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Identification of runoff generation processes using hydrometric and tracer methods in a meso-scale catchment in Rwanda

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Abstract

Understanding of dominant runoff generation processes in the meso-scale Migina catchment (257.4 km^2) in Southern Rwanda was improved using analysis of hydrometric data and tracer methods. The paper examines the use of hydrochemical and isotope parameters for separating streamflow into different runoff components by investigating two flood events occurred during the rainy season "Itumba" (March–May) over the period of 2 yr at two gauging stations. Dissolved silica (SiO_2), electrical conductivity (EC), deuterium (^2H), oxygen-18 (^{18}O), major anions (Cl^- and SO_4^{2-}) and major cations (Na^+, K^+, Mg^{2+} and Ca^{2+}) were analyzed during the events. ^2H, ^{18}O, Cl^- and SiO_2 were finally selected to assess the different contributing sources using mass balance equations and end member mixing analysis for two- and three-component hydrograph separation models. The results obtained applying two-component hydrograph separations using dissolved silica and chloride as tracers are generally in line with the results of three-component separations using dissolved silica and deuterium. Subsurface runoff is dominating the total discharge during flood events, More than 80 % of the discharge was generated by subsurface runoff for both events. This is supported by observations of shallow groundwater responses in the catchment (depth 0.2–2 m), which show fast infiltration of rainfall water during events. Consequently, shallow groundwater and contributes to subsurface stormflow and baseflow generation. This dominance of subsurface contributions is also in line with the observed low runoff coefficient values (16.7–44.5 %) for both events. Groundwater recharge during the wet seasons leads to a perennial river system, and wet season recharge is isotopically characterising all discharge components.

1 Introduction

The use of environmental isotopes in combination with hydrochemical tracers and hydrometric measurements can help to gain further insights into hydrological processes.

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Combined methods can be used to quantify the contributions of runoff components during different hydrological situations (floods and low flows) in small and meso-scale catchments (Didszun and Uhlenbrook, 2008; Wenninger et al., 2008). Generally, hydrochemical and isotopic hydrograph separations of stream discharge are commonly used to determine the fractions of surface/subsurface or old/new water contributions to streamflow (e.g. Richey et al., 1998).

Most hydrograph separations involve the standard two-component mixing models of Sklash and Farvolden (1979), in which the stream water is separated into old (pre-event) and new (event) water components. This approach identifies the age of streamflow components, but cannot be used to assess the spatial origin (Ladouche et al., 2001). To obtain both temporal and spatial origins, some investigations using stable isotopes associated with chemical tracers, have been undertaken in different basins world-wide (for example, Kennedy et al., 1986; Wels et al., 1991; Ladouche et al., 2001; Uhlenbrook and Hoeg, 2003; Hrachowitz et al., 2011). However, hydrochemical tracers may only be used to separate streamflow into runoff components according to their flow paths (Kennedy et al., 1986).

Only a few recent studies on the application of two and three-component hydrograph separation models improved our understanding of hydrological processes in semi-arid areas in Sub-Sahara Africa (Mul et al., 2008; Hrachowitz et al., 2011), where Rwanda is also located. These studies contribute to appropriately manage the available surface water and groundwater resources, both in terms of quality and quantity. This is essential in Rwanda where the population is growing with an annual rate of about 3.5 % (MINIPLAN, 2002), and it is already the most densely populated country on the African continent (NELSAP, 2007). The related increase of water demand for domestic, agricultural, and industrial uses is causing significant water scarcity in the country, and ecosystems are under enormous pressure.

Good insights into the hydrology of a meso-scale catchment like the Migina can help to increase the crop production and to sustain long-term food security (e.g. Mul, 2009; Hrachowitz et al., 2011). In order to achieve this, insights into the behavior of the

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water fluxes and the interactions between groundwater and surface water is of utmost importance. Munyaneza et al. (2011) conducted their study in the Migina catchment to predict river flows. Van den Berg and Bolt (2010) also conducted their research in the same catchment using hydrochemical and isotope analysis during the dry season. They found that a baseflow recession curve could be made, showing a decreasing trend in baseflow contribution for the last 30 yr. It is now becoming almost constant at a rate of $0.19\,m^3\,s^{-1}$ for the main outlet during the end of the dry season. Furthermore, they concluded that a significant flow from (deep) groundwater has to be the source of this water. Hence, the suggestion was made to perform detailed hydrochemical and isotopic hydrograph investigations also during floods to obtain a better understanding of groundwater-surface water interactions as well as the different sources and flow pathways.

The objective of this paper is to improve the understanding of hydrological processes in a meso-scale catchment for two flood events occurred during the rainy season "Itumba" (March–May) over the period of 2 yr, 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 different runoff components under semi-arid, tropical conditions. Therefore, hydrometric techniques (measurement of rainfall, stream discharge, springs and groundwater levels monitoring) were combined with tracer studies. The study explores the importance of combining hydrometric data, isotope information and hydrochemical tracers to identify runoff components (Ladouche et al., 2001; Uhlenbrook et al., 2002).

2 Study area

The study was carried out in the meso-scale Migina catchment ($257.4\,km^2$) and in the Kansi sub-catchment ($129.3\,km^2$), which are located in Southern Rwanda (Fig. 1).

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Approximately 103 000 inhabitants with an annual growth rate of about 3 % are living in the Migina catchment (Nahayo et al., 2010; van den Berg and Bolt, 2010). The site is mountainous with elevation ranging from 1375 m a.s.l. at the outlet to 2278 m a.s.l. at Mount Huye, which is located in the north-western part of the catchment. The topographic conditions are very variable and slopes of the valleys vary from 5 to 10 % in the upstream and 1 to 15 % in the downstream part (average slope is between 2 and 3 %) (see Nahayo et al., 2010). Land use is dominated by pasture and farm land where rice, sorghum, maize, cassava, beams and (sweet) potatoes are cultivated usually with irrigation (Munyaneza et al., 2010). This indicates that most of the water in the Migina catchment is used for agricultural purposes (irrigation) because all of these activities take place in the valleys close to the rivers.

The investigated catchments in this paper are: Cyihene-Kansi catchment, further called Kansi sub-catchment (129.3 km^2) after combining 3 sub-catchments: Munyazi-Rwabuye (41.6 km^2), Mukura (38.1 km^2) and Cyihene-Kansi (49.6 km^2); and Migina catchment (257.4 km^2) which covers the whole catchment including Akagera (34.9 km^2) and Migina (93.2 km^2) sub-catchments (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.

The mean annual rainfall in the Migina catchment is approximately 1200 mm a^{-1} and the mean annual temperature is about 20 °C (SHER, 2003). The annual average evaporation in the area is estimated to 917 mm a^{-1} (Nahayo, 2008). Migina catchment has a moderate climate with relatively high rainfall and an annual cycle of two rainy seasons (FAO, 2005): (1) a short rainy season, locally known as "Umuhindo", lasts from September to November with November characterized by heavy rainfall; this season is followed by a short dry season, locally known as "Urugaryi", lasts from December to February; (2) a long rainy season, locally known as "Itumba", lasts from March to May. This accounts for about 61 % of the total annual rainfall. The Itumba season is the investigated season in this paper for the years 2010 and 2011.

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3 Data and methods

3.1 Data collection

The catchment has been equipped with hydrological instruments (Fig. 1) and after installation, hydrochemical and isotope data were collected over two years (May 2009 to June 2011). Two events were examined in further detail during the long rainy season "Itumba". Intensive monitoring (hourly samples) was carried out between 1 and 2 May 2010 and between 29 April 2011 and 6 May 2011 at Kansi and Migina gauging stations, respectively. Samples were analyzed in the lab for isotopes and hydrochemical tracers. The collected samples include groundwater from 11 shallow piezometers, 15 springs, river discharge measurements from 5 river gauging stations (Rwabuye, Mukura, Kansi, Akagera, and Migina); stream water sampled at 8 sites in the catchment (weekly or monthly intervals), and monthly catchment rainfall from 5 locations where tipping buckets are installed (see Fig. 1). One rainfall event during the Itumba'11 season (from 29 April 2011 to 6 May 2011) was also sampled at Gisunzu rain gauge for isotopic composition analysis.

3.2 Field and laboratory methods

In-situ measurements have been continuously conducted at the outlet of each subcatchment for pH value and water temperature (T) using a pH-meter and for electrical conductivity (EC) using an EC-meter. 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 for dissolved silica (SiO_2) 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. The concentrations of major cations like Mg^{2+}, Ca^{2+} and K^+ were determined by Atomic Absorption Spectroscopy (AAS) at NUR and sodium (Na^+) was determined by AAS at UNESCO-IHE, Delft, The

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Netherlands. The concentrations of major anions like SO_4^{2-} were determined using a Hach-DR/890 Colorimeter in the lab of WREM at NUR, and Cl^- was analyzed by using an Ion Chromatograph at UNESCO-IHE and verified by using Colorimetry in the lab of NUR. The isotopes were analyzed at UNESCO-IHE with a LGR Liquid-Water Isotope Analyzer, which provides measurements of $\delta^{18}O$ and $\delta^{2}H$ in liquid-water samples with accuracy better than 0.2 ‰ for $^{18}O/^{16}O$ and better than 0.6 ‰ for $^{2}H/^{1}H$.

During the investigated two flood events, the water levels were measured continuously at two river gauging stations (Kansi and Migina) using automatic recorders (Mini-Diver; DI501) and transferred to discharges using rating curves ($r^2 = 0.94$, $n = 24$ at Kansi station and $r^2 = 0.97$, $n = 18$ at Migina station).

3.3 Hydrometric and tracer methods

Hydrograph separation to separate the runoff during floods in two or more components (end-members), based on the mass balances for tracer fluxes and water, was applied in this study. Environmental isotopes (^{18}O and ^{2}H), dissolved silica (SiO_2) and chloride (Cl^-) were selected as tracers.

The fundamentals and assumptions of the hydrograph separation method are further discussed in e.g. Sklash and Farvolden (1979), Wels et al. (1991), and Buttle (1994). The mass balance expression for a two-component hydrograph separation model used in this paper is described as follows:

$$Q_T = Q_1 + Q_2 \tag{1}$$

$$c_T Q_T = c_1 Q_1 + c_2 Q_2 \tag{2}$$

Where Q_T is the total runoff ($m^3 s^{-1}$); Q_1, Q_2 are runoff contributions ($m^3 s^{-1}$); c_T is the concentration in the total ($mg\,l^{-1}$ or ‰); and c_1, c_2 are the end-member concentrations of the tracers in the respective runoff component ($mg\,l^{-1}$) or (‰).

The exact definition of the two or three runoff components depends on the properties of the tracer used (Wels et al., 1991). Two commonly used groups of tracers are:

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(1) stable isotopes of water, oxygen-18 (^{18}O) and deuterium (^{2}H) (e.g. Sklash and Farvolden, 1979; Sklash et al., 1986) and (2) weathering products such as Mg^{2+}, Ca^{2+}, Cl^{-} and SiO_2 (e.g. Pinder and Jones, 1969; Wels et al., 1991).

With a known concentration of the end members for subsurface and surface runoff, the contribution from these sources can be calculated (Mul et al., 2008). The concentration for sub-surface (including soil water and groundwater) runoff was assumed to be the concentration of the pre-event water at the sampling point and the concentration of the surface runoff was assumed to be similar to concentrations observed in a rainfall sample (Buttle, 1994; Mul et al., 2008). Therefore, the total discharge Q_T and concentrations c_T, c_1 and c_2 are known and it follows:

$$Q_2 = \frac{c_T - c_1}{c_2 - c_1} Q_T \qquad (3)$$

$$Q_1 = Q_T - Q_2 \qquad (4)$$

Hrachowitz et al. (2011) applied hydrochemical tracers in combination with isotopic tracer methods for hydrograph separation in a semi-arid catchment. They found that the assumption of stable isotopic end members was not met for both the groundwater samples and the rain water samples. At the small scale the spatial variability could be negligible and the technique becomes better applicable, although for each event, end member concentrations needed to be determined separately to account for the temporal variability. Due to this temporal variation occurrence, hydrograph separation was performed in this paper using the cumulative incremental weighting approach, Eq. (5), based on sampled rainfall amount as recommended by McDonnell et al. (1990):

$$\delta^{18}O = \frac{\sum_{i=1}^{n} P_i \delta_i}{\sum_{i=1}^{n} P_i} \qquad (5)$$

Where P_i and δ_i denote fractionally collected rainfall amounts and δ value (isotope concentration), respectively. The weighted mean represents the average isotopic composition of the new water input to the catchment but does not address the within-storm

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isotopic variability or the time response of the catchment to new water (McDonnell et al., 1990).

4 Results

4.1 Rainfall-runoff observations for Itumba'10 and 11 seasons (March–May)

The observed discharges in the center of the Migina catchment at Kansi station, for data recorded from 1 May 2009 to 31 June 2011, were in the range of 0.24–9.16 $m^3 s^{-1}$ and average discharge was estimated to 1.71 $m^3 s^{-1}$. The observed discharges at the outlet of Migina catchment (at Migina station), for data recorded from 1 August 2009 to 31 June 2011, were in the range of 0.43–15.60 $m^3 s^{-1}$ with an average discharge of 3.35 $m^3 s^{-1}$.

Rainfall measurements have been done at 13 manual rain gauges installed in the Migina catchment (only Gisunzu and Murama rain stations were not considered for the areal rainfall of the Kansi sub-catchment) (see Fig. 1). The amount of rainfall in both Kansi and Migina catchments were estimated using the Thiessen polygon method, which seems appropriate due to spatial distribution of the rainfall stations and the low topographic gradients.

Figure 2 shows the rainfall and discharge patterns observed at Kansi (Fig. 2a) and Migina (Fig. 2b) gauging stations during the investigated periods (Itumba'10 and Itumba'11). The in detail investigated two flood events are event K6 for Kansi station and event M3 for Migina station (Tables 1 and 2). Seasonal rainfall totals to 552 mm and 508 mm for Kansi sub-catchment and Migina catchment, respectively. These seasonal rainfall totals generate on average a runoff of 2.42 $m^3 s^{-1}$ (148.7 mm) at Kansi station, and 5.75 $m^3 s^{-1}$ (177.7 mm) at Migina station.

The time series of rainfall and runoff for storm event K6 and M3 represent the intensive monitoring periods in this research. Maximum daily rainfall of 32.9 mm d^{-1} was

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observed on 2 May 2010 in Kansi sub-catchment and the runoff generated by this rainfall at Kansi station reaches its peak at the same day at 03:00 LT (9.05 $m^3 s^{-1}$). The river discharge returns to pre-event values on 5 May 2010 when the surface runoff contribution stopped. Similarly, a maximum daily rainfall of 23.7 mm d^{-1} was observed on 2 May 2011 in 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 $m^3 s^{-1}$). The river discharge returns to pre-event values on 6 May 2011 when the surface runoff contribution stopped.

Tables 1 and 2 show the main hydrological characteristics of 8 different events during Itumba'10 and 5 different events monitored during Itumba'11 at Kansi and Migina gauging stations, respectively. Runoff coefficients were observed ranging from 16.7 % to 44.5 % with maximum rainfall intensities up to 16.6 mm h^{-1} for Itumba'10 and 17.6 mm h^{-1} for Itumba'11. The observed runoff coefficient values are considered low and are in the range for an agricultural dominated catchment (e.g. Larsen et al., 2007). This gives a hint towards the importance of infiltration and subsurface flow generation during events.

Most rain events during both seasons Itumba'10 and Itumba'11 are moderate (2.5 to 7.5 mm h^{-1}) or heavy (> 7.5 mm h^{-1}). Only light rain is observed on 2 March 2010 at 07:05 a.m. (2.0 mm h^{-1}) and on 5 March 2010 at 04:20 a.m. (0.8 mm h^{-1}) for the Itumba'10 season (Table 1). The observed low runoff coefficients, for Kansi sub-catchment (16.7–44.5 %) and Migina catchment (31.5–44.4 %) indicate that a high percentage of the rainfall becomes subsurface runoff. Rainfall amount and runoff volume show a strong correlation ($r = 0.93$, $n = 18$) for Kansi sub-catchment and ($r = 0.95$, $n = 19$) for Migina catchment.

4.2 Results of hydrochemical tracer studies

The most important hydro-chemical parameters of the water samples from springs, rivers, rainfall and shallow groundwater wells are presented in Table 3.

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Table 3 shows that the concentrations of all chemical components in surface water are close to the concentrations of water sampled from springs and piezometers during flood events. Only the opposite can be seen in dissolved silica (SiO_2) and electrical conductivity (EC) concentrations. This indicates that surface discharge is dominated by subsurface runoff components during flood events in the Migina catchment. This agrees with the low runoff coefficients observed in the catchments (Tables 1 and 2).

Figure 3 shows the concentrations of dissolved silica and chloride during the two investiagted events. The hydrograph is rising from $2.6\,m^3\,s^{-1}$ to $9.1\,m^3\,s^{-1}$ at Kansi river and from $6.5\,m^3\,s^{-1}$ to $11.8\,m^3\,s^{-1}$ at the outlet of Migina catchment. Unfortunately, baseflow was not sampled for the season Itumba'10 (Fig. 3a) but sampled for season Itumba'11 (Fig. 3b).

Hourly SiO_2 and Cl^- concentrations observed in stream water during the event of 1 to 2 May 2010 do not show clear trends but a small increase was observed during the peak flow and followed by constant concentrations for Cl^-, and smooth recession towards background concentration for SiO_2 (Fig. 3a). The observed concentrations during low flows for season Itumba'11 do not present clear trends as well but increase and decrease near the peak can be seen during the flood event (Fig. 3b). This means that the hydrochemical parameters (SiO_2 and Cl^-) show a similar behavior for this event, remain constant during low flows, between 10–$12\,mg\,l^{-1}$ for SiO_2 and 5.8–$7.6\,mg\,l^{-1}$ for Cl^-, and distinct variations were observed during flood events, between 4–$18\,mg\,l^{-1}$ for SiO_2 and 4.6–$7.7\,mg\,l^{-1}$ for Cl^- (Fig. 3b).

Figure 4 shows that hydrograph separations using dissolved silica (Fig. 4a) and chloride (Fig. 4b) as tracers show that subsurface runoff during the event on 2 May 2010 is dominating the surface runoff and contributes from 54 to 89 % (about 75 % on average) and from 50 to 85 % (about 70 % on average), respectively. This confirms the results of low contribution of direct surface runoff, supported by low runoff coefficients (Tables 1 and 2). Due to the fact that the whole rising limb, peak and recession limb were not captured completely for this event, the entire streamflow generated by groundwater could not be quantified. However, the dominance of subsurface runoff was observed

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during the staring time of the event sampling and subsurface runoff contributed 77.2 %, which allows assuming that the overall contribution of surface runoff is relative small. The fact that surface runoff could be detected even before the main event is due to rainfall distribution during the rainy season that triggered some surface runoff generation and (delayed) inflow to the river throughout the season.

The observed maximum contributions of surface runoff during the peak flows are not similar in terms of timing for the separations using dissolved silica (SiO_2) and chloride (Cl^-). Using SiO_2 the maximum surface runoff contribution (45 %) was observed on 2 May 2010 at 15:00 LT, then one hour later the peak runoff was reached at 16:00 LT while using Cl^- about 50 % of this contribution was observed at the same time as the peak runoff (on 2 May 2010 at 15:00 LT). The observed subsurface runoff dominance is also supported by the findings of Munyaneza et al. (2011) who showed that groundwater in the valleys in the Migina catchment is very shallow (depth between 0.2–2 m) and infiltrated rain water can reach the groundwater quickly and contribute to subsurface stormflow and baseflow.

Figure 5 shows the hydrograph separations using dissolved silica (Fig. 5a) and chloride (Fig. 5b) as tracers during the event of 29 April 2011 to 6 May 2011 at Migina station. The results are similar as the separations for event of 1–2 May 2010 at Kansi station. Subsurface runoff is dominating the surface runoff and contributes from 53 to 89 % (about 75 % on average) and from 56 to 99 % (about 80 % on average) using dissolved silica and chloride, respectively.

The results of the two-component hydrograph separations show that almost the entire flood was generated by subsurface runoff (80 %) and the surface runoff contribution hardly varies during the event except some increase during the peak times. Similar to the event of May 2010 (Fig. 4), the maximum contribution of surface runoff during the event of May 2011 was observed at slightly different times for both tracers. Using dissolved silica for hydrograph separation, maximum surface runoff contribution was observed three hours before the peak runoff was reached (on 2 May 2011 at 07:00 LT) and contribute 47 %, while for chloride the maximum was observed two hours before

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the peak runoff was reached (on 2 May 2011 at 08:00 LT) and contribute up to 44 %. The falling limb is largely dominated by subsurface runoff.

4.3 Results of isotopes tracer studies

The assumptions of hydrograph separation (Sect. 3.3) have been investigated by comparing the temporal and spatial variability of the different tracers in rain water and groundwater from springs and piezometers. In other words, the stability of end members was tested for the application of the three-component hydrograph separation technique.

Table 4 shows that the mean values of δ^2H and δ^{18}O in surface water runoff are −11.4 ‰ and −3.5 ‰ for δ^2H; and −3.0 ‰ and −1.5 ‰ for δ^{18}O, respectively. The values of these isotopes in rainfall water are −16.9 ‰ and −7.8 ‰ for δ^2H; and −4.3 ‰ and −3.3 ‰ for δ^{18}O, respectively. The mean values of δ^2H and δ^{18}O were also investigated in the same two catchments (Kansi and Migina) in the whole period of research (May 2009–June 2011) for groundwater monitoring during floods and low flows. Their values in shallow groundwater from piezometers are −15.2 ‰ and −3.7 ‰, respectively. The mean values of δ^2H and δ^{18}O in water sampled from springs are −9.4 ‰ and −8.8 ‰ for δ^2H and −3.1 ‰ and −3.2 ‰ for δ^{18}O, respectively.

End member concentrations for deep and shallow groundwater were estimated based on data from piezometers located on the upper part of a hillslope and on a near stream location (Munyaneza et al., 2010). The end member for rainfall samples was taken as an average of rainwater sampled at 4 automatic rainfall stations (see Fig. 1).

Figure 6 shows stable isotopes (^{18}O and ^{2}H) in the water sampled in the Kansi sub-catchment and Migina catchment during the 2-yr study period. The slope of the constructed Local Meteoric Water Line for Butare (LMWL Butare, $\delta^2\text{H}=7.72\cdot\delta^{18}\text{O}+16.12$ ‰; $n=103$) is close to the one of the Global Meteoric Water Line (GMWL, $\delta^2\text{H}=8.13\cdot\delta^{18}\text{O}+10.8$ ‰), but has a significantly different intercept. The isotopic composition of the rainfall is clearly different in the dry and wet season, and the wet season

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rainfall signature dominates the other water balance components (surface and subsurface water). Interestingly, the isotope values of the observed springs are not influenced by dry season rainfall values, as they all plot below 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.

The figure shows also that most of the stables isotopes of groundwater and spring water in the catchments are lighter than those of the stream waters and they are even plotted below the LMWL. This means probably that infiltrated water is affected by evaporation before reaching the groundwater system (temporary storage in soil zone). Similar results were found for instance by Kabeya et al. (2007) in a forested watershed.

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).

Figure 7 shows the results of the three-component separation method using dissolved silica and deuterium as tracers for the investigated event of 2 May 2010 at Kansi station. The results are comparable to the results obtained from the two-component hydrograph separations (see Sect 4.2). Old water (deep and shallow groundwater, $Q_{dgw} + Q_{sgw}$) is dominating the discharge generation in this event and is contributing 38–98 % (about 80 % on average) to the total discharge (Q_t). New water (direct runoff, Q_{dir}) dominates at few hours (on 1 May 2010 at 17:00 LT) during the rising limb and contributes there about 60 %. The peak flow is also dominated by old water (76.7 %) and occurred on 2 May 2010 at 03:00 LT. Note that the shallow groundwater has been samples in the valley, and the deep groundwater has been analyzed at perennial springs with constant discharge and hydrochemical characteristics.

In the present study, the rainfall was sampled intensively during the event of 29 April 2011 to 6 May 2011 with a high temporal resolution of rainfall samples for isotope analysis (Fig. 8). The δ^{18}O value of the rainfall event ranges between −1.93 ‰ to −1.24 ‰ and the mean bulk rainfall δ^{18}O value for the whole event is equal to −1.52 ‰

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(see Fig. 8). Due to the observed low temporal variations of isotopes in rainfall the incremental weighting approach based on rainfall amount was applied, Eq. (5), as recommended by McDonnell et al. (1990).

Figure 8 shows the δ^{18}O values of rainfall calculated using the incremental weighting approach, Eq. (5), and the values fluctuate between −1.71 ‰ to −1.48 ‰ (Fig. 8a). For the three-component hydrograph separation of this event the isotopic signature of rain water (incremental means) was considered (Fig. 9). Therefore, the end member value for rainfall is not constant, but varied over time.

Figure 9 shows the results of the three-component separation using dissolved silica and oxygen-18 as tracers. During this event, old water (deep and shallow groundwater, $Q_{dgw} + Q_{sgw}$) was chiefly responsible for stream generation and is contributing to the total discharge 10–98 % (about 60 % on average). Maximum dilution occurred at the hour of peak discharge (on 2 May 2011 at 10:00 LT) and new water (direct runoff, Q_{dir}) contributes for a short period about 70 %. In this case the peak is dominated by direct runoff but the total discharge (Q_T) is dominated by subsurface water as found in the event of May 2010. The results found for this separation are somewhat different from previous results, but the assumptions of the methods vary (Sect. 3.3) and we do not have independent experimental data that can prove the stormflow composition during peak flow.

5 Discussion

Rainfall and discharge data used in this research were collected over two years (May 2009–June 2011) and the rainy season "Itumba" was investigated in further detail. Low runoff coefficients for different events were determined ranging between 16.7 and 44.5 % for Kansi sub-catchment (Table 1) and between 31.5 and 44.4 % for Migina catchment (Table 2). This indicates that the stormflow reaches the stream largely through the soil by subsurface runoff due to high infiltration rates. This type of runoff

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generation was supported by observed chemical concentrations in surface water which are closer to the concentrations of water sampled from springs and piezometers during flood events (Table 3).

The high infiltration 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 5 m d^{-1} to 30 m d^{-1}). Munyaneza et al. (2011) also found the average runoff coefficient of Migina catchment to be 25 %, which is in the range of the results found in this study. In the same study, they also found that Migina catchment is dominated by agricultural land use (92.5 %) while the range of runoff coefficients found in this current study (16.7–44.5 %) agrees with the range for agricultural dominated catchments found by Larsen et al. (2007). However, it is concluded from the rainfall-runoff response analysis that runoff generation at the Kansi and Migina catchments is dominated by subsurface flows (see Tables 1 and 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^+, Mg^{2+}, and Ca^{2+}) could not be used for hydrograph separations, because they showed constant concentrations during the events (like to due to non-conservative transport behaviour) and did not provide additional insights. Their concentrations in surface runoff and groundwater were too similar to do reliable hydrograph separations. Richey et al. (1998) used the same method and found that chemical tracers like SiO_2 and Cl^- may be non-conservative in subsurface water on longer timescales, but they can be assumed to behave conservatively on the time scale of a single runoff event. These findings indicate that spatial variability in the components may be more important when determining the precision of the old water fraction. In fact, direct runoff or new water data generated by the selected four tracers in this study offer insights into how the catchments respond hydrologically and were used to develop a conceptual model of how catchment generates runoff.

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The two-component hydrograph separation model using dissolved silica and chloride led to a high amount of subsurface contribution (up to 80 %) in both catchments. For both investigated events at Kansi and Migina station, the direct runoff component did not exceed 33.7 and 28.7 % of the total event runoff, respectively. The observed dominance of subsurface runoff in these two storm events was probably facilitated by the wet conditions during the long rainy season (Fig. 2).

The three-components runoff separation model using dissolved silica and deuterium, and using dissolved silica and oxygen-18 shows somewhat different results but both confirmed the high contribution of pre-event runoff components (about 80 % using SiO_2 and ^2H; and about 60 % using SiO_2 and ^{18}O). The observed differences could be due to the consideration of spatial and temporal variability of oxygen-18 concentrations in rainfall during the event of May 2011 where rain water was sampled. For the two investigated events (Figs. 7 and 9), the mean value of the new water component is 31.9 and 38.8 % of the total runoff for event of May 2010 and 2011, respectively.

The dominance of subsurface water found using three-component separations confirms the assumption of a relatively small contribution of surface runoff. The observed dominance of old water (up to 80 %) in the Migina catchment confirms the finding of van den Berg and Bolt (2010) in their study during the dry season. They found that the locations of shallow groundwater in the Migina catchment are between 0.2 m and 2 m, which enables infiltrated rain to reach the groundwater quickly and contribute to subsurface stormflow and later to baseflow. This dominance was also explained by McDonnell (1990) by the fact that the rapid flow of new rainwater through downward crack macropores backs up into the soil matrix at the soil-bedrock interface. The findings of this current paper were also supported by results from several other hydrochemical (and isotopic) studies that found old water and subsurface flows 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).

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6 Conclusions

The applicability of tracer methods in conjunction with hydrometric measurements for identifying dominant runoff generation processes in a meso-scale catchment was tested. The two- and three-components hydrograph separation models using hydrochemical (dissolved silica and chloride) and isotope (deuterium and oxygen-18) tracers show that intensive water sampling (hourly) during events is essential. The whole rising limb, peak and recession limb need to be captured completely for the event in order to gain more understanding of runoff generation processes. In addition, different geographic sources of runoff need to be observed before, during and after the events. The outcomes of such an investigation are essential for sustainable water resources management.

The results of this study demonstrated the importance of subsurface flows for stream flow generation in the study area. 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. Oxygen-18 (^{18}O) and deuterium (^{2}H) were found to be suitable tracers to detect old water sources. Additionally, it was found that groundwater has two different origins: one source originates from a near stream location in the valleys (shallow groundwater) and the other source is deep groundwater sampled at piezometers and springs located on the upper part of the hillslopes (Sect. 4.3). It is apparent from the rainfall-runoff response analysis that runoff generation at the Kansi sub-catchment and Migina catchment is dominated by shallow groundwater (Tables 1 and 2). The significant groundwater recharge during the wet seasons led to the perennial river system observed in the catchment. The isotope analysis showed that all runoff components including baseflow is dependent on wet season rainfall.

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Table 1. Rainfall-runoff events during Itumba'10 season in the Kansi sub-catchment (129.3 km^2). The investigated event K6 is given in bold.

Event N°	Date	Time	Rainfall event: Duration (h)	Rainfall event: Maximum rainfall intensity ($mm\,h^{-1}$)	Rainfall amount (mm)	Runoff event: Peak runoff ($m^3\,s^{-1}$)	Runoff event: Peak storm runoff ($mm\,h^{-1}$)	Runoff volume ($10^4\,m^3$)	Total Runoff (mm)	Runoff coef. (%)
K1	2 Mar	07:05	8.0	2.0	41.98	3.91	0.109	119.5	9.24	22.0
K2	5 Mar	04:20	7.0	0.8	27.92	4.47	0.124	144.0	11.13	39.9
K3	28 Mar	10:35	7.0	5.6	70.09	5.23	0.146	229.9	17.78	25.4
K4	16 Apr	07:35	8.0	11.2	74.04	6.47	0.180	159.9	12.37	16.7
K5	19 Apr	10:50	11.3	9.2	79.51	6.63	0.185	293.5	22.70	28.5
K6	**2 May**	**03:00 LT**	**22.0**	**16.6**	**113.27**	**9.05**	**0.252**	**265.0**	**20.49**	**18.1**
K7	11 May	23:50	5.5	10.6	47.12	4.69	0.131	120.6	9.32	19.9
K8	14 May	18:20	6.0	3.6	50.57	5.26	0.147	291.3	22.53	44.5

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Table 2. Rainfall-runoff events during Itumba'11 season in the Migina catchment (257.4 km^2). The investigated event M3 is given in bold.

Event N°	Date	Time	Rainfall event			Runoff event				
			Duration (h)	Maximum rainfall intensity ($mm\,h^{-1}$)	Rainfall amount (mm)	Peak runoff ($m^3\,s^{-1}$)	Peak storm runoff ($mm\,h^{-1}$)	Runoff volume ($10^4\ m^3$)	Total Runoff (mm)	Runoff coef. (%)
M1	5 Mar	09:38	11.0	12.0	75.87	7.89	0.110	615.8	23.92	31.5
M2	28 Mar	00:08	6.2	14.8	49.87	10.46	0.146	570.5	22.16	44.4
M3	**2 May**	**10:00 LT**	**14.0**	**17.6**	**96.32**	**11.78**	**0.165**	**883.6**	**34.32**	**35.6**
M4	11 May	03:51	2.5	7.6	42.47	7.57	0.106	421.4	16.37	38.5
M5	22 May	02:20	10.0	9.4	54.31	7.69	0.108	447.3	17.37	32.0

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Table 3. Hydrochemical concentrations observed in the Kansi sub-catchment and Migina catchment during the investigated research period. *n* represents the number of samples. The entries in brackets represent the standard deviation values.

			Rainfall ($n=103$)		Surface water ($n=173$)		Groundwater ($n=59$)		Springs ($n=34$)	
	Parameter	Unit	Kansi	Migina	Kansi	Migina	Kansi	Migina	Kansi	Migina
	pH	–	6.0 (0.7)	6.1 (1.3)	6.9 (1.0)	6.8 (0.8)	6.0 (1.1)	6.0 (1.1)	5.0 (1.0)	5.1 (0.9)
	EC	$\mu S\,cm^{-1}$	67.7 (44.2)	52.3 (47.4)	99.1 (9.6)	135.5 (63.2)	217.3 (73.8)	217.3 (73.8)	131.7 (21.4)	127.6 (24.4)
	SiO_2	$mg\,l^{-1}$	2.8 (3.9)	1.8 (3.3)	8.8 (5.1)	11.3 (5.2)	16.2 (8.5)	16.2 (8.5)	21.7 (3.9)	22.9 (5.8)
Anions	SO_4^{2-}	$mg\,l^{-1}$	1.2 (2.3)	1.3 (2.0)	8.3 (2.1)	8.4 (2.0)	9.2 (2.8)	9.2 (2.8)	3.1 (1.6)	5.0 (1.7)
	Cl^-	$mg\,l^{-1}$	0.52 (0.4)	1.0 (1.5)	4.16 (2.4)	6.4 (2.1)	1.2 (2.1)	1.2 (2.1)	5.6 (3.6)	5.6 (3.4)
Cations	K^+	$mg\,l^{-1}$	1.0 (0.9)	1.5 (1.0)	1.1 (0.2)	1.3 (0.2)	3.3 (0.7)	3.3 (0.7)	2.1 (0.5)	3.2 (1.4)
	Mg^{2+}	$mg\,l^{-1}$	0.3 (0.4)	0.5 (0.5)	1.9 (0.4)	2.5 (0.4)	2.9 (1.3)	2.9 (1.3)	3.2 (1.0)	3.4 (1.1)
	Ca^{2+}	$mg\,l^{-1}$	0.7 (1.1)	1.5 (0.9)	3.2 (0.6)	5.0 (0.7)	13.7 (7.8)	13.7 (7.8)	10.1 (2.5)	8.8 (2.6)
	Na^+	$mg\,l^{-1}$	–	24.4 (14.1)	–	36.4 (9.4)	55.7 (11.3)	55.7 (11.3)	6.7 (1.1)	6.1 (0.9)

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Table 4. Isotope concentrations observed at Kansi sub-catchment and at Migina catchment during the investigated research period. *n* represents the number of samples. The entries in brackets represent the standard deviation values.

			Rainfall ($n = 145$)		Surface water ($n = 173$)		Groundwater ($n = 28$)		Springs ($n = 18$)	
	Parameter	Unit	Kansi	Migina	Kansi	Migina	Kansi	Migina	Kansi	Migina
Isotopes	δ^2H	(‰)	−16.9 (21.3)	−7.8 (16.6)	−11.4 (7.3)	−3.5 (6.7)	−15.2 (3.9)	−15.2 (3.9)	−9.4 (1.2)	−8.8 (2.3)
	$\delta^{18}O$	(‰)	−4.3 (3.6)	−3.3 (2.5)	−3.0 (1.0)	−1.5 (1.0)	−3.7 (0.6)	−3.7 (0.6)	−3.1 (0.3)	−3.2 (0.3)

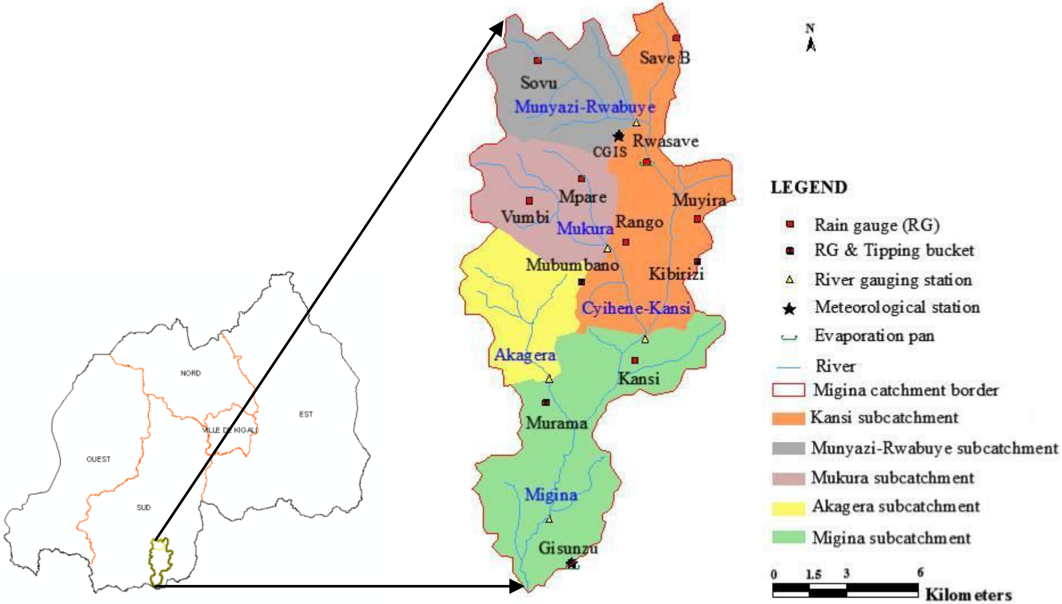

Fig. 1. Location of the Migina catchment in Rwanda and instrumentation set-up within this research framework showing the positions of Kansi and Migina gauging stations.

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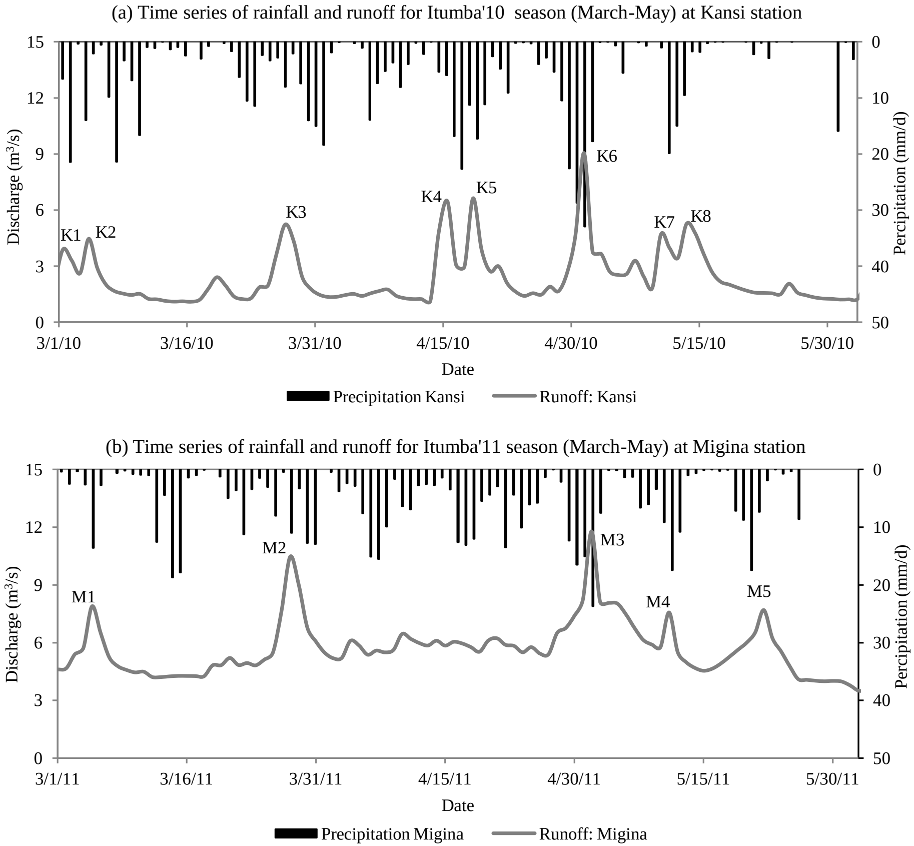

Fig. 2. Time series of rainfall and runoff events during March–May 2010 at Kansi station **(a)** and March–May 2011 at Migina station **(b)**.

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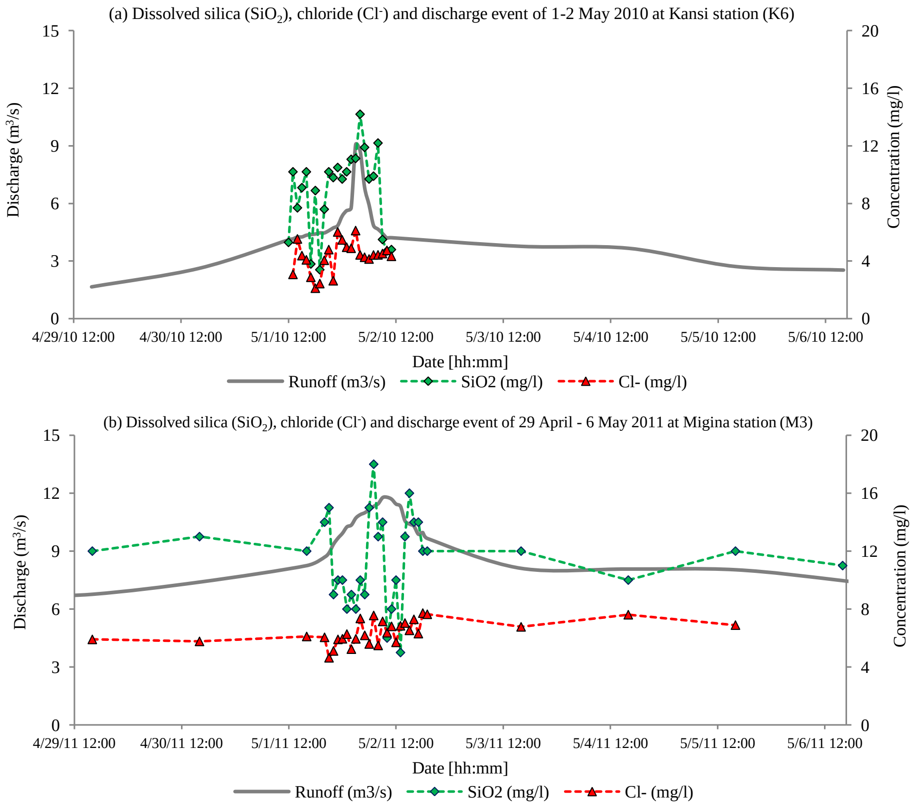

Fig. 3. Hydrochemical parameter responses at Kansi station during 1 to 2 May 2010 storm event **(a)** and at Migina station during 29 April to 6 May 2011 storm event **(b)**.

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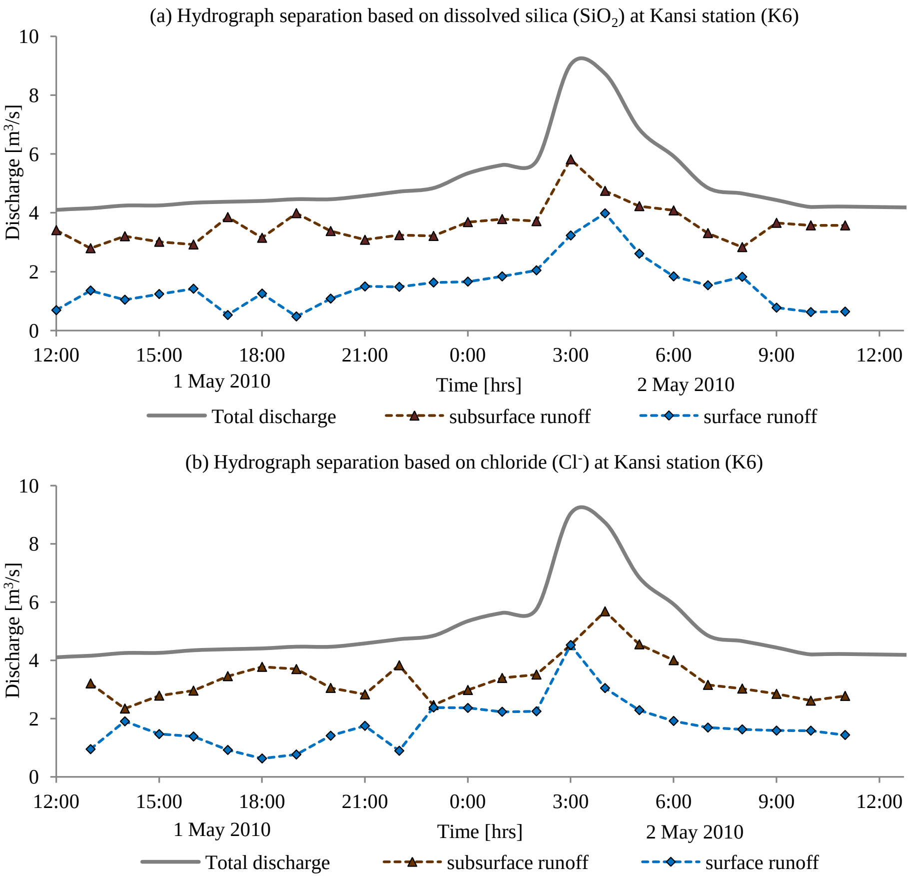

Fig. 4. Results of two-component hydrograph separations based on dissolved silica **(a)** and chloride **(b)** for subsurface and surface runoff for event K6 (see Fig. 2a) investigated from 1 May 2010 at 12:00 LT to 2 May 2010 at 11:00 LT at Kansi station.

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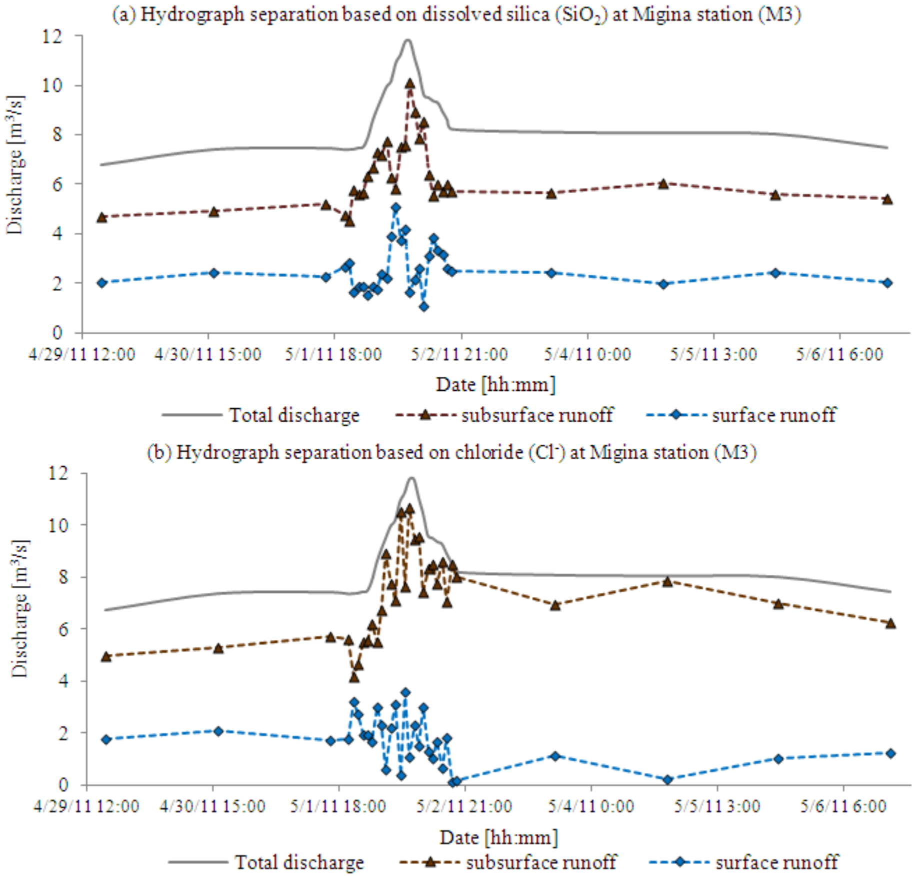

Fig. 5. Two-component hydrograph separations based on dissolved silica **(a)** and chloride **(b)** for subsurface and surface runoff for event M3 (see Fig. 2b) investigated from 29 April to 6 May 2011 at Migina station.

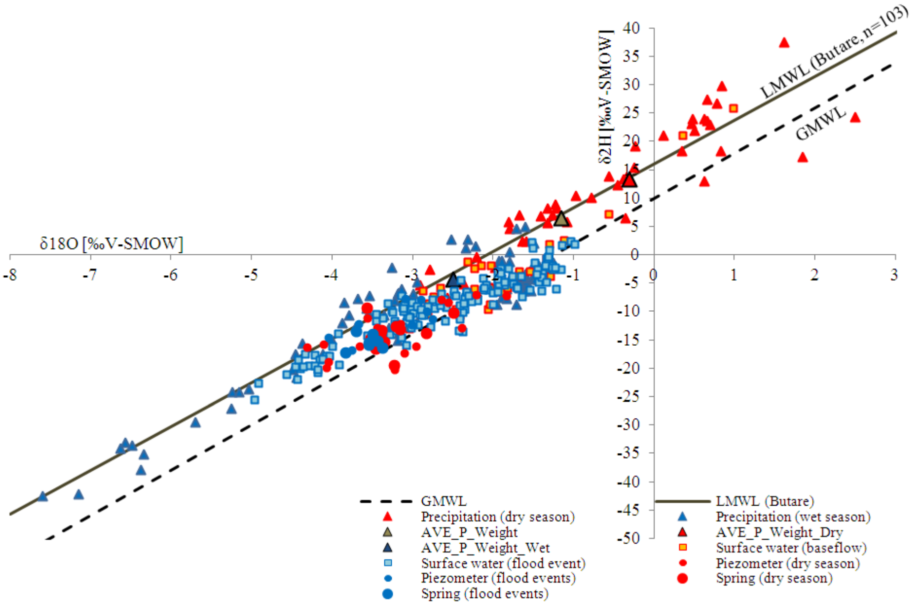

Fig. 6. Stable isotope compositions of rainfall, surface water, springs, shallow groundwater, and amount weighted rainfall for dry and wet seasons. GMWL: $\delta^2\mathrm{H}=8.13\cdot\delta^{18}\mathrm{O}+10.8$ (Source: Clark and Fritz, 1997).

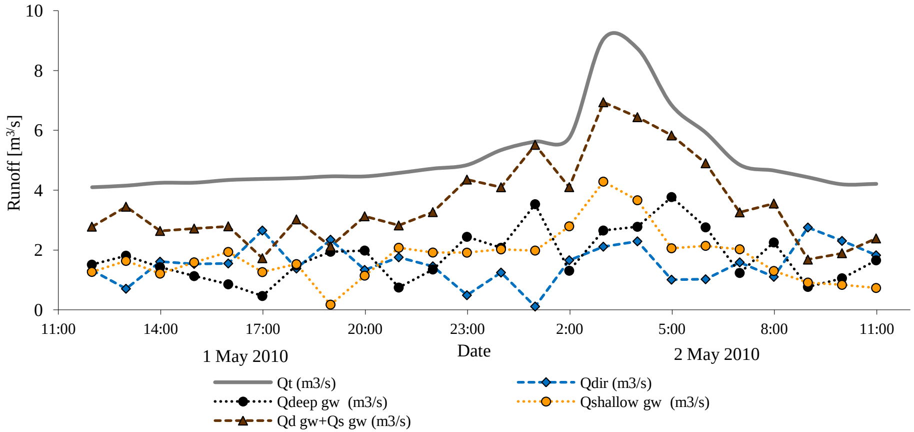

Fig. 7. Results of the three-component separation using dissolved silica and deuterium as tracers for event K6 (see Fig. 2a) investigated from 1 May 2010 at 12:00 LT to 2 May 2010 at 11:00 LT at Kansi station.

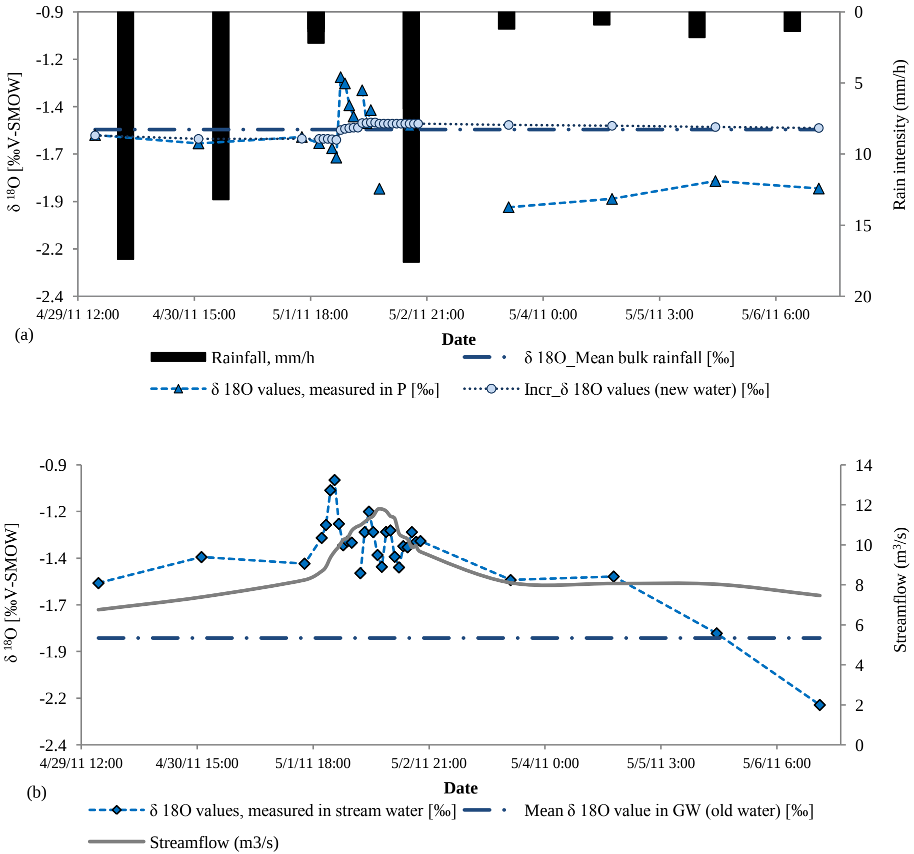

Fig. 8. Hourly rainfall and variations of δ^{18}O in rainfall **(a)**, discharge and variations of δ^{18}O in the stream water **(b)** during the 29 April 2011 to 6 May 2011 storm event.

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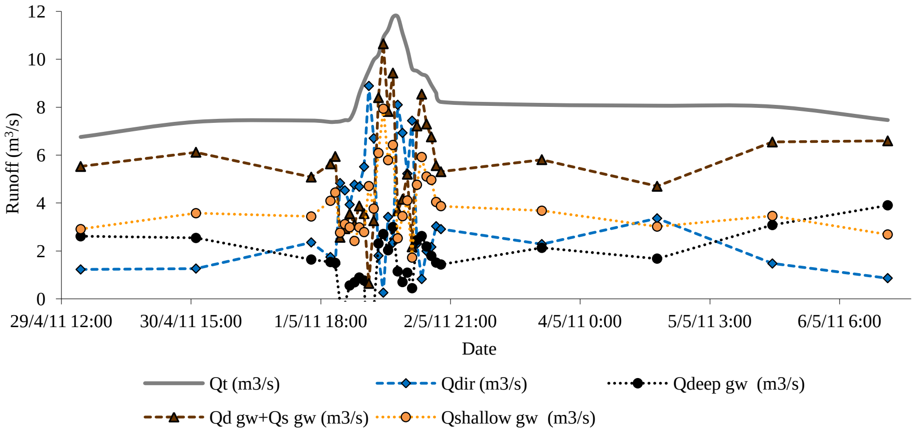

Fig. 9. Results of the three-component separation using dissolved silica and oxygen-18 as tracers for event M3 (see Fig. 2b) investigated from 29 April 2011 to 6 May 2011 at Migina station.

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