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Valens Habineza & Dr. Pancras Ndokoye (PhD)

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Effects of Rapid Urbanization on the Hydrological Process of Nyabarongo River in Rwanda

[*1]Valens Habineza & [2]Dr. Pancras Ndokoye

[1]Department of Environmental Economics and Natural Resource Management, Faculty of Environmental and Development Studies, University of Lay Adventists of Kigali UNILAK, Kigali, Rwanda

[2]Department of Environmental Management and Renewable Energy, Faculty of Agriculture, Environmental Management and Renewable Energy, University of Technology and Arts of Byumba (UTAB), Byumba, Rwanda

***Email of the Corresponding Author: valensh6@gmail.com**

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Abstract

The rapid growth of cities, fueled by population growth and economic development activities, has resulted in significant changes in land use within the Nyabarongo River basin. This study measured changes in hydrological parameters, such as river discharge, that can be attributed to urban expansion. The study uses a combination of remote sensing data, meteorological data, Geographic Information Systems (GIS) tools, an Excel database, and the HEC HMS simulation model to analyze historical land use patterns and correlate them with observed hydrological changes over the last five years. The key findings show that the Nyabarongo River basin has experienced significant land use and land cover (LULC) changes over the last five years, most notably a 6.79% annual decrease in rangeland, which has resulted in an annual increase of 9.1% in agricultural land and 12.73% in built area. This shift, fueled by urbanization, has converted significant rangeland into impervious surfaces, altering hydrological processes by increasing runoff coefficients. In addition, the HEC HMS simulation revealed an average annual peak discharge increase of 1.61%. The linear regression model revealed a correlation coefficient (r) of 0.84 between LULC changes and river discharge, implying that the conversion of natural land and forests in the Nyabarongo catchment into built-up areas (impervious surface) increases Nyaborongo river discharge. This study aimed to contribute to a broader understanding of the environmental impacts of urbanisation in developing countries and provide a baseline for policymakers to establish a framework to balance urban development with ecological preservation.

Keywords: *Urbanization, Hydrological Process, Nyabarongo River, Rwanda*

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1.0 Introduction

Land use/land cover (LULC) changes caused by urbanization contribute to the transformation of open spaces (natural land) into impervious surfaces (Shukla et al., 2018). These changes have a significant impact on hydrological processes across multiple temporal and spatial scales (Chen et al., 2009). Changes in LULC have an impact on critical hydrological processes within a watershed, including infiltration, groundwater recharge, base flow, and surface runoff (Talib, 2015). As a result, flood frequency and intensity may vary (Chen et al., 2009). Urban development imposes the covering of natural ground with artificial surfaces, resulting in a significant increase in surface runoff when compared to infiltration and evapotranspiration (Gatwaza et al., 2016). Human activity in a watershed disrupts the hydrologic cycle. The presence of impermeable surfaces such as roofs and paved areas such as roads, driveways, and parking lots reduce water's ability to seep into or infiltrate the ground (Beckline & Yujun, 2014). The majority of land is impervious, which increases runoff while decreasing infiltration and lowering groundwater levels. Urbanization development is expected to have a number of effects, including reduced infiltration, baseflow, and lag times while increasing storm flow volumes, peak discharge, flood frequency, and surface runoff (Du et al., 2012).

(UN, 2022) Urbanization, combined with global population growth, is expected to result in an increase of 2.5 billion people living in cities by 2050. The majority of this increase, around 90 percent, is expected to occur in Asia and Africa. According to the National Institute for Statistics and Research (NISR, 2023), the majority of Rwanda's population lives in rural areas, accounting for 72.1% of the total population (9,545,149 people), while only 27.9% live in cities. Despite being one of the least urbanized countries, with an urban population of 27.7% in 2022, recent data show that certain areas of the country have experienced unusual climate variability over the last three decades. These irregularities include changes in rainfall frequency and intensity, as well as the occurrence of extreme weather conditions like heavy rain in the north and drought in the east and south (Gatwaza et al., 2016). Housing systems triggered by intensive precipitation are classified as one cause of flooding, erosion, and landslides affect the northern and western regions, including Kigali city.

1.1 Problem Statement

The Nyabarongo River, which is 351 km long, is Rwanda's primary source of the Nile River. It has the distinction of being the longest river in the country. The river's catchment area covers approximately 33% of Rwanda's surface and spans 24 districts. Rapid urbanization is encouraged in these districts, and (NISR, 2023) through RPHC5 ranked Kigali as the first city with 86.9% urban population, among others. Many researchers have used various techniques to model, evaluate, and forecast the effects of urbanization on the hydrological response of watersheds (Du et al., 2012). Given that hydrological processes vary with rapid urbanization, particularly infrastructure development, which is associated with a change in land morphology, it is critical to assess the effects of rapid urbanization on the Nyabarongo River. In addition, (Yifru et al., 2022), it is critical to investigate and consider the effects of urbanization on hydrological systems when developing land use plans in order to ensure the sustainability of future urban areas.

There is a direct link between population growth, urbanization, industrial development, and human activities that alter the natural environment. For example, urban land use changes have increased the frequency of flood disasters in the Taihu Lake watershed compared to the previous period

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(Chen et al., 2009). The acceleration of the surface hardening rate causes an increase in the impermeable rate, which reduces infiltration during rainfall events (Sun et al., 2022). Further, urbanization has an impact on ground water recharge because it shifts from pervious to impervious areas, causing it to decline. According to the United Nations (UN, 2022), more than half of the world's population lives in cities, with this figure expected to rise to nearly 70% by 2050. urbanization poses significant challenges for municipalities and city planners. According to NISR, the urban population in the Nile Nyabarongo Lower Catchment (NNYL) is 30.37%, while the urban population in the Nile Nyabarongo Upper Catchment (NNYU) is 11.96%, compared to 88.04% in the rural population. The City of Kigali and its surrounding urban centres of Gicumbi, Kamonyi, and Rwamagana had the highest population density. Gatwaza et al. (2016) identified rapid population growth and cropland expansion as primary water pollutants in Rwanda.

In 2015, more than half of the country's land was converted into agricultural land to meet food demands, resulting in widespread deforestation (Karamage et al., 2016. (Karamage et al., 2016) The Nyabarongo River is currently heavily polluted due to mining, encroachment, landslides, unsustainable agriculture, and domestic and industrial waste. Climate change, informal settlement, urbanization, and poor agricultural practices are the primary causes of flooding in Kigali (Icyimpaye, 2018). Urbanization has a variety of hydrologic consequences, including higher flood peaks, increased stream flashiness, and, in some cases, higher runoff volumes. It also contributes to increased stream loads of nutrients, salts, heavy metals, and sediments, as well as changes in urban stream temperature patterns (Sharp, 2010). As a result, assessing the effects of rapid urbanization on variations in rainfall-runoff, water level, and flood risk in the Nyabarongo River is of great concern. The study of the impact of urbanization on river networks and their storage capacity has become significant in order to efficiently advocate for environmental restoration and sustainable development (Yang et al., 2016).

1.2 Research Objectives

The general goal of this study is to evaluate an existing link between the rapid urbanization and the hydrological process of Nyabarongo river in Rwanda from 2017 to 2022 in order to take care of water resources conservation in Rwanda.

1.2.1 Specific Objectives

The following are specific objectives of the study:

i. To assess the urbanization growth in Nyabarongo catchment;
ii. To examine the hydrological process of Nyabarongo river; and
iii. To analyze the effects of urbanization on hydrological process of Nyabarongo river.

2.0 Materials and Methods

The Nyabarongo River has an estimated length of 315 km and drains a total area of 8496.02 km^2 equivalent to 32.25% of Rwanda national territory. The catchment is predominantly characterized by a mountainous terrain with an average slope of 30% and elevations ranging from 1341 m to 4491 m. The underlying geology comprises 59.3% Acrisols, 19.2% Regosols, 9.2% Andosols, 6.7% Ferralsols, 2.8% Cambisols, 0.8% Histosols, 0.4% Gleysols, and the remaining 1.5% is covered by water (RoR, 2018). This catchment area experiences a tropical climate with two distinct rainfall seasons annually, from March to May and September to December, an average temperature of 17°C, and an average precipitation of 1231 mm per year (REMA, et al., 2020).

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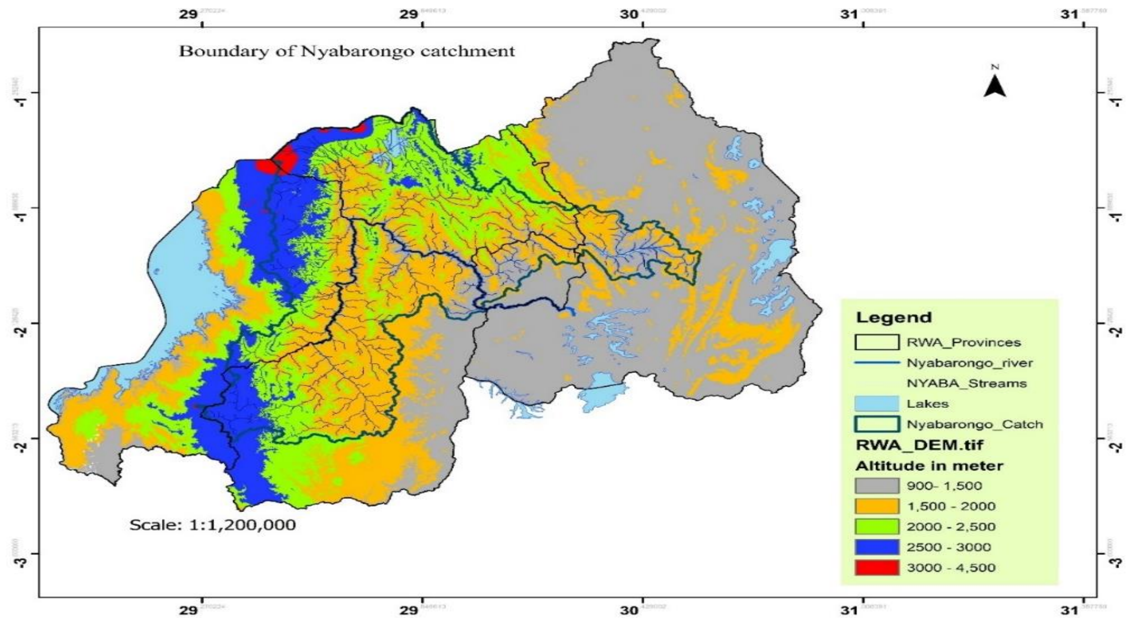

Figure 1: Geographical location of Nyabarongo catchment. Source ArcGIS map.

2.1 Materials

2.1.1 Techniques

a) The rainfall-runoff modeling was used to simulate the transformation of precipitation into runoff in a Nyabarongo watershed. It encompasses various processes such as infiltration, surface runoff, interflow, and baseflow to accurately predict streamflow behavior. The technique divided the watershed into hydrological response units (HRUs) and applying rainfall data along with watershed characteristics such as land use, soil properties, and topography to simulate the runoff response.

b) LULC change analysis was used to assess the transformation of landscapes over time. Initially, satellite imagery or aerial photographs are acquired for multiple time periods to capture land use/land cover (LULC) patterns. These images are then processed and classified using ArcGIS tools, such as supervised algorithms, to delineate different land cover types such as urban areas, agricultural land, forests, water bodies, etc.

c) Hydrological soil groups (HSG) analysis was applied to assess the runoff potential in Nyabarongo watershed. It ended up by grouping soil characteristics into groups.

e) Linear regression model, a fundamental statistical technique, aim to understand and quantify the relationships between multiple independent variables and a single dependent variable. In the context of studying the effects of rapid urbanization on hydrological processes of a river, a linear regression model could be employed to explore how various urbanization indicators influence hydrological variables within the river basin. The model estimates the coefficients for each independent variable, indicating the strength and direction of their relationship with the dependent variable.

2.1.2 Tools used

Software tools such as HEC-HMS, ArcGIS, and Excel databases played crucial roles in data analysis, modeling, and visualization for effects of rapid urbanization on the hydrological processes of a river: HEC-HMS 4.11 (Hydrologic Engineering Center - Hydrologic Modeling System) is utilized for hydrological modeling of Nyabarongo river, enabling simulating rainfall-runoff processes and assess the impacts of urbanization on river flow characteristics. With HEC-HMS, land use data, precipitation data, and other relevant parameters were entered in the system in order to simulate runoff generation, peak flows, and hydrograph responses to urbanization scenarios. ArcGIS 10.7.1, geographic information system software, facilitates the spatial analysis and visualization of urbanization patterns and their relationship with hydrological processes. The ArcGIS has been used to analyze land use changes, generate curve numbers, calculate impervious surface coverage, and generate spatial representations of hydrological variables within the river basin. In addition, Excel databases served as a valuable tool for managing and organizing large datasets, performing statistical analyses, and presenting research findings. Linear regression modeling was applied to explore the relationships between urbanization and hydrological variables.

2.1.3 Procedures

a) Data collection

The climatological data were collected via online and obtained from different institutions in charge of their management. Through technology advancement all required data have been downloaded from institutions websites. In addition, a desk review has examined the literature on effects of rapid urbanization on the hydrological process of a river, various published sources textbooks, articles, and government documents. The geospatial data and meteorological data were from United States Geological Survey (USGS), National Aeronautics and Space Administration (NASA), Rwanda water resource board (RwB), Rwanda Meteorologic Agency (RMA) and Environmental Systems Research Institution (ESRI).

b) Formation of Nyabarongo watershed subbasins

HEC-HMS tool was used to process the DEM of Nyabarongo watershed. The model created flow directions, main streams, subbasins and outlet figure 2. The subbasins were automatically formed as many as possible such that a regional change of peak discharge for subbasins can be easily assessed. Each subbasin has physical characteristics as shown in the Table 1 including subbasin area, slope, etc.

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Table 1: Characteristics of subbasins in Nyabarongo watershed

Name	Subbasin area (Km^2)	Longest flow path (Km)	Basin slope (m/m)	Basin Elevation (m)	Drainage density
Subbasin-1	1780.80	90.78	0.28	3060	0.03
Subbasin-10	628.33	64.20	0.26	848	0.03
Subbasin-11	7.08	6.01	0.42	833	0.43
Subbasin-12	123.93	26.71	0.29	731	0.11
Subbasin-13	72.68	18.26	0.49	1001	0.18
Subbasin-2	466.36	55.20	0.37	1271	0.02
Subbasin-3	902.62	71.59	0.31	1007	0.06
Subbasin-4	1651.60	113.74	0.24	929	0.04
Subbasin-5	202.32	29.29	0.21	513	0.11
Subbasin-6	504.82	45.31	0.37	1121	0.02
Subbasin-7	529.04	70.62	0.33	1413	0.03
Subbasin-8	405.50	56.44	0.39	1441	0.00
Subbasin-9	1138.50	95.61	0.30	1207	0.06

The generated Nyabarongo watershed subbasins include information on losses, unit hyetograph transforms and baseflow for each subbasin. The model produced also reaches which serve to link elements and store flood routing information before it discharges to the break point (sink) figure 2.

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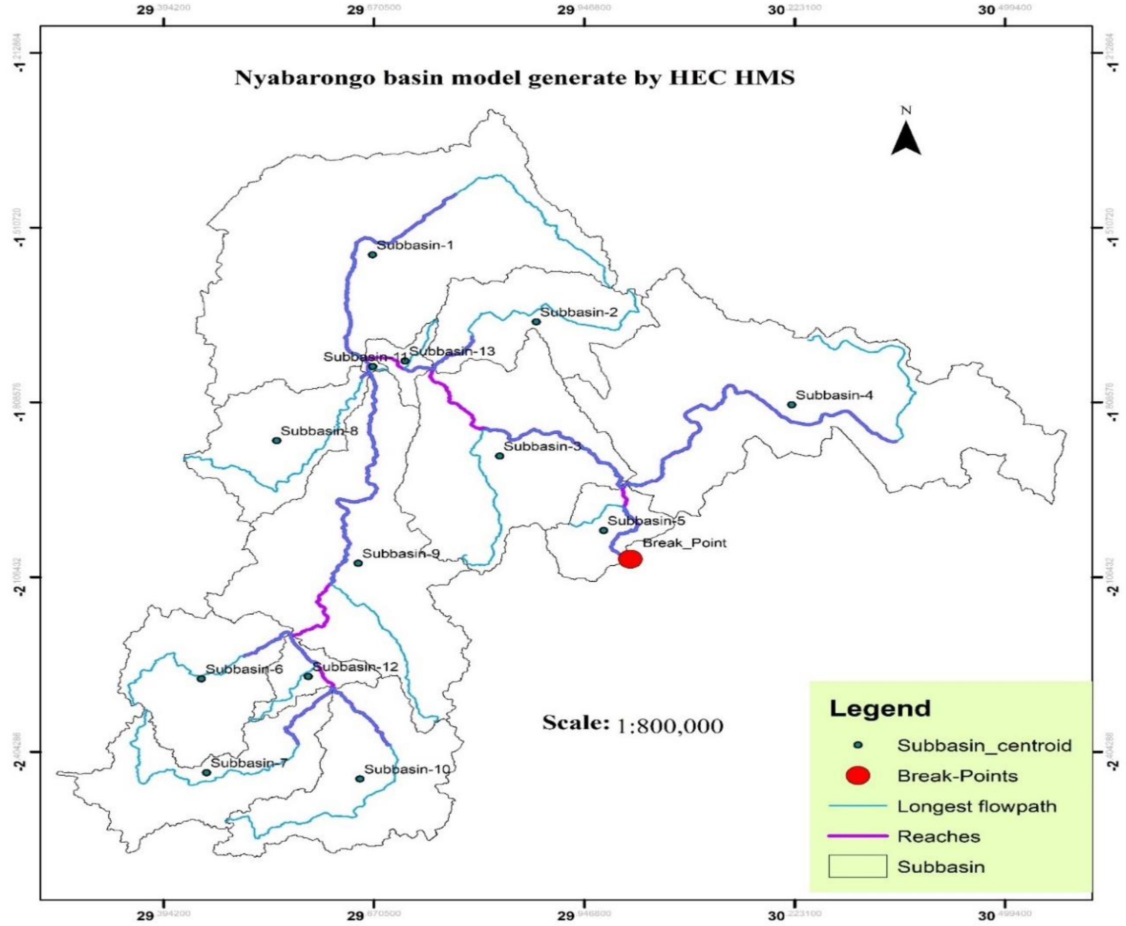

Figure 2: Subbasins in Nyabarongo watershed created by means of HEC HMS Model.

c) HEC-HMS inputs

Curve number (CN)

The Curve Number (CN) serves as an empirical factor utilized in hydrology for predicting direct runoff resulting from precipitation in a particular region. This parameter was formulated by the USDA Natural Resources Conservation Service and falls within the range of 30 to 100. The ArcGIS 10.7.1 software and Microsoft excel were applied to produce curve numbers. To achieve this, the widely utilized Soil Conservation Service (SCS) curve number method classifies soils into eight hydrological soil groups: A, A/D, B, B/D, C, C/D, D and D/D. Among these groups, A exhibits the most favorable infiltration characteristics, while D/d represents the least desirable. The LULC reclassification technique was applied to simply the complex mathematical matrices as follows:

Water and flooded vegetation were reclassified as simply water

Trees were reclassified as forest,

Rangeland, crops, bare land and clouds were reclassified as agricultural

Buit area was reclassified as built area

After LULC reclassification with ArcGIS, the mean curve numbers have generated as a result of combination of LULC and hydrological soil group. The matrix table helped to calculate the mean curve number of each subbasin. The precipitations entered in the model were average daily rainfall for 31 days of the month January 2017. The precipitations were constant whereas CNs, lag times were changing corresponding their respective years.

Table 2: Values of curve number after reclassification

LULC		Soil Hydrologic Group							
LCLU Description	LULC value	A	B	C	D	A/D	B/D	C/D	D/D
Water	1	100	100	100	100	100	100	100	100
Forest	2	30	58	71	78	54	68	75	78
Agricultural	3	67	77	83	87	77	82	85	87
Built area	4	57	72	81	86	72	79	84	84

The Figure 3 defines the three groups of hydrologic soil conditions encountered in Nyabarongo catchment. For a high runoff potential defines the soil which is dominated by clay while moderate high runoff potential the soil is dominated by sand. The soil generally has a reduced potential for runoff within a particular hydrologic soil group influenced by soil cover type and treatment.

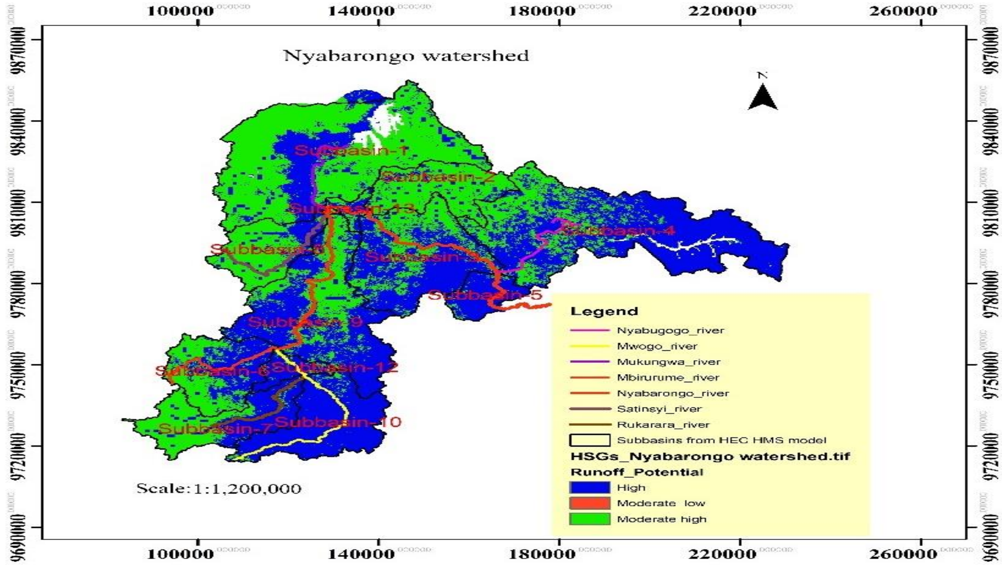

Figure 3: Characteristics of hydrological soil group in Nyabarongo watershed

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Time of concentration (Tc)

Time of concentration (Tc) is the time required for runoff to travel from the hydraulically furthest point in a body of water to the outlet. Time of concentration is usually applied only to surface runoff and can be calculated using several different methods and the Kirpich/Ramser formula is mostly used to calculate the time of concentration.

$$Tc = \frac{l^{0.8}(S+1)^{0.7}}{1140Y^{0.5}}$$

Where Tc is time for concentration in hour (h), length (l) is the flow length of stream in foot (ft), Y is average watershed land slope in % and S is the maximum potential retention in inch (in). The excel software was applied to calculate time of concentration for each subbasin in different periods.

Lag time

Lag time plays a crucial role in hydrological modeling as it signifies the delay between the center of the rainfall excess and the peak of the runoff hydrograph. It is a key factor in accurately predicting the timing of flood peaks in river basins and urban watersheds.

$$Lag = 0.6Tc$$

Where Tc is time for concentration in h and Lag time in minutes (m).

The excel software was applied to calculate time of concentration for each subbasin in different periods.

Precipitation/rainfall

The daily monthly average rainfalls have been computed for 45 stations within or near Nyabarongo catchment boundaries. The Figure 4 shows the distributions of rainfall stations in the study area.

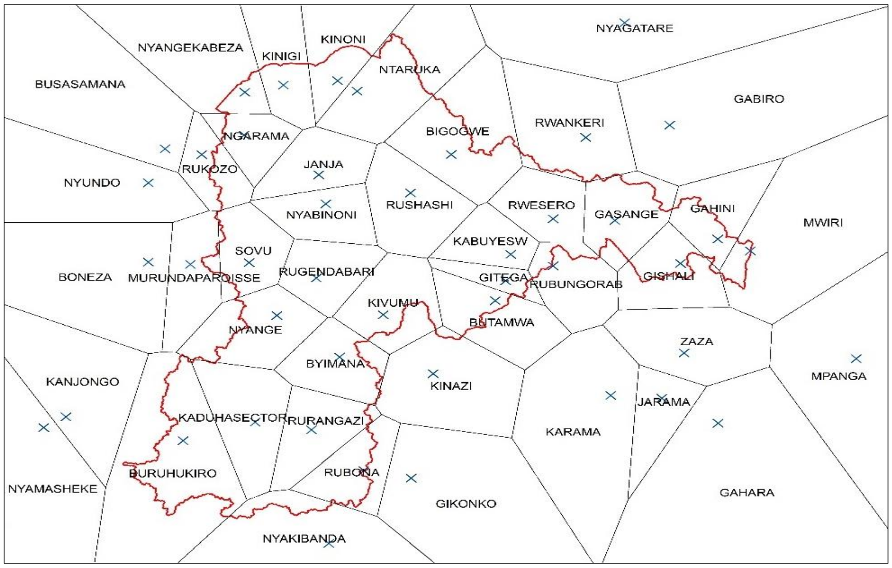

Figure 4: Rainfall stations distribution as by Thiessen polygon in Nyabarongo watershed

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d) Results analysis

With help of linear regression model (LRM), the correlations between urbanization growth factors and runoff (peak flows and river discharge) proportionality were deduced and conclusions were drawn accordingly.

3.0 Results and Analysis

3.1 Urbanization Assessment in Nyabarongo Watershed

Population growth

The population in Nyabarongo catchment was increasing with an average of urban population 25.46% versus 74.54% of rural population (RPHC5) compared to 17.97% versus 82.03% of rural of urban and population (RPHC4) respectively. From 2017 to 2022, the urban population has been increased by a total average rate of 1.85%. This created demand of human settlements and economic activities which result in expansion of district cities and creation of urban centers. This expansion of urban centers and district towns is associated to the increase of infrastructures such as industrial parks, paved roads, warehouse, commercial buildings, dwelling houses, etc.

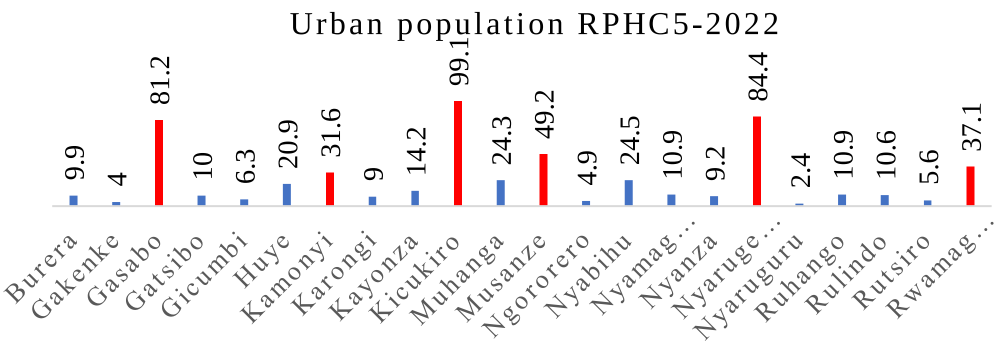

Figure 5: Urban population with districts in Nyabarongo catchment (NISR, RPHC 2022)

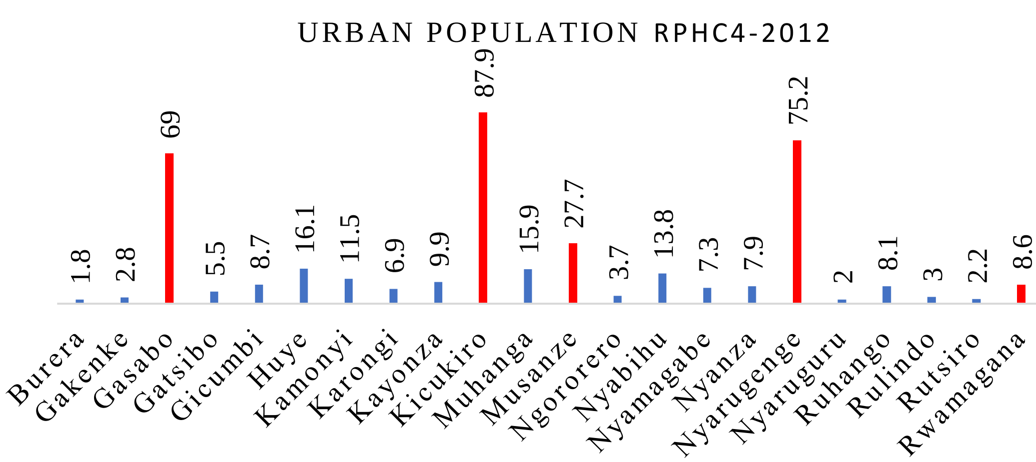

Figure 6: Urban population within districts in Nyabarongo catchment (NISR, RPHC)

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Expansion of built-up area

The population growth and economic activities are major cause of LULC change. In this study the assessment has tracked built-up area which is frequently utilized in urban planning and architecture to characterize locations where buildings or developments have gathered gradually, leading to a densely populated encompassing different elements of urban development, such as building density, land use intensity, and the general urban structure (Shukla et al., 2018).

By means of ArcGIS 10.7.1 software, images (range: 20217-2022) at a resolution of 10 m were processed to quantify land use/land cover (LULC) in Nyabarongo catchment and variations were tabulated in the table 2. The land use and land cover were classified into different classes as per global land use/land cover Sentinel-2. Those classes are water, trees, flooded vegetation, crops, bareland, built up are, clouds, snow/ice and rangeland.

Table 3: LULC classification in Nyarabongo catchment

	LULC area (km^2)							
Year/ Type	Bare ground	Built up area	Clouds	Crops	Flooded vegetation	Rangeland	Trees	Water
2017	2.64	823.83	235.16	1881.92	3.17	4060.46	1353.94	141.93
2018	0.88	1153.45	96.57	2452.11	4.09	2948.48	1704.56	142.91
2019	0.23	1328.71	16.21	2675.98	3.35	2636.76	1698.75	143.06
2020	0.41	1347.74	127.50	2737.67	4.24	2788.85	1349.21	147.43
2021	0.35	1375.11	309.38	2633.69	4.08	2626.32	1405.80	148.32
2022	0.64	1384.06	340.70	2749.62	3.36	2448.61	1429.34	146.71

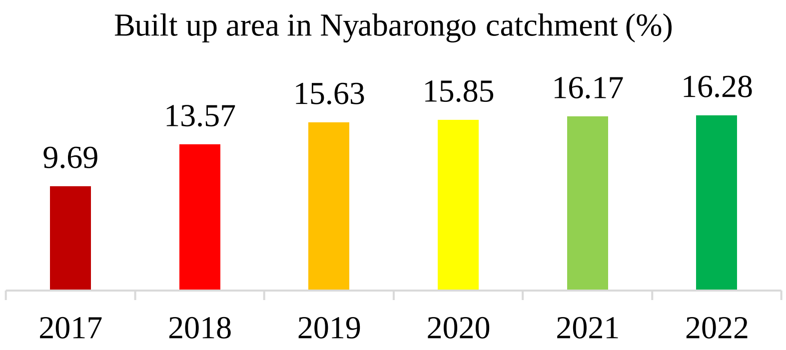

Figure 7: Change of built-up area from for a period of six year (2017-2022)

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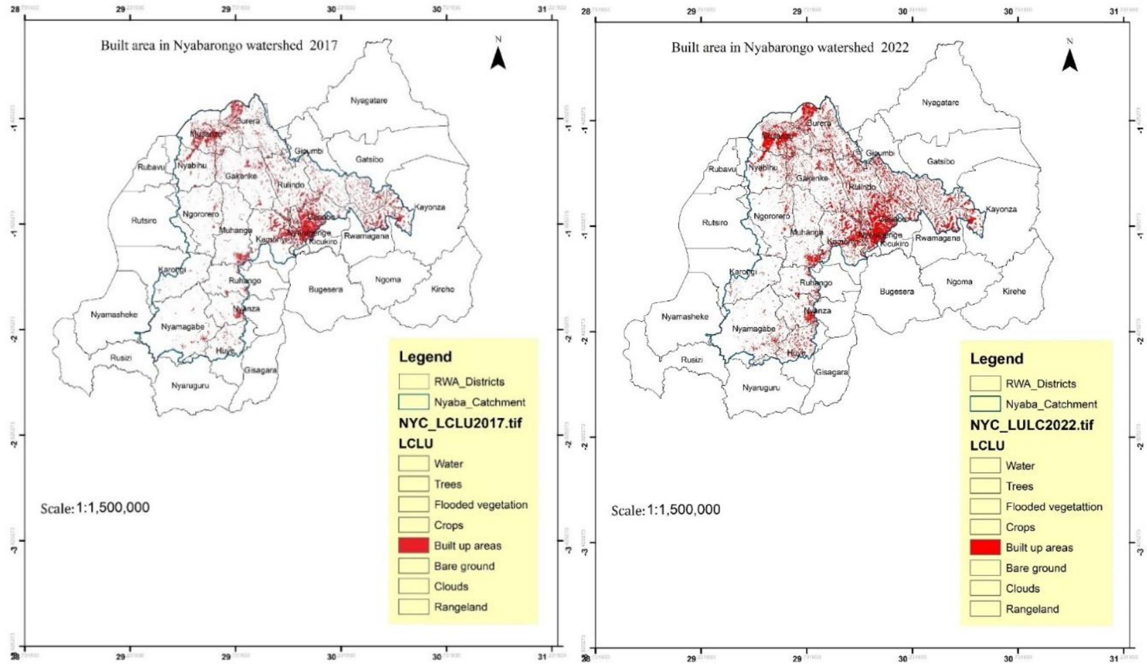

Figure 8: Built area in Nyabarongo watershed (Year 2017&2022)

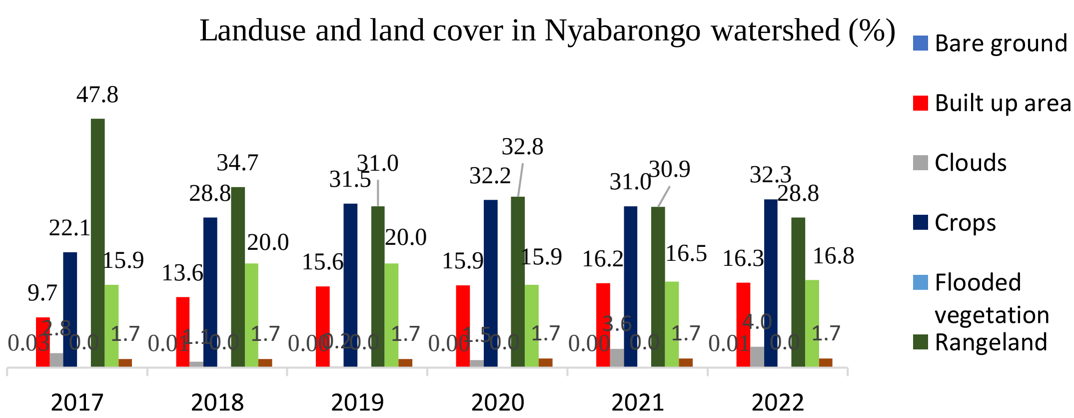

Figure 9: Change of LULC in Nyabarongo watershed from 2017 to 2022

The built-up area in Nyabarongo catchment is composed of different structures such as dwelling houses, paved roads, industrial buildings, commercial buildings, warehouse, social and religious buildings, etc. Districts of city of Kigali (mainly Nyarugenge, Gasabo) satellite cities (Rwamagana, Kamonyi, Rulindo), secondary cities (Musanze, Huye, Muhanga) and others such as Kayonza, Burera are located in zones where built-up area is increasing at high speed see the figure 8.

4.0 Descriptions the Hydrological Process of Nyabarongo River

Precipitation/rainfall

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In general, for a give watershed, the rainfall/precipitation is the input of hydrological process and discharge (runoff) is the output as shown on the figure 10. The daily monthly average rainfalls have been computed for 45 stations within or near Nyabarongo catchment boundaries figure 3.4. For a period of five years, the variation of annual average daily rainfall is not significant with a coefficient of variation equivalent to 15.2%. The reason is that the climate change is studied for a long period of time more than 10 years. But there is significant variation within a period of one year of monthly average daily rainfall where the maximum daily average rainfalls were observed in the months of January, February, March, April and May for each year see figure 10. The highest rainfall was found in April 2018 with an average of 8.2mm.

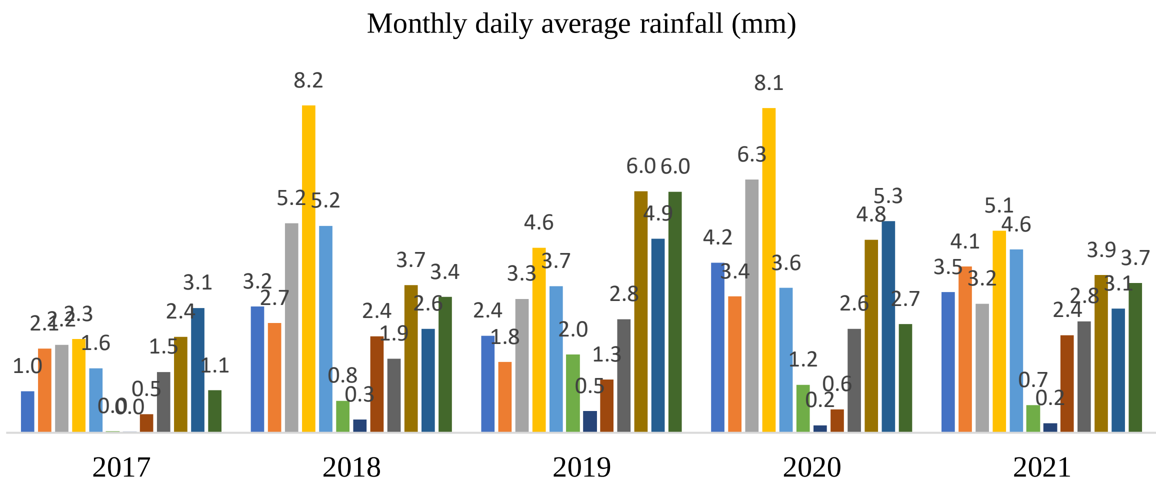

Figure 10: Monthly average daily rainfall for a period of five years (data source RMS)

Nyabarongo river discharge (peak discharge)

The HEC-HMS model computed peak discharges of Nyabarongo watershed. The values generated are shown in the figure 11. The main inputs were curve numbers, time of concentration, lag times and precipitations. This process combined Hydrological Soil Groups (HSGs) and LULC., rainfall data and Curve Numbers (CNs) to simulate peak discharge of Nyabarongo river.

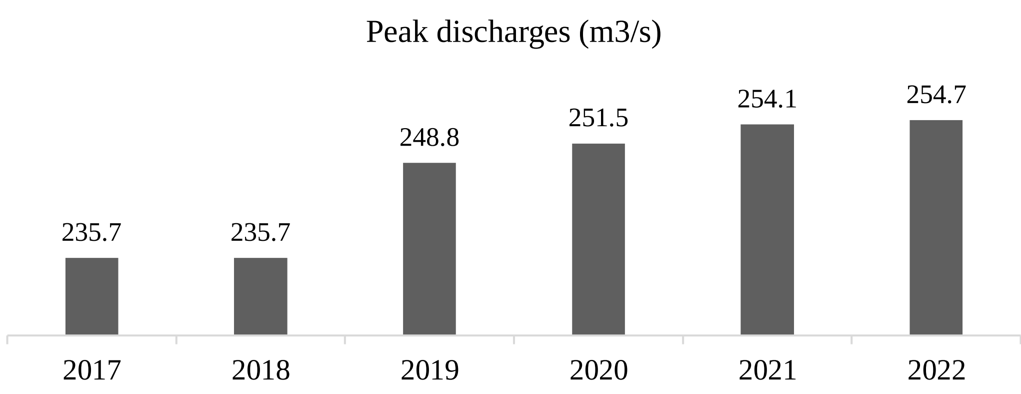

Figure 11: Chart showing variation of peak discharges in Nyabrongo river

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The results in figure 11 shows an increase of discharge over mentioned periods. The increase depends on the changer of land cover and correspond to increase of built area in Nyabarongo catchment figure 7.

4.1 Effects of Urbanization on Hydrological Process of Nyabarongo River

LULC changes due to urbanization are associated with changing natural land into impervious surface (Shukla et al., 2018). Land use change is a major force altering the hydrological processes over a range of temporal and spatial scales (Chen et al., 2009). It was found in the literature that the impervious surfaces (roofs, pavements) have greater coefficients of runoff 0.7 to 0.95 compared to other types of land use which vary between 0.1 to 0.4. Within a period of five (5) years, the figure 9 shows a change in LULC where the area of natural land (range land and forest) approximately equivalent to 1611.85 km^2 (18.96%) has converted into built area equivalent to 560.28 km^2 (34.76%) and agricultural area 867.7 km^2 (53.83%) which increased the mean curve number values. For an observed precipitation, an increment of curve number value affects the river runoff that to mean that there is an effect of rapid urbanization on Nyabarongo river discharge. The Nyabarongo catchment mean annual curve number and river discharge showed a positive correlation. A strong linear correlation has been found between the CN and peak discharge values with a period of five years. The LRM found coefficients of correlation (R) and determination (R^2) to be 0.84 and 0.75 respectively figure 12 which define a good model to be used in forecasting future hydrological parameters.

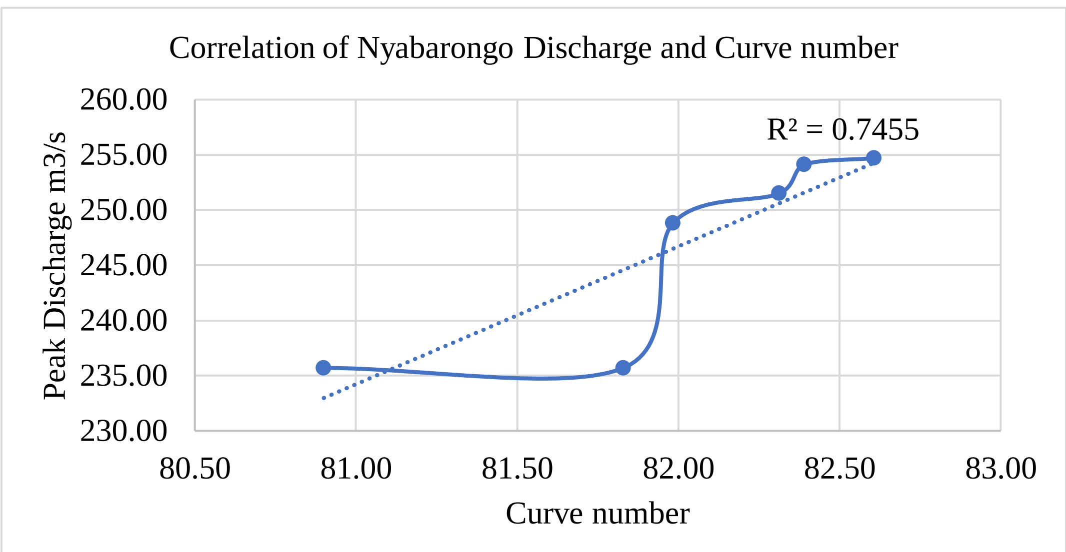

Figure 12: Statistical relationship of peak discharge and mean CN for Nyabarongo watershed.

5.0 Conclusion

This study of effects of rapid urbanization on the hydrological process of Nyabarongo river came up with detection of change in LULC which associated by conversion of natural land into built area and agricultural land. The rapid urbanization in Nyabarongo watershed was mainly observed in districts such as Nyarugenge, Gasabo, Musanze, Muhanga, Rwamagana, Kamonyi and Nyabihu with more 20% of urban population. The urban population growth contributed to the expansion of cities/towns followed by built area increase at a rate 9.1 % per year. The rainfall which is input of hydrological process can increase river runoff in case the impervious surfaces are dominant in the catchment. The simulation model resulted in increase of river discharge with a rate of 1.61% per year. The expansion of LULC in Nyabarongo catchment significantly contributes to the development of impervious surfaces and the analysis demonstrated a positive link between changes in land use and land cover (LULC) due urbanization and the Nyabarongo river runoff. The intense precipitation in different period increased river discharge which raised water levels and triggered floods in the Nyabarongo catchment. Therefore, green/smart cities, environmental protection enhancement need to be sustained by allowing green spaces, forests/wetland restoration which increase soil infiltration capacity.

6.0 Recommendations

With reference to the study findings, the Government of Rwanda with its economic partners are recommended to enhance the implementation of smart cities strategies and educate the citizen on green spaces development and Nyabarongo wetlands management which can minimize the excess storm water runoff as major factor which can trigger river flooding.

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