Morphodynamic Study of A River to Attenuate Flood Waves, Case Study of Nyabugogo River in Rwanda

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Abstract

Floods are the most frequent and damaging of all type of natural disasters and annually affect the lives of millions people all over the globe. The strategies (fight) against this natural disaster require knowledge mainly about river morphology, rainfall, land use, etc. The aim of this study is to assess different hydrological parameters that contribute to the Nyabugogo river flooding and evaluate whether geometric alteration would allow for a deduction in flood waves. Different approaches were used, firstly the analysis of hydro-meteorological data collected nearby the Nyabugogo catchment in 2011 and ArcGIS approaches to delineate, calculate the area, slope of the catchment and the length of the river. Thereafter, statistical and hydrological analyses of the existing and acquired data were done by the use of Unit hydrograph method and computer program like MS Excel and ArcMap. The Exner principle was applied to analyze the law of mass conservation for sediment, also named "sediment balance". Results showed that the total area of Nyabugogo catchment is 1,647 km^2 while the length of the Nyabugogo River is 42.69 km. This length allows the river to drain most of runoff in the catchment. The calculated discharge of the surface runoff due to a 3 hours storm of 13 April 2007 was 33.04 m^3/s. The knowledge of probability and frequency of high discharges and rainfall of Nyabugogo catchment that cause flooding helped to make strategies of flood management. Flooding occurred in Nyabugogo river and in its surrounding areas during rainy season are caused mainly by meanders at some Nyabugogo river reaches. These floods are not flash floods because they like to occur every year and for a long event. It is to say, response to flood hazards that can be undertaken in two ways; engineering approach, to control flooding such as elimination of meanders by a straight reaches of the river. In addition, regulatory approach like forestation of side hills where the agriculture is no longer practiced as well as creation of buffer zone along the Nyabugogo river channel, should be designed to decrease vulnerability to flooding.

Keywords: Morphodynamic, rainfall-runoff analysis, discharge, Nyabugogo River, catchment, Rwanda.

1. INTRODUCTION

In the past century the main streams of many rivers have been straightened and channelized worldwide for both hydraulic and socio-economic reasons such as, flood protection, land use changes, agriculture or spreading of infectious diseases (Brookes, 1988).

The understanding of river morphodynamics is functional to the correct management and prediction of important erosion and sedimentation processes involved in river activities, such as bank erosion, overflows, sediment balance in dam regulation, sediment wave propagation, interactions with anthropic structures (bridges, weirs), silting up of reservoirs, sediment mining, degradation/aggradation, plan form changes, regulation of equilibrium setting of slope and hydraulic geometry, and renaturalization issues.

As reported by Rwanda natural resources Ministry, Rwanda 's major problem with regard to the management and protection of Environment and Natural Resources is the imbalance between population and natural resources (land, water, environment, forests, minerals ...) which have been degraded over the decades. This imbalance is the cause of serious ecological and socio-economic problems which are likely to lead to an unprecedented disastrous situation if no adequate recovery measures are taken on time.

Rivers in nature display a variety of forms, from meandering to braiding, as a result of feedback processes among water flow, sediment transport, and vegetation. Many of these phenomena are relatively poorly understood, requiring the integration of mathematical, experimental and field techniques. The interaction of human activities with the environment can severely modify these processes often resulting in undesired and unexpected consequences at a variety of spatial and temporal scales. This leads to safety problems, environmental hazards, as well as to environmental degradation, with huge resources and economic losses for the whole society (Wiki, 2000). The study of river morphodynamics is therefore crucial to understand how these feedback processes operate in order to support decision-making at multiple levels that can promote economically effective and environmentally friendly river basin and land management.

Nowadays the Nyabugogo River is being flooded due to the interaction between human activity and urbanization observed through covering the land with impermeable surfaces which decreases the infiltration rate of the rain water**;** this increases the danger of sudden flooding of rivers in catchments (Karuhunga, 2011). The effects of these floods in Nyabugogo area, can be classified as follows: (1) Primary effects: Physical damage which can damage any type of structure including bridges, cars, buildings, sewerage systems, roadways and canals (Brammer, 1990); (2) Secondary effects: Water supplies, diseases, crops and flood supplies, tress, vegetation and transport; (3) Tertiary and long-term effects: Economic (Rozens, 1994).

The recent floods occurred in 2013 affected Nyabugogo wetland and caused loss of properties, loss of 4 human lives through a car which was drawn by the water and animal life and disruption of socio-economic activities, disruption of the business in the area and other issues related to transport facilities that at times became stand still (Munyaneza et al., 2013). Figure 1(a) shows the skeleton of car drawn by water and paid (the cost of) a loss of 4 people who were inside the car. Figure 1(b) shows the flood on the same day caused by the rise in water level in Nyabugogo river and backwater waves propagated towards the big channel drained water into Nyabugogo river from constructed urban areas of one side of road surrounding the Nyabugogo wetland. This caused also the rise of water level and channel banks were overtopped and flooded the road and buildings.

(a) *(b)*

Figure 1: Flooding occurred at Nyabugogo area on 23rd February 2013.

The measures have to be taken in order to attenuate and control floods in Nyabugogo catchment, especially in Nyabugogo wetland. Because once they happen, many different effects occur and they destroy some development activities. This study proposed the shortening some Nyabugogo river reaches to mitigate flood risk. Therefore, the aim of this paper is to contribute to the mitigation of flood in Nyabugogo wetland by proposing the morphological response caused by the shortening of Nyabugogo river reaches which, if implemented, can attenuate flood waves in the area.

2. STUDY AREA

The Nyabugogo wetland is located between 1354 m and 2,278 m above sea level and between $1^0$94'S and $30^0$04'E. The wetland drains a total area of 1,647 km^2 (Fig. 2). Nyabugogo wetland is located within the Nyabugogo catchment and it covers both rural and urban areas including the city of Kigali, the capital city of Rwanda (Munyaneza et al., 2013).

Nyabugogo wetland cuts across two districts Nyarugenge and Gasabo with an estimated population of 825,767 inhabitants (NISR, 2012). The wetland is part of the Nyabugogo catchment which cuts across Eastern Province (Kayonza, Rwamagana, and Gatsibo districts), and Northern Province Gicumbi and Rulindo and other districts of Kigali city such as Kicukiro, Nyarugenge, and Gasabo districts where the current study area is located. Its estimated population is about 1,135,428 inhabitants (NISR, 2012).

The Nyabugogo river, the main river crossing the wetland, has a total length of 42.69 km. This river has many tributaries such as Mwange, Rusine and Marenge river on its upstream portion. It is also fed up other rivers from the urbanized part of Kigali, like Rwanzekuma, Ruganwa, Mpazi, and Yanze River (Munyaneza et al., 2013).

The major land use activity in the catchment is agriculture that occupies about 897 km^2 (about 54%) of the catchment. Its climate is mostly of temperature ranging between 16°C and 23°C depending on the altitude of the area (Nhapi et al., 2011).

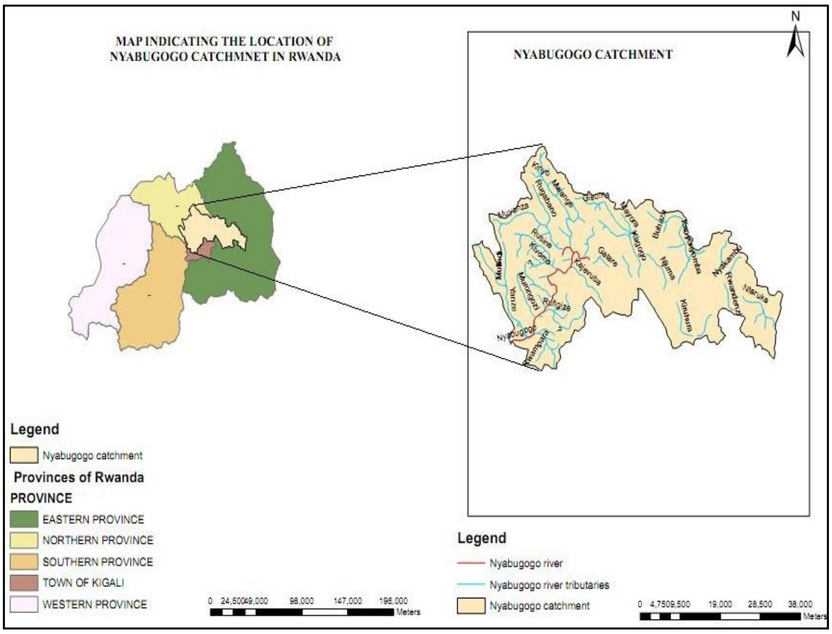

Figure 2: Location of Nyabugogo catchment in the Rwanda Administrative map.

3. METERIAL AND METHODS

3.1 Meteorological Data Collection

In this study, it was considered only one meteorological station of Kigali International Airport (located around southern part of the Nyabugogo wetland: lat: -01°58’, longitude: 30^{o}08’, and Altitude: 1,490 m a.s.l with the records rainfall data for 20 years (1993-2012). We analyzed and computed the mean atmospheric temperature which varies with time but normally between 19°C and 21°C. There are 15 rainfall stations in and around the Nyabugogo catchment. However, since after the genocide of 1994, meteorological data have not been recorded in almost all stations except at Kigali Airport Station which was used in this study as recorded by Rwanda Meteorological Agency.

3.2 Catchment Delineation

The Nyabugogo catchment was delineated from a Digital Elevation Model (DEM) in ArcGIS environment where Geographic Information Systems (GIS) technology was used to extract various information from the satellite images by computing the flow direction and using it in the catchment function. The catchment or watershed function used a raster of flow direction to determine the contributing area.

3.3 Estimating Effective Rainfall

The surface runoff in m^3 divided by the catchment area gives the effective precipitation ($\boldsymbol{P_e}$). The part of the average rainfall $\boldsymbol{P}$ that does not belong to the fast runoff component (the surface hydrograph) is known as the losses, thus $Losses = P - P_e$ where $\boldsymbol{P}$ is the average rainfall. The precipitation that caused the surface hydrograph fell in the period 01-08 April 1979. The daily rainfall data are available in Kigali station, nearest station of Nyabugogo catchment.

3.4 Runoff In The Nyabugogo Catchment

The runoff in Nyabugogo catchment was analyzed and estimated using the Unit hydrograph method. The theory of the unit hydrograph was introduced by Sherman in 1932. The method is based on the assumption that the physical characteristics within a river basin (such as slope, size, drainage network, etc.) do not change significantly, and consequently there should be a great similarity in the shape of the hydrographs resulting from similar high intensity rainfalls. The unit hydrograph is defined as the runoff of a catchment to a unit depth of effective rainfall (e.g. 1 mm) falling uniformly in space and time during a period *T* (minute, hour, day). It should be noted that the intensity of the rainfall during this period *T* is equal to 1/*T* in order to obtain unit depth (De Laat and Savenije, 2002).

Certain limitations are inherent in the unit hydrograph theory. The runoff hydrograph reflects the combined effects of rainfall factors, loss factors and physiographic factors. The design storm continuing for several unit periods may not have the same areal distribution for each time increment. Storm movements also affect the proportions of the unit hydrograph if the basin is large. Hence, the unit hydrograph cannot be applied for basins larger than 5,000 km^2 (Raghunath, 2006). For basins larger than 5,000 km^2, unit hydrographs for the principal sub-areas or sub-basins are developed and the hydrographs of runoff determined for each sub-area. These hydrographs are then combined, through flood routing procedure, to get the resulting hydrograph at the required section (Raghunath, 2006).

In the Nyabugogo catchment, the unit storm period is chosen based on the long duration of rainfall. In April and November of almost each year, the rainfall duration is over 4 days. With this unit storm period, the shape of the hydrograph is not significantly affected by changes in the time distribution of the excess rainfall over this unit storm period. This means that equal depths of excess rainfall with different time-intensity patterns produce hydrographs of direct runoff which are the same when the duration of this excess rainfall is equal to or shorter than the unit storm period.

The unit hydrograph theory is based on the following assumptions (De Laat and Savenije, 2002):

- The rainfall-runoff system is linear,
- The principle of superposition applies,
- Time-invariance. This means that the unit hydrograph does not change with time.

Consider a rain storm lasting three time steps (say days) for which the effective rainfall is given by P1, P2 and P3. The unit hydrograph consists of 4 ordinates, U1, U2, U3 and U4. The convolution procedure may be written as follows:

$$Q_1 = P_1U_1 \qquad \text{Eq.3-1}$$

$$Q_2 = P_2U_1 + P_1U_2 \qquad \text{Eq. 3-2}$$

$$Q_3 = P_3U_1 + P_2U +_2 P_1U_3 \qquad \text{Eq.3-3}$$

$$Q_4 = 0 + P_3U_2 + P_2U3 + P_1U_4 \qquad \text{Eq.3-4}$$

$$Q_5 = 0 + 0 + P_3U_3 + P_2U_4 \qquad \text{Eq.3-5}$$

$$Q_6 = 0 + 0 + 0 + P_3U_4 \qquad \text{Eq.3-6}$$

Since $\sum U_i = 1$, it follows that $\sum Q_i = \sum P_i$, thus the total of effective rainfall equals the surface runoff.

The set of equations shows that if M is the total number of rainfall ordinates and J the length of the unit hydrograph, the total number of runoff ordinates N is found from: $N = M + j - 1$ Eq. 3-7

The general expression for the set of equations may be written as: $Q_n = \sum_{i=1}^{n} U_i P_{n-(i-1)}$ Eq.3-8

Where $U_i = 0$ for $i \succ J$ and $P_i = 0$ for $i \succ M$

The set of equations may also be written in matrix form:

$$\begin{pmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \\ Q_5 \\ Q_6 \end{pmatrix} = \begin{pmatrix} P_1 & 0 & 0 & 0 \\ P_2 & P_1 & 0 & 0 \\ P_3 & P_2 & P_1 & 0 \\ 0 & P_3 & P_2 & P_1 \\ 0 & 0 & P_3 & P_2 \\ 0 & 0 & 0 & P_3 \end{pmatrix} x \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{pmatrix}$$ Eq. 3-8

Or

$$Q = P\,U$$ Eq.3-9

From which **U** could be solved as QP^{-1}. However, the inverse of matrix P can only be obtained if P is a square matrix. Multiplying both sides of equation Eq.4 by the transpose P^T yields a square matrix $(P^T P)$ for which the inverse exists. Hence $P^T Q = P^T PU$ Eq. 3-10

And the unknown vector U is found from $U = (P^T P)^{-1} P^T Q$ Eq. 3- 11

The matrix inversion method is one of the methods to solve the unit Hydrograph from a set of rainfall-runoff data (De Laat and Savenije, 2002).

3.5 Identification of flooding areas

The flooding areas were identified in Nyabugogo wetland and in downstream of this wetland. Based on flood level distribution, Munyaneza et al., (2013) has divided the flooding areas into 3 zones. The first zone is in the southwest which lies near the confluence of the Yanze and Nyabugogo Rivers. The second zone is located near the Kiruhura market, in downstream of the bridge joining Gatsata zone and Nyabugogo zone. The buildings obstruct the water ways and delay or hold back water flow. The third zone (north-east) is located in Nyabugogo wetland, upstream of the aforementioned bridge. This zone is the one which is very constraint to the road and buildings infrastructures. During flooding in this third zone, the backwater waves stop the inlets from urbanized areas on the side of Nyabugogo and water level rises and water obstructs the traffic. This zone damages the road surrounding Nyabugogo wetland. This study is specifically based in this third zone and will be generalized for remaining zones.

3.6 River Discharge Measurement

Series of data river discharges were measured at the station of Nemba which is at outlet of Nyabugogo catchment, from May 1972 up to May 2012. These data are daily discharge. The hydrograph developed from these data will be compared to hydrograph drawn from rational method.

3.7 Estimation of Base Flow

The period 1 March -10 June of almost every year is normally the period of rainfall in Rwanda. The dashed line is base flow separation line joining the rise point of ground water level and ground water depletion. Depletion starts after a dry period when the contribution of the fast runoff component has ceased and ends when the next rainstorm causes surface runoff. This rainfall hydrograph of Nyabugogo river in the period aforementioned will help to estimate the base flow. From this hydrograph the base flow is estimated at 9 m^3/s (Fig. 3).

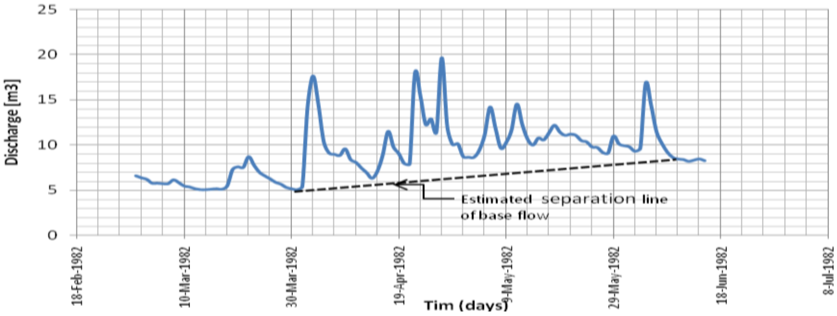

Figure 3: Stream flow hydrograph of Nyabugogo river

3.7.1. Land cover and land use information

The Nyabugogo catchment is composed of rural areas, urban areas and wetland. The complicity of this catchment complicates the hydrology analysis of this catchment such as runoff and infiltration capacity of the soil. In recent years, some areas of the catchment were subjected to the removal of the vegetation and soil, grading the land surface, and constructing paved surfaces, drainage networks which increased runoff to streams from rainfall. The information about land use in Nyabugogo catchment was obtained from shape files delivered by Rwanda Natural Resources Authority (RNRA).

3.8 Morphodymics of Nyabugogo River

The plan form of the Nyabugogo river was obtained using the Kigali aerial photo from the RNRA. The photo shows that the river is meandering on some reaches. The water delays in meandering reaches, because of long distances to cover, low velocity due to gentle slope, etc. Also, water in a natural river will have a slower velocity because the course of the river is altered (Uwurukundo, 2012). Because of some factors stated above, floods occur most of time, during rainy season in Nyabugogo river, especially in Nyabugogo wetland (Munyaneza et al., 2013).

3.8.1. The exner principle

To shorten some reaches of Nyabugogo close to the areas where floods occurred frequently, the Exner principle was applied to evaluate the immediate effects of interventions at the reach scale (Exner, 1925). The principle is formulated by analyzing the law of mass conservation for sediment, also named “sediment balance”. The analysis considers a small control volume between two river cross-section and having unit width (i.e. 1m). This control includes the flowing water and the active part of the river bed. It is assumed that Froude number is below 0.8, in which case the bed level changes are relatively slow, and that the sediment is transported by the flowing water as bed load mainly or that suspended load adapts to changes of flow conditions within a short distance. In this case the transport of sediment can be assumed to respond almost immediately to the changes of flow velocity. This means that the sediment transport can be derived using a sediment transport capacity formula. If the suspended load has a relatively long adaptation length, it has a retarded response to changes of flow velocity, which makes that the local sediment transport cannot be equated to the local transport capacity. It is also assumed that the conditions for sediment transport are well above the threshold for initiation of motion (Crosato, 2010).

3.8.2. Assessment of long-term response of sand-bed rivers

According to this methodology, the long-term morphological response is represented by the new morphodynamic equilibrium that the river attains a long time after the intervention/event. This new equilibrium is characterized by different longitudinal slope, water depth, and channel width and sediment size. The methodology focuses on the natural changes in longitudinal slope and water depth (Crosato, 2010).

If a river reach adjusts its slope and water depth, the changes affect the upstream and downstream reaches, with long-term consequences for the structures along the river, flood and ground water levels also far from the intervention. The new reach scale equilibrium is broken when another intervention or natural event takes place.
In general, the assessment of the long term river response is described by the difference between the final river configuration and the river configuration before the intervention. The following notation is adopted: the conditions of equilibrium up to the intervention, initial state, are distinguished by the subscript “0”, which stands for *t=0 (with t =time),* where as the conditions of equilibrium after intervention, final state, are distinguished by the subscript “∞”, which stands for $t = \infty$.

As a general rule, morphodynamic equilibrium is reached if the sediment transport capacity is everywhere equal to the sediment input and output (no on-going accumulation of sediment and no erosive trends). If an intervention changes the sediment input, the new equilibrium is reached when, after slow natural morphological changes involving longitudinal slope and water depth, the sediment transport capacity has become equal to the new sediment input rate. If an intervention changes the sediment transport capacity, for instant by changing the water discharge, the new morphodynamic equilibrium is reached when the river reach has stored the initial sediment transport capacity, i.e. the original value of the flow velocity, but in the final state with a different value of the discharge.

3.8.3. Morphological response caused by the shortening of river reach

The shortening of river reach is carried out for several reasons, mainly to improve navigation and to mitigate flooding risk. It is assumed that the new channel has the same width, B, as the original river channel. The initial water depth (design water depth) is equal to the normal water depth considering the initial slope of the shortened part (higher than in the original channel). The sediment forming the bed of the new channel is assumed to be the same as the one in the old channel (Crosato, 2010).

4 RESULTS AND DISCUSSION

4.1 Hydro-Meteorological Results

4.1.1Precipitation in the Nyabugogo catchment

The rainfall data recorded from Kigali International Airport (Kanombe station) located near Nyabugogo catchment was used to estimate average monthly rainfall. This catchment receives a high intensity of rainfall during the long rain seasons, as described by Figure 4. It shows the mean monthly rainfall in the Nyabugogo wetland; where the maximum rainfall was found in April 132.7 mm, and the minimum in July 13.8 mm. The total monthly average rainfall was found to be 80.6 mm and the annually rainfall average is 966.9 mm.

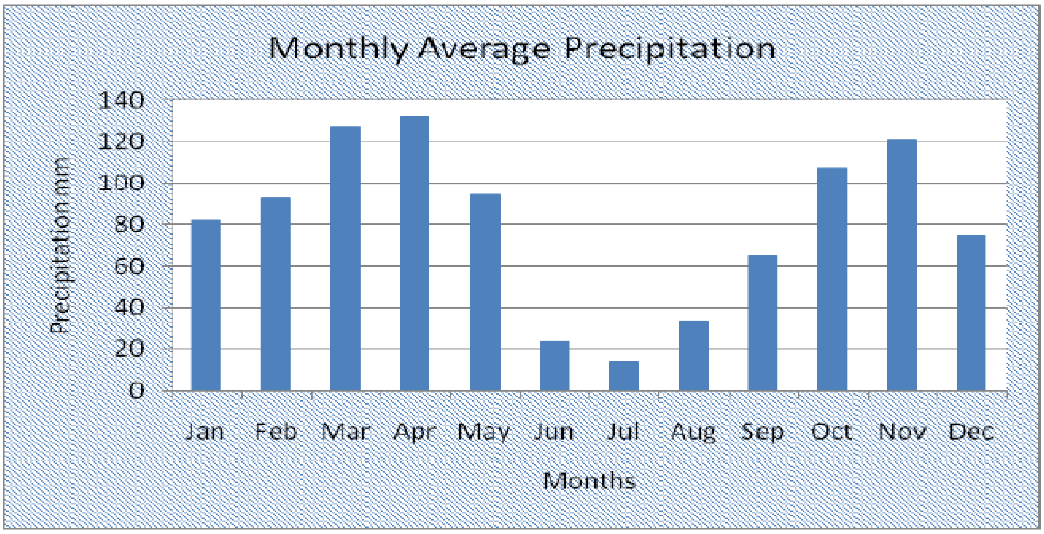

Figure 4: Monthly average precipitation of 20 years from 1993 to 2012 (Kagabo, 2013) in Nyabugogo catchment.

The calculated area of the Nyabugogo Catchment from ArcGis was 1647 km^2. Such an area has a direct significant impact on runoff generation directing to Nyabugogo River, after the soil becomes saturated the rate of infiltration decreases and the runoff conversely increases. It is obvious that the size of the catchment is an important watershed characteristic affecting runoff which influences river flooding. Even with the same amount of precipitation, river flooding most luckely happens in a large catchment than in a small catchment because the larger the contributing drainage area the more the river will be subjected to flooding.

4.1.2. Land use in Nyabugogo catchment

The land use of the Nyabugogo catchment was found to be predominantly of a combination of rural areas where there are rain-fed herbaceous crop and a Combination of Shrub Plantation and Rain-fed Herbaceous Crop, and urban areas where most areas are covered by the buildings and infrastructures such as roads, drainage channels, etc. Figure 5 shows the land cover map in Nyabugogo river in 2013.

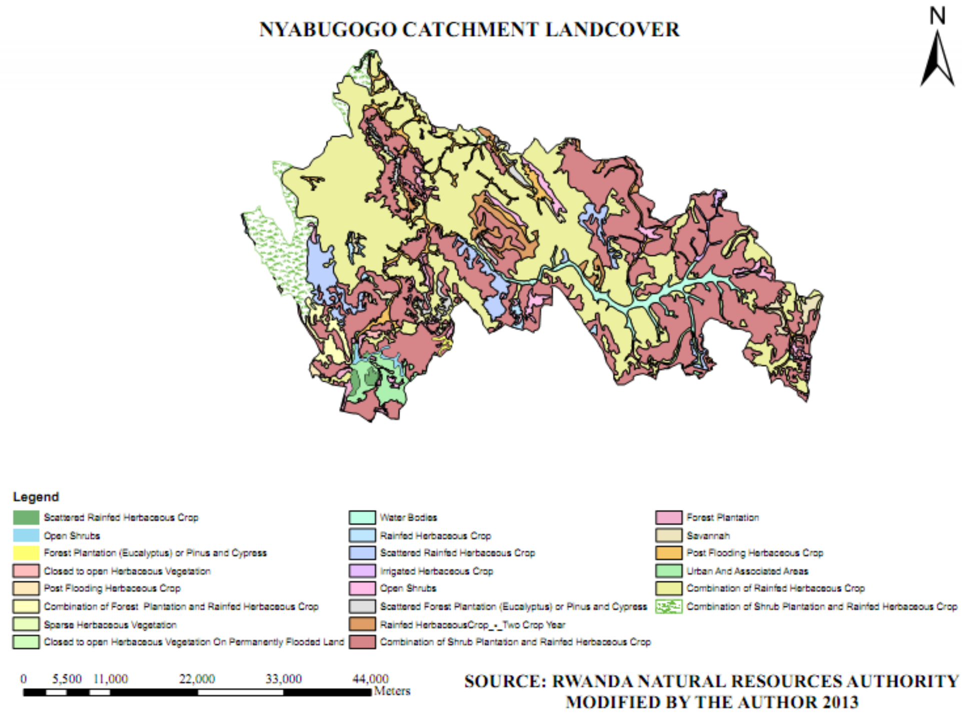

Figure 5: Land cover map of Nyabugogo catchment in 2013.

Almost one third of the area of the Nyabugogo catchment is now urbanized area. It is covered by various infrastructures. This has a great impact on increase of surface runoff and reduction of infiltration capacity of the soil in Nyabugogo catchment.

4.1.3. Discharge of Nyabugogo river

The Unit hydrograph method is used to determine excess rainfall of Nyabugogo river. The estimated excess rainfall is compared to the measured runoff in order to know the flood hydrograph (Raghunath, 2006). Munyaneza et al. (2013) determined the water levels of 2011 from records at the hydrometric station of Nemba at the outlet of Nyabugogo catchment which is between Nyabugogo and Giticyinyoni in Nyarugenge District, Kigali city. These records were used to estimate the daily discharge, and then mean monthly discharge. There is a rating curve of Nyabugogo river, at this station, developed by Rwanda Natural Resources Authority (Munyaneza et al., 2015) and the water levels were transferred to discharges using the same developed rating curves. Table 1 shows the mean monthly discharges and average annual discharge for 2011 time series records.

Table 1: The mean monthly discharges and mean annual discharge for 2011(Munyaneza, 2012).

Month	Discharge (m^3/s)
January	5.97
February	4.03
March	6.01
April	6.40
May	6.89
Jun	5.44
July	5.13
August	4.59
September	8.34
October	10.65
November	9.54
December	10.10
Annual average	**6.92**

Figure 6 below shows the flow variation of Nyabugogo river through the year 2011.

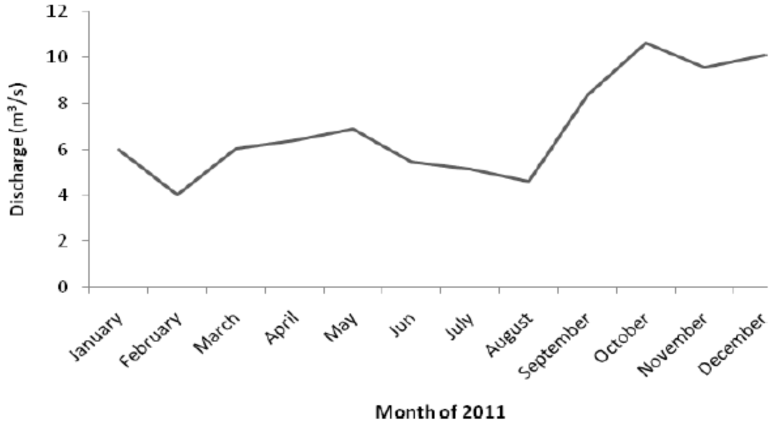

Figure 7: The flow variation of Nyabugogo river through the year 2011 (Munyaneza et al., 2013).

The daily discharge records of Nyabugogo river recorded from Nemba station, the maximum discharges recorded from 1972 up to 2011, close or greater than 25 m^3/s are displayed in Munyaneza et al. (2013).

4.1.4 Development of unit hydrograph of Nyabugogo river

4.1.4.1. Effective rainfall.

From Figure 3 of **s**tream flow hydrograph of Nyabugogo river, the equation Y=0.04282 X+7.06 defining base flow separation determines the base flow. Neglecting rainfall losses during rainy season, the effective rainfall will be computed by subtracting base flow from recorded discharge at Nyabugogo river. The obtained value will be divided by the area of the catchment (1,647 km^2).

Table 2: Shows the effective rainfall in the period 23 April -29 April 1982.

Date	Observed discharge [m3/s]	Base flow[m3/s]	Observed rainfall [mm]	Surface Runoff [m3/s]	Effective rainfall [m]	Effective rainfall [mm]
23-Apr-1982	15.50	6.2	14.6	9.30	6.09932E-05	0.060993
24-Apr-1982	12.29	6.4	2.1	5.89	3.86103E-05	0.03861
25-Apr-1982	12.92	6.55	14.7	6.37	4.17454E-05	0.041745
26-Apr-1982	11.45	6.62	3.3	4.83	3.16757E-05	0.031676
27-Apr-1982	19.68	6.7	0	12.98	8.51415E-05	0.085142
28-Apr-1982	12.13	6.8	0	5.33	3.49741E-05	0.034974
28-May-1982	9.12	6.85	0	2.27	1.4878E-05	0.014878
29-May-1982	11.01	6.9	0	4.11	2.69274E-05	0.026927

4.1.4.2. Unit hydrograph

Figure 3 shows that runoff hydrograph from 1 March 1982 up to 15 June 1982, the base flow may be estimated. It is determined by the base flow separation line which is represented by the equation Y=0.0653X+5.

Neglecting the losses, the surface runoff will be obtained by subtracting base flow from observed discharge recorded at Nemba station (outlet of Nyabugogo catchment). This surface runoff due to three successive storms of 14.6; 2.1 and 14.7 mm of 3 hours is divided by the area of the catchment to get effective rainfall or excess rainfall in Nyabugogo catchment. Equation 3-11 is used to get unit hydrograph. The corresponding values are U_1= 0.3, U_2= 0.1, U_3= 0.02 and U_4=0.1. Apply these values, the peak discharge for a certain storm may be derived. Table 3 below shows the computation procedure.

Table 3: Peak discharge of a storm recorded on 13 April 2007.

Time	1	2	3	4	5	6	7
DUH	0.3	0.1	0.02	0.1			
P	2	5	3				
Q1	0.6	0.2	0.04	0.2			
Q2		1.5	0.5	0.1	0.5		
Q3			0.9	0.3	0.06	0.3	
Q	0.6	1.7	1.44	0.6	0.56	0.3	

The peak discharge from this single storm of 3 hours is estimated to 5.2 mm which is equivalent to direct runoff 33.04 m^3/s while the discharge recorded at Nemba station on 13 April 2007 is.

The bridge joins Nyabugogo and Gatsata, close to the outlet of Nyabugogo catchment, through which whole discharge drained from Nyabugogo catchment passes, has enough cross section to convey the peak flow from Nyabugogo catchment. Therefore, the floods occur in its upstream. It is not because the river channel is narrow at the bridge cross section, but there are other causes such as meandering, low velocity of the flow, etc.

4.2 River Shortening

Figure 7 is the top view of a river with a shortened reach. L_0 is the original length of the shortened reach and L_1 the final length, with $L_1<L_0$.

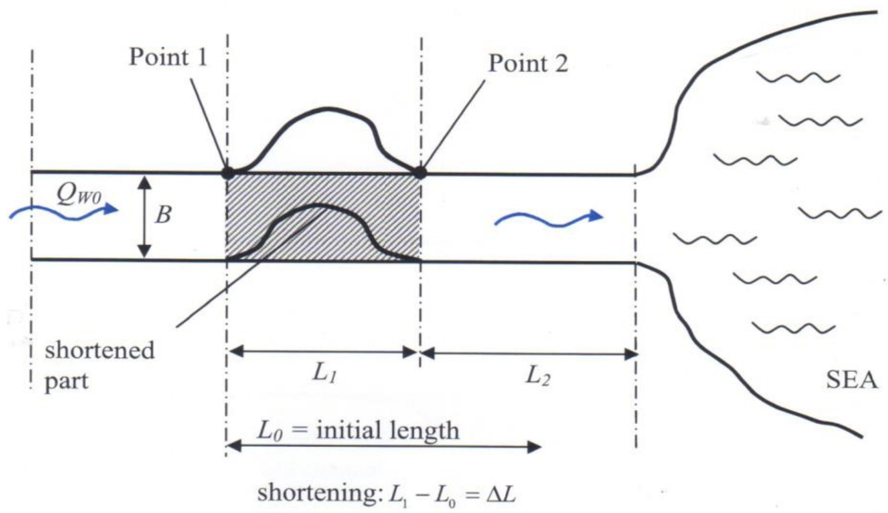

Figure 7: Top view of a shortened reach. L0 is the initial length of the meandering reach and L1 the final length, with $L_1< L_0$. Shortening is L_0-L_1 (Crosato, 2010).

The short-term and long term responses to the shortening of a river are illustrated in Figure 7, assuming that sediment transport formula and Chézy coefficient are the same in all situations. Initially, the shortened reach has higher longitudinal bed slope, higher velocity and smaller water depth. Erosion takes place near the upstream end of the shortened reach (point 1) and sedimentation near the downstream end (point 2). The shortened reach has higher sediment transport capacity than the old channel. Erosion and sedimentation also progress upstream until the river channel has reached the same slope and water mouth (distances computed along the river axis). The result is the lowering of the bed and water levels upstream of point 2. For all locations upstream of point 1, i.e. $L>L1+L2$.

$$\Delta z_b(L,\infty) = \Delta L i_0 \qquad \text{Eq.4-1}$$

$$\Delta z_w(L,\infty) = \Delta z_b(L,\infty) = \Delta L i_0 \qquad \text{Eq.4-2}$$

For the shortened reach the comparison between final and initial configuration depends on the specific situation. Figure 8 illustrates the case in which the width is equal to the one of the original channel and the water depth is equal to the normal water depth.

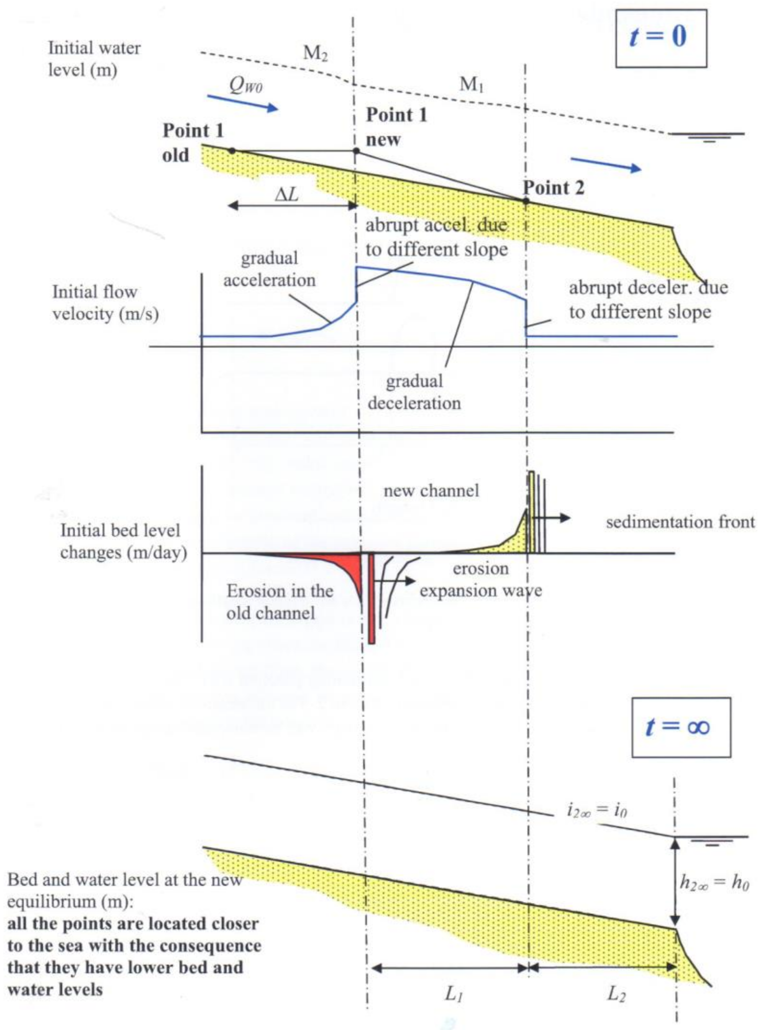

Figure 8: Short and long term variations caused by shortening of river course.

Where Δz_w and Δz_b are the changes of water level and river bed respectively.

Along Nyabugogo catchment, in zone 3, the meanders as it is shown on Figure 9, the shortened reach will mitigate flood waves at this location. The slope of the river bed will increase as well as flow velocity. The water will no longer delay there, it will be evacuated quickly. This process will allow water flow from the channel, side of urbanized area of Nyabugogo, to enter easily in the confluence of the channel and Nyabugogo river.

Figure 9 shows the location of Nyabugogo river reach to be shortened for mitigation of flood waves in Nyabugogo areas.

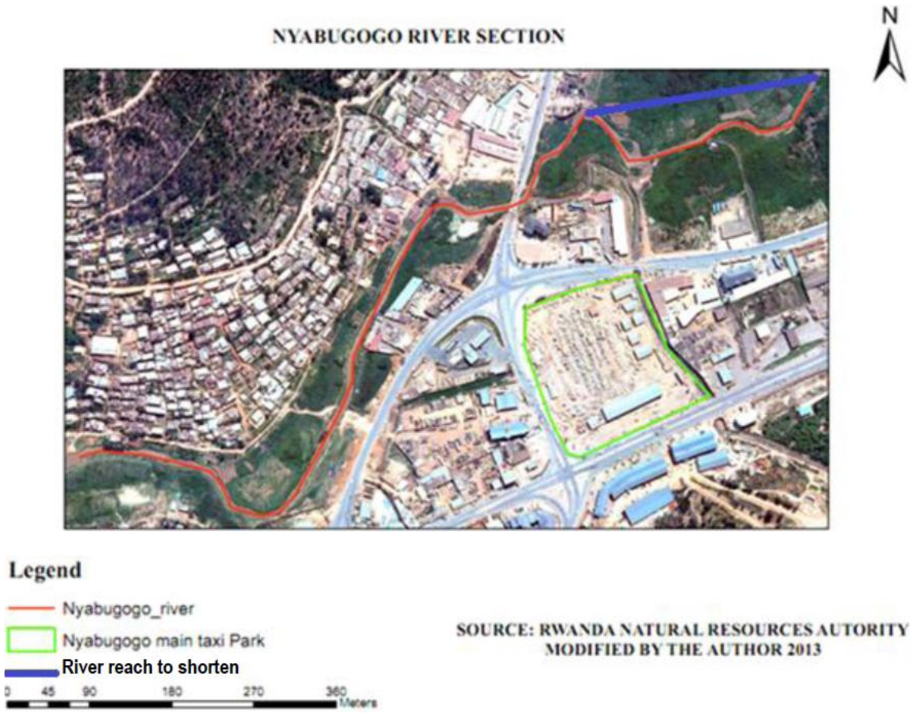

Figure 9: The location of Nyabugogo river reach to shorten.

Note that from Figure 9 the morphological response of the shortening is short and long-term. This study does not show after how long the equilibrium will be established. To realize this, the modeling of this process is required. However, this may be recommended for further studies.

5 CONCLUDING REMARKS

Flooding occurred in Nyabugogo river and in its surrounding areas during rainy season are caused mainly by meanders at some Nyabugogo river reaches. These floods are not flash floods because they like to occur every year and for a long event.

The morphological response caused by the shortening of a river reach is one of proposed solutions to mitigate frequent floods in the Nyabugogo locality. This solution is less costly and reestablishes, after the man intervention, the natural river channel.

Another cause of floods in the Nyabugogo wetlands is sediment deposition which decreases the river bed level. The aforementioned man intervention will be a solution also for sediment deposition but other measures have to be taken. A watershed as an area of land that water flows across as it moves toward a common body of water, such as a stream, river, lake or coast, must be well managed for example against erosion. As a result, water transport capacity will increase and the sediment deposition level will decrease of the water course.

The Governmental agencies that have in their attributions water and natural resources management have to gather regularly information on rainfall, water levels and stream flows especially in the Nyabugogo wetland. This allows flood prediction, control, and mitigates them effectively. In addition, we recommend the design of regulatory approach like forestation of side hills where the agriculture is no longer practiced as well as creation of buffer zone along the Nyabugogo river channel, in further researches. They will contribute to decrease vulnerability to flooding.

We conclude with recommendation of developing modeling studies at the proposed shortened Nyabugogo river reach, to predict when the equilibrium will be reached and check the optimal length of reach to shorten**.** The capacity of culvert under bridge locally namely Mirimo bridge should be checked to be sure if it can convey Nyabugogo river water.

ACKNOWLEDGEMENTS

The work reported here was undertaken as part of a project carried out by the University of Rwanda (UR), School of Engineering. The authors wish to acknowledge the support of Government of Rwanda, through Student Funding Agency of Rwanda (SFAR). We also express sincere gratitude to governmental agencies such as Rwanda Natural Resources Authority and Rwanda Meteorological Agency that provided all data used in this study.

REFERENCES

1. Axel Bronstert et al., 2002, "*Effects of climate and land-use change on storm runoff generation present knowledge and modeling capabilities*", University of Potsdam, Institute for Geo-Ecology, Germany.
2. Crosato, 2010, "*Morphological response at the reach scale*", Lecture notes, UNESCO-IHE Institute for Water Education, Delft, The Netherlands.
3. De Laat, P.J.M., Savenije, H.H.G., 2002, *"Hydrology",* Lecture notes. UNESCO-IHE Institute for Water Education, Delft, The Netherlands.
4. Exner, F.M., 1925, "*Uber die Wechselwirkung zwischen Wasser und Geschiebe in Flussen*", Sitzungber Akad. Wiss Wien, Part IIa, Bd.134, pp.165-180 (in German).
5. Garly J. Brierley and Kirstie A. Fryirs, 2005, *"Geomorphology and river management", School of Environment, University of Auckland, New Zeland*.
6. Karuhunga, J., 2011, "*Nyabugogo flood River. New times, Kigali, Rwanda."*.
7. Munyaneza, O., 2012, *"Applied Hydrology",* Lecture notes, Agricultural High Learning Institute ISAE-Busogo, Rwanda.
8. Munyaneza, O., Musoni, J.P. and Wali, U.G., 2009, *"Runoff coefficient classification on Nyabugogo catchment, Proceedings of the Hydrology"*, 10th International WaterNet/WARFSA/GWP-SA Symposium, Entebbe, Uganda, 28-30 October 2009.
9. Munyaneza, O., Uhlenbrook, S., Wenninger, J., van den Berg, H., Bolt, H. R., Wali, G. U., and Maskey, S., 2010, *"Setup of a Hydrological Instrumentation Network in a Meso-Scale Catchment- the case of the Migina Catchment, Southern Rwanda"*. Nile Water Sci. Eng. J., 3(1): 61-70.
10. Munyaneza**,** O., Nzeyimana, Y.K. and Wali, U.G., 2013, *"Hydraulic structures design for flood control in the Nyabugogo wetland, Rwanda",* Nile Water Sci. Eng. J., 6(2): 26-37.
11. Munyaneza, O., Ndayitegeye, O., Uwamaliya, V. and Sekomo, C.B., 2015, *"Quantification of runoff components and processes using hydrochemical tracer studies in the Nyabugogo swamp",* In Press, Nile Water Sci. Eng. J., 8: ISSUE 1-2015-306.
12. Nhapi, I., Wali, U.G., Uwonkunda, B. K., Nsengimana, H., Banadda N. and Kimwaga, R., 2011, *"Assessment of water pollution levels in the Nyabugogo Catchment, Rwanda"*, The Open Environmental Engineering Journal, 2011, 4, p40-53.
13. NISR, 2012, *"The Fourth Rwanda Population and Housing Census (RPHC4)"*, National Institute of Statistic of Rwanda (NISR), Kigali, Rwanda.
14. Raji et al., 2011, *"Rainfall-Runoff Analysis of a compacted area"*, The new times, December 2011
15. University of southern Qeensland, 2013, *"Hydrology",* Australia.
16. Van den Berg, J.H., 1987, *"Bedform migration and bed –load transport in some rivers and tidal environments",* Sedinmentology, Vol.34, pp.681-698.
17. Wali, U.G., 2011, *"GIS and RS for water and Application"*, Lecture notes, National University of Rwanda, Butare, Rwanda.
18. Waterloo, M.J., Post, V.E.A., and Horner, K., 2007, *"Introduction to Hydrology"*, Lecture notes, Course Code 450024, 5 ECTS, Vrije University Amsterdam, The Netherlands.
19. William K. Nuttle, 1991, *"Effect of Rising Sea Level on Runoff and Ground water Discharge to Coastal Ecosystems,* Ontario, Canada*"*.

LIST OF SYMBOLS

DEM	Digital Elevation Model
GIS	Geographic Information Systems
GWP	Global Water Partnership
ISAE	High Institute of Agriculture and Animal Husbandary
P_e	Effective Precipitation
RNRA	Rwanda Natural Resources Authority
SFAR	Student Funding Agency of Rwanda
UH	Unit Hydrograph
UR	University of Rwanda