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Assessment of surface water resources availability using catchment modeling and the results of tracer studies in the meso-scale Migina Catchment, Rwanda

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Abstract

In the last couple of years, different hydrological research projects were undertaken in the Migina catchment (243.2 km^2), a tributary of the Kagera river in Southern Rwanda). These projects were aimed to understand hydrological processes of the catchment using analytical and experimental approaches and to build a pilot case whose experience can be extended to other catchments in Rwanda. In the present study, we developed a hydrological model of the catchment, which can be used to inform water resources planning and decision making. The semi-distributed hydrological model HEC-HMS (version 3.5) was used with its soil moisture accounting, unit hydrograph, liner reservoir (for base flow) and Muskingum-Cunge (river routing) methods. We used rainfall data from 12 stations and streamflow data from 5 stations, which were collected as part of this study over a period of two years (May 2009 and June 2011). The catchment was divided into five sub-catchments each represented by one of the five observed streamflow gauges. The model parameters were calibrated separately for each sub-catchment using the observed streamflow data. Calibration results obtained were found acceptable at four stations with a Nash–Sutcliffe Model Efficiency of 0.65 on daily runoff at the catchment outlet. Due to the lack of sufficient and reliable data for longer periods, a model validation (split sample test) was not undertaken. However, we used results from tracer based hydrograph separation from a previous study to compare our model results in terms of the runoff components. It was shown that the model performed well in simulating the total flow volume, peak flow and timing as well as the portion of direct runoff and base flow. We observed considerable disparities in the parameters (e.g. groundwater storage) and runoff components across the five sub-catchments, that provided insights into the different hydrological processes at sub-catchment scale. We conclude that such disparities justify the need to consider catchment subdivisions, if such parameters and components of the water cycle are to form the base for decision making in water resources planning in the Migina catchment.

1 Introduction

Water resources availability is often the most vital factor controlling the economic growth in developing countries, which depend on agriculture (Abushandi, 2011). It is obvious that the water challenges will be of utmost and increasing significance throughout the next decades. Extensive care should therefore be given to the operation and management of river basins, focusing on water supply, irrigation, and drought or flood control, in order to cope with water related problems. This situation also applies to Rwanda, where the implementation of sustainable water management interventions is essential to increase or sustain water resources, especially for the agriculture and livestock sectors (UNEP, 2005). The same situation drove the Rwandan government to implement new projects that provide the country with more usable fresh water and increase water availability in the marshlands for agricultural purpose (MINITERE, 2005). Unfortunately, the farmers who use these marshlands do not have appropriate methods for maximizing their production due to the lack of knowledge on water availability in the marshlands. Water resources assessment at the catchment scale is therefore one of the key activities to provide insight on water available for agricultural purpose (Abdulla et al., 2002; Al-Adamat et al., 2010).

The water resources availability assessment requires detailed insights into hydrological processes. However, studying the complexity of hydrological processes, needed for sustainable catchment management, is basically based on understanding rainfall characteristics and catchment properties (Abushandi, 2011), which calls for rainfall–runoff modeling studies (Yener et al., 2007). Rainfall–runoff models have been broadly used in hydrology over the last century for a number of applications, and play an important role in optimal planning and management of water resources in catchments (e.g. Pilgrim et al., 1988; O'Loughlin et al., 1996). Pilgrim et al. (1988) and Oyebande (2001) reported that the main challenge associated with applying successfully rainfall–runoff model lies in the lack of monitored data, mainly rainfall spatial distribution over the catchment area, since rainfall is the primary input in any hydrological model. Another potential problem is having no reliable flow data that can lead to reliable calibration and validation of catchment parameters. In particular, the latter challenge applies to Rwanda, where many catchments are ungauged or even those gauged have unreliable information.

In the present study, the Hydrologic Engineering Center – the Hydrologic Modeling System (HEC-HMS) was adopted as hydrologic modeling tool for assessing the water resources availability in a meso-scale catchment, due to its simplicity in setting-up, low data demand for running simulations, and the fact that it is a public domain software.

The HEC-HMS is a semi-distributed hydrological model, designed to simulate the rainfall–runoff processes for catchment systems (USACE, 2008; Scharffenberg and Fleming, 2010). Its design allows applicability in a wide range of geographic areas for solving diverse problems including large river basin water supply and flood hydrology, and small urban or natural catchment runoff (Merwade, 2007). The model contains parameters that cannot frequently be measured directly, but can only be estimated by calibration using historical records of measured input and output data. The simulation results, especially the water balance components, provide information on water resources available in a catchment for different purposes including, but not limited to, agriculture and domestic purposes. The flow results coupled with the basin characteristics (slopes and imperviousness) can also be used in planning for watershed management measures including but not limited to erosion control, soil moisture and land management related measures (Sardoii et al., 2012).

Many researchers have used the rainfall–runoff simulation methods contained in HEC-HMS (e.g. Christopher and Yung, 2001; Emerson et al., 2003; Radmanesh et al., 2006; Sardoii et al., 2012). For instance, Radmanesh et al. (2006) calibrated and validated the HEC-HMS model in a catchment using different methods incorporated in the model. Their results showed that the SCS method resulted in better agreement between peak discharge of observed and simulated hydrographs than other HEC runoff computation methods. Rainfall–runoff correlation in HEC-HMS was modeled by Emerson et al. (2003). Results revealed that natural reserved and protected areas decrease the peak of storm events. Christopher and Yung (2001) carried out a study by using HEC-GeoHMS and HEC-HMS to perform a grid-based hydrologic analysis of a catchment. They compared distributed, semi-distributed and lumped models. The results showed reasonable predictions to observations of flood and runoff volume. All the above successful stories justify the attempt in determining water budget components in the Migina catchment using HEC-HMS model.

In the last five years, Rwanda has been moving from centralized to decentralized water resources management. The ultimate goal is to manage water resources in an integrated way and at the lowest possible basin level. The Rwanda National Water Resources Master Plan (RNRA, 2013) has divided the country's watershed into four levels with two main basins of the first order (Congo and Nile). The Migina catchment falls under the third level basin, within which minor catchments have more or less uniform hydrological characteristics (mostly defined by land use, topography and geology). The surface areas of basins of the third level are typically of the order of at least 10 to possibly some hundreds of km^2 (RNRA, 2013), and it is at that level that all water resources interventions shall be planned. In other words, for sustainable water resources planning and management, development and related environmental interventions shall be tailored to the characteristics of a specific catchment. Therefore, not only the findings of this study will contribute to enhance the knowledgebase, but will also contribute on informed decision making in water resources development planning in the Migina catchment.

The main objective of this study is to analyse spatial variation of runoff generation characteristics of the Migina catchment using a semi-distributed hydrological model with a view to potentially use it for informing water resources planning and decision making. The model is calibrated using detailed two years of rainfall and runoff data collected as part of this study and tracer-based hydrograph separation results from a previous study (Munyaneza et al., 2012) are used for a limited validation of the model in terms of runoff components.

2 Study area

The study was carried out in the meso-scale Migina catchment which is located in southern Rwanda (Fig. 1). The total area of the Migina catchment is 243.2 km^2. The basin is located in a mountainous area with elevation ranging from 1375 m a.s.l. at the outlet to 2278 m a.s.l. at Mount Huye. Table 1 summarizes the main characteristics of the five sub-catchments.

A number of research studies have been conducted in this catchment during the last few years (Nahayo et al., 2010; van den Berg and Bolt, 2010; Munyaneza et al., 2010, 2012). The University of Rwanda (UR), Huye Campus, which lies in the Migina catchment, supported the idea of to build a pilot demonstration site on which models can be built, tested, and results integrated in water resources development planning processes. The approach applied on the Migina can be used for similar studies in other catchments in the region.

The topographic conditions vary from sub-catchment to sub-catchment, and the slopes vary from 5 to 10 % in the upstream, and from 1 to 21 % in the downstream part of the basin (average slope of the sub-catchments vary between 2 and 3 %) (see Table 1 and Nahayo et al., 2010).

As depicted in Fig. 1, the land cover/land use in the Migina catchment is dominated by agricultural activities (91.2 %). Forests occupy 6.5 %; grass/lawn areas 0.2 %, and urban areas 2.0 % only. This land use distribution indicates that most of the water in the Migina catchment is used for agricultural purposes (rain-fed or irrigation).The catchment boundaries were delineated from the Digital Elevation Model (DEM) map obtained from the USGS website[1] with a resolution of 90 m using GIS tools and sub-catchment areas were generated automatically by HEC-GeoHMS 5.0 with ArcGIS 10.0. The catchment was subdivided into 5 sub-catchments as shown in Fig. 2. Two sub-catchments are located upstream; Munyazi-Rwabuye (38.62 km^2) and Mukura (41.73 km^2); two in the center, Akagera (32.20 km^2) and Cyihene-Kansi (69.61 km^2);

[1] http://www.dgadv.com/srtm30/

and one, which also contains the outlet of the whole catchment: Migina (61.05 km^2) (see Table 1). Migina is the name of the perennial river until it flows into the Akanyaru River, which forms the border between Rwanda and Burundi. The Akanyaru River drains into the Kagera River, which in turn flows into Lake Victoria and later generates the White Nile.

The Migina catchment has a moderate climate with relatively high rainfall and an annual cycle of two rainy seasons, March to May and September to November (FAO, 2005). The mean annual rainfall in the Migina catchment is approximately 1200 mm yr^{-1} and the mean annual temperature is about 20 °C (SHER, 2003). The annual average evaporation in the area is estimated to 917 mm yr^{-1} (Nahayo et al., 2010).

3 Data and methods

The assessment involved collecting and screening required data, selecting and building the rainfall–runoff model, calibrating the simulated flows for each individual subcatchment, and analyzing and interpreting the results.

3.1 Data

In order to build the model, the following hydrological and meteorological data were collected: (i) rainfall; (ii) temperature; (iii) solar radiation; (iv) relative humidity; and (v) stream flows. In the framework of this work, the Migina catchment was equipped with 12 and 5 stations rainfall and streamflow instruments, respectively. Rainfall and runoff data were collected over two years (May 2009 to June 2011), whereas other climatic data were obtained from the CGIS station (Butare), which is operational since February 2006. During this period, rainfall measurements were carried out using 13 manual rain gauges installed in the Migina catchment. Rainfall data from 12 stations were used in this study, given that the rainfall data collected at the CGIS station

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were not complete. The water levels were measured continuously at five river gauging stations using manual recorders (staff gauges) and automatic recorders (mini-diver). Rating curves were established using discharge measurements at different periods. The recorded water levels were converted into discharge values using rating curves ($r^2 = 0.88$, $n = 25$ at Rwabuye station; $r^2 = 0.96$, $n = 25$ at Akagera station; $r^2 = 0.94$, $n = 24$ at Kansi station; $r^2 = 0.80$, $n = 28$ at Mukura station; and $r^2 = 0.97$, $n = 18$ at Migina station).

Daily temperature and solar radiation data used to compute evaporation were collected at the CGIS-Meteo station using Priestley–Taylor method. Rainfall data at 12 stations scattered in the study area were analysed using the Mass Curve Method as shown in Fig. 3.

Figure 3 shows that all plotted mass curves of rainfall in the Migina catchment have similar behavior except for Rango station which shows significantly higher rainfall than other stations due to unknown reasons. The station was still used in the analysis as there was no obvious reason identified to reject it. Other climatic data including temperature, relative humidity, and solar radiation were used as collected at the CGIS station, Butare, in the absence of similar nearby stations for comparison.

Based on the findings of the data quality analysis, it was decided to limit the simulation work in the period between 1 August 2009 and 31 July 2010, with a condition of covering the entire calendar year. However, owing to lack of reliable long time observed flow data, the model validation could not be done in this study and all available data were used for model calibration.

3.2 Methods

Two main tools were used in this study; the HEC-HMS 3.5 for the rainfall–runoff simulation and HEC-GeoHMS 5.0 for catchment delineation.

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Hydrological model (HEC-HMS 3.5)

The latest available version HEC-HMS 3.5 was used in this study. Given rainfall values as input data, the HEC-HMS calculates outflow from the sub-catchment element by subtracting evaporation, calculating surface/direct runoff and adding base flow. The HEC-HMS model requires different input datasets including rainfall, discharge, temperature and solar radiation. A full description of all components in HEC-HMS can be found in the user manual (USACE-HEC, 2010).

The Migina catchment was divided into 5 sub-catchments for computing evaporation and percolation, base flow, transform and routing computation methods, and parameters were defined to convert rainfall into runoff. While running different scenarios, the HEC-HMS creates an output Data Storage System (DSS) file, which stores calculated data from all runs for a given project so that results from a preceding run can be directly compared to results from a new run. For purposes of reading and extracting the DSS file for results analysis, the HEC-DSSVue 2.0.1 tool was used.

The Hydrologic Engineering Center's Geospatial Hydrologic Modeling System (HEC-GeoHMS) Version 5.0 was used with ArcGIS 10.0 to derive river network of the catchment and to delineate sub-catchments of the Migina catchment from a Digital Elevation Model (DEM) with 90 m resolution. With GeoHMS, the project area was automatically delineated and its basin characteristics were generated (area, reach length, river slopes, etc). In addition, the HEC-GeoHMS created background map files and basin model files, which were later used by HEC-HMS to develop a hydrologic model. The sub-catchments delineation resulted into sub-catchments: Munyazi-Rwabuye (W380), Mukura (W410), Cyihene-Kansi (W400), Akagera (W650), and Migina (W640) (see Fig. 4).

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3.3 Computation methods

To compute the different water balance components, the following computation methods, as referred to in the HEC-HMS literature, were applied to the sub-catchments (e.g. Yawson et al., 2005) and reaches.

i. The Loss Method (name as per HEC terminology as in the hydrological cycle a real loss does not exist) allows computing basin surface runoff, groundwater flow, total evaporation, as well as deep percolation over the entire basin. The Soil Moisture Accounting (SMA) was selected as the appropriate approach to convert rainfall hyetograph into excess rainfall. In conjunction with the SMA, the canopy and surface losses (interception) were also considered and computed using simple canopy and simple surface methods (HEC, 2011).

ii. Transform Method (runoff generation module) allows specifying how to convert excess rainfall into direct runoff. This method employs the Soil Conservation Service (SCS) technique (dimensionless unit hydrograph). The method requires only one parameter as input for each sub-catchment: lag time (T_{lag}) between rainfall and runoff in the sub-catchment (Eq. 1). The SCS developed a relationship between the time of concentration (T_{c}) and the lag time (T_{lag}). HEC-HMS includes an implementation of Snyder's Unit Hydrograph (UH). In his work, Snyder (1938) selected the lag, peak flow, and total time base as the critical characteristics of a UH. He defined a standard UH as one whose rainfall duration ($\frac{\Delta t}{2}$) is related to the basin lag (T_p) as shown in Eq. (2).

$$T_{\mathrm{lag}} = 0.6 T_{\mathrm{c}} \tag{1}$$

$$T_p = \frac{\Delta t}{2} + t_{\mathrm{lag}} \tag{2}$$

where: T_{lag} = lag time [min], T_{c} = time of concentration [min], T_p = basin lag [min], and $\frac{\Delta t}{2}$ = rainfall duration [min].

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iii. Base flow method performs subsurface flow calculation. *The Linear reservoir base flow method* was considered due to its simplicity and suitability for the SMA approach and was used to simulate continuously the recession of base flow after a storm event.

iv. The Muskingum-Cunge method, which is the routing technique used for the reaches, was selected in this model because of its numerical stability. The reach characteristics used were mainly produced by the HEC-GeoHMS (length and slope), and others borrowed from the previous publications carried out in the same catchment such as in SHER (2003), Van den Berg and Bolt (2010) and Munyaneza et al. (2010, 2011, 2012).

3.4 Basin model setup and simulations

3.4.1 Basin model

In the present study, the basin model was created using the HEC-GeoHMS and then imported into the HEC-HMS with all its hydrologic elements: 5 sub-catchments, 10 junctions, 11 reaches, and a sink used to represent the outlet of a basin [node with inflow and without outflow] (Fig. 4). Where applicable, the junction elements were assigned observed flow data, for use in comparison with simulated flows during the calibration process. Each hydrologic element was supplied with initial conditions and parameters based on the requirements of the different computation methods as discussed in Sect. 3.3 above. Initial parameters were selected based on the previous works where available, otherwise default values from the manual were applied.

3.4.2 Meteorological model

The Meteorological Model was created after having created the Basin Model. The Meteorological model in HEC-HMS includes rainfall and evaporation methods to be used in the simulations (Arbind et al., 2010).

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In this study, the rainfall and evaporation data which are essential to simulate catchment processes were stored in the meteorological model. Twelve rain gauges and inverse distance method for rainfall computation were used in this model. The Priestley–Taylor method was used for computing total evaporation using temperature and radiation data. The current HEC-HMS 3.5 version allows total evaporation computation using temperature and radiation based method in combination with Soil Moisture Accounting (SMA) model.

3.5 Calibration methods

In the present study, a combination of manual and automated calibration techniques was used. Automated calibration known as "trial optimization" in HEC-HMS was used to obtain optimum parameter values that give the best fit between observed and simulated flow volumes values (Ruelland et al., 2008).

Given the availability of flow at the outlet of different sub-catchments, calibration was done catchment-wise starting from the farthermost upstream catchments (Munyazi, Mukura, and Akagera), since what happens upstream affects the results downstream. Each sub-catchment was calibrated independently and at the end of the calibration process, each was assigned its specific parameters. At the end of the calibration process, manually, the Nash–Sutcliffe Model Efficiency method (NS) was used to measure how the model fits the real hydrologic system (discussed in the next section).

Model performance evaluation

The calibrated model performance was evaluated using the Nash–Sutcliffe Model Efficiency (NS) methods (Nash and Sutcliffe, 1970; Miao et al., 2013). The NS is used to assess the predictive power of hydrological models. Mathematically, it is expressed as:

$$NS = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2} \quad (3)$$

where Q_o^t is observed discharge at time t, $\overline{Q_o}$ is average observed discharge, and Q_m is modeled discharge at time t; all Q variables have the unit runoff volume per time step (e.g. $m^3\,s^{-1}$).

Nash–Sutcliffe efficiencies can range from $-\infty$ to 1. An efficiency of 1 (NS = 1) corresponds to a perfect match between the modeled and observed time series. Whereas, an efficiency of 0 (NS = 0) indicates that the model predictions are as accurate as the mean of the observed data. If the efficiency is less than zero (NS < 0) the observed mean is a better predictor than the model. More detailed information on NS can be found in Legates (1999), McCuen et al. (2006), Schaefli and Gupta (2007) and Kashid et al. (2010).

3.6 Tracer techniques for model validating

Hydrograph separations to separate the total runoff during floods in two or more components, based on the mass balances for tracer and water fluxes, were applied in Munyaneza et al. (2012). Environmental isotopes (oxygen-18 (^{18}O) and deuterium (^{2}H)) and hydrochemical tracers (dissolved silica (SiO_2) and chloride (Cl^-)) were used as tracers.

The study showed that the results using the two-component hydrograph separations method using hydrochemical tracers are generally agree with the three-component separations using dissolved silica and deuterium. It was demonstrated that subsurface runoff is dominating streamflow generation during floods and baseflow periods. Particularly, more than 80 % of the streamflow was generated by subsurface runoff (mainly

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shallow groundwater from valley floors) for two events that were investigated in detail. The tracer results were supported by shallow groundwater observations and the observed runoff coefficients. These results have been used to check the model simulation in this paper.

4 Results and discussion

4.1 Calibration results

After running initial parameters over the simulation period and plotting the results against the observed flows, the first run did not yield acceptable results, and the initial parameters were subjected to calibration. The initial and finally calibrated parameters for each sub-catchment are presented in Table 2.

Table 2 shows that despite the basin under consideration being a meso-catchment, the calibrated parameter values obtained varied from sub-catchment to sub-catchment, even for adjacent ones. The differences observed between the parameter values across the different sub-catchments were relatively small, except in some few cases where differences were considerable. The parameters with considerable differences include: (i) maximum infiltration, (ii) maximum soil storage (iii) GW1 storage, (iv) lag-time, and (v) GW1 coefficient; and all the four formed sensitive parameters for the catchment. The initial values for soil moisture were collected from Mukura sub-catchment at Kadahokwa marshland. Because the soil parameters were collected in only one sub-catchment, we could not verify these parameter values for other sub-catchments, but had to rely on calibration.

Although correlation between infiltration rate and sub-catchment slopes was not strong ($r = 0.33$), the higher infiltration rate value is observed in the most lowland areas of the Migina sub-catchment, where the slopes are gentle and herbaceous and shrub crops dominate the land cover (almost 100 %) (see Table 1).

Groundwater storage values were higher in sub-catchments that due to their physiographic, settings have larger valley floors (Cyihene-Kansi and Migina). Sub-catchments of Mukura and Akagera showed small storage mainly due to their high surface runoff induced by very steep slopes. This translates also in their low contribution of the base flow to the total flow.

The difference observed in the groundwater coefficients across the basin shows the varying behavior of the different sub-catchments in transforming groundwater into base flow. The groundwater coefficient represents time lag applied on the linear reservoir for transforming water in groundwater storage into lateral flow, which generate base flow in the river. The correlation analysis showed that a stronger correlation exists between the groundwater coefficient and the groundwater storage capacity ($r = 0.94$) compared to correlation between groundwater storage and size of the sub-catchment ($r = 0.39$).

With respect to Lag time, which represents the duration of time between the centroid of rainfall mass and the peak flow of the resulting hydrograph, it was noticed that despite a weak correlation between lag time and basin mean slope, the sub-catchment with very steep slopes (Mukura) showed faster response than those with gentle slopes (Munyazi).

4.1.1 Flow results

Generally, the model predicted the flows volumes well, though difficulties in matching simulated and observed daily flows were observed.

Particular attention was given mainly to control points that collect water from more than one sub-catchment (Cyihene-Kansi and Migina outlets). During the calibration process, we tried to minimize the absolute values of the residuals of the observed flow volumes. In addition, the NS (Eq. 3) was used to better evaluate the performance of the calibrated model. Table 3 summarizes the obtained NS coefficients and total flow residual values for each discharge computation point in the basin.

Table 3 shows that the model performed reasonably well in simulating total flow volumes (Roy et al., 2013). The residues in % of total observed range between

−1.86 and 8.58 % of observed flow. Results indicated by NS coefficients also depicted reasonable model performance in most cases (NS > 0.5) with the exception of Munyazi sub-catchment (NS = 0.38). Furthermore, the model simulated well the base flow while reproducing at the same time the observed peaks in term of timing and quantity. For instance, the model was able to reproduce the peak recorded at all stations on 2 May 2010 as shown in Fig. 5. Similar results were obtained by Munyaneza et al. (2012), who investigated the peaks discharge in the same catchment and observed the same peaks at the same time as in the current study (see Sect. 4.3.1).

In individual sub-catchments, the model performed relatively well in sub-catchments Akagera, Mukura and Migina (the outlet) with NS coefficients of 0.61, 0.62 and 0.65, respectively.

Moreover, base flows were also well simulated in most cases, with the exception at Cyihene-Kansi (Fig. 5a) and Migina outlet (Fig. 5b) where the model overestimated and underestimated the base flow in dry seasons (June–July 2010), respectively.

4.1.2 Simulated water budget components

Recalling one of the main objective of water resources assessment (determination of water availability at local sub-catchment level), the catchment water budget components from the model results were analyzed. The components are the total rainfall, actual evaporation and percolation, direct runoff, base flow, and total flow. The quantities are presented in Table 4 and represent the total volume over the simulation period of 12 months (1 August 2009 to 31 July 2010).

Table 4 shows the evaporation which is the sum of percolation and actual evaporation (E_{actual}), hence the latter is probably much more due percolation is not leaving the catchment (bypassing the gauging station). This is (partly) generating baseflow in the same 12 months period.

It was observed that contributions of direct runoff and base flows vary from sub-catchment to sub-catchment, despite the small size and closeness of the sub-catchments. Table 4 shows that the outflows for Mukura and Munyazi sub-catchments depend highly on direct flow, whereas base flow contribution was evaluated only at 27.4 and 30.4 % of total flow, respectively. The observed dominance of high direct runoff in both sub-catchments may be attributed to the urbanization observed in the catchment areas such as Ngoma, Matyazo and Rwabuye towns (Fig. 1 and Table 1), resulting in relatively large areas of mainly imperviousness surfaces for rural catchments of 2.8 % for Mukura and 3.5 % for Munyazi of the total catchment areas. Opposite results were observed at Cyihene-Kansi and Migina outlet sub-catchments where the base flow contributes 64.6 and 69.2 % of total outflow, respectively (see Table 4 and Fig. 6).

In the absence of enough data to validate the model, an attempt was made to compare outputs of the present study with those obtained using other techniques than computational modeling. Munyaneza et al. (2012) applied the two-component hydrograph separation model in two sub-catchments of Cyihene-Kansi and Migina using dissolved silica (SiO_2) and chloride (Cl^-) as tracers determining the contributions of direct and base flows to the total outflows from the two sub-catchments. Two rainfall events were investigated during the rainy season in 2010 and 2011, using flow data collected at Kansi and Migina flow stations. The results showed that direct runoff component did not exceed 33.7 and 28.7 % of the total event runoff, respectively. The model estimations of 35 and 31 %, respectively, are close to the values obtained by tracer methods (Fig. 6). These values are the % values for exactly these two events and not for the longer simulation period.

Note that in the HEC-HMS model output, the runoff components use the terms direct runoff and base flow (Merz et al., 2009), but this is not in line with the terminology used in tracer based analysis (e.g. Munyaneza et al., 2012) in which the components were defined in a process-oriented way (subsurface runoff, later flows, etc.). In presenting the comparison here, we have chosen to follow the terminology as used in HEC-HMS. Munyaneza et al. (2012) also used the three-component runoff separation model with dissolved silica and deuterium, and dissolved silica and oxygen-18,

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that also demonstrate the importance of subsurface flow components (i.e. shallow and deep groundwater runoff).

Even though the results were slightly different, both tracer methods confirmed the dominance of base flow (HEC-HMS terminology) contribution to total streamflow in the two sub-catchments, and the dominance is also confirmed by the modeling approach. In addition, the convergence of modeling and tracer techniques shows that tracer data can serve as multi-response data to assess and validate a model, which was also concluded by Uhlenbrook and Leibundgut (2002) and Uhlenbrook et al. (2004). Hence, the model can be trusted from a process point of view and, therefore, seems useful for water resources planning purposes in the Migina catchment. The high contributions of base flow to total flow translate into high reliability/security of water resources even during dry seasons, hence explaining the predominance of agricultural activities (91.2 %) in the two sub-catchments as also found by Munyaneza et al. (2011).

Looking at other parts of the basin, for the Akagera sub-catchment (32.15 km^2), the base flow and direct flow contribute about equal amounts to the sub-catchment outflow (50.5 and 49.5 %, respectively). Compared to other sub-catchments within the same size, Munyazi (38.61 km^2) and Mukura (41.65 km^2), Akagera (32.15 km^2) has a considerable high direct runoff (3 times the direct runoff of the other two) mainly attributed to the steep slopes (20.8 %) and to the high portion of impervious (8.5 %) areas in this sub-catchment (see Table 1). However, nothing fully explains the higher base flow contribution to the total runoff compared to Munyazi and Mukura sub-catchments, apart from the three sub-catchments are different in nature (e.g. topography, shape of river channel).

Cyihene-Kansi sub-catchment (69.63 km^2) yields a lot of water compared to the other 4 sub-catchments. Its high outflow of 414.4 mm over the simulation period is explained by its high amount of base flow (267.6 mm), and higher direct flows (146.9 mm) resulting most probably from its bigger size than other sub-catchments (Table 1).

In general, the Akagera sub-catchment simulations gave better results with high correlation between rainfall–runoff ($r = 0.97$) than the other four sub-catchments (Munyazi, Cyihene-Kansi, Mukura and Migina) (see Table 4). The better result in this sub-catchment may be partly attributed to the Akagera river channel of a rectangular shape that favors more accurate discharge measurements compared to other rivers in the catchment. The other reason could be that the used daily time step is less suitable for small steep catchments.

5 Concluding remarks

In this study, the model HEC-HMS version 3.5 hydrologic modeling software was applied to the Migina meso-scale catchment, and the model parameters for total evaporation (Soil Moisture Accounting method) and base flow (linear reservoir) were calibrated using the observed stream flows. The model performed reasonably well over the calibration period by reproducing the observed flow volumes and simulating the observed peaks in terms of timing and quantity.

The HEC-GeoHMS/HMS model was applied to 5 sub-catchments and the model results were compared with tracer results in two sub-catchments (Cyihene-Kansi and Migina), however, the model was not validated in a classical way due to the lack of reliable data (cf. Du et al., 2007). Based on the success of the HEC-HMS model and tracer method comparison, the present study concluded that the framework works effectively well in the meso-scale catchment.

The simulation results gave indication of zones of high surface runoff and for recharge/base flow generating areas. Those zones present potential areas where watershed protection interventions can be implemented. For example, interventions leading to protection of the water sources can be implemented in the zones of recharge where infiltration, recharge and temporary groundwater storage are higher. Areas of higher direct runoff, mainly due to the slopes, may also be suitable for interventions leading the reduction of slopes by terracing, and hence increasing infiltration and subsequent recharge.

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Moreover, at the meso-scale catchment level, considerable disparities in the parameters and hydrological processes exist. Lumping the entire Migina catchment would lead to missing important aspects of some of the sub-catchments and, subsequently, potentially misinforming the planning and decision making processes. Depending on the purpose of the assessment and the intended use of the information to be generated, individual units at an appropriate scale may require particular attentions even in very small catchments.

Given that the initial value used for soil moisture were estimated at only one place in the whole study area (at Kadahokwa marshland), more infiltration and soil moisture measurements should be conducted in the catchment at different soil types and land uses for a better model parameterization in future modeling works.

In addition, continuous quality assurance and control of hydrological and weather data sets recorded at different stations in the entire catchment is of great importance for the future.

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Table 1. Migina catchment and sub-catchments characteristics.

Sub-catchment name (code)	Catch. area (km^2)	Total rainfall ($mm\,yr^{-1}$)	Basin slopes (%)	Imperviousness (%)	Land use (%)			
					Agriculture	Forests	Grass/Lawn	Urban areas
Munyazi (W380)	38.62	1453.0	15.8	3.5	90.2	8.2	0.0	1.6
Mukura (W410)	41.73	1665.5	19.5	2.8	84.9	11.5	1.4	2.2
Cyihene-Kansi (W400)	69.61	1456.6	12.5	6.3	89.4	5.8	0.0	4.8
Akagera (W650)	32.20	1507.0	20.8	8.5	87.9	12.1	0.0	0.0
Migina outlet (W640)	61.05	1415.2	18.6	4.5	100.0	0.0	0.0	0.0

Table 2. Initial and finally calibrated parameter values for each sub-catchment.

Method	Parameter	Munyazi (W380)		Mukura (W410)		Cyihene (W400)		Akagera (W650)		Migina outlet (W640)	
		Initial	Calibrated	Initial	Calibrated	Initial	Calibrated	Initial	Calibrated	Initial	Calibrated
Canopy	Max storage (mm)	6	3	3	3	6	2	1	1	2	2
Surface	Max storage (mm)	5	5	20	20	3	3	2	2	3	3
Loss	Soil (%)	60	35	60	35	60	35	60	35	60	55
	Groundwater 1 (%)	72	65	72	65	90	75	72	75	90	81.4
	Max infiltration (mm h^{-1})	208	10	208	7.5	208	5.5	208	7.5	208	12
	Impervious (%)	0.5	3.5	0.5	2.75	0.5	6.3	0.5	8.5	0.5	4.5
	Soil initial storage (%)	40	48	40	30	50	50	40	40	50	13.8
	Tension storage (mm)	22	15	22	5	8	5	22	4	18	5
	Soil percolation (mm h^{-1})	2	4	2	2	1.75	0.8	2	1.75	10	1.97
	GW 1 Storage (mm)	307.5	237.0	307.5	50.0	307.5	150.0	307.5	100.0	307.5	303.6
	GW 1 percolation (mm h^{-1})	3	2	3	3.6	0.04	0.5	0.7	1.3	0.3	8.159
	GW 1 coefficient (h)	150	4320	150	1296	150	1440	150	1014	150	1014
Transform	Lag time [min]	150	120	150	30	120.22	60	120	45	120.56	45
Base flow	GW 1 initial ($m^3 s^{-1}$)	0.002	0.004	0.028	0.021	0.358	0.782	0.002	0.204	0.273	0.373
	GW 1 coefficient (h)	8100	6480	8100	3240	2430	3746	1100	3240	8100	6480

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Table 3. Residual values for each discharge computation point with corresponding NS. The simulation period is 12 months (1 August 2009 to 31 July 2010). The positive sign (+) means that the model overestimated the flows while the negative sign (−) means that the model underestimated the flows.

Sub-catchment name (code)	Station name	Total observed Q (mm yr^{-1})*	Total simulated Q (mm yr^{-1})*	Residual in % of total observed Q	NS [−]
Munyazi (W380)	Rwabuye	64.98	67.11	3.28	0.38
Mukura (W410)	Mukura	60.32	59.20	−1.86	0.62
Cyihene (W400)	Kansi	366.93	382.63	4.28	0.51
Akagera (W650)	Akagera	296.89	322.35	8.58	0.61
Migina outlet (W640)	Migina	324.71	318.98	−1.76	0.65

* The discharges are expressed in mm per entire simulation time.

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Table 4. Budget components quantities for all sub-catchments in the simulated period of 12 months.

Sub-catchment name (code)	Total rainfall ($mm\,yr^{-1}$)	Evaporation ($mm\,yr^{-1}$)	Direct runoff ($mm\,yr^{-1}$)	Base flow ($mm\,yr^{-1}$)	Total flow ($mm\,yr^{-1}$)	Base flow in % of the total flow	Direct flow in % of the total flow
Munyazi (W380)	1453.0	1408.1	44.9	19.7	64.6	30.4	69.5
Mukura (W410)	1665.5	1622.5	43.0	16.2	59.2	27.4	72.6
Cyihene-Kansi (W400)	1456.6	1309.7	146.9	267.6	414.4	64.6	35.4
Akagera (W650)	1507.0	1382.1	125.0	127.5	252.5	50.5	49.5
Migina outlet (W640)	1415.2	1353.8	61.5	138.1	199.6	69.2	30.8

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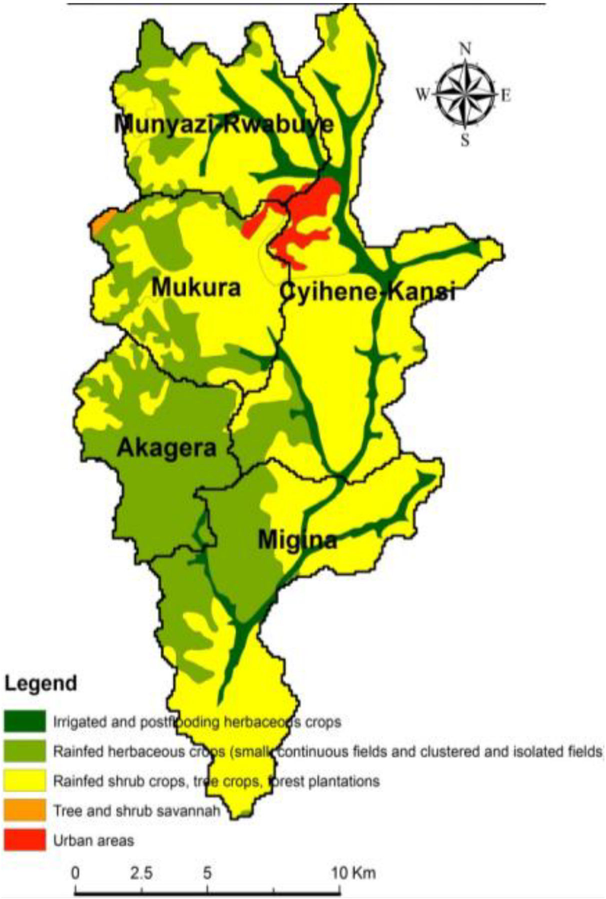

Fig. 1. Land use of Migina catchment and sub-catchments (Munyaneza et al., 2011; adapted).

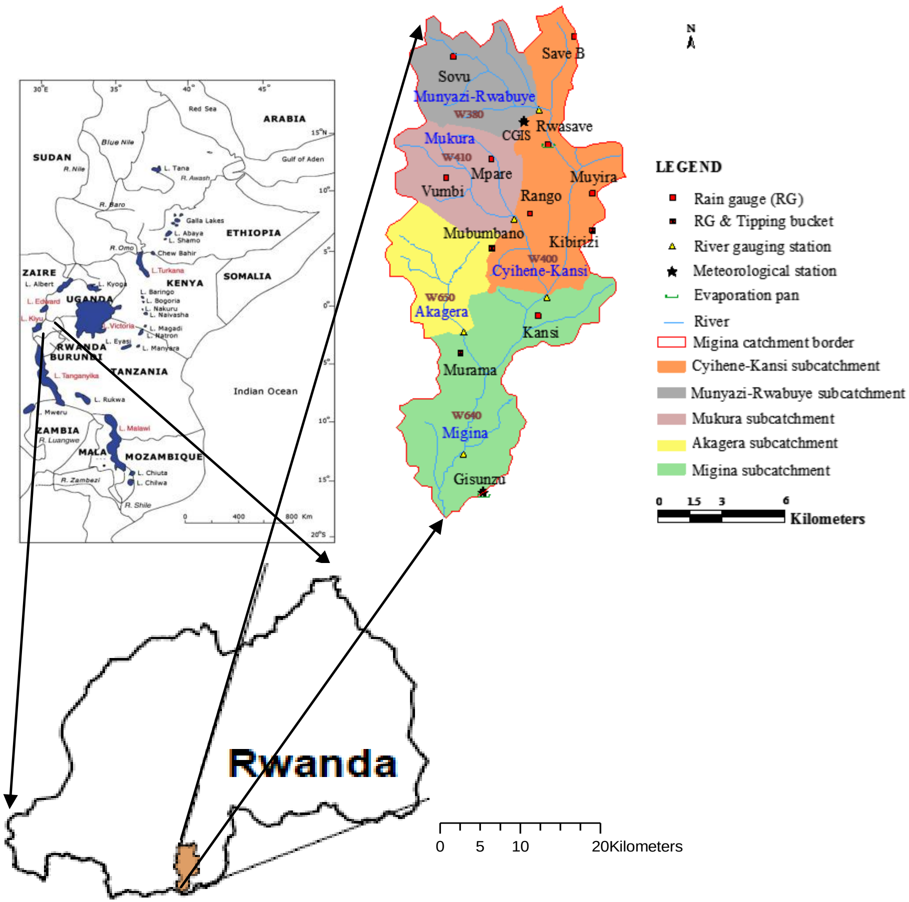

Fig. 2. Location and subdivision of the Migina catchment (Munyaneza et al., 2012; adapted).

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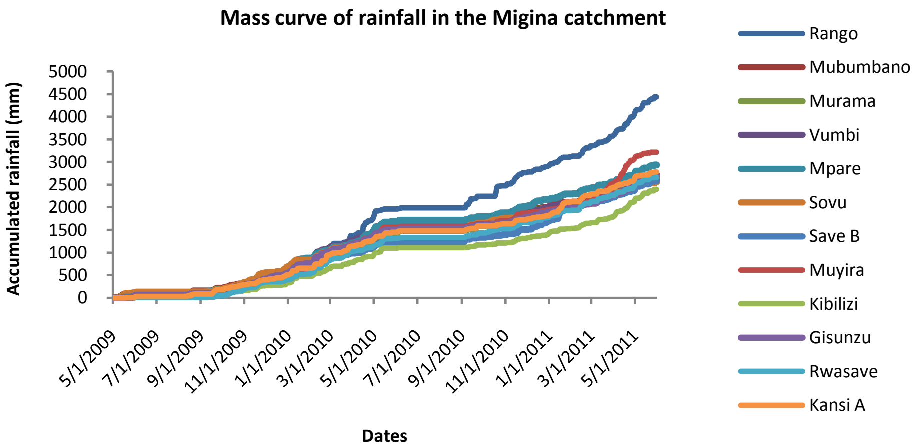

Fig. 3. Mass curve of rainfall at 12 stations around the Migina catchment for the period of May 2009 to June 2011.

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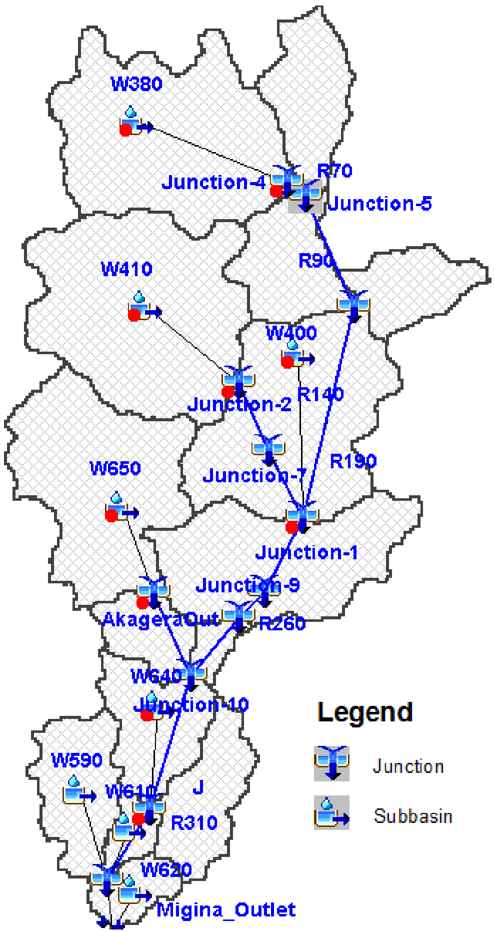

Fig. 4. Migina catchment model set up in HEC-HMS.

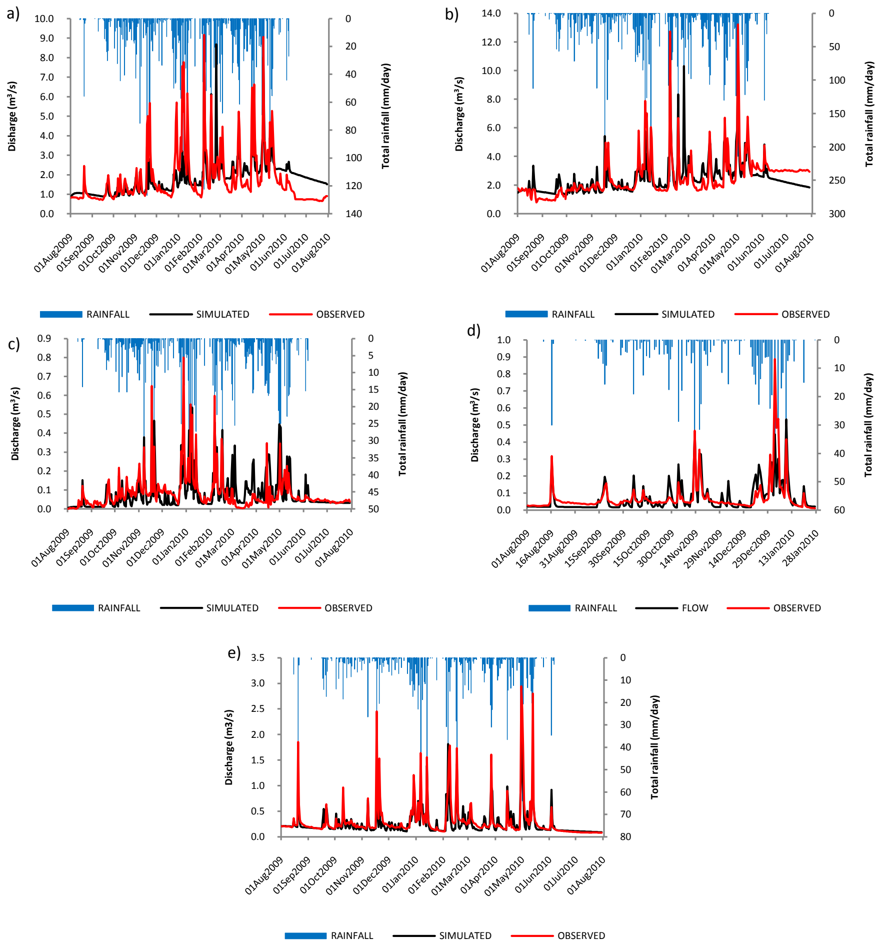

Fig. 5. The simulated and observed hydrographs at **(a)** Cyihene-Kansi, **(b)** Migina outlet, **(c)** Munyazi, **(d)** Mukura, and **(e)** Akagera sub-catchments.

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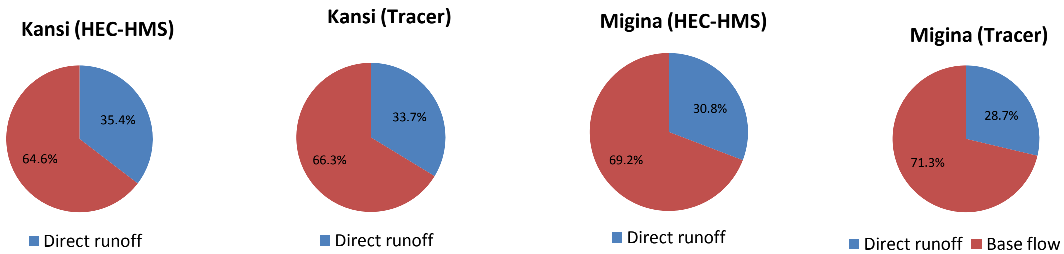

Fig. 6. Comparison of flow components results using HEC-HMS model (current study) and hydrochemical tracer method (obtained from Munyaneza et al., 2012) for two investigated events in the rainy season in 2010 and 2011, using flow data collected at Kansi and Migina flow stations.