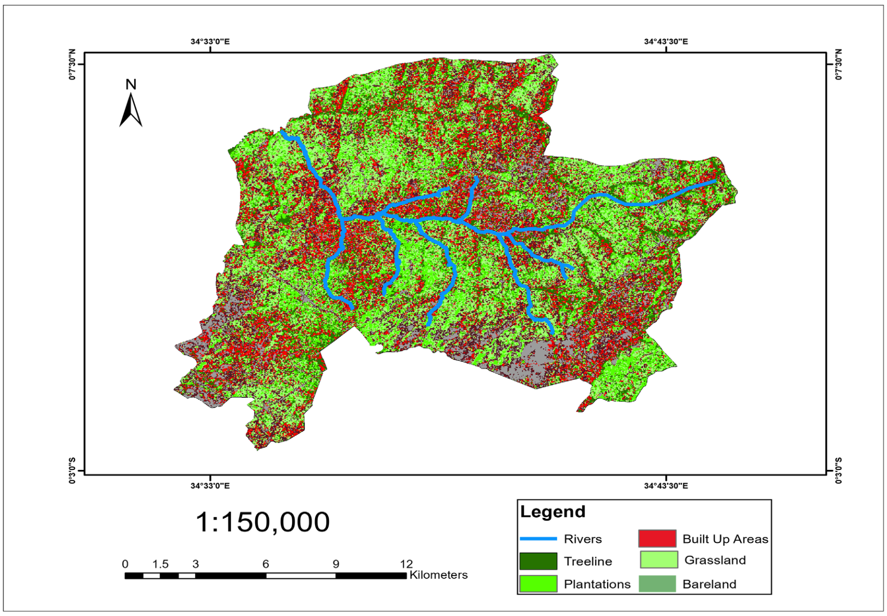

Figure 13. Land cover map for 2011.

Table 5. Discharge variation for MAM and OND seasons in 2001, 2011 and 2020.

YEAR	2001	2011	2020
Discharge for MAM season	156	348.71	206.98
Discharge for OND season	64.92	110.67	101.78

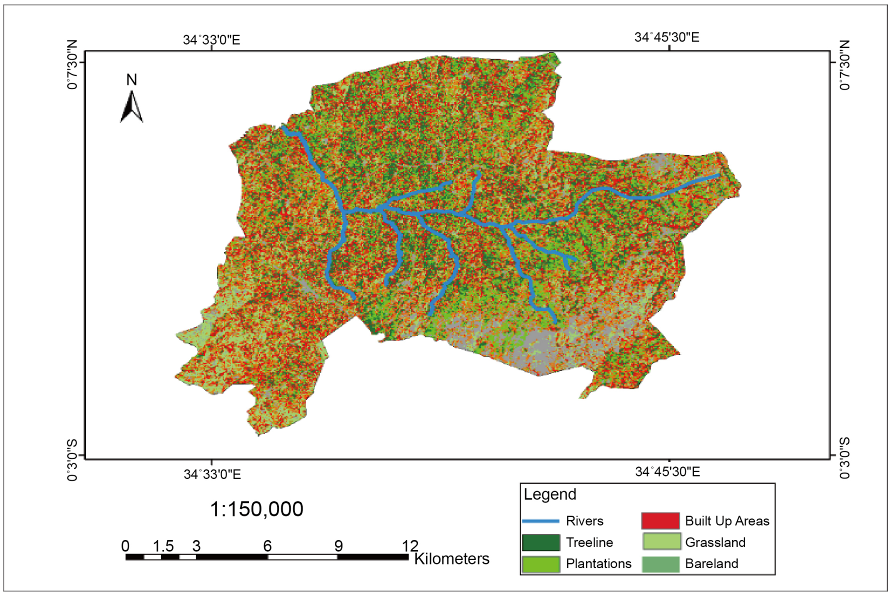

Figure 14. Land cover map for 2020.

3.4.2. Other Factors

According to 83% of respondents, mixed agriculture is the major economic activity where crops grown include maize, beans, nuts, root crops and vegetables and livestock bred are cattle, sheep, goats, pigs, rabbits and poultry farming. Other commercial activities include small scale trade and mining, pottery and brick making, sand harvesting from the streams and crushing of the Kavirondian and Nyanzian rock formations for building stones. The respondents noted that these commercial activities have destroyed vegetation cover and led to increased runoff. In addition, 69 % of the respondents noted that increased population led to fragmentation of land along inheritance lines, expansion of existing urban areas and encroachment into river banks and wetlands therefore increasing runoff that sometimes led to flooding of the lower course of the river.

76% of respondents note that variation in discharge is mainly due to variation in rainfall. However, various socio-economic activities have intervened to determine the discharge volume. 73% of respondents agreed that high streamflow was caused by increased agricultural activities and settlement (54%) and decreased forest area (32%). The other factors considered to have led to changes in discharge are expansion and establishment of urban centres at 8% and encroachment into wetlands and stream channelization at 6%. This also included encroachment onto steep slopes and forests for agricultural purposes which rendered these areas more vulnerable to increased runoff especially with the intensive farming methods as depicted in Figure 15.

These human activities have induced catchment degradation through clear cutting of forests for agriculture, fuelwood and charcoal, destruction of cut off drains, bench terraces and works designed to conserve soil, overgrazing and cultivation on riverbanks and steep slopes have depleted vegetation cover therefore decreasing ground water recharge and increased surface runoff.

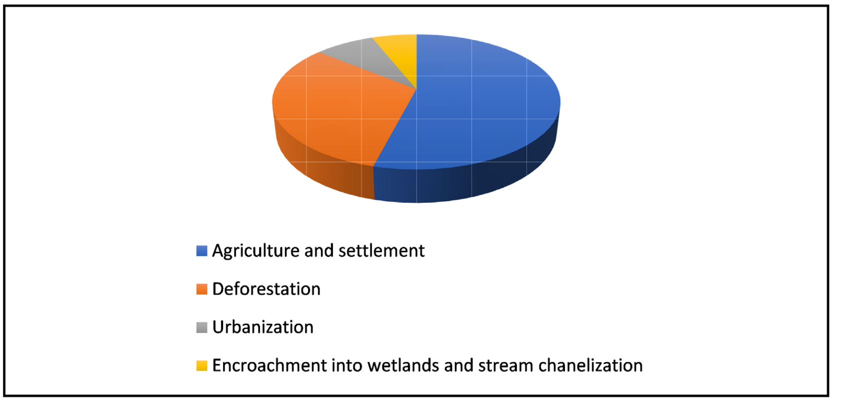

Figure 15. Major causes of variation in discharge.

4. Conclusions

Rainfall trend analysis at $\alpha = 0.05$ revealed rainfall was variable at monthly analysis with p-value = 0.037 and Sen's slope of 0.182; seasonal rainfall had p-value = 0.043 and Sen's slope of −0.030 for MAM and p-value = 0.046 and Sen's slope of 0.136 and for OND while annual rainfall had p-value = 0.010 and Sen's slope of 1.081.

Discharge trend analysis at $\alpha = 0.05$ revealed existence of trend on seasonal and annual time steps. Seasonal trends had Sen's slope of 0.51 and p-value = 0.009 for MAM and Sen's slope of 0.521 and p-value = 0.008 for OND and annual trends had Sen's slope of 0.085 and p-value = 0.001.

Regression analysis between rainfall and discharge at 95% confidence interval revealed insignificant correlation existed in MAM and OND seasons with r = −0.124 and 0.067 respectively and annual data with $r = 0.051$.

Statistical analysis revealed that major land cover changes were agricultural area that decreased from 50.05% (2001) to 41.07% (2011) and 32.8% (2020) and increased buildup areas from 5.06% (2001) to 9.29% (2011) to 17.68% (2020) attributed to increased population, expansion of urban areas and encroachment into river riparian that decreased from 5.18% (2001) to 1.18% (2011) and 0.87% (2020).

These findings would encourage capacity building on increasing rainfall trends and take measures to control floods.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest.

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