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Hydrology and
Earth System
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Discussions

Interactive comment on "Identification of runoff generation processes using hydrometric and tracer methods in a meso-scale catchment in Rwanda" *by* O. Munyaneza et al.

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We appreciated very much your thorough review of the manuscript and the provision of constructive comments which are very helpful for the improvement of the manuscript. All the corrections suggested have been addressed in the revised manuscript. Several sentences/paragraphs have been re-formulated for clarification and/or for addressing your comments. In the following, the most important changes are addressed point by point.

Major issue related to introduction

We agree that we have to improve the introduction section by giving clearer objectives,

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showing the novelty and/or necessity of this study and explaining what differentiates this study from a simple case study. More literature studies and recommended references have been used and added in the revised manuscript such as Burns (2002), James and Roulet (2009), and Buttle (1994) and all comments have been addressed. Furthermore, a better link to studies dealing with runoff generation in semi-arid catchments and studies combining hydrometric observations and hydrograph separation has been made. The introduction was improved by considering the following:

1. Formulation of clear objectives The study objectives were formulated in the revised manuscript to make it more clear for the reader (see bellow point 3).

2. Why do we need this in hydrology? The importance of this study in process hydrology was highlighted in the introduction of the revised manuscript. Burns (2002) found that the thrill of doing isotope-based hydrograph separations in forested, humid catchments is gone. Therefore, he recommended carrying out new studies in catchments with different climatic and human disturbance regimes. Additionally, these studies which combine water-isotope and solute isotope measurements should provide hydrologists with rich thrills and even surprises in the coming years. The current study was carried out in a semi-arid catchment and contributed to the advancement of hydrologic science of this hydro-climatic zone by quantifying runoff components and processes. Hardly any studies can be found in related hydro-climatic zones in the literature; therefore, we feel this study is a good addition to our knowledge base.

3. Clear objectives at the end of the introduction The study objectives were reformulated at the end of the introduction in the revised manuscript. The objective of the paper is to quantify the runoff components and processes in a meso-scale catchment for two flood events occurred during the rainy season “Itumba” (March–May) over the period of 2 years, i.e. 1 to 2 May 2010 at Kansi sub-catchment and 29 April to 6 May 2011 at Migina catchment in southern Rwanda (Fig. 1). Specifically, the study emphasizes on the use of two- and three-component hydrograph separation mixing models for separating streamflow into surface and subsurface runoff and quantifying

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different runoff components under tropical conditions. In order to learn more about hydrologic flow paths, hydrochemical tracers and hydrometric measurements such as rainfall, stream discharge, springs and groundwater levels were combined with tracer studies. The study explores the importance of combining hydrometric data, isotope information and hydrochemical tracers to identify runoff components (e.g. Ladouche et al., 2001; Uhlenbrook et al., 2002).

4. Why another case study? The introduction of this work was improved by highlighting the importance of using hydrometric observation methods. Burns (2002) put it nicely by stating: “As the science matured further in the 1990s, a point was reached at which isotope-based hydrograph separations alone were insufficient to guarantee publication of study results in the leading water resources journals. Many studies seemed only to reconfirm that stormflow in small forested catchments is dominated by ‘pre-event’ or ‘old’ water, and hydrologists did not need to be told so over and over again. Thus, isotope-based hydrograph separation had become simply another tool - one that could not lead to a more profound understanding of catchment runoff processes unless combined with many other tools.” Since then, the application of hydrograph separation together with hydrometric observation became state of the art in the global North, but much less in the South in particular in remote area of Africa with its unique hydro-climatic and other physiographic settings. However, hydrograph separation methods were applied before to semi-arid or better sub-humid catchments with the support of well data (Cras et al., 2007; Marc et al., 2001, Hrachowitz et al. 2011), but these studies site are different than the study area in Rwanda. Furthermore, the role of spatial and temporal variability in the input signal is known and the combined isotope based hydrograph separations with hydrometric measurements were suggested in this study.

Specific comments

Comment 1: Abstract Line 21, “. . . (16.7%-44.5%). . .” has been corrected with (16.7% and 44.5%) and the last sentence of the abstract was corrected as follow: Groundwater recharge during the wet seasons leads to a perennial river system. The low runoff coefficient values from other catchments have been mentioned later in the discussion part of revised manuscript. The following paragraph was added in the discussion: It depends on other factors such as the degree of slope, soil type, vegetation cover, antecedent soil moisture, rainfall intensity and duration. The low runoff coefficient ranges usually between 1% and 50% in the cultivated catchments (FAO, 2006). Ley et al. (2011) found that the annual mean runoff coefficients in nested catchments of Rhineland-Palatinate, Germany, may range from 2% to 15% in summer period, while in winter they range from 5% to 56%. However, the current research was also done during the rainy season called Itumba in local language.

Comment 2: Introduction P672, L26: One sentence which is more general was added and the current sentence was rephrased to make the paragraph clearer as follow: Understanding of runoff components separation processes is essential for the proper assessment of water resources availability within catchments. The use of environmental isotopes in combination with hydrochemical tracers and hydrometric measurements can help to gain further insights into hydrological processes because the methods separate and quantify different runoff components during rainfall events.

P673, L27 ff. the paragraph was rephrased and described more clearly in the revised manuscript. Good insights into the hydrology of a meso-scale catchment like the Migina contributes to the acquisition of an increased level of knowledge regarding the water resources of the catchment; an important first step in protecting existing users and ensuring a sustainable level of development in the future. This knowledge can help famers to increase their crop production and to sustain long-term food security (e.g. Mul, 2009; Hrachowitz et al., 2011)

P674, L5: the sentence was reformulated in the revised manuscript as follow. Based on a baseflow recession curve they showed a decreasing trend in baseflow in the overall river discharge.

Comment 3: Study area P675, L7ff.: Coverage in percent has been given and the

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sentence was revised as follow: Land cover and hydrological soil group analyses in the Migina catchment show that the catchment is dominated by agriculture activities (92.5%) while forest occupy 5%; grass/lawn 2% and buildings cover 0.5% (Munyaneza et al., 2011).

P675, L12-19: the section has been rewritten and subcatchments were deleted in the revised manuscript. The investigated catchments in this paper are: Cyihene-Kansi catchment, further called Kansi sub-catchment (129.3 km2) and Migina catchment (257.4 km2) which covers the whole catchment including Kansi sub-catchment (see Fig. 1). The perennial Migina River drains into the Akanyaru River, which forms the border between Rwanda and Burundi. The Akanyaru River drains into the Kagera River, which flows into Lake Victoria and later generates the White Nile.

P675, L28: "The Itumba...". The sentence was reformulated based on reviewer suggestion as follow. The investigated invents occurred during the Itumba season (March to May) for the years 2010 and 2011.

Comment 4: Methods P676, L17ff.: Information about the devices for field and laboratory measurements was supplied. In-situ measurements have been continuously conducted at the outlet of each subcatchment for pH value and water temperature (T) using a portable pH-meter (Hach 157) and for electrical conductivity (EC) using a Hanna Gro'Chek Portable EC-meter (HI9813-0). Stream, spring and rain water samples were collected in 30 ml plastic bottles. Samples were collected during low flows and flood events. Samples were analyzed in the laboratory for dissolved silica (SiO2) using a Spectrophotometer DR 2400 at the laboratory of Kadahokwa water treatment plant and at the laboratory of the National University of Rwanda (NUR), Butare, Rwanda.

P677, L11: Section 3.3 was also improved by giving more details about the 3-comonent separation. End members and runoff coefficient were explained better in the revised manuscript. A three-component hydrograph separation was applied in this study by using dissolved silica and deuterium for the event of 1–2 May 2010 at Kansi station (Fig.

7) and using dissolved silica and oxygen-18 as tracers for the event of 29 April 2011 to 6 May 2011 at Migina station (Fig. 9). The same method was used by James and Roulet to estimate the relative contributions of throughfall, a perched water or shallow subsurface flow component and groundwater for each individual storm event in small forest catchments of Mont Saint-Hilaire, Quebec, Canada. During our research, three end members (old: deep and shallow groundwater, and new: rainfall) were used in the separation. End member concentrations were collected from each event in order to account for the temporal variability (McDonnell et al., 1990). End member for deep groundwater samples was selected to be the one from springs and from piezometers installed on hillslope and was considered as deep water flow while piezometers closer to streamflow were considered as end member for shallow groundwater. End member for rainfall samples was taken as average rainwater sampled at 4 automatic (tipping buckets) rainfall stations installed in the study area (see Fig. 1). Annual runoff coefficient estimations were determined from Thiessen polygon representation of rainfall and continuous runoff records (Kadioglu, 2001). Rainfall measurements have been carried out at 13 manual rain gauges installed in the Migina catchment.

Comment 5: Results Parts of the results which are discussion were moved from results to the discussion part, therefore the chapter 4 section 4.2 was shortened in the revised manuscript.

P680, L4-5: the last sentence of the paragraph was corrected in the revised manuscript to avoid the confusion about the surface runoff contribution. L4-5 became: Similarly, a maximum daily rainfall of 23.7 mmd−1 was observed on 2 May 5 2011 in the Migina catchment and the runoff generated by this rainfall at Migina station, reaches also at the same day its peak at 10:00 LT (11.78 m3 s−1). The river discharge returns to pre-event values on 6 May 2011.

P680, L13-14 and 680, L15-16: runoff coefficient values were provided and the sentences were rephrased and described better and also moved to the discussion part of the revised manuscript (see comment 1: Abstract).

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P680, L20ff: We totally agree with your following statement: “If a high percentage of rainfall becomes subsurface runoff, it would be still runoff and thus contribute to stormflow”. But in our opinion, the argument that low runoff coefficient can be explained by that makes sense because it contributes to stormflow through the soil as groundwater flow not surface water runoff.

Page 681, Ll2: the sentence was reformulated; hence the argument in Line 4-5 makes sense. Table 3 shows that the concentrations of most of the chemical components in surface water are related to the concentrations of water sampled from springs and piezometers during flood events. Only the opposite can be seen in dissolved silica (SiO2) and electrical conductivity (EC) concentrations. This indicates that surface discharge is dominated by subsurface runoff components during flood events in the Migina catchment.

Page 682, L3-5: End members were more described in the methodology part of the revised manuscript to support the argument presented in this paragraph (see Comment 4: Methods, P677, L11)

P684, L5ff. We don’t see the influence of evaporation on the springs. But the previous sentence was revised to support the idea of the next sentence. Thus, the two sentences became in the revised manuscript: Interestingly, the isotope values of the observed springs are not influenced by dry season rainfall values, as they all plot below, show lighter isotope values than the amount weighted rainfall values of the wet season rainfall input. Thus, it can be concluded that the perennial springs in the area are recharged during the wet season.

P684, L11ff. the purpose of changing the tracers was clearly explained in the discussion part of the manuscript, Section 5.2. Stream flow hydrograph separations were found to be possible using dissolved silica and chloride as tracers due to their variations in concentrations observed during two investigated flood events. However, the remaining analyzed chemical components (SO_4^{2-} , Na+, K+, Mg2+, and Ca2+) could not be used for hydrograph separations, because they showed constant concentrations during the events (likely due to non-conservative transport behavior) and did not provide additional insights.

P684, L16ff. The used end member was explained better in the method section and can be read in comments 4, P677, L11 of this response.

P684, L20. Yes, we agree that new water must not be direct runoff and this was corrected in the revised manuscript. The term new water was replaced by event water.

Comment 6: Discussion The discussion part has been improved and linked to the objectives of the study. Sub-headers were included in the revised manuscript as follow: 5.1 Rainfall influence on runoff generation; and 5.2 Quantification of runoff components and processes in a meso-scale catchment.

Comparison to other studies on runoff generation processes in semi-arid catchments was made such as the studies of Mul et al. (2008); van den Berg and Bolt (2010); and Hrachowitz et al. (2011). Furthermore, the uncertainty in the work was also highlighted. The findings of this current paper were also supported by results from several other hydrochemical (and isotopic) studies that found old water and subsurface flow to be the major (more than 50 %) component of stormflow in different hydro-climatic rainfall (e.g. Sklash et al., 1976; Sklash and Farvolden, 1979; Kennedy et al., 1986; Rice and Hornberger, 1998; Uhlenbrook et al., 2008; Hrachowitz et al., 2011). Our results are not far from the results of Mul et al. (2008) who did the same study in semi-arid area using hydrochemical tracers for hydrograph separation and found that over 95% of the discharge could be attributed to sub-surface runoff during smaller events, while the remainder was due to faster surface runoff processes. Hrachowitz et al. (2011) carried out a study in a semi-arid catchment using hydrometric observation and found that the use of multiple tracers allowed estimating uncertainties in hydrograph separations occurring from the use of different tracers. Applying hydrograph separation methods to larger catchments >40 km2 often leads to only qualitative results (Uhlenbrook and

Hoeg, 2003). However, hydrograph separation on Migina meso-scale catchment helps in process understanding. The runoff components and processes in a meso-scale catchment for two flood events were quantified.

P686, L6. Units in mm/h were provided and compared with rainfall intensity as follow. The high infiltration in the Migina catchment can be explained by very high hydraulic conductivity as observed by van den Berg and Bolt (2010) using double ring infiltrometer test in the same catchment (infiltration rate is between 208 mm $h{-}1$ to 1250 mm $h{-}1$). The rainfall intensities which are less than 17.6 mm h-1 are much lower than the infiltration rates (capacities) (see Tables 1 and 2).

Comment 7: Conclusion Page 688, L1-3: The sentence was corrected in the revised manuscript to avoid testing something that is already known. The methods are known and were applied in other catchments, but were not yet applied in the Migina catchment, even not in any other catchment in the region (Rwanda and Lake Victoria region). The sentence was reformulated as follow: The applicability of tracer methods in conjunction with hydrometric measurements for identifying dominant runoff generation processes in the meso-scale Migina catchment was tested.

The discussion part was also improved and linked to other studies (see comments 6). The conclusion was improved as follow: The results of this study demonstrated the importance of subsurface flows for stream flow generation in the study area. It shows the value of hydrological data collection over two whole rainy seasons using different tracers and hydrometric observation to understand dominant hydrological processes. Furthermore, it demonstrated the significance of considering spatial and temporal variations of rainfall in the hydrograph separations (Figs. 8 and 9); this is of greater importance in meso-scale catchments than in small headwaters.

Comment 8: Figures Figure 1: The location within Africa was plotted and the figure title was updated in the revised manuscript as follow.

Figure 1 Location of the Migina catchment in Rwanda and East Africa, and instrumentation set-up within this research framework showing the positions of Kansi and Migina gauging stations.

Figure 3: Font size of axis was made bigger in the revised manuscript as follow.

Figure 3 Hydrochemical parameter responses at Kansi station during 1-2 May 2010 storm event (a) and at Migina station during 29 April to 6 May 2011 storm event (b).

Figure 4: The rainfall was also plotted in the revised manuscript.

Figure 4 Results of two-component hydrograph separations based on dissolved silica (a) and chloride (b) for subsurface and surface runoff for event K6 (see Fig. 2a) investigated from 1 May 2010 at 12:00 to 2 May 2010 at 11:00 at Kansi station.

Figure 5: The rainfall was plotted and the visibility of captions was improved in the revised manuscript.

Figure 5 Two-component hydrograph separations based on dissolved silica (a) and chloride (b) for subsurface and surface runoff for event M3 (see Fig. 2b) investigated from 29 April to 6 May 2011 at Migina station.

Figure 6: Font size of axis was made bigger and the abbreviations of data points were included in the figure captions and corrected in the revised manuscript as follow.

Figure 6 Stable isotope compositions of rainfall, surface water, springs, shallow groundwater, and amount weighted rainfall for dry and wet seasons. GMWL: δ2H = 8.13*δ18O+10.8 (Source: Clark and Fritz, 1997). GMWL is the Global Meteoric Water Line; LMWL is the Local Meteoric Water Line for Butare; AVE_P_Weight means the average weight rainfall concentration for water sampled during wet and dry seasons; AVE_P_Weight_Dry means the average weight rainfall concentration for water sampled in summer season; and AVE_P_Weight_Wet represents the average weight rainfall concentration for water sampled during in rainy season.

Figure 7: The rainfall was plotted and the used three components were clearly ex-

plained in the figure captions and corrected in the revised manuscript as follow.

Figure 7 Results of the three-component separation using dissolved silica and deuterium as tracers for event K6 (see Fig. 2a) investigated from 1 May 2010 at 12:00 to 2 May 2010 at 11:00 at Kansi station. Qdgw + Qsgw is the sum of deep and shallow groundwater components.

Figure 8: Font size was made a bit bigger to increase the visibility in the revised manuscript.

Figure 8 Hourly rainfall and variations of δ18O in rainfall (a), discharge and variations of δ18O in the stream water (b) during the 29th April 2011 to 6th May 2011 storm event.

Figure 9: The rainfall was plotted and the used three components were clearly explained in the figure captions and were corrected in the revised manuscript as follow.

Figure 9 Results of the three-component separation using dissolved silica and oxygen-18 as tracers for event M3 (see Fig. 2b) investigated from 29 April 2011 to 6 May 2011 at Migina station. Qdgw + Qsgw is the sum of deep and shallow groundwater components.

Comment 9: References We appreciated the provided added references and we used them in the revised manuscript to improve the quality of this paper.

On behalf of the authors, Omar Munyaneza, Kigali, Rwanda

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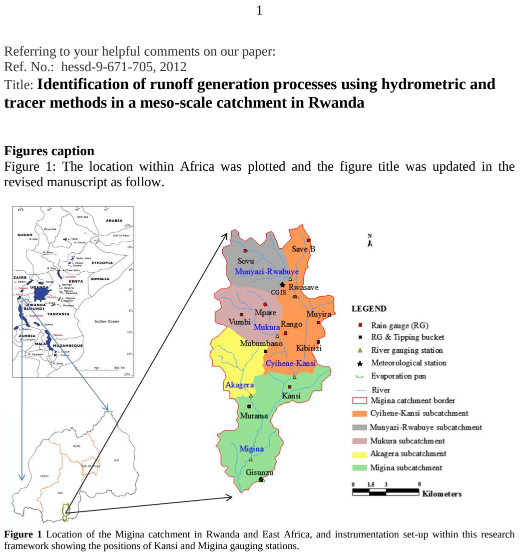

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Figures caption

Figure 1: The location within Africa was plotted and the figure title was updated in the revised manuscript as follow.

Figure 1 Location of the Migina catchment in Rwanda and East Africa, and instrumentation set-up within this research framework showing the positions of Kansi and Migina gauging stations.

Fig. 1.

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