

Chapter 10

Hydrology and Climate Impacts on Streamflow and Sediment Yield in the Nyando River Basin, Kenya



J. U. Kitheka, S. Okoyo, and N. Mboya

Abstract This study seeks to establish the extent to which climate change and/or variation is affecting streamflow variability and sediment transport in the Nyando River Basin in Kenya. The basin is one of the country's most important, because it is a source of water for domestic use and irrigation. The river also discharges water and sediment into Lake Victoria, one of the largest freshwater lakes in the world. Data used in this study were obtained from the Water Resources Management Authority (WARMA) and Kenya Meteorological Department (KMD), and include river discharge, rainfall, and total suspended sediment for stations located in the basin. Statistical methods and application of various hydrological data analyses of time-series, flow duration, and Gumbel Distribution for flood flow analysis were used. Land-use change was determined through analysis of Landsat satellite images and use of overlay GIS techniques. Results show that there is significant variability in rainfall and river discharge of the Nyando River, which can be attributed to climate variability. There has also been major change in land use in the basin, which is evidenced by heavy deforestation in the catchment areas for agriculture and settlement of the rapidly increasing population. This increase in degraded areas, coupled with an increase in runoff, has led to increased peak flood flows. The increase in frequency of flood flows is attributed to rapid flow of surface runoff in degraded areas with low water infiltration and percolation rates. However, the relationship between rainfall and river discharge is strongly positive, reflecting the rapid hydrologic response to rainfall input in the basin. There is also a strong positive relationship between sediment discharge and river discharge. The increase or decrease of river discharge leads to a corresponding change in sediment yield. As a result of land degradation and high hydrologic response, the basin experiences high rates of soil erosion and sediment yield. High hydrologic response also leads to flooding in the low-lying Kano plains. Extreme streamflow variability in the plains has both direct and indirect impacts that are ultimately increasing poverty levels in the basin. This study shows that the effects of climate change and/or variability on the hydrologic systems in tropical Africa are being compounded by population growth that has driven land-use change.

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Therefore, it is unlikely that efforts to reduce sediment load and control floods in the basin can be successful without a deliberate effort to mitigate the root causes of land degradation in the basin: rapid population growth and land-use changes.

Keywords Streamflow · Climate variability · Land use · Sediment loads · Floods · Nyando river basin · Kenya

1 Introduction

Climate change is affecting many river basins in Africa through increased occurrence of extreme hydrologic events, such as floods and droughts. In Kenya, like in other countries in Africa, the manifestation of climate change is evident in increased variability of streamflows. There is evidence that the frequency of occurrence of both extremely low and extremely high streamflows has increased in the recent past. The Nyando River Basin in Western Kenya is typical in experiencing increased streamflow variability with increased risk of floods and droughts due to climate change (see also Opere and Ogallo 2006; Opere and Okello 2011a, b). Extreme hydrological events in the basin have major socio-economic impacts because extreme variability of streamflow is causing changes to ecosystems on which local communities depend for survival. This has increased the vulnerability of communities to the impacts of climate change, and is expected to increase more in the near future due to the compounding impacts of climate change that can be attributed to land-use change due to the rapidly increasing population and urbanization in the basin.

The status of the Nyando Basin is similar to other basins in Africa where occurrence of extreme hydrologic events has increased noticeably in the recent past, affecting millions of people and significantly decelerating economic development. As a result, considerable effort has been invested in the mitigation of drought- and flood-induced damage over the last decade. In Kenya, floods are second to droughts in terms of frequency and severity of impacts on land use, as droughts continue to cause physical damage in major river basins, including the Nyando Basin. Within the Nyando River Basin, interventions to address the impacts of extreme hydrologic events have not yielded the desired results. This is partly because most mitigation measures have not been based on hydrologic research and have also largely ignored local perceptions and experiences. There has also been relatively limited research to characterize the hydrologic response of tropical river basins in this era of climate change. Similarly, there have been few hydrologic studies targeting degraded tropical river basins such as Nyando that are already experiencing the impacts of climate change. The lack of such studies limits the effectiveness of drought and flood management intervention. There is therefore a need for studies to determine the extent to which tropical river basins in Africa are being impacted by climate change in terms of streamflow variability, soil erosion, and sediment yield. This need is amplified by the fact that extreme hydrologic events have cumulative impacts that can in turn have

major socio-economic impacts on communities. However, these are generally undervalued by both national and international disaster management and development policies and represent a challenge for disaster risk reduction (Mutua 2001).

The problem of sediment production and transport subject to climate change within the basin must be examined, because it has major socio-economic implications for communities and the country. Past studies have shown that land degradation occurring on fragile slopes in the Nyando River Basin is responsible for high rates of soil erosion (ICRAF 2000), which leads to high sediment load, and is thought to be influenced by factors such as land use, vegetation cover, runoff dynamics, and rainfall variability. There is, however, limited data and information on the extent to which extreme hydrologic events and land-use change have altered the sediment load delivered to Lake Victoria by the Nyando River. Because of this, assessment of the influence of rainfall, river discharge, and land-use change is important because these factors are highly variable as a result of climate and land-use change, with big implications for the Nyando River Basin. The object of this study is therefore to establish the extent to which climate change is affecting streamflow variability and sediment transport in the Nyando River Basin in Kenya, an important aspect of the current debate on the impacts of climate on water resources in Africa.

2 Description of the Study Area

2.1 Location

The Nyando River Basin is located in the Western region of Kenya between longitudes $0^{\circ} 50'S$ and $0^{\circ} 10'S$ and between latitudes $33^{\circ} 05'E$ and $34^{\circ} 25'E$ (Fig. 1). The river originates from the Nandi Hills and Nyabondo Escarpment and drains into the Winam Gulf in Lake Victoria (LBDA 1992; Republic of Kenya 2001a). It has a total length of 170 km and a surface area of $3,517 \text{ km}^2$. The main source of the rivers is in the forested highlands at an altitude of 3,000 m above sea level (Kamau 2016).

2.2 Climate

The Nyando River Basin experiences two rainfall seasons. The long rainy season is between March–April–May (MAM), and the short rainy season is between September–October–November (SON). The average annual total rainfall ranges from about 1100–1600 mm. The highland areas of the basin experience higher amounts of rainfall (1800 mm) compared to the middle and lower areas that receive between 600 and 1100 mm of rainfall annually (ICRAF 2000 and 2002). The mean minimum annual temperatures ranging from 14°C to 18°C are recorded from June to July. The

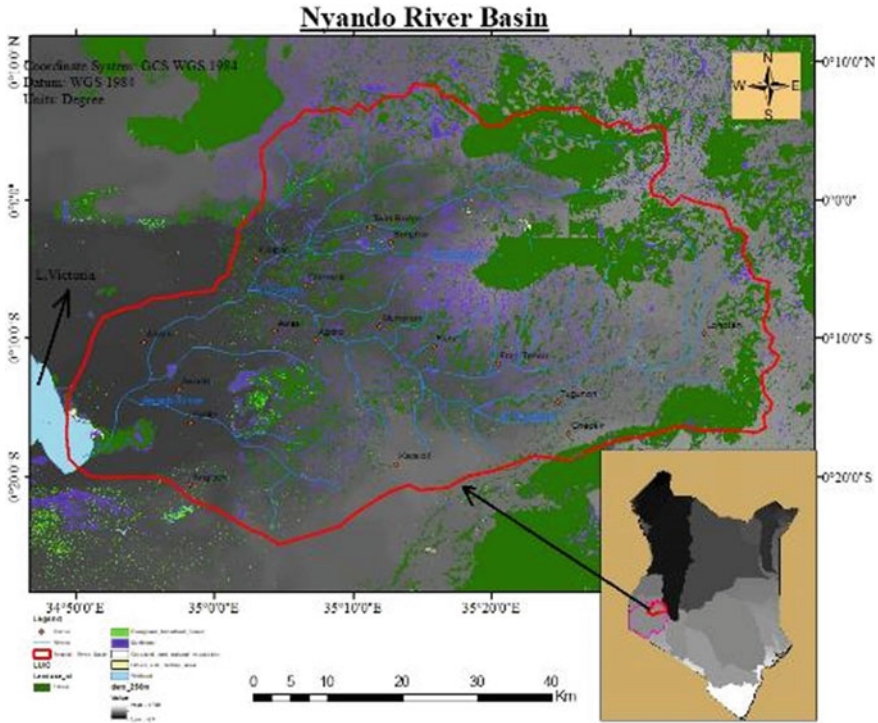


Fig. 1 The Nyando River Basin in Kenya

highest annual temperatures, ranging from 27 °C to 32 °C, are recorded in August and September. The monthly mean evaporation ranges from 1300 to 2200 mm.

2.3 Vegetation Cover

Vegetation cover in the Nyando River Basin also shows significant spatial variation; the influence of altitude is predominant in determining vegetation types. In the highlands, vegetation consists of evergreen broadleaf forest, and there are also many tea plantations, on both large- and small-scale farms. Large areas are covered with plantation forests, especially *Pinus patula* and *Cupressus lustanica*. Eucalyptus trees have also been planted, especially on tea estates. The lowland areas are covered with grasslands and scattered acacia trees.

2.4 Land Use

Land use and land cover types in the Nyando Basin are diverse (Van Der Kwast and Zomer 2002; Onyango 2003). The main land-use types are forestry and agriculture. Forests are found on government-designated land in Timboroa, Tinderet, Londiani, Western Mau, and parts of South Nandi. Some parts of these forests are planted with exotic tree species (*Pinus patula*, *Pinus radiata* and *Cupressus* spp), which are used for commercial purposes. The lower parts of the basin are composed of a flood-prone lakeshore area which is mostly used for subsistence farming of maize, beans, and sorghum, and commercial production of sugar cane and irrigated rice. The vegetation in the basin has changed considerably from the woods of the past to the present shrubs. The dominant land use in the highlands is for tea, both on large estates and small-scale farms. Other crops found in these areas are maize, potatoes, pyrethrum, wheat, and cabbage. In the last 40 years, the basin has experienced dramatic land-use changes, as the land has been converted from small-scale farming to intense smallholder cultivation (Verchot 2008; Swallow et al. 2002; Omuto 2003; ICRAF 2000 and 2002).

3 Methodology

3.1 Data Types and Sources

Data used in this study were gathered from both primary and secondary sources. These include unpublished reports of the National Environment Management Authority (NEMA), Directorate of Water Development (DWD), Water Resource Management Authority (WRMA), and LVEMP. Reports from other NGOs and the private sector also provide valuable information on land-use activity in the basin. The main data used in this study are rainfall, river discharge, suspended sediment concentrations, sediment loads, and land-use change. These data were obtained from the Water Resources Management Authority (WRMA) and Kenya Meteorological Department (KMD).

3.2 Secondary Data

Data on daily river discharges and Total Suspended Sediment Concentrations (TSSCs) for the periods between 2000 and 2015 were collected at River Gauging Station (RGS) 1GD07 (Nyando: Long. 35 10'E and Lat. 0 10'S) and RGS 1GD04 (Ainomotua: Long. 335 02'E and Lat. 0 07'S). River discharge data were obtained from the WRMA Regional Offices in Kisumu. These two river gauging stations were considered suitable for this study because the area upstream of the basin is the most

affected by changes in rainfall and river discharge levels. The mean monthly rainfall data were obtained from the Kenya Meteorological Department (KMD) rainfall stations located at Ahero, Kibos, Koru, Lumbwa, and Nyando. Rainfall data were used to determine the relationship between rainfall and streamflow.¹ There is, however, a huge gap in the sediment data because the only available data on TSSC for RGS 1GD04 were for the period between 2000 and 2015.

3.3 Analysis of Land-Use/Land Cover Changes

Cloud-free Landsat images were downloaded from the United States Geological Survey (USGS) website for the years 2000 and 2015. To obtain complete coverage of the study area, two scenes, of paths 169 and 170, and raw satellite images were subjected to atmospheric correction and then projected to UTM 37 using WGS 84 data. Bands 4, 3, 2 for these images, and 5, 3, 2 for OLI images, were used to obtain a false color composite. Three subsets were created using the shape file of the study area. Images were enhanced to facilitate image interpretation. To obtain a rough idea of the number of classes in the study area, unsupervised clustering of ISODATA was used. Training sites were developed from Google maps. Supervised classification using maximum likelihood algorithm was used to classify the images. The classified images were then subjected to post-classification smoothing using a majority filter to remove the “salt and pepper” appearance and enhance cartographic display. Post-classification change detection was used.

3.4 Methods of Data Analysis

Data were analyzed using both qualitative and quantitative methods. The frequency distribution model (Gumbel Extreme Value) was used to determine the return periods of various categories of streamflow of the Nyando River. In this analysis, the magnitude of floods was related to frequency of occurrence. The frequency and magnitude of flood flows were determined using the Gumbel Extreme Value Probability Model that also compares different return periods to predict future flows. Return periods of rainfall and river discharges were also determined in this study. The inverse of probability is generally expressed in percentage, given the estimated time interval between events of a similar size or intensity. Trend analysis was undertaken to determine seasonal and annual variations of both rainfall and river discharges. The study also employs the use of measures of central tendency in the analysis of data (Lane 2008). Various quantitative methods used in data analysis include regression and correlation analyses and Analysis of Variance (ANOVA).

¹Data collected were coded, processed, and analyzed using Microsoft Excel.

4 Results

4.1 Variability of Rainfall

Streams contributing to the streamflow of the Nyando River originate from high altitude (1700–3000 m asl). These are high rainfall (1200–2400 mm) areas located in Kericho and Nandi counties (Fig. 1). The river flows through V-shaped valleys in the upper mountainous region with a channel width of 20 m (NEMA 2004). At the middle region, the width of the river is about 40 m, but this increases to a channel width of 50 m further downstream in the low-lying region (WARMA 2004; Kamau 2016). The peak rainfall experienced in the month of April during the long rainy season ranges between 150 and 270 mm (Fig. 2). There is also a peak rainfall in August, when it ranges from 125 to 170 mm, as well as in November during the short rains when the peak ranges between 70 and 140 mm. Peak river discharge is also experienced in the same periods. The lowland area lies in a region of low rainfall, receiving a mean of between 800 and 1,200 mm annually, while sections of the basin in the north and south experience rainfall >1,600 mm per annum. The highest rainfall occurs in the Nandi Hills toward the northeastern region, which gradually decreases in the southeastern direction. The mean annual rainfall in the basin has been estimated using Thiessen’s Polygon method to be 1431 mm (Kamau 2016).

The results of the analysis of hydrological data show that there was an increase in rainfall in the period between 2003 and 2012 (Fig. 3). Due to lack of data, the trend for earlier years is not established. It is important to note that the increasing trend in the period 2003–2012 could be attributed to normal inter-annual rainfall variability.

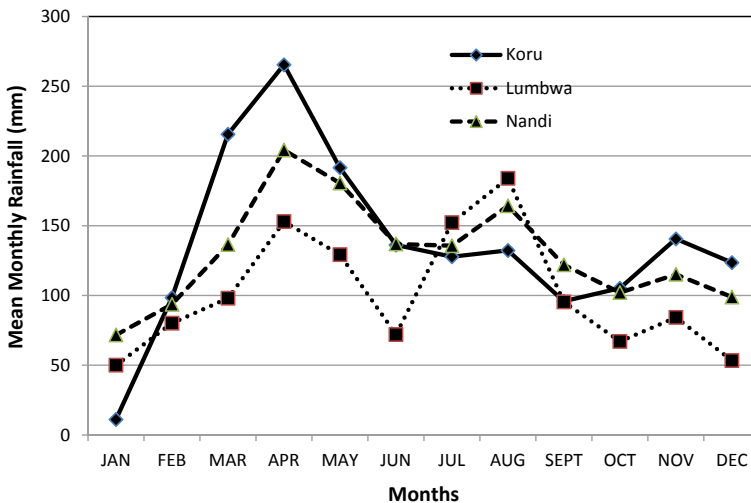


Fig. 2 The mean monthly rainfall in the Nyando River Basin. The plots are based on averages of 11 years for Koru and Lumbwa rainfall stations and 41 years for Nandi Rainfall Station

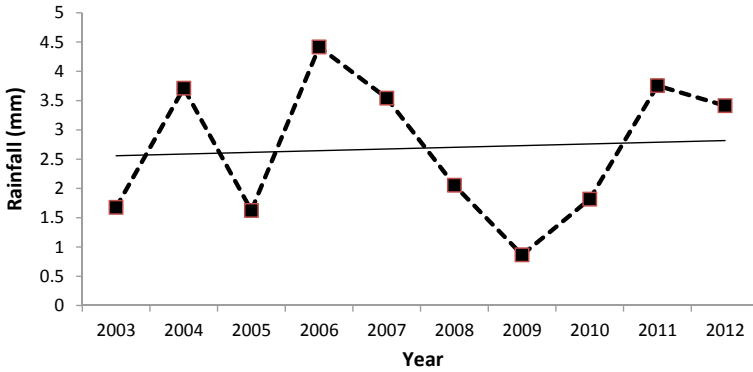


Fig. 3 Inter-annual variation of rainfall in the Nyando River Basin, 2003–2012, based on records obtained at RGS IGD03

As with rainfall, river discharges also show normal year-to-year variations that are related to fluctuation of rainfall (Fig. 3). There is also indication of an increase in the degree of variability, with an increase in the frequency and magnitude of extreme rainfall observed in the basin. It is possible that the declining trend is either a result of climate variability and/or land-use change. It is, however, difficult at this stage to determine the main driver. While rainfall shows a declining trend, the degree of variability seems to have increased since 2013 (Fig. 4).

The basin experiences distinctive seasonal variation throughout the year, with two maximum rainy seasons from April to May and also from October to November (Figs. 5, 6, and 7). The lowland area lies in a region of low rainfall, with a mean between 800 and 1200 mm annually, while sections of the basin in the north and south experience >1600 mm of rainfall. The greatest rainfall of >2000 mm occurs

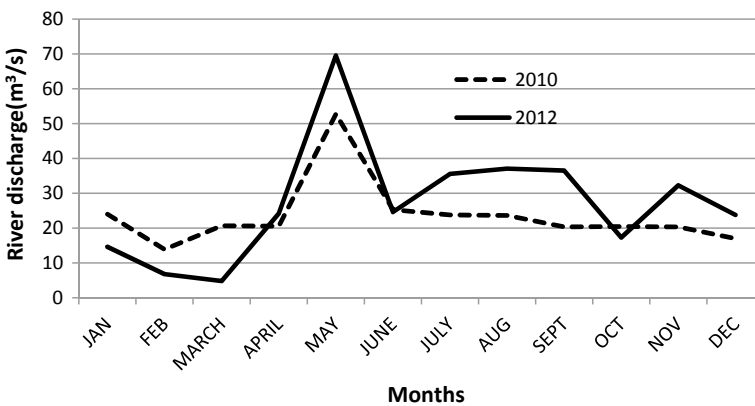


Fig. 4 Seasonal variations of Nyando River discharge between 2010 and 2012 based on records at RGS IGD03

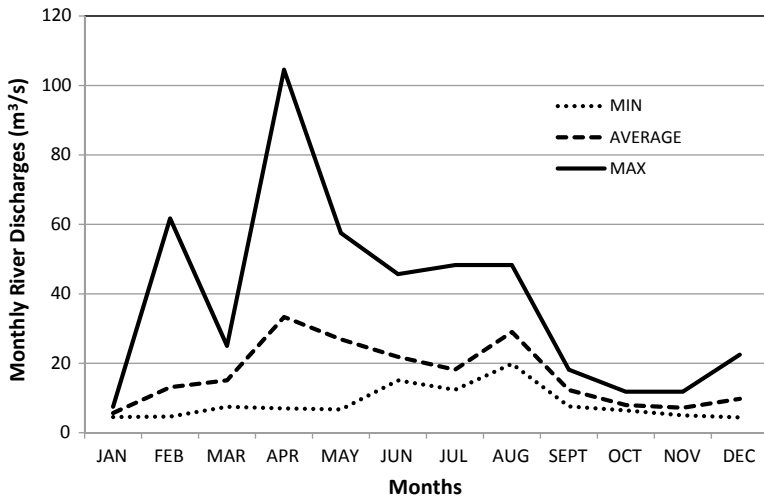


Fig. 5 Mean monthly river discharge in the Nyando River Basin at RGS 1GD4

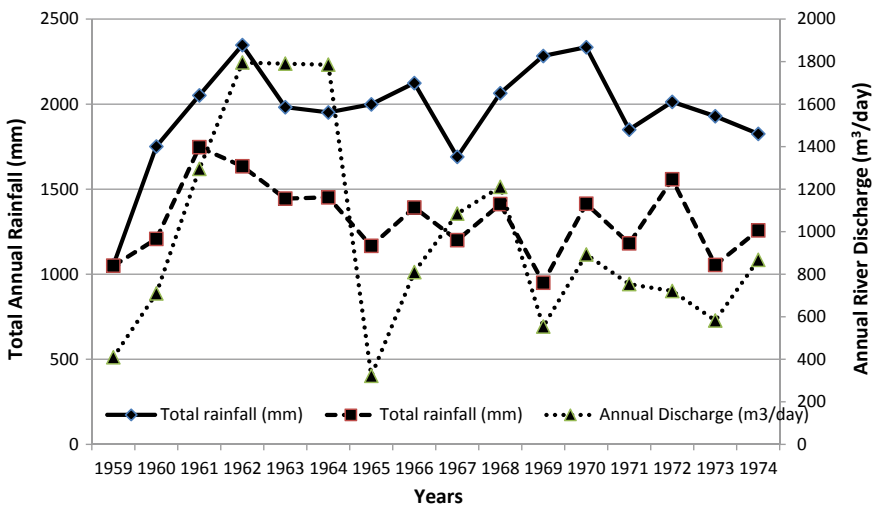


Fig. 6 Annual river discharge and total annual rainfall in the Nyando River Basin at Koru and Lumbwa Rainfall stations

in the Nandi Hills, and gradually decreases in the southeastern direction, bringing variations in discharge.

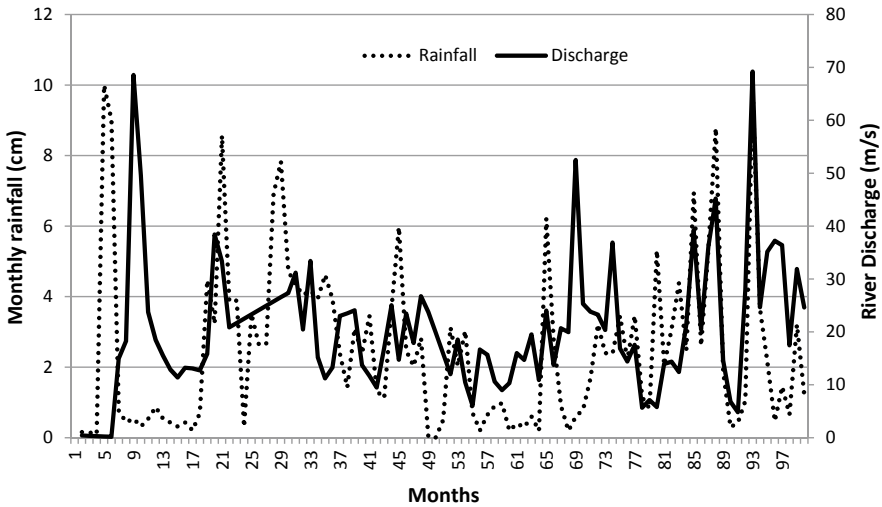


Fig. 7 Variations of rainfall and river discharge from 2003 to 2012 based on records obtained at RGS IGD03

4.2 Variability of River Discharges

River discharge in the Nyando River shows significant seasonal and inter-annual variability (Fig. 5, 6, and 7). High streamflows are experienced during the long rainy season (March–May) and also during the two short rainy seasons (August–September and October–December), as shown in Fig. 6. The highest streamflows are experienced during the long rainy season (April–May) and are of the order $969 \text{ m}^3/\text{s}$. Low streamflows in the dry period between December and February are on the order $7 \text{ m}^3/\text{s}$. Peak river discharges in the tributaries of the river are, however, much lower. The high inter-annual variation in river discharge is also discerned from records. For instance, the peak river discharge in May 2013 was $89 \text{ m}^3/\text{s}$, while in 2015, the river discharge was well below $50 \text{ m}^3/\text{s}$. However, in 2013, discharge was relatively higher, and greater than that experienced in other years.

Although there is an indication of an increase of rainfall, the corresponding increase in streamflow is not clear in the data, although previous studies have reported an increase (GOK 2009; Opere and Okello 2011a, b). High seasonal and inter-annual variability of streamflow is, however, evident in the data. This could be linked to climate change or to normal inter-annual rainfall variability (Figs. 7 and 9). Previous studies have indicated that the increasing variability of rainfall in the basin has made it difficult to predict high flood flows with certainty (ICRAF 2000 and 2002).

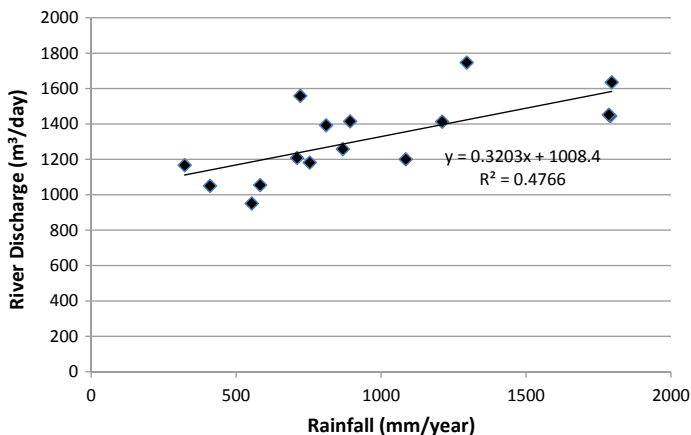


Fig. 8 Relationship between total annual rainfall and annual river discharge in the Nyando River, 1956–1974

4.3 Relationship Between Rainfall and River Discharge

The relationship between rainfall and river discharge in the Nyando River Basin is complex. Data for the period 1956–1974 yield a correlation coefficient r of 0.71 with a coefficient of determination R^2 of 0.51. The relationship between rainfall and streamflow in the basin established using 2003–2012 data yield a R^2 of 0.63 and correlation coefficient r of 0.80. These results could be interpreted to indicate that rainfall in the Nyando River Basin explains 51%–63% of the variation in river discharge. Therefore, in addition to rainfall, catchment characteristics could also be contributing to variation in river discharge. These catchment characteristics include land use, vegetation cover, and topography. The results also show that there exists a strong relationship between rainfall and river discharge in the Nyando Basin (Fig. 8). An increase in rainfall in the basin therefore leads to a corresponding increasing in river discharge.

4.4 River Discharge and Rainfall Deficits

Rainfall and river discharge deficits were computed as the difference between monthly values and long-term mean values. Figure 9 shows rainfall and river discharge deficit from 2003 to 2012 at RGS IGD03, which indicate that river discharge was above the long-term mean value 16 times. River discharge was also below the long-term mean value 16 times. However, the magnitude of above-average flows seems to be much higher than the below-average river discharge. Above-average flows normally last four to eight months, and below-average flows last about the same.

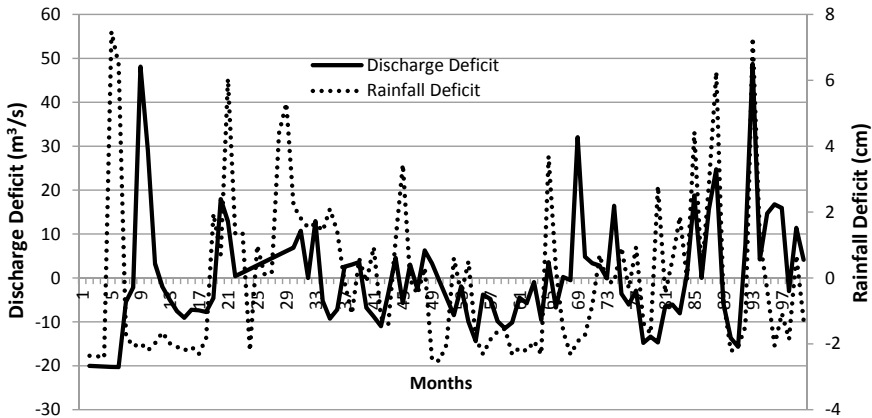


Fig. 9 Rainfall and river discharge deficit in the period 2003–2012 at RGS IGD03. The rainfall deficit was computed as the difference between monthly discharge and long-term mean discharge

The results also show that rainfall deficits are more dominant than the shortages associated with droughts. Positive deficits are associated with high rainfall and flooding. The duration of excess and shortages of rainfall are similar (Fig. 9). Results also show that periods of river discharge deficit correspond to those of rainfall deficits. Above-average river discharge occurs in periods of above-average rainfall. Results generally show that the occurrence of above-average rainfall in the Nyando River Basin is more dominant than the occurrence of below-average rainfall over the same period (2003–2012).

4.5 Catchment Characteristics and Flood Flows

Floods in the Nyando River Basin are normally associated with peak streamflows. Flooding is predominant in the lower parts of the basin, which are generally low-lying Kano plains. Figure 10 shows the flow duration curve of the Nyando River, which provides an important indication of the nature of the basin, including the frequency of occurrence of flow of a given magnitude. The curve indicates that the basin is highly degraded and experiences rapid hydrologic response. Also, most of the flows in the basin are low magnitude, with 95% of river discharges being on the order $3 \text{ m}^3/\text{s}$. In contrast, 50% of river discharges are on the order of $10 \text{ m}^3/\text{s}$. Streamflows that are greater than $100 \text{ m}^3/\text{s}$ are relatively infrequent as they occur less than 1.0% of the time. Therefore, high flood flows have a lower probability of occurrence in the Nyando Basin compared to other river basins in Africa. The magnitudes of 50- and 100-year floods were computed as $1135 \text{ m}^3/\text{s}$ and $1200 \text{ m}^3/\text{s}$, respectively. River discharge data for 1956–1974 for RGS IGD4 shows that the highest flood flows between 1961 and 1964 were $605 \text{ m}^3/\text{s}$ and $823 \text{ m}^3/\text{s}$, respectively. After 1964, there has continued to be

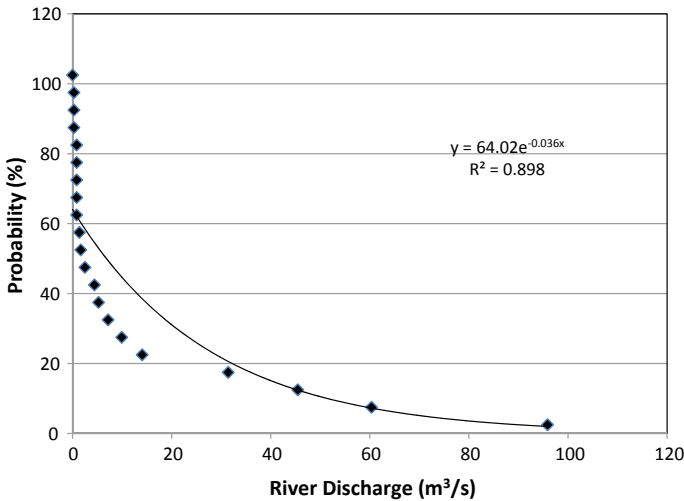


Fig. 10 Flow duration curve of the Nyando River

much lower annual peak river discharges, which in most cases are less than 300 m³/s. In fact, river discharge data showed a declining trend after 1964. In view of the lack of long-term river discharge data, it is not certain if this decrease can be attributed to climate change. It is important to note that in Kenya, rainfall amounts have generally been declining, as reflected by the growing frequency of droughts in most part of the country (ICRAF 2000 and 2002). Excess rainfall occurrences have been cyclical, as evidenced by El Niño episodes. It can therefore be argued that an increase in rainfall since the late 1970s, together with changes in catchment characteristics, has led to changes in the magnitude and duration of peak river discharges in the Nyando Basin.

4.6 River Discharge and Suspended Sediment Load

The Total Suspended Sediment Concentration (TSSC) in the Nyando River varies from 0.08 g/l to 0.66 g/l, with a mean TSSC of 0.44 g/l. There is a significant relationship between TSSC and river discharge, with a correlation coefficient r of 0.90. Therefore, as river discharge increases, the suspended sediment concentration in river water also increases. Variations in the concentration of suspended sediments in the Nyando River can be attributed largely to variations in river discharge. Low flow river discharge events are characterized by relatively low TSSC (<0.2 g/l), while high river discharges are characterized by TSSC > 0.40 g/l. The relatively high TSSC during high flows can be attributed to increased capacity of the river to transport a higher volume of sediment load capacity under high streamflow conditions.

The influence of rainfall on TSSC in the basin is complex, with a correlation coefficient r of 0.40. This means that in addition to river discharge, rainfall variability influences variations in TSSC in the Nyando River. The TSSC, and therefore water turbidity, increases as rainfall increases. The relationship between rainfall and TSSC is complicated by the availability of sediment within a given stage of the river during the rainy season. During early stages of the rainy season, low vegetation cover means that more loose sediment is available for transport by runoff into the river channel. In later stages, improvement of vegetation cover reduces sediment availability, leading to relatively low TSSC (and low turbidity), even when river discharge may be increasing. TSSC usually increases with river discharge because the increased flow generally results from direct surface runoff, which is associated with soil erosion. The supply of suspended sediments usually limits the variation of TSSC in the river.

The relationship between sediment load of the river and river discharge is strong, with a correlation coefficient r value of 0.99 and coefficient of determination R^2 of 0.98. This indicates a strong correlation between sediment load and river discharge. Increase in river discharge results in an increase in the total suspended sediment load. The computation of sediment load of the Nyando River is based on the mean and maximum river discharge of 20 m^3/s and 89 m^3/s , respectively. We used the mean TSSC of 0.4 g/l, which seems to be the long-term mean for the river. The results show that the mean sediment load is 691 tons/day, which translates to 252,288 tons/year. But the maximum sediment load is 3.07×10^3 tons/day, which translates to 1.12×10^6 tons/year. The sediment load of the Nyando River can therefore be assumed to vary from 0.25×10^6 to 1.12×10^6 tons/year. It should, however, be noted that during periods of extreme flood flows ($> 400 \text{ m}^3/\text{s}$), the sediment load of the river can be 100 times greater than average. During flood flows, the river discharges 22,809 tons of sediment per day, which for a period of one month is equivalent to 684,288 tons. Therefore, during periods of flood flows, the river can discharge 50% of the total annual sediment load in just one month. Based on the above data, we compute the sediment production rate in the basin to be in the range of 72–318 tons/ km^2/year . This is comparable to those reported for the Upper Tana Basin in the Central Kenya Highlands (Njogu et al. 2018; Mwendwa et al. 2019; Kitheka et al. 2019).

4.7 Analysis of Land-Use Change

There has been significant change in land use in the Nyando River Basin from the pre-colonial to post-colonial periods (Table 1). In the past 100 years, there have been major changes in land use and vegetation cover in the basin (see Swallow et al. 2002; Onyango 2003). The analysis of Landsat satellite images and aerial photographs for the period between 2003 and 2012 show that forest cover increased by 8.32% in this period due to reforestation activities in the basin. There was, however, in the same period a 100% increase in the area under human settlement. The wetlands area decreased by 82% in the lower parts of the basin in the same period due to conversion

Table 1 Land-use changes in the Nyando River Basin for the years 2000 and 2015

Land Cover	2000	2015	Change (Area)	Change (%)
Cropland (km ²)	2,760	2,727	-34	-1.2
Forestland (km ²)	669	725	56	8
Grassland (km ²)	156	162	6	3.8
Settlements (km ²)	2	4	2	100
Wetlands (km ²)	36	7	-29	-81.7

of wetlands for agricultural use (Fig. 11). There was also a slight decrease in the area under cultivation, which is attributed to the impacts of flooding in the lower parts of the basin.

Soil erosion is a serious problem in the Nyando River Basin. It is estimated that 60% of the basin is experiencing accelerated soil erosion, making it one of the major sources of sediment discharged into Lake Victoria (Swallow et al. 2002; Onyango 2003; Walsh et al. 2004). The high rates of soil erosion in the basin can be attributed to inappropriate land-use practices. Most cultivation is done on steep slopes on highly erodible soils without the application of appropriate soil erosion protection measures.

Most of the land-use/land cover changes observed in the basin can be attributed mainly to rapid population growth and expansion in the basin. For instance, the population in the basin has increased from fewer than 20,000 people in the 1960s to the 2009 population of more than 750,000 people (KNBS 2009). Although the population growth rate appears to be slowing, the relatively high population growth

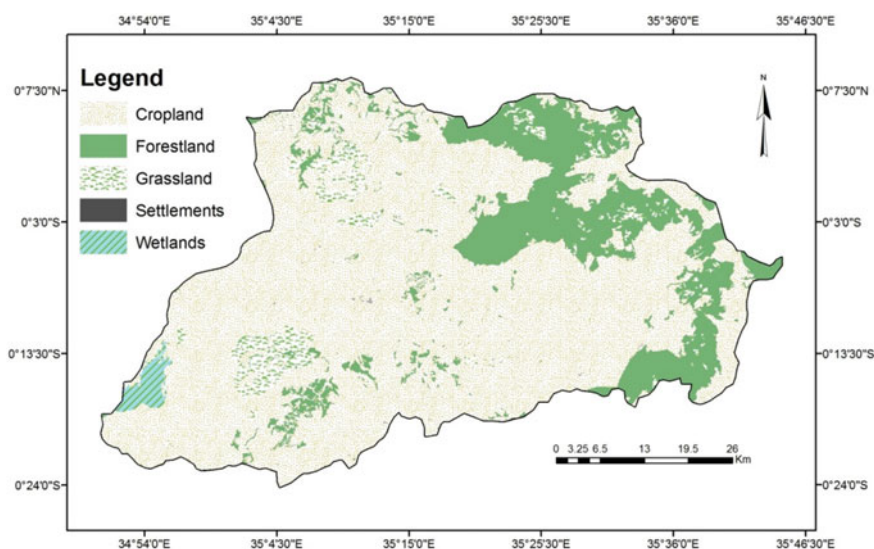


Fig. 11 Current land use in the Nyando River Basin. The proportion of land under cultivation in the basin is relatively high compared to other river basins in the Lake Victoria Basin

rate (3.7% per annum) in the last three to four decades led to an increase in the clearance of land for agriculture and settlements. More than 80% of the population in the basin depends on agriculture for its livelihood. Poverty in the basin is among the highest in Kenya, with 65% of the population in the basin living below the poverty line (KNBS 2009; ICRAF 2000). The majority of the people living in the basin are highly dependent on land for their daily sustenance. Therefore, without addressing poverty in the basin, it is unlikely that the current high rates of soil erosion and land degradation in the basin can be adequately addressed.

5 Discussion

5.1 *Relationship Between Rainfall and Discharge*

The influence of rainfall on Nyando River discharge is depicted in flow duration curves and also in hydrograph patterns. Data analyzed in this study reveal a rainfall trend with normal inter-annual variability, with no clear long-term trend that can be attributed to climate change. River discharges show normal year-to-year variation that is related to rainfall variability in the basin. Although the relationship between rainfall and river discharge is generally weakly correlated, rainfall variation explains only 50%–60% of the variation in river discharge. Therefore, there are parameters other than rainfall in the basin that contribute to streamflow variations. The imperfect correlation could also be due to the lag between rainfall and river discharge. Peak flow at the outlet of a river usually occurs some hours after peak rainfall in the highlands located 170 m away. When storms occur at the extreme end of the basin, it takes up to a day before this is reflected as peak flow in the lower parts of the basin. The strong relationship between rainfall and river discharge can also be attributed to land-use changes, which lead to rapid hydrologic response of the basin due to land degradation. The data show that Nyando River discharge tends to respond rapidly to rainfall in the basin, which is typical of degraded basins (cf. Hai et al. 2000). The occurrence of above-average rainfall in the Nyando River Basin is greater than the occurrence of below-average rainfall over the same period (2003–2012). However, the extent to which this can be attributed to climate change needs to be investigated further.

5.2 *Sediment Yield and Rainfall and Discharge*

There has been significant change in land use/land cover in the Nyando River Basin in the last 100 years. While there are year-to-year variations in land use in the basin, the overall trend is toward increased land degradation which can be attributed to rapid population growth and expansion (Oruma et al. 2017). There has also been

a massive increase in human settlement and cultivation on steep slopes without application of appropriate soil conservation measures, which accounts for the high rates of soil erosion in the basin (see also Walsh et al. 2004). Soil erosion in the basin is influenced by several factors, including topography, rainfall pattern, land-use type, degree of vegetation cover, and soil erodibility (cf. ICRAF 2000 and 2002; Swallow et al. 2002; Walsh et al. 2004). Soil erosion and resulting land degradation have cumulatively altered the hydrologic response of the basin such that streamflow responds quite rapidly to rainfall storms. The basin is characterized by relatively high rates of sediment load which are estimated to range between 252,288 tons/year and 1.12×10^6 tons/year (see also ICRAF (2000 and 2002). These results are consistent with those reported from other degraded river basins in the Kenya highlands (Oruma et al. 2017; Njogu et al. 2018; Mwendwa et al. 2019; Kitheka et al. 2019).

During flood periods, the sediment load of the Nyando River increases more than 100-fold, although this occurs for a relatively short period of less than one month. This study shows that during flood flows, the river discharges 684,288 tons of sediment into Lake Victoria, which means that during flood conditions, the river discharges almost 50% of its total annual sediment load in just one month. This indicates that the Nyando River discharges a high volume of sediment to Lake Victoria on an annual basis. There is a need to implement a long-term sediment load monitoring program in order to establish the significance of discharge contributions from other rivers to total river sediment load discharged into Lake Victoria (cf. Oruma et al. 2017). The entire basin is characterized by severe soil erosion and land degradation (ICRAF 2002).

There is a relationship between sediment transport and river discharge. An increase in river discharge results in an increase in TSSC and consequently an increased suspended sediment load. The TSSC usually increases with river discharge because the increased flow generally originates from direct surface runoff on degraded lands (cf. Hai et al. 2000). Because of significant inter-annual variations in rainfall that subsequently induce inter-annual variations in streamflow, it is expected that sediment yield will also exhibit significant inter-annual variation. There appears to be an increase in the degree of variability, including an increase in frequency and magnitude of extreme rainfall events and high streamflow in the basin. It is therefore expected that the variability of sediment yield will also increase. These variations may be a result of climate change and/or of normal climatic variation. Previous studies have shown that within the basin, most of the surface runoff is generated from degraded lands which are also the source areas of sediment transported by the river. Therefore, any serious soil conservation program must focus on reducing erosion of soil from degraded areas (cf. Swallow et al. 2002).

5.3 Flooding in the Lower Nyando Basin

Flooding in the Nyando River Basin is mainly limited to the lower parts of the Kano plains. Most floods occur during the long rainy season between March and May.

Three major flood events have occurred in the recent past: 1961/1964, 1997/1998, and 2003/2004. During floods, the entirety of the Kano Plains is usually inundated with water for a period of up to one month. Data show that since the 1961/1964 floods, subsequent floods in the plains have been of relatively lower magnitudes. There is, however, an indication that the frequency of occurrence of these low-magnitude floods has increased.

The data do not indicate clearly whether there is a long-term increase in streamflow that could be related to increasing rainfall (see also Opere and Okello 2011a, b). Although data for the period 2003–2012 show an increasing trend in streamflow, it declined in the period 1964–1974. This suggests that in addition to inter-annual variation in river discharges, there may also be inter-decadal variations in streamflow that could be explained by inter-decadal climatic variability. This requires further hydrological and climatological research. Regardless, it is significant that land-use/cover change has substantial effects on streamflow in the basin. While forest cover has been increasing slowly due to the implementation of reforestation programs in the basin, more must be done, as suggested by previous studies that have shown that increased forest cover in the basin results in decreased peak flood flows there (Opere and Okello 2011a, b).

Flooding in the Kano plains has both direct and indirect impacts, which can have positive and negative effects. Impact analysis based on various reports (see ICRAF 2002) shows that direct negative impacts of floods include water quality deterioration, habitat degradation or alteration, river channel modification, siltation of water bodies (dams, water pans, canals), destruction of fishing grounds, reduced fish catches, destruction of infrastructure (water supplies, roads, bridges), loss of human life, loss of livestock, creation of habitat for disease vectors, damage to farms, loss of crops, reduced crop production, interruption of education/school programs, destruction of property (e.g., houses, buildings and pit latrines), contamination of water supplies, lack of clean water and disruption of social and economic activity.

Indirect negative impacts include loss of income, unemployment, economic stagnation, waterborne disease, and other health impacts (diarrhea, cholera, malaria, typhoid, skin diseases, stress, and anxiety), increased incidence of livestock diseases, a decline in education performance, lack of economic diversification, lack of diversification of income, reduced human productivity, conflicts, increased rural-urban migration, increased dependency on donor assistance and grants, increased government expenditure (repairs, evacuation, health, relief), and degradation of recreation opportunities.

Positive impacts of flooding include recharge of groundwater aquifers, supply of fertile silt to the flood plains (including paddy fields), recharge of wetlands and riparian zones, increased nutrient supply to Lake Victoria, and regeneration of wetlands.

The overall adverse impact of flooding in the basin is increased poverty levels among the majority of the people living in the basin. More than 65% of the population there live below the poverty line (see also Swallow 2005).

6 Conclusions

The Nyando River Basin experiences significant seasonal and inter-annual variability in both rainfall and river discharge. There has been an increase in the variability of both rainfall and streamflow in the basin since 1970. However, it is difficult to fully attribute this variability to climate change due to lack of long-term data. It is possible that increased variability in streamflow is also due to increased degradation of the catchment areas and land-use change as a result of population increase. Because of land degradation, the basin is characterized by a relatively high sediment load. The lower parts of the basin also experience periodic flooding that impacts the socio-economy of local communities, including ecosystems in the basin. The overall impact of flooding has been increased poverty among the communities living in the lower parts of the basin. Without sustainable land management in the basin, climate change and land degradation will continue to reduce streamflow significantly, leading to major impacts on the livelihoods of the local communities. A comprehensive soil and water conservation program for the entire river basin is necessary in order to control soil erosion and reduce the high sediment load of the river.

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