A simple Method to Predict River Flows in the Agricultural Migina Catchment in Rwanda

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Abstract

Valid criticisms have been raised about the adequacy of the rational method. However, it continues to be used for storm water drains because of its simplicity. The main aim of this work is to contribute to the knowledge of water resources availability in the catchment through the development of a simple method to assess the maximum peak flow discharge of the Migina River (ca. 260 km^2) in Southern Rwanda. A Digital Elevation Model (DEM) with resolution of 90m was used to delineate the catchments. A digitized land use map and hydrological soil group classification of the catchment were used to estimate the runoff coefficient of the sub-catchments to calculate a weighted runoff coefficient. The rainfall intensity was determined using the records obtained from 13 rain gauges installed in the catchment from June 2009 to May 2011 and considering the time of concentration. The catchment profile and empirical formula were used to compute the time of concentration. A simple rational formula method with area correction was used to estimate the total discharge from the catchment. The results show that agricultural land use dominates in the catchment with about 92.5%. The weighted runoff coefficient was found to be 0.25, the time of concentration was determined to be 3 hours and 26 minutes for the whole catchment and the maximum peak flow was estimated to be 16.12 m^3/s. Because of non-linear processes and many changes including the fast development of urban areas and possible climate change, which have significant impact on hydrological processes especially on generation of surface runoff, it is recommended to develop river discharge models using advanced methods such as distributed hydrological modelling.

Key words: Catchment hydrology, land use, land cover, discharge, rainfall intensity, water resources, Rwanda

1. INTRODUCTION

The Rwandan economy is rapidly developing with a rate of 3.5% in 2010. However, over 85% of the population depends on subsistence agriculture for their livelihoods. This makes the issue of water resources availability very crucial. So far, the water resources of the country have not been quantified and there are no reliable data on the amount of water resources.

Accurate and comprehensive information about water resources form the basis for effective water resources management. It is now widely recognized that the monitoring and assessment of water resources, in terms of both quantity and quality, require adequate hydrological and meteorological data (Maathius *et al.*, 2006), which is an often a challenge due to the spatio-temporal variation of processes (Uhlenbrook, 2006). Wagener *et al.* (2008) stated that about one billion people live in water-scarce or water-stressed regions, and by 2025 this number is expected to increase further significantly. The magnitude of this water scarcity and its variations in both space and time are largely unknown and all estimations are uncertain, and one of the main reasons is the lack of hydro-climatological data (Oyebande, 2001; Kipkemboi, 2005).

In Rwanda, the rapid population growth is increasing the competition for the available water resources amongst domestic, agricultural, industrial and other user, there by increasing water scarcity. In addition the limitation of knowledge in water resources assessment and management is making the problem of water scarcity in Rwanda more pronounced. This has a negative impact on the agriculture development and the country's economy is mostly based on agriculture with 85% of the population depending on agriculture (Nahayo *et al.*, 2010).

As a solution for food security and poverty alleviation problems, Rwandan marshlands are being developed for intensive agricultural activities (World Bank, 2008) and the implementation of Rwanda irrigation master plan by the Ministry of Agriculture have commenced. To achieve efficient implementation of these activities would be difficult without knowing the water resources availability in the catchment (Munyaneza *et al.*, 2010). Therefore, it is very important to improve the understanding of different components of the hydrological cycle and the spatial and temporal distribution of water at present and in the future so as to improve the management of water resources.

The rational method, which can be traced back to the middle of the 19th century, is still probably the most widely used method for design of storm water drains (storm drains). The Irish engineer, Mulvaney (1850), was probably the first to publish the principles on which the method is based, although Americans tend to credit Kuichling (1889) and the British, Lloyd Davies (1906) for the method (Viessman *et al.,* 1989). It is an empirically developed model, with simplifying assumptions including uniform rainfall with uniform intensity over the entire watershed for duration equal to the time of concentration (Haan *et al*., 1982).

The objective of this paper is to introduce this simple method to estimate peak flow in a typical agricultural catchment located in Southern Rwanda. Therefore, different land cover, land use and soil type in the Migina catchment are classified; the runoff coefficients within Migina catchment through regrouping of land cover/land use and hydrological soil group maps are determined; and a simple method for maximum peak flow estimation is applied.

2. DESCRIPTION OF THE STUDY AREA

The study was conducted in the Migina catchment located between latitudes 2^{o}32’ to 2^{o}48’South and longitudes 29^{o}40’ to 29^{o}48’ East, in southern part of Rwanda (Fig. 1). The Migina catchment is one of the Rwandan sub-catchments of the Kagera River basin with an area of around 260 km^2 (with a population of about 103,000 people with growth rate of about 3%; van den Berg and Bolt, 2010). The catchment is divided into 5 sub-catchments according to the main rivers draining the area: two are located at the upstream (Munyazi-Rwabuye and Mukura), the other two in the center (Cyihene-Kansi and Akagera) and one at the downstream area.

The Migina River is a tributary of Akanyaru River which serves as a border between Rwanda and Burundi. Akanyaru River meets with Nyabarongo River at Bugesera (Eastern Rwanda) and becomes the Kagera River which is the largest tributary of Lake Victoria (discharge point in Uganda), and it is also called the source of river Nile (NELSAP, 2007).

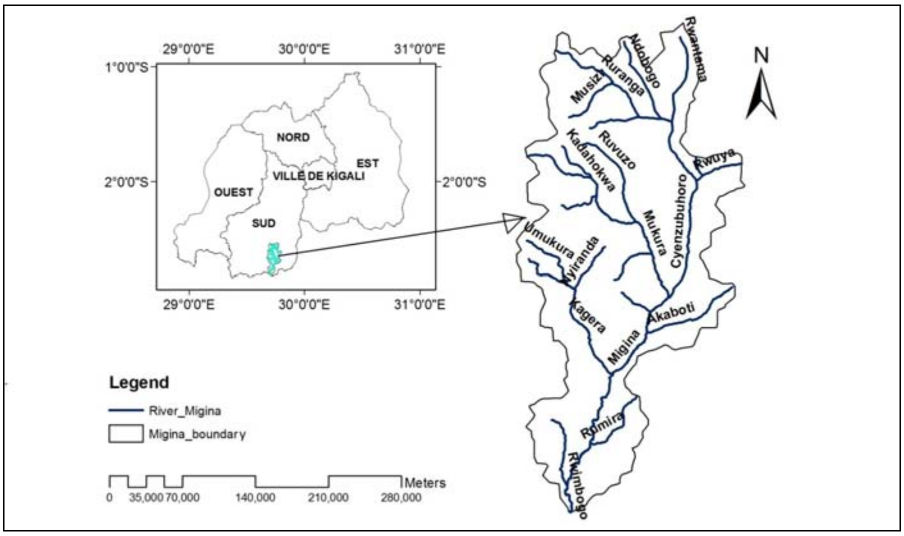

Figure 1: Location of the Migina catchment in Rwanda and its river network

The mean annual temperature and rainfall in the Migina catchment are about 20^{o}C and 1200 mm/a, respectively, and the mean annual actual evaporation was estimated to be 917 mm/a (Nahayo, 2008).

The mean relative soil moisture calculated for over 11 years is 75.7% with minima of 59.8% in June and the maximum in of 86.3% April (Nahayo, *et al.,* 2010).

3. DATA COLLECTION AND PROCESSING TECHNIQUES

3.1. Physical Characteristics of the Catchment

The topography of the Migina catchment was extracted from the Digital Elevation Model (DEM) obtained from the USGS website with the resolution of 90m. The topography was described in terms of slope, aspect, and elevation. These three basic characteristics affect the movement and storage of water in the catchment. The catchment boundary was delineated from the DEM within the ArcGIS environment. The land cover map of Rwanda was used to extract the Migina catchment's land cover. The map was collected from the Center of GIS at Butare and was taken in 2009.

Hydrological soil groups: The type of soil in a catchment plays an important role in the catchment's hydrology and in particular in the runoff generation processes. The composition and texture of the soil determines whether rainfall or irrigation water will be retained in the soil and released gradually, percolating downward to the groundwater, or if these inputs of water instead contribute to surface runoff, leading to increased erosion. The hydrological soil group (HSG) of the study area was extracted from a map the soil texture classes of the dominant soil units in Rwanda in the ArcGIS environment (source: Verdoodt and van Ranst, 2003).

3.2. Determination of Rainfall Intensity

The catchment is equipped with meteorological instruments such as: two weather stations that record rainfall, temperature, relative humidity, soil moisture, wind speed and direction, that were installed downstream at the Gisunzu Primary School and at in upstream area at the CGIS Center in the city of Butare (Fig. 2). Three tipping buckets were installed in the western, eastern and central part of the catchment. These locations were selected because of the other tipping buckets installed at the weather stations and to have a regional spread (Fig. 2). Data from these tipping buckets were not used in this paper to estimate rainfall intensity because they were poorly taken with so many missing.

The rainfall intensity, *I*, is the average rainfall rate in mm/sec or mm/hr for a particular drainage basin or sub-basin. The intensity should be selected on the basis of the design storm duration and return period (Dawod *et al.,* 2011). The design storm duration is equal to the time of concentration for drainage area under consideration. The return period is established by design standards or chosen by the hydrologist as a design parameter.

Deciding upon a suitable return period for the design storm should be based on cost benefit analysis, which quantifies the physical and social damage caused by flooding. However, no conclusive word appears to have been done which quantifies the actual costs of flooding. Thus the selection is normally arbitrary. In many cases, the hydrologist has a standard IDF curves or table available for the site and does not have to perform this analysis (Bulter and Davies, 2004).

The average of rainfall intensity in Migina catchment was estimated after calculation of the average rainfall by the use of an arithmetic mean method (Eq. 1) and considering the time of concentration t_c (Dawod *et al.,* 2011). Data used to assess the rainfall intensity were collected from 13 rain gauges in the period of 2 years on daily basis (June 2009-May 2011). The arithmetic mean of the rainfall amounts measured in the area provides a satisfactory estimate for a relatively uniform rain.

$$P = \frac{P_1 + P_2 + P_3 + \cdots + P_n}{n} \quad (1)$$

Where: P = Precipitation in mm and n = total number of rain gauges

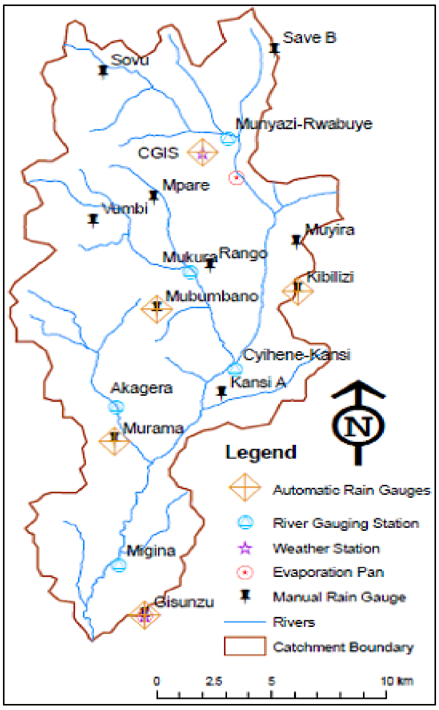

Figure 2: Location of hydrological and meteorological instruments in the Migina catchment (Munyaneza *et al.*, 2010)

For rainfall intensity double-check, the recommended standards IDF equations (Bulter and Davies, 2004) were used and the Equation (2) was selected due to the field investigation on the decade floods occurred in the Kagera River basin (Munyaneza *et al.*, 2011). Note that Migina catchment is the sub-catchment of Kagera River basin. According to the interview of the local people and local authorities, the serious floods which cause many catastrophes like loss of life and property damage happened after each 10 years (Munyaneza *et al.*, 2011), and the return period was considered as 10 years in the Migina catchment as well.

$$I_{10} = \frac{140}{tc + 0.7} \quad (2)$$

where I_{10} is intensity in (mm/hr) for the return period of 10 years and t_c is time of concentration in mins.

The applied method assumes that the maximum runoff rate in a catchment is reached when all parts of the catchment are contributing to the outflow. This happens when the time of concentration is reached. The Kirpich/Ramser formula is mostly used to calculate the time of concentration (Dawod *et al.*, 2011):

$$t_c = 0.0195 * L^{0.77} * S^{-0.385} \quad (3)$$

where: t_c = Time of concentration [min], L = Length of main river [m], S = Slope of main stream [m/m]

3.3. Estimation of Runoff Coefficient

The product of rainfall intensity, I, and watershed area, A, is the inflow rate for the system, IA, and the ration of this rate of peak discharge, Q, (which occurs at time t_c) is termed runoff coefficient C ($0 < C \leq 1$) (Mihalik, 2007). The runoff coefficient, C, is the least precise variable of the rational method. Its use in the formula implies a fixed ratio of peak runoff rate to rainfall rate for the drainage basin, which in reality is not the case. All catchment losses are incorporated into the runoff coefficient, which is usually a function of the land use. This means that the magnitude of this coefficient is not constant, but varies with time and in space depending on a number of different factors such as the topography of the catchment, magnitude and intensity of the storm rainfall, vegetation cover and land use, infiltration rate

and the initial soil moisture condition, groundwater depths and subsurface flows (e.g. EFM, 1984 in Musoni *et al.,* 2010, Uhlenbrook 2007).
The Table 1, 2 and 3 describe the Migina land cover, the runoff coefficient for agricultural watersheds and the hydrologic soil group conversion factors. These three tables were used to estimate the runoff coefficient of Migina catchment. This is due the runoff coefficient is dependent on the character and condition of the soil.

Table 1: Migina land cover description (source: Verdoodt and van Ranst, 2003)

Land cover ID	Land cover name	Land use/ Land cover
AG-10*/5	Combination of Banana Plantation and Rain fed Herbaceous Crop	Agriculture: Small grain, good practice
AG-2	Irrigated Herbaceous Crop	
AG-5/9	Combination of Rain fed Herbaceous Crop-Two crop per year and Shrub Plantation	
AG-9/5	Combination of Shrub Plantation and Rain fed Herbaceous Crop-Two crop per year	
AG-6	Forest Plantation - (Eucalyptus or Pinus and Cypress)	Forest: Woodland, mature, good
AG-6B	Scattered (in natural vegetation or other) Forest Plantation (Eucalyptus or Pinus and Cypress)	
AG-6C	Isolated (in natural vegetation or other) Forest Plantation (Eucalyptus or Pinus and Cypress)	
RL-2	Savannah (shrub or tree and shrub)	Grass/Lawn: Pasture, permanent, good
UR	Urban And Associated Areas	Building

Table 2: Runoff coefficient C for agricultural watersheds (soil group B) (source: Schwab et al., 1993)

Crop and hydrologic condition	Coefficient C (-) for rainfall rates of		
	25mm/h	100mm/h	200mm/h
Row crop, poor practice	0.63	0.65	0.66
Row crop, good practice	0.47	0.56	0.62
Small grain, poor practice	0.38	0.38	0.38
Small grain, good practice	0.18	0.21	0.22
Meadow, rotation, good	0.29	0.36	0.39
Pasture, permanent, good	0.02	0.17	0.23
Woodland, mature, good	0.02	0.10	0.15

Table 3: Hydrologic soil group conversion factors (source: Schwab et al., 1993)

Crop and hydrologic condition	Factors for converting the runoff coefficient C from group B soils to		
	Group A	Group C	Group D
Row crop, poor practice	0.89	1.09	1.12
Row crop, good practice	0.86	1.09	1.14
Small grain, poor practice	0.86	1.11	1.16
Small grain, good practice	0.84	1.11	1.16
Meadow, rotation, good	0.81	1.13	1.18
Pasture, permanent, good	0.64	1.21	1.31
Woodland, mature, good	0.45	1.27	1.40

In this paper, the runoff coefficient of the Migina catchment was estimated after making an overlay of a land cover map and hydrological soil group map using ArcGIS tools. A weighted average runoff coefficient was calculated using Equation (4) as modified from Chow *et al*. (1988) to be applicable to larger watersheds.

$$C = \sum_{n=1}^{n} \left(\frac{Ai * Ci}{\sum_{1}^{n} Ai} \right) \quad (4)$$

where, A_i (km^2) represents partial areas and C_i (-) the partial runoff coefficients, according to five sub-catchments of Migina catchment.

3.4. Determination of Peak Runoff

After getting the rainfall intensity of the Migina catchment, information on Migina catchment describing topographical configuration and the runoff coefficient from land cover and HSG, the peak runoff was computed using the following form of the rational formula (Haan *et al*., 1982).

$$Q_p = 0.00278 * C * I * A \quad (5)$$

Where: Q_p = Peak runoff rate [m³/s], C = Runoff coefficient [-], I = Rainfall intensity [mm/hr], and A = Drainage area/catchment area [ha].

The idea behind the rational method is that if a rainfall of intensity, I, begins instantaneously and continues indefinitely, the rate of runoff will increase until the time of concentration, t_c, when all of the watershed is contributing to flow at the outfall/outlet. The duration used for determination of the design storm intensity is the time of concentration of the watershed. The rational method was applied in this paper by considering the following assumptions (Haan *et al*., 1982):

1. Rainfall intensity is constant throughout the storm duration.
2. The time of concentration employed is the time for the runoff to become established and flow from the most remote part of the drainage area to the inflow point of the drain being designed (Fig. 4).
3. The computed peak rate of runoff at the outlet point is a function of the average rainfall (I) rate during the time of concentration, that means the peak discharge does not result from a more intense storm of shorter duration, during which only a portion of the watershed is contributing to runoff at the outlet; and
4. It has been found by experiments that as the catchment area increases (>2km^2) the rational formula becomes less accurate (Langousis, 2005). In such case the point area should be multiplied by ARF (Area Reduction Factor) as shown in Fig. 3. The application of ARF to larger catchments was supported by Chow *et al.* (1988) and its accuracy was tested successfully by Bulter and Davies (2004). Bulter and Davies (2004) said "Point rainfall is not necessarily representative of rainfall over a larger area because average rainfall intensity decreases with increasing area. In order to deal with this problem, and avoid overestimating flows from larger catchments, *areal reduction factors* (ARF) have been developed. The expression is valid for the storm durations of 5 mins to 48 h".

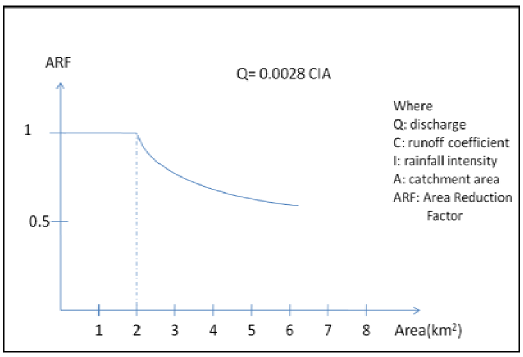

Figure 3: Area reduction factor curve for larger catchments (adopted from Langousis, 2005).

4. RESULTS AND DISCUSSIONS

4.1. Data Processing and Results

4.1.1. Catchment delineation

Figure 4 shows topographic character of the Migina catchment that is very mountainous with elevation ranging from 1434 m, where the Migina River is entering Akanyaru River, to 2251 m at Huye Mountain (Western-North). The longitudinal slopes of the valleys vary from 5 to 10% upstream and from 1 to 15% downstream (average slope is between 2 and 3%). This has been also reported by Nahayo *et al*. in 2010.

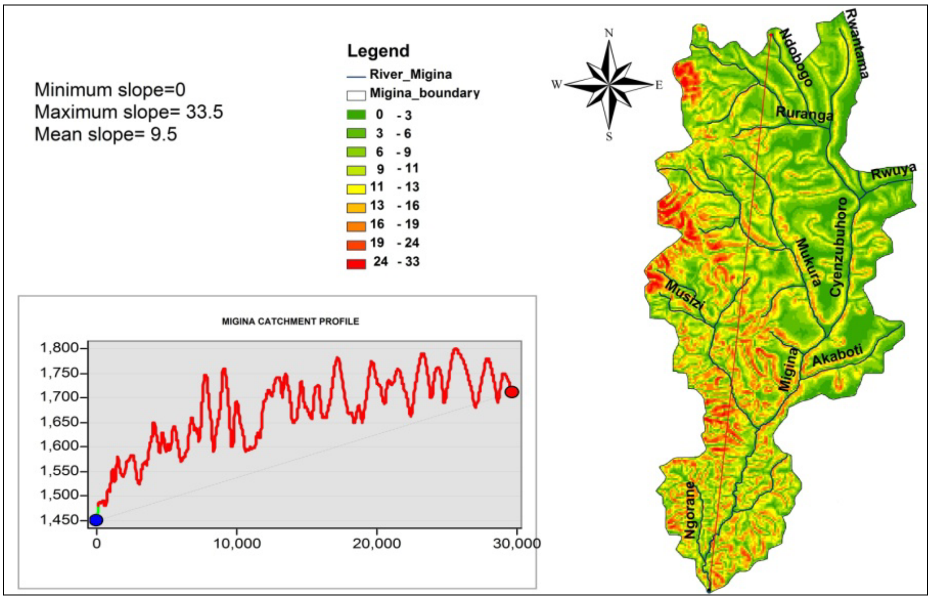

Figure 4: The map shows the Migina catchment slope gradient and the inset figure displays the catchment profile.

The slope of main stream from a profile in the Figure 4 is around 5.7% and average slope of 9.50^o. The total area, which is $257.45km^2$, has been calculated by use of Arc map geometry analysis. The main stream length is around 40.29km (Fig. 4). The used map in this paper has a resolution of 90m. High resolution satellite images are not easily available and hence lower resolutions images can be applied (Munyaneza *et al.,* 2009), which could affect the accuracy during the computation of the slopes.

4.1.2. Calculation of time of concentration

The Kirpich/Ramser formula (Eq. 3) has been used to calculate the time of concentration of Migina catchment considering the length of main river and the average slope of main stream, and was found to be 3hrs 26min.

4.1.3. Calculation of rainfall intensity

Average rainfall intensity was estimated using average (arithmetic) method (Eq. 1) from the daily rainfall data taken during 2 years (June 2009-May 2011) and by considering the time of concentration of 3hours 26mins, though the estimated average rainfall intensity is around 1.06 mm/hr. Then the empirical formula 2 was also used for double-checking and the rainfall intensity was found to be 0.68 mm/h. After the application of those two methods, the rainfall intensity which is high was used to predict the Migina River peak flows.

4.1.4. Determination of the Migina runoff coefficient

Computation of Migina land cover

The Figure 5 shows that land cover of Migina catchment is composed of the followings types: Agriculture (small grain, good practice), Forest (woodland, mature, good), Grass/lawn (pasture, permanent, good), and Urban areas as also found by Verdoodt and van Ranst in 2003. The only difference found in this paper is the percentage of covering areas. Therefore the catchment land use is widely dominated by agriculture activities at 92.5% on D (sandy 50%), C (loamy 47%) and B (clayey 3%) soil groups; forest at 5% on C (loamy 15.5%), D (sandy 37.3%) and B (clayey 47%) soil groups; grass/lawn at 2% on C (sandy 100%) soil group and finally buildings which cover 0.5% on D (loamy 100%) soil group. Based on field information, the catchment land use is dominated by pasture and arable farming like rice, sorghum, maize and sweet potatoes (Munyaneza *et al.,* 2010).

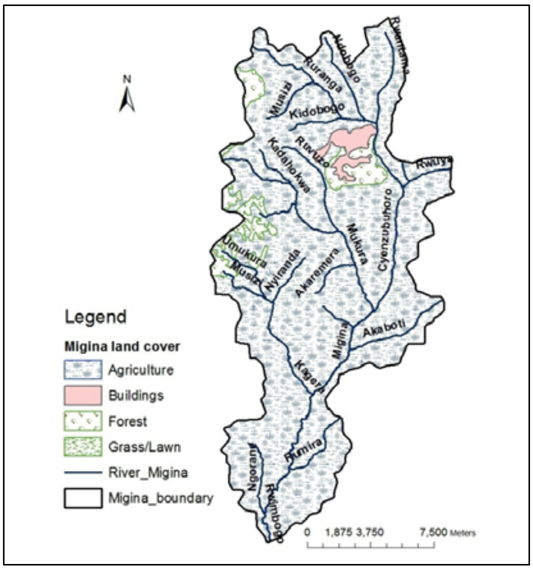

Figure 5: Land cover of Migina catchment.

Classification of hydrological soil groups of Migina catchment

The Figure 6 shows that Migina catchment is dominated by group D and C which means very high runoff potential and moderate to high runoff potential, respectively. Group A which represents low runoff potential is not available in the Migina catchment. Only the group B of low to moderate runoff potential was found (Fig. 6).

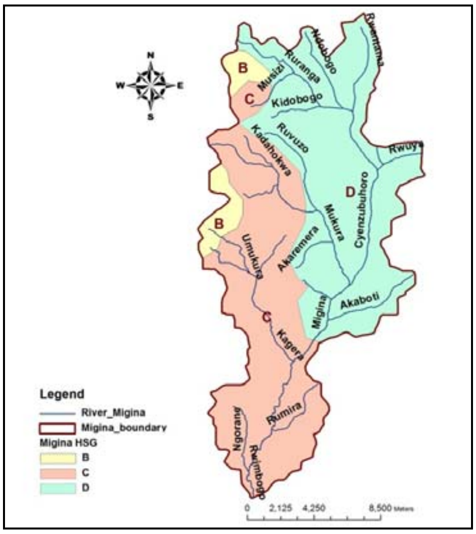

Figure 6: Hydrological soil groups of Migina catchment.

Overlay of land cover and hydrological soil groups maps of Migina catchment

Figure 7 was computed by overlaying the land cover and hydrological soil groups of Migina catchment. The information from the figure was used in Table 4 to estimate the runoff coefficient of Migina catchment.

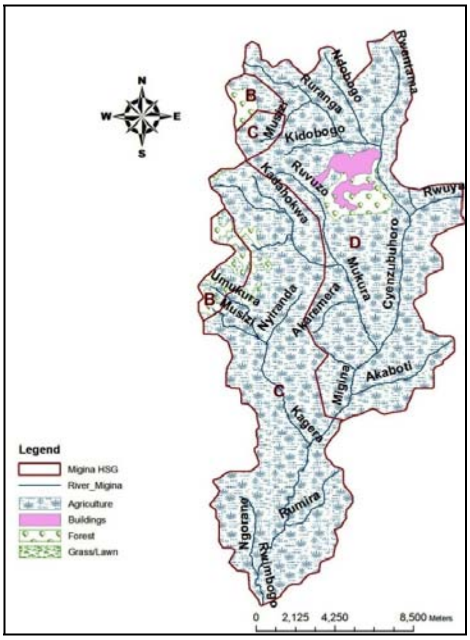

Figure 7: Overlay of land cover and hydrological soil groups of Migina catchment.

The Migina catchment runoff coefficient was calculated (Table 4) and the runoff coefficient was obtained after an overlay of a land cover map and soil type map (Fig. 7). It has been found to be around 0.25 (Table 4).

Table 4: Summary of determination of runoff coefficient

Land cover	Hydrological soil group	Area (A_i) km^2	Runoff coefficient (C_i)	(A_i)× (C_i)
Agriculture: Small grain, good practice	D	119.92	0.24	29.21
	C	111.61	0.23	26.02
	B	6.81	0.21	1.43
Forest: Woodland, mature, good	C	2.14	0.127	0.27
	D	5.23	0.14	0.73
	B	6.51	0.10	0.65
Buildings	D	4.94	1.00	4.94
Grass/ Lawn: Pasture, permanent, good	C	0.28	0.242	0.07
∑		257.43		63.32

$$C = \sum_{n=1}^{n} \left(\frac{Ai * Ci}{\sum_1^n Ai} \right) = \frac{63.32}{257.43} = 0.2459 \cong 0.25$$

The values of C_i were obtained by the use of Tables 1, 2 and 3.

4.1.5. Determination of the Migina peak runoff

The Migina catchment peak runoff was calculated using the Equation 5 and considering the area reduction factor (Fig. 3) and was found to be = 0.00278*0.25*1.06 mm/h*25445 ha = 18.97 m^3/s. Assume the area correction factor ARF as 0.85, hence the Migina catchment peak runoff is 16.12 m^3/s.

4.2. Discussion

4.2.1. Migina river discharge prediction

In order to establish a relationship between water levels and discharge for the five main streams in the Migina catchment, several discharge measurements were carried out at the gauging stations at different water levels (Munyaneza *et al.,* 2010). The rating curve was generated according to the recommendations of Shaw (2004) and the Migina mean daily discharges were also discussed in Munyaneza *et al.* (2010) after considering data from all stations.

Average rainfall intensity was estimated using average (arithmetic) method and considering the time of concentration of 3hours 26mins and is around 1.06 mm/hr while the total catchment area is equal to 257.45 km^2 (Fig. 4). The high time of concentration value found in the Migina catchment has a big influence on the appearance of low rainfall intensity and could even be justified by the low runoff coefficient computed in the same catchment which is around 0.25 (Table 4). This coefficient found in the Migina catchment agrees with the range for an agricultural dominated catchments as found by Purdue *et al.* (2007).

The Migina catchment was considered as large catchment for the application of rational method (meso-scale catchment of around 260 km^2), though the correction factor ARF was applied (Fig. 3), and the maximum peak flow was predicted to be 16.12 m^3/s. The agriculture activities in wetlands were much contributed in computation of this peak runoff (Table 4). The runoff coefficient value was less than highest value of 1 due to the dominance of agriculture activities in the Migina catchment. This method of river flow prediction may be applied to other agricultural catchments in the region, but hydrological studies have to be done for getting the required data to plot runoff and rainfall intensity relationship curve.

4.2.2. Challenges

Challenges related to urbanization

The country of Rwanda is quickly progressing in terms of development; this implies a change from rural areas to urban areas. Urbanization can have great impacts on the hydrological cycle. It involves covering ground with impervious artificial surfaces. These artificial surfaces increase significantly the amount of runoff in relation to infiltration, evaporation and transpiration and, therefore, increase the total volume of water reaching the river during or soon after the rain.

Challenges related to base flow contribution

Once groundwater table is not far from the ground surface, as it is the case in many areas of the Migina catchment (often between 0.8m and 2m, in particular in the valleys; van den Berg and Bolt, 2010), part of the infiltration rain can reach the groundwater quickly and contribute to subsurface storm flow and base flow. Unfortunately, in the suggested simple runoff estimation method, the groundwater contribution during an event was assumed constant. This needs to be addressed in future developments to improve the method further.

5. CONCLUDING REMARKS

With the suggested simple approach and by using data from field investigations, the Migina catchment peak runoff discharge could be predicted. The catchment is a mountainous watershed with area of around 257.45km^2, main water stream length of 40.28km, an average slope of main stream around 5.7% and average slope of 9.5^o. The runoff coefficient obtained after an overlay of a land cover map and a soil type map was estimated to 0.25. This value falls in the range for an agricultural dominated catchment as found by Purdue, *et al.* in 2007. The maximum peak flow generated in the Migina catchment is around 16.12 m^3/s by use of an area reduction factor and the rainfall intensity fallen in the whole Migina catchment. The time of concentration was estimated to 3hours 26minutes. Land cover and hydrological soil groups analyses in the Migina catchment show that it is dominated by agriculture activities (92.5%) while forest occupy 5%; grass/lawn 2% and buildings cover 0.5%.

Agricultural Engineers can estimate the crops water requirements. Therefore, they can use this information of soil group classification together with the shown water resources availability in the Migina catchment to contribute to sustainable development of agriculture in Rwanda. It is also recommended that this approach could be applied to other catchments in the country and results could be used in flood management, water allocation planning, decision making and policy formulation. This applied rational method was also recommended by Bulter and Davies (2004).

As these are preliminary results of a PhD research which is ongoing, field hydrograph should be used to compare this model approach to field measurements to determine the better correction factor and to verify the approach. Because of non-linear processes and many changes including the fast development of urban areas and possible climate change, which have significant impacts on hydrological processes especially on generation of surface runoff, it is recommended to develop river discharge models in the future using advanced methods such as distributed hydrological modelling.

6. ACKNOWLEDGEMENTS

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