Quantification of runoff components and processes using hydrochemical tracer studies in the Nyabugogo swamp, Rwanda

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Abstract

Chemical hydrograph separations of stream discharge are commonly used to determine the fractions of old and new water contributing to the stream flow. The aim of this study is to estimate the contribution of water from surface and subsurface runoffs. Furthermore other researches could compute the volume of water from the two components, which will facilitate the management of damaging floods appearing regularly in the Nyabugogo swamp area. Two rain events of 17^{th} May and 06^{th} June 2014 were analysed. Hydrochemical tracers such as Chloride (Cl^-) and dissolved Silica (SiO_2) were used to quantify the dominant runoff generation process in the Nyabugogo swamp and a hydrograph separation was conducted during two events. Results showed that the contribution of subsurface runoff is more important than the one of surface runoff, 65.3 % and 34.7 %, respectively. In urban areas like Kigali city, where Nyabugogo swamp is located, one could think that surface runoff should be more important than subsurface runoff, but this was not the case. The hydrochemical tracer concentrations revealed a relationship of river water and ground water confirming the importance of subsurface contribution to the stream flow. These results could contribute to the water resources management, infrastructure planning and design of Kigali city.

Keywords: Hydrograph separation, runoff generation, stream flow, hydrochemical tracer, Nyabugogo swamp.

1. INTRODUCTION

Runoff processes are pathways that water can take when moving downhill to streams after rain or snow melts. The use of environmental isotopes in combination with hydrochemical tracers and hydrometric measurements can help to gain further insights into hydrological processes including runoff process because the methods separate and quantify different runoff components during rainfall events (Wenninger et al., 2008; Munyaneza et al., 2012). In general, hydrochemical hydrograph separation of stream discharge is commonly used to determine the fractions of surface/subsurface or old/new water contributions to stream flow (Richey et al., 1998). Standard two-component mixing models of Sklash and Farvolden (1979) are used for hydrograph separations, in which the stream water is divided into old (pre-event) and new (event) water components. However, Kennedy et al. (1986) found that hydrochemical tracers could be used to separate stream flow into runoff components according to their flow paths.

Unfortunately, few recent studies on the application of two-component hydrograph separation models which improved our understanding on hydrological processes in semi-arid areas in Sub-Sahara Africa where Rwanda is also located; were conducted (Mul et al., 2008; Hrachowitz et al., 2011; Munyaneza et al., 2012). Munyaneza et al. (2012) used hydrometric and tracer methods to identify the runoff generation processes in the meso-scale Migina catchment in Rwanda. They found that subsurface runoff is dominating the total discharge during flood events where more than 80% of the discharge was generated by subsurface runoff for two rainy seasons “Itumba” (March–May) of 2010 and 2011. The Migina catchment which is located in southern Rwanda was found to be dominated by Agriculture activities with about 92.5% (Munyaneza et al., 2011) but the hydrochemical tracer studies can be also applied in urban areas where floods disaster are observed (Zagreb, 2013).

In Rwanda, regular flooding occur along the Nyabugogo flood plain near Kigali causing major disruption of the circulation on the 'Avenue des Poids Lourds' in Gatsata sector and inundation of properties in this market area (SHER, 2013). From a recent study of SHER (2013) on the Flood risk

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mitigation strategies, recommendations have been proposed. Storage and retention in Nyabugogo basin upstream of the Nyabugogo floodplain was one of the main recommendations. It is in this regards that a quantification of the runoff components is of utmost importance.

Hydrochemical tracers, such as Ca^{2+}, Mg^{2+}, SO_4^{2-} Cl^{-} and Silica (SiO_2) are relatively inexpensive to analyse and easy to use for hydrograph separation (Ribolzi et al.,2000; Soulsby et al., 2004; Tardy et al., 2004; Wels et al., 1991). The understanding of dominant runoff process and the ratio of old and new water contribution to the stream flow will help in further research for flood mitigation strategies in the Nyabugogo flood plain.

The objective of this study is to quantify runoff components and processes using hydrochemical tracer studies in the Nyabugogo swamp. Natural hydrochemicals can be used to separate runoff components using mass balance for the tracer fluxes and water (Sklash et al., 1979). The understanding of dominant runoff process and the ratio of old and new water contribution to the stream flow will help in further research for flood mitigation strategies in the Nyabugogo flood plain.

2. STUDY AREA

The Nyabugogo swamp which is part of the Nyabugogo catchment (1,647 km^2) is located between 1,354 m and 2,278 m above sea level. . The swamp covers a total area of 220 ha and a perimeter of 16 km (Fig. 1).

The Nyabugogo flood plain area collects the flow from the Nyabugogo river as it winds down its way from Muhazi Lake. Muhazi lake buffers about half of the catchment area and from some smaller but heavily urbanized catchments such as the Rugunga (Gikondo and Kigarama neighborhoods) and the Mpazi (Nyamirambo). The floodplain drains into the Nyabarongo river through a narrow valley where several small tributaries (including the Yanze River with a catchment of just about 10 km^2) increase peak discharges from 15 m^3/s to about 25 m^3/s (SHER, 2013).

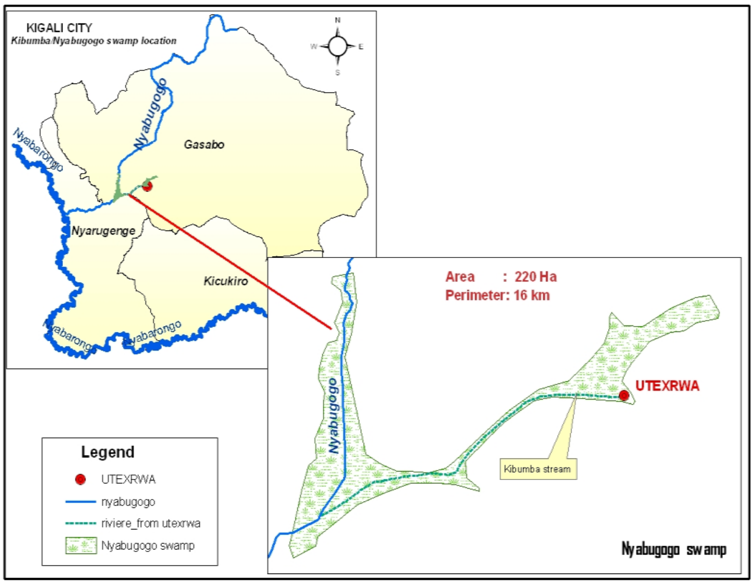

Figure 1: Location of the Nyabugogo swamp within Kigali City (Munyaneza et al., 2013).

Figure 1 shows the Nyabugogo swamp within Kigali City. The wetland covers both rural and urban areas. (Munyaneza *et al.*, 2013).

The major land use activity in the wetland is agriculture, which occupies about 897 km^2 (about 54%) of the wetland and is mostly of temperate and equatorial type with the average temperature ranging between 16^{o}C and 23^{o}C, depending on the altitude of the area (Munyaneza et al., 2013).

3. METHODOLOGY

3.1 Data Collection

Data were collected during a period of six months, from 15th January to 15th July 2014. Samples of the Nyabugogo river, groundwater and rain water were collected. More attention was brought on two rain events of 17th May and 06th June 2014 of which hourly samples was taken at the Mirimo Bridge. Samples were analyzed in the lab for hydrochemical tracers. The hydrochemical parameters measured include Electrical conductivity (E.C), Chloride (Cl^-), Sulfate (SO_4^{2-}), Silica (SiO_2), Sodium (Na^+), Potassium (K^+), Magnesium (Mg^{2+}) and Calicium (Ca^{2+}). Hydro-meteorological instruments including 3 piezometers for groundwater monitoring, 3 river gauging stations and 1 rain gauge were installed in the Nyabugogo swamp during this research implementation to facilitate the data collection. Stream water samples were collected every day at the same hour (10h00'), ground water and rainwater were collected every two weeks. After collection, samples were kept in a cooler box to avoid their deterioration at 0 ^oC.

3.2 Field and Laboratory Methods

In-situ measurements have been continuously conducted at the outlet of Nyabugogo wetland for electrical conductivity (EC) using a Hanna Gro'Chek Portable EC-meter (HI9813-0). Stream, piezometers and rain water samples were collected in 50 ml plastic bottles. Samples were collected during low flows and flood events.

All the samples from ground water, rain water and stream water were analyzed in the laboratory of the University of Rwanda (UR), Huye campus. Natural tracers have become a commonly used method in hydrograph separation (Wels et al., 1991, Ribolzi et al., 2000; Soulsby et al., 2004; Tardy et al., 2004). Dissolved silica (SiO_2) using a spectrophotometer CECIL/CE 2041, 2000 series. The concentrations of major cations like Mg^{2+}, Ca^{2+}, Na^+ and K^+ were determined by Atomic Absorption Spectroscopy (AAS). The concentrations of major anions like SO_4^{2-} were determined using a Hach-DR/890 Colorimeter whereas Cl^- was measured using a spectrophotometer DR/2000/Hach.

3.3 Method for Runoff Components Quantification and Process

For the purpose of quantifying the runoff processes we conducted a hydrograph separation that is a method used to separate runoffs in two or more components (end-members). This method is based on the mass balances for tracer fluxes and water (Bohte, 2010). During the two investigated flood events (17th May and 06th June 2014), the water levels were measured continuously at Mirimo river gauging station using automatic recorders (Mini-Diver; DI501) and transferred to discharges using rating curves. The automatic recorder (diver) that was installed at the site to record water level has been stolen during the period of data collection after four months. Fortunately, Munyaneza et al. (2013) had generated rating curve of Nyabugogo river using data collected from 2011 to 2014 and the discharge data provided by the RNRA. However, the following Equation 1 between discharge and water levels (rating curve) have been found:

$$(Q = 0.2052 * WL - 0.421) \tag{1}$$

In this study, quantification of runoff components has been done using hydrochemical tracer method. Instantaneous old and new water contributions to stream flow were calculated at any time using the mass balance equations for the water and isotopic, chemical, and ionic fluxes in the stream:

$$Q_o = \frac{(C_s - C_n)}{(C_o - C_n)} Q_s \tag{2}$$

$$Q_n = Q_s - Q_o \tag{3}$$

where Q is the discharge, C is the tracer concentration, and the subscripts s, o, and n correspond to the stream, old water and new water, respectively (Sklash et al., 1976). Hydrochemical tracers such as Ca^{2+}, Mg^{2+}, $SO^{2-}{}_4$, Cl^- and dissolved silica (SiO_2) are relatively inexpensive to analyse and easy to use for hydrograph separation (Ribolzi et al., 2000; Soulsby et al., 2004; Tardy et al., 2004; Wels et al., 1991) and have been adopted in this study for runoff component quantification.

Surface runoff can be generated either by rainfall, snowfall or by the melting of snow, or glaciers. In areas where there is no snow like Rwanda, runoff will come from rainfall. But not all rainfall will produce runoff because storage from soils can absorb light showers. However, to conduct the two-component hydrograph separation, we used dissolved silica (SiO_2) and Chloride (Cl^-). As mentioned above two rain events of 17th May and 06th June 2014 were considered. Chloride (Cl^-) salts are highly soluble. Cl^- is also relatively free from effects of exchange, absorption, and biological activity (Davis, 1966). Thus, Cl^- is believed to be the most chemically inert ion in the system (Neal et al. 1988), and is seen as the conservative tracer in groundwater. Dissolved silica (SiO_2) was chosen because of the difference in concentrations of the pre-event water and the event water.

The concentration of old water is considered to be similar to the one of the pre-event water and the concentration of new water is considered like the one of rain water (Sklash et al., 1976). The same method has been used by Munyaneza et al. (2012) in one of Rwandan catchments called Migina which is located in the southern part of the country.

4. RESULTS AND DISCUSSION

4.1 Results of Hydrochemical Tracer Studies

The results of the parameters measured are shown in Table 1. The table shows the results of river discharge, ground water, rain water and event samples. The values presented in Table 1 correspond to the average concentration of all samples for each parameter.

For the two rain events of 17th May and 06th June 2014, chloride (Cl^-) and dissolved silica (SiO_2) have been used for hydrograph separation (see Table 2) due to their variations in concentrations observed during two investigated flood events (Munyaneza et al., 2012).

Table 1: Average concentration of measured parameters.

Parameters	**E.C (µs/cm)**	**Cl^- (mg/l)**	**SO_4^{2-} (mg/l)**	**SiO_2 (mg/l)**	**Na^+ (mg/l)**	**K^+ (mg/l)**	**Mg^{2+} (mg/l)**	**Ca^{2+} (mg/l)**
River water (n=55)	271.0	2.4	17.3	16.4	3.3	13.5	9.1	11.0
Ground water (n=27)	764.6	5.1	22.3	16.5	3.7	40.82	8.8	31.0
Rain water (n=7)	224.7	19.1	N.D	N.D	19.2	28.6	21.3	26.2
Event-17/05/2014 (n=24)		2.4		11				
Event-06/06/2015 (n=24)		8.6		17.4				

n represents the number of samples.

Table 1 shows the concentration of hydrochemical tracers measured during the observed period (15th January to 15th July 2014). The results show that the concentrations of most of the chemical components in river water are related to the concentrations of groundwater. The examples can be seen on dissolved silica (16.4mg/l and 16.5mg/l), sodium (3.3mg/l and 3.7mg/l) and manganese (9.1mg/l and 8.8mg/l) concentrations for river water and groundwater, respectively.

Table 2: Concentration of dissolved silica and chloride for the two investigated rain events.

	17-05-2014 Event		**06-06-2014 Event**	
	SiO_2 (mg/l)	Cl^- (mg/l)	SiO_2 (mg/l)	Cl^- (mg/l)
C_o	15.06	3.3	14.637	14.4
C_n	4.329	0.4	24.608	0.6

C_o and C_n denote tracer concentrations of old water and new water, respectively.

Table 2 shows a difference in concentration of Silica and chloride for “old water” and “new water”.

Below are figures 2 to 4 that show the results of hydrograph separation based on dissolved silica and chloride for two rain events of 17th May and 06th June 2014.

In general, the two-component hydrograph separation model using dissolved silica and chloride led to a dominating proportion of subsurface contribution (up to 65.3%) as shown in Fig. 5.

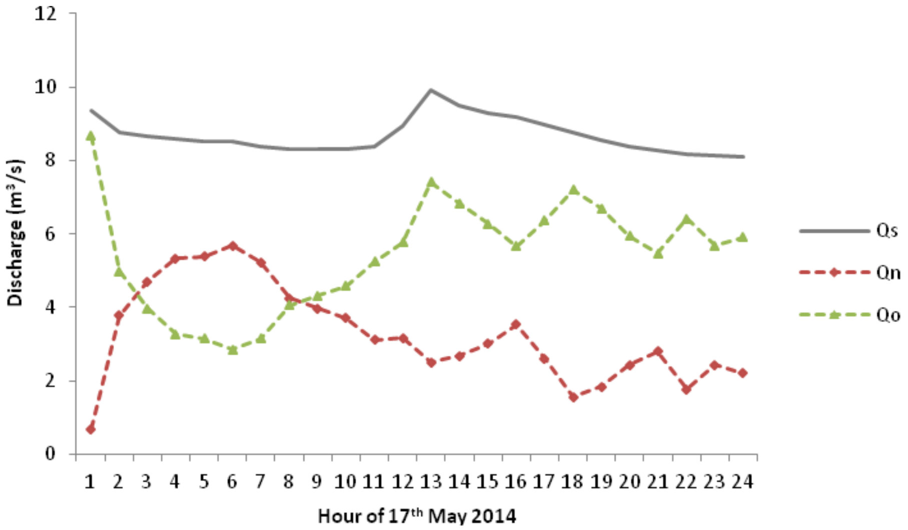

Figure 2: Hydrograph separation based on dissolved silica (SiO_2) for the event of 17th -05-2014.

Figure 2 shows the hydrograph separation based on dissolved silica for the event of 17th May 2014. In this figure Q denotes the discharge and the subscripts *s*, *o*, *n* denote respectively the stream, old water and new water. The subsurface water dominates surface water with 62.1% against 37.9%. At the beginning of the event, from hour 3 to hour 7 the contribution of overland flow dominates the contribution of ground water.

Figure 3 indicates the hydrograph separation based on chloride for the event of 17th May 2014.The subsurface water dominates surface water with an average of 70.3% against 29.7%.

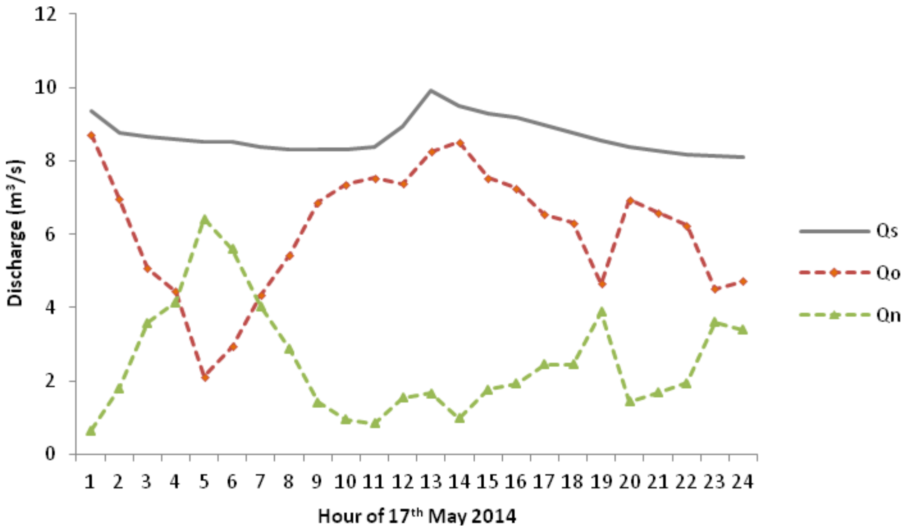

Figure 3: Hydrograph separation using chloride (Cl^-) for the event of 17th -05-2014.

Figure 3 shows that from the 4th to the 7th hour, the contribution of surface runoff is more important than the contribution of ground water and later becomes more and more less important. Q denotes the discharge and the subscripts s, o, n denote respectively stream flow, old water and new water.

The two-component hydrograph separations based on dissolved silica and chloride for event of 6th June 2014 showed the similar results as the separations for event of 17th May 2014 (Fig. 4).

(a)

(b)

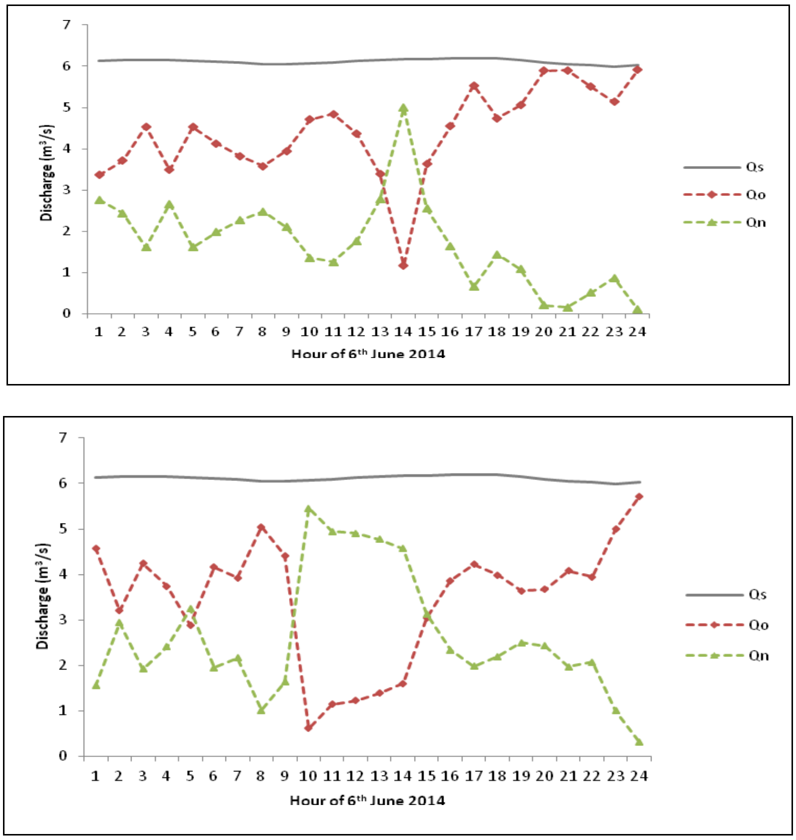

Figure 4: Two-component hydrograph separations based on dissolved silica (a) and chloride (b) for subsurface and surface runoff for event of 6th June 2014.

Figure 4 shows that the contribution of subsurface runoff dominated the contribution of surface runoff for both separations based on dissolved silica (Fig. 4a) and chloride (Fig. 4b). Q denotes discharge and the subscripts s, o, n denote respectively stream flow, old water and new water.

For the event rain of 17th May 2014 subsurface runoff contributed 62.1 % and 70.3 % using dissolved silica and chloride, respectively (Fig. 5). For the event rain of 06th June 2014 subsurface runoff contributed respectively 71.9 % and 56.9 % using dissolved silica and chloride as shown in the same Fig. 5.

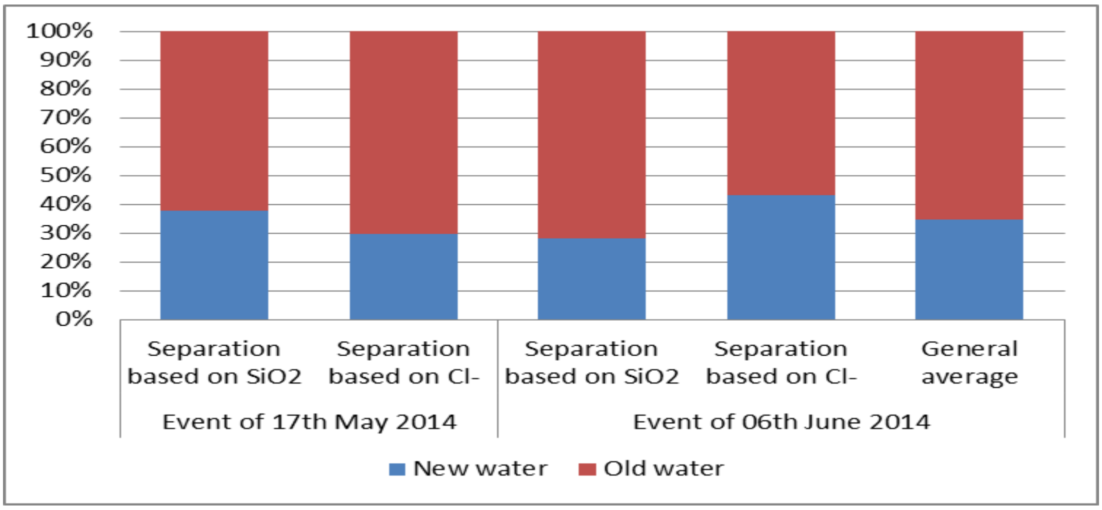

Figure 5: Contribution of subsurface water (Old water) and surface water (New water) to the stream in percentage for the monitored events of 17th May and 6th June 2014

4.2 Discussion on Quantification of Runoff Components and Processes

Streamflow hydrograph separations were initiated using dissolved silica and chloride as tracers due to their variations in concentrations detected during the two investigated rain events (Munyaneza et al., 2012). Munyaneza et al. (2012) used the same method in the meso-scale Migina catchment in Rwanda.

The two-component hydrograph separation model using dissolved silica and chloride led to a dominating proportion of subsurface contribution (up to 65.3 %) (see Fig. 5).

The hydrograph separation of the rain event of 17th May 2014 using dissolved silica shows that at the beginning of the event there has been a great increase of new water as the contribution of overland flow to the stream. This was most likely due to the impervious area covered by the rain. However, the total contribution of old water dominated the one of new water, 62.1 % and 37.9 %, respectively (Fig. 2 and Fig. 5). The important contribution to the peak discharge does not correspond to the new water as one could think considering an urban area where the Nyabugogo swamp is located with important impervious layer. Old water has important contribution (62.1 %) to the peak discharge; this behavior could be explained by the partial coverage of the rain to the catchment. The rain has covered a big part of the swamp where infiltration has been more important than overland flow before entering the river. This is especially land covered by vegetation. However, this groundwater recharge during the wet seasons leads to a perennial Nyabugogo river system.

Based on chloride concentration, the hydrograph separation of the same event of 17th May 2014 has shown almost similar results. The contribution of old water is greater than the contribution of new water, 70.3 % and 29.7 % respectively. Recent research in hill slope hydrology involving tracers, especially in humid catchments like Rwandan catchments, has found that the dominant contributor to the storm flow in the stream is old water (averaging 75 % worldwide, Buttle, 1994). At the peak discharge subsurface water has more contributed to the steam water than surface water. This should be probably explained by the rain which has been observed to cover areas with vegetation where the infiltration rate is high (Van den Berg et al., 2010 and Munyaneza et al., 2011).

Munyaneza et al. (2012) did a similar study in Rwanda to quantify the runoff components and to identify the dominant hydrological processes in the meso-scale Migina catchment using hydrometric data and modern tracer methods. They found that over 80 % of the discharge could be attributed to subsurface runoff while the remainder was due to faster surface runoff processes. The high percentage value of subsurface runoff contribution of the Migina catchment can be explained by the fact that the infiltration rate is high in a rural catchment where agriculture is the main activity (Munyaneza et al., 2011). Nyabugogo catchment is an urban catchment, the reason why the subsurface runoff contribution was reduced compared to the findings of Munyaneza et al. (2012).

Some other studies also concluded that ground water contribution to storm runoff is dominant in different and hydrogeologically diverse watersheds (e.g. Pinder and Jones, 1969; Sklash and Farvolden, 1979).

The hydrograph separation of the rain event of 06th June 2014 based on dissolved silica shows an important contribution of " Old water" to the stream water without any increase of the total discharge. This could only be explained by the recharge of ground water from the stream (Simmers et al., 1997).

5. CONCLUDING REMARKS

This study has tested the applicability of tracer methods to identify the dominant runoff generation processes in the Nyabugogo swamp. The two components hydrograph separation models using hydrochemical (dissolved silica and chloride) tracers show that rigorous water sampling (hourly) during events is essential.

The dominant runoff process is a subsurface runoff compared to surface runoff, 65.3 % and 34.7 % respectively (Fig. 5). The relationship of most of the hydrochemical tracers concentration of ground water and stream flow confirmed the important contribution of subsurface runoff to the stream flow (see Table 2). This could let us think that, even if the Nyabugogo flooding plain is in an urban area, the surface runoff could not be the dominating process even in flooding events due the fact that the rain has covered essentially areas with vegetation before entering the Nyabugogo river where the infiltration rate is high.

The results of this study demonstrated some important ground water recharge from river water. This behavior has been observed with the absence of streamflow raise after heavy rainfall. Nyabugogo River is characterized by a permanent river system undoubtedly because of the important ground water recharge during the rainy seasons (Fig. 5).

For both rain events of 17^{th} May and 06^{th} June 2014, no floods were observed. The daily amount of rainfall was 8 mm and 11 mm, respectively. More attention should be brought to events of intensive rainfall to assess if the contribution of surface and subsurface runoff remain as the same as the one of light rains. Further researches are needed to estimate the volume of water for floods mitigation purpose in the Nyabugogo flooding area.

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8. LIST OF SYMBOLS

EC	Electrical conductivity
SiO_2	Silica
Cl^-:	Chloride
Ca^{2+}	Calcium ions
Mg^{2+}	Magnesium ions

SO_4^{2-} Sulfate ions
AAS Atomic absorption spectroscopy
UR University of Rwanda
RNRA Rwanda Natural Resources Authority
UNESCO United Nations, Educational, Scientific and Cultural Organization
IHP International Hydrological Program