Regional Flow Duration Curve Estimation and its Application in Assessing Low Flow Characteristics for Ungauged Catchment. A Case Study of Rwegura Catchment-Burundi

Joel Nobert[1], Jackson Ndayizeye[2], Simon Mkhandi[3]

[1] University of Dar es Salaam, Water Resources Engineering, Box 35131, Dar es Salaam, Tanzania.
[2] Water Engineer, World Vision Burundi, P.O Box
[3] University of Dar es Salaam, Water Resources Engineering Department, Box 35131, Dar es Salaam, Tanzania

Abstract

On Kitenge River in September 1986. Recently, the water level in the Rwegura reservoir has decreased and this has resulted in a reduction in generated power and hence power rationing. The reservoir is situated in an un-gauged catchment and therefore, there is a fundamental need to develop a method that can be used to assess the hydrology in periods of low flow.

A flow duration curve for Rwegura ungauged catchment was developed through Regionalization approach. Based on spatial rainfall pattern, a hydrological homogeneous region in which the catchment belongs was derived. For each gauged site, a dimensionless monthly flow duration curve was derived and a regional dimensionless flow curve was found by averaging the dimensionless flow duration curves of all gauged sites. Multiple regression equation was then developed to find relationship between mean monthly flow (index flow) for the gauged sites and catchment characteristics such as catchment area, mean catchment slope, mean elevation of the catchment, station elevation, stream length, stream slope and mean annual precipitation. The derived regression equation was used to find the index flow at Rwegura ungauged site and thereafter the flow duration curve was found as a product of dimensionless regional flow duration curve and index flow. The validation was based on the comparison of the few available observed stream flow data (1980 – 1983) and the Nash efficiency criterion was found to be 91%. The derived flow duration curve was used to characterize the low flow in the range from 70% and 90% of time flow is equalled or exceeded. The monthly flow which is equalled or exceeded 90% of time $\left(Q_{90}\right)$ is $16.8\,m^3/s$. This flow is known as the lowest flow estimated for Rwegura and therefore it can be used to assess the reliability of hydropower generation in Rwegura ungauged Catchment.

Key words: Regionalization, ungauged catchments, Flow Duration Curve (FDC), Hydropower

1 INTRODUCTION

Burundi is faced with a range of problems in the energy sector. DRC has been the major source of electric energy for Burundi since 1958 when Rusizi hydroelectric generation plant was constructed on Rusizi River on the border between Rwanda and DRC at the outlet of Lake Kivu. In order to have a secure source of energy within the country, Burundi constructed Rwegura hydropower plant on Kitenge River in September 1986. This new power station was designed to produce 18 MW and 64 GWh of electrical energy annually supplying electric energy to the different towns in Burundi using two transmission lines; the Rwegura-Bujumbura and Rwegura-Ngozi via Kayanza.

During the Rwegura project, Kitenge River was believed to have sufficient water for both irrigation and future power projects downstream contradictorily to the current situation. In fact, Rwegura power plant is actually even facing many problems due to the decrease of water level in the reservoir which has resulted in a reduction in generated power, creating shortfalls on the demand. This has resulted in a system of allocation of power by priority by the national company of Water and power distribution administration (REGIDESO) which gives precedence to hospitals, followed by industries, whereas residences rarely get power, and this has become an issue of concern. Nevertheless, Rwegura reservoir is situated in an un-gauged catchment and the stream flows were recorded for a short period of four years consecutively from 1980 to 1983, the period through which Rwegura hydropower plant was designed. The lack of adequate hydrological data introduces uncertainty in both the design and management of water resources. Consequently, there is a fundamental need to develop methods that can be used to assess the hydrology during times of low flow.

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The estimation of flow characteristics of ungauged catchments is usually based on transferring or extrapolating information from gauged to ungauged sites, a process called regionalization (Nathan *et al*, 1990). The regionalization of flow duration curves appears therefore to be an operative tool when dealing with ungauged catchments or short stream flow records (Castellarin *et al*, 2004). An initial step in regionalization is the process of delineation of sub-catchments with similar hydrological response. In this case, the region may be defined by stream flow characteristics (Burn & Boorman, 1993) or by physical and climatic characteristics (Acreman & Sinchair, 1986). Once a homogeneous region is successfully identified, the regionalized flow duration curves could be implemented using statistical approach or non statistical (parametric and graphical) approaches (Castellarin *et al*, 2004).

In this study, all available data (climatic and streamflow data) within the chosen study area were used to identify gauged catchments with similar hydrological responses with Rwegura catchment. Regional multiple regression equation was then derived to illustrate relationship between streamflows and catchments characteristics.

1.1. Description of the Study Area

Burundi is divided into two major river basins i.e. Congo basin and Nile basin. Rwegura catchment is entirely located in Kibira National park of Burundi where climate is tropical. The monthly average temperature recorded at the weather station of Rwegura over a period of fifteen years (1990-2005) is 15.4^{o}C. A major part of the year experiences rainfall, with intermittent periods of dryness. Rainfall is heavier from September to May with a short dry season from January to February. Rwegura catchment has an estimated area of 231.5 km^2. The major inlet river is Kitenge and Mwokora at the outlet of the catchment. The geographical location of the catchment is as shown in Figure 1.

1.2. Data Availability and Analysis

Every hydrological analysis depends on the acquisition of relevant data. In this study both time series (rainfall and streamflows) and spatial data (Digital Elevation Model (DEM) of 90m- resolution) were used for the analysis. Rainfall data was used to classify preliminary homogeneous region while stream flow data were used for homogeneity test and discordance measurement to validate the region initially delineated either geographically or climatically. Rainfall and stream flows data were obtained from the Geographic Institute of Burundi (IGEBU), Ministry of Water Resources, Environment and Land Management of Burundi. The records vary in starting and ending dates and the length of the available records. The selection of the time series data was based on the quality of the data collected from the various stations at various times. The main purpose for rainfall analysis is to derive the spatial rainfall distribution so as to identify the rainfall region in which Rwegura catchment is located. In this case, the World Meteorological Organization (WMO) suggests a record length of at least 30 years.

The rainfall gauge stations included in the whole country were checked and only rainfall stations whose record length is greater or equal to thirty years were selected from the set. In Rwegura catchment, only one rainfall gauge station with record length of 44 years (1964-2008) was identified. The similarity in terms of spatial rainfall distribution is more accurate when the concurrent period of record is considered for the whole rainfall stations. For this reason, the starting and ending date of record became a criterion for selecting the rainfall gauge stations which could be used to identify the regions with similar spatial rainfall characteristics with the Rwegura catchment. The selected rainfall data for the analysis and the computed mean annual rainfall is presented in Table 1.

Currently, there are few direct stream flow measurements. The rating curves of some rivers are not yet determined and most of the gauging stations have short records. Therefore, the stage- discharge relationship was used to determine the required streamflows record where the stage data were available.

Digital Elevation Model (DEM) was used to identify catchments characteristics (catchment area, mean catchment slope, mean elevation of the catchment, station elevation, stream length and stream slope). These catchments characteristics are very important in deriving multiple regression equation showing relationship between stream flows and catchment's characteristics as independent variables.

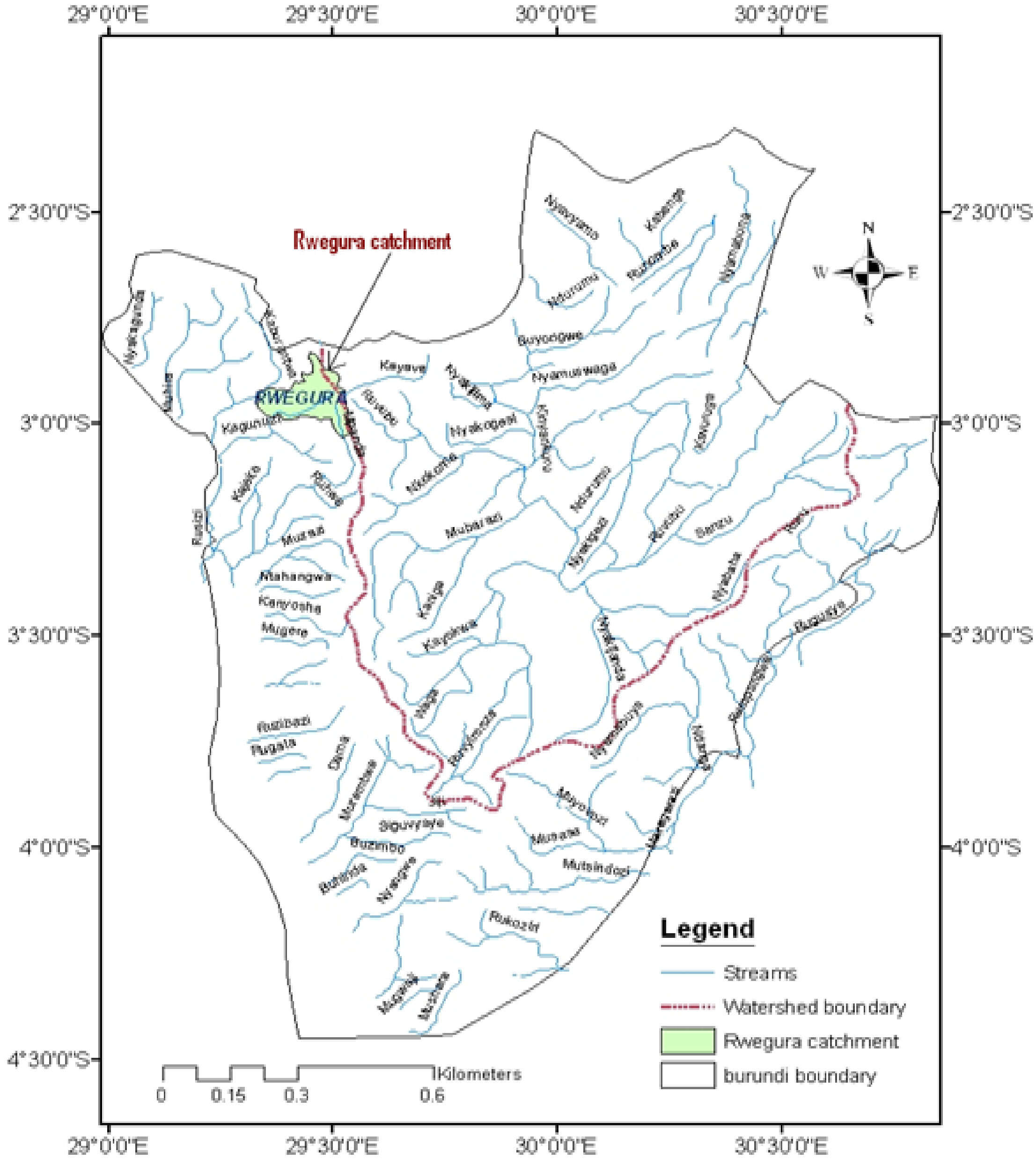

Figure 1: Hydrological Map of Burundi Showing Location of Rwegura

Table 1: Rainfall data used in the analysis

Station ID	Longitude	Latitude	Altitude	Starting year	Ending Year	Period of Record	Mean Annual Rainfall
10011	29.32	-3.32	783.0	1927	2008	81	816.16
10027	29.82	-2.85	1760.	1938	1994	56	1306.10
10036	29.65	-2.98	1806.	1931	1998	67	1341.96
10039	30.23	-3.78	1250.	1962	2005	43	1222
10040	29.85	-3.37	1624.	1930	2008	78	1179.57
10044	29.68	-3.57	2097.	1931	2008	77	1464.47
10046	29.92	-3.42	1645.	1964	2008	44	1189.46
10061	30.17	-3.10	1600.	1953	2008	55	1156.3
10068	29.75	-3.37	1814.	1933	2002	69	1338.42
10075	30.33	-3.65	1308.	1967	2008	41	1151.6
10080	29.42	-3.28	877.0	1935	1990	55	1064.5
10082	29.23	-2.72	1509.	1954	2008	54	1840.9
10083	29.82	-4.13	1450.	1935	2008	73	1255.3
10085	30.00	-3.60	1770.	1934	2004	70	1221.47
10112	30.08	-3.53	1616.00	1954	2008	54	1126
10116	30.10	-4.00	1260.00	1960	2008	48	1162
10123	29.35	-3.60	971.00	1956	2000	44	966
10125	30.55	-3.23	1750.00	1931	2008	77	1196
10127	30.35	-2.85	1756.00	1927	2008	81	1091
10149	30.40	-2.73	1650.00	1930	2000	70	1085
10161	29.77	-3.82	1822.00	1960	2008	48	1334
10164	29.52	-2.92	2302.00	1964	2008	44	1664
10167	29.57	-3.18	2166.00	1963	1996	33	1607
10169	30.07	-3.15	1170.00	1934	2001	67	1234

1.3. Delineation of Homogeneous Regions

The preliminary delineation of the homogeneous regions considered the climatic conditions and the topographical characteristics of a particular region. The catchments which belonged into the same climatic zone or topographic zone formed a preliminary homogeneous region. Climatic regions were derived from the spatial distribution of the mean annual rainfall. The spatial coverage of the mean annual rainfall was estimated using Kriging interpolation techniques. The topographical zones were derived from the topographic map for the area.

A homogeneity tests based on Coefficient of Variation (CV) and discordance measure were then applied to verify if the preliminary delineated region is homogeneous. In this case the streamflows data was used and the region is confirmed to be homogeneous if it satisfies both criteria of homogeneity tests. In regionalization, assumptions must be made about the statistical similarity of the sites in a region. To investigate the similarity the values of mean coefficient of variation (CV) and the site-to-site coefficient of variation of the coefficient of variation (CC) were used.

For coefficient of variation (CV) homogeneity test, for each site in a region the mean, standard deviation and coefficient of variance are calculated.

$$\overline{Q}_i = \frac{\sum_{j=1}^{n_i} Q_{ij}}{n_i} \qquad (1)$$

$$\sigma_i = \sqrt{\frac{\sum_{j=1}^{n_i} \left(Q_{ij} - \overline{Q}_i\right)^2}{n_i - 1}} \qquad (2)$$

$$CV_i = \frac{\sigma_i}{\overline{Q}_i} \qquad (3)$$

Where $\overline{Q}_i =$ Mean flow rate of site i, $Q_{ij} =$ Flow rate of station j in region i, $\sigma_i =$ Standard deviation $CV_i =$ Coefficient of variance.

The regional mean coefficient of variation and standard deviation were then estimated as presented below.

$$\overline{CV} = \sum_{i=1}^{N} \frac{CV_i}{N} \qquad (4)$$

$$\sigma_{cv} = \sqrt{\frac{\sum_{i=1}^{N} \left(CV_i - \overline{CV}\right)^2}{N}} \qquad (5)$$

According to Mkhandi & Kachroo (2000), a region is homogeneous if the coefficient CC is small while Sine and Ayalew (2004) suggested that a region is declared to be homogeneous if $CC = \frac{\sigma_{cv}}{\overline{CV}}$ is less or equal to 0.3. The discordance measure is intended to identify those sites that are grossly discordant with the group as a whole. It estimates how far a given site is from the centre of the group.

L-moment is developed for this purpose and the formulas are summarized below:

$$\hat{M}_{10K} = \frac{1}{N} \sum_{i=1}^{N} \left[\binom{N-i}{K} \Big/ \binom{N-1}{K} \right] X_i \qquad k = 0,1,2,\ldots,N-1 \qquad (6)$$

$$\hat{M}_{1j0} = \frac{1}{N} \sum_{i=1}^{N} \left[\binom{i-1}{J} \Big/ \binom{N-1}{j} \right] X_i \qquad j = 0,1,2,\ldots,N-1 \qquad (7)$$

$i =$ Rank of observed flow data in ascending order
The first few moments are given by the expressions shown below:

$$L_1 = M_{100}$$

$$L_2 = M_{100} - 2M_{101}$$

$$L_3 = M_{100} - 6M_{101} + 6M_{102}$$
$$L_4 = M_{100} - 12M_{101} + 30M_{102} - 20M_{103} \quad (8)$$

L-moment ratios are defined as:

$$t = {L_2}/{L_1}$$
$$t_r = {L_r}/{L_2} \quad \text{Where } r \geq 3 \quad (9)$$

t: Measure of scale and dispersion (LC_V), t_3 : Measure of skewness (LC_s), t_4 : Measure of kurtosis (LC_k)

If $U_i = \left[t^{(i)}, t_3^{(i)}, t_4^{(i)}\right]^T$ is the vector containing the t, t_3, t_4 values for site (i), then the group average for N sites within the region is given by:

$$\overline{U} = \frac{1}{N}\sum_{i=1}^{N} U_i \quad (10)$$

The regional standard deviation is given by:

$$S = (N-1)^{-1}\sum_{i=1}^{N}\left(U_i - \overline{U}\right)\left(U_i - \overline{U}\right)^T \quad (11)$$

The discordance measure is defined by:

$$D_i = \frac{1}{3}\left(U_i - \overline{U}\right)^T S^{-1}\left(U_i - \overline{U}\right) \quad (12)$$

According to Sine and Ayalew (2004), a suitable criterion to classify a station as discordant is that D_i should be greater or equal to 3 $(D_i \geq 3)$.

1.4. Relationship Between Index Flow and Physical Catchment Characteristics

The multiple regression equation showing a linear relationship between index flow and catchment characteristics and mean annual rainfall was determined using LINEST function of MS Excel spreadsheet. Note that the index flow can be either mean annual flow or mean monthly flow depending on the time interval considered for the Flow Duration Curve (FDC). In this study, the monthly flow duration curve was adopted, therefore the mean monthly flow for the gauged sites was considered as index flow. The multiple regression equation is as shown in equation (13).

$$Y = m_1X_1 + m_2X_2 + m_3X_3 + \ldots + m_nX_n + b \quad (13)$$

Where X_1, X_2,……X_n represents the physical catchment characteristics and the mean annual rainfall m_1, m_2, ….., m_n and b are coefficients and Y is the index flow.

1.5. Derivation of Flow Duration Curve (FDC) for Ungauged Site

The following steps were adopted by the author in deriving the flow duration curve: (1) Standardizing the flow duration curve for all gauged river basins by dividing the empirical flow duration curve by the index stream flow; the index stream flow in this case was the average of monthly streamflows for all the stations with records; (2) A graphical regional dimensionless flow duration curve is then obtained by averaging the standardized empirical flow duration curve of all gauged river basins in the study region. The flow duration curve for ungauged catchment located within the study area was then estimated as the product of the dimensionless regional flow duration curve and an estimated index stream flow for the catchment.

1.6. Low Flow Characteristics

According to the World Meteorological Organization, low flow percentiles from the FDC are often used as key indices of low flow, the flow that is exceeded for 95 percent of the period of record (Q_{95}) is commonly used to characterize the low flow. In this study, since the river is not perennial, instead of Q_{95} which is specific for perennial rivers, Q_{70} and Q_{90} were used as indicators of low flow characteristics at Rwegura catchment.

2 RESULTS AND DISCUSSIONS

2.1. Delineated Homogeneous Regions

The spatial distribution of the mean annual rainfall as estimated using kriging interpolation technique indicates that Rwegura catchment is entirely located in rainfall region whose range of annual rainfall is between 1300 mm and 1900 mm. Homogeneity tests for all the streamflow gauging stations within the region is as presented in Tables 2 & 3.

Table 2: Coefficient of variation (CV) homogeneity test results

Stream flow gauging Stations	$\overline{Q}_i = \frac{\sum_{j=1}^{n_i} Q_{ij}}{n_i}$	$\sigma_i = \sqrt{\frac{\sum_{j=1}^{n_i}\left(Q_{ij} - \overline{Q}_i\right)^2}{n_i - 1}}$	$CV_i = \frac{\sigma_i}{\overline{Q}_i}$
11006	8.84	8.58	0.97
11021	4.51	4.06	0.90
11019	6.05	3.30	0.55
11020	5.92	4.34	0.73
11032	4.37	3.03	0.69
11033	13.27	7.83	0.59
		$\overline{CV} = \sum_{i=1}^{N} \frac{CV_i}{N} = 0.73$	
		$\sigma_{cv} = \sqrt{\frac{\sum_{i=1}^{N}\left(CV_i - \overline{CV}\right)^2}{N}} = 0.17$	
		$CC = \frac{\sigma_{cv}}{\overline{CV}} = 0.23$	

Table 3: Discordance measure homogeneity test results

Stream flow Station	$\left(U_i - \overline{U}\right)\left(U_i -\right.$	$\left(U_i - \overline{U}\right)^T \left(U_i - \overline{U}\right.$	$D_i = \frac{1}{3}\left(U_i - \overline{U}\right)^T S^{-1}\left(U_i - \overline{U}\right)$
11006	0.021324	0.010201	0.2125208
11021	0.032560	0.005098	0.1062075
11019	0.005202	0.004134	0.0861352
11020	0.004799	0.049E-06	1.0208E-05
11032	0.010562	0.00311364	0.0648675
11033	0.004013	0.002809	0.0585208
			$S = (N-1)^{-1}\sum_{i=1}^{N=14}\left(U_i - \overline{U}\right)\left(U_i - \overline{U}\right)^T = 0.016$

From Tables 2 & 3, it can be observed that both homogeneity tests have confirmed the homogeneous region. However, the entire region comprises of both ungauged and gauged catchments. All ungauged catchments were automatically excluded from the analysis because the statistical test is based on the available stream flow data. Furthermore, the results of homogeneity tests are valid if the considered gauged catchments form a geographic continuous region. Therefore, only the catchments forming the geographically continuous region (Figure 2) were considered in deriving the flow duration curve for the ungauged catchment.

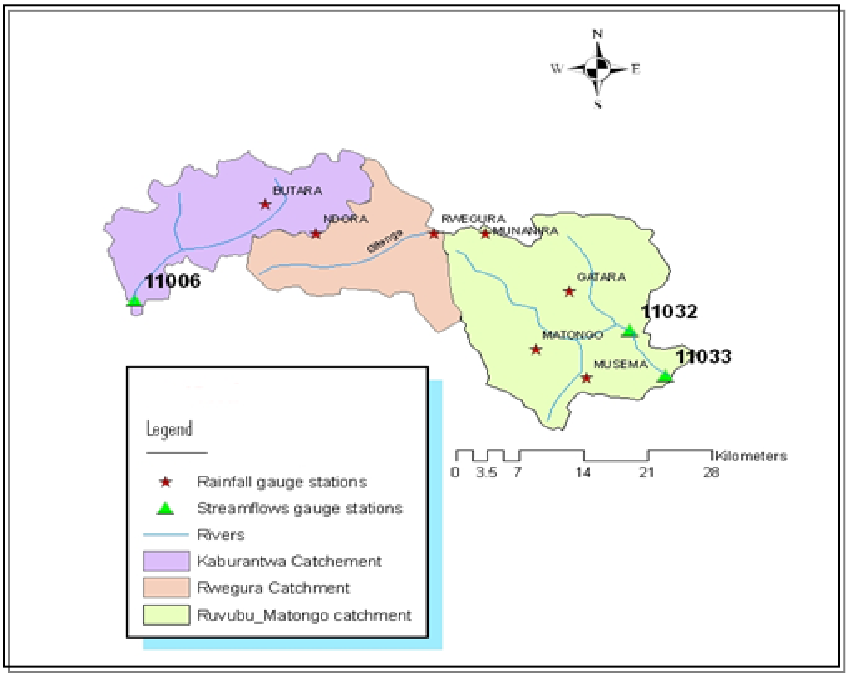

Figure 2: Delineated hydrologically homogeneous regions

2.2. Flow Duration Curve and Low Flow Analysis

A dimensionless flow duration curve was obtained by averaging the standardized empirical flow duration curve of all gauged sites as shown in Figure 3.

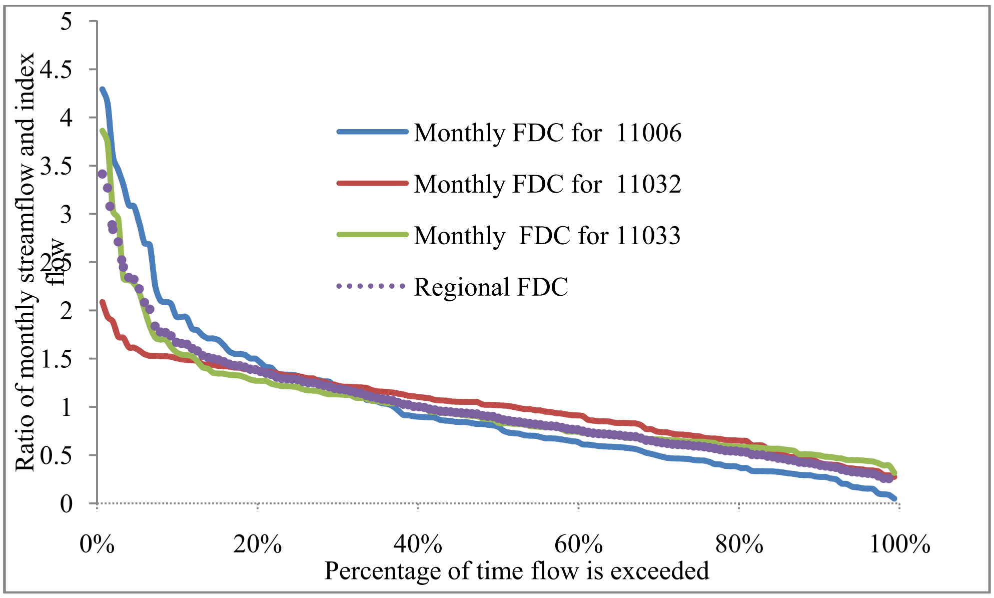

Figure 3: Dimensionless flow duration curves

Index flow and catchments characteristics derived from DEM are shown in Table 4. The Multiple regression equation coefficients describing the relationship between catchment characteristics, mean annual rainfall and the index flow are presented in equation (14). The multiple regression equation was used to estimate the index flow (scale factor) for ungauged Rwegura catchment with an area of 231.5 km^2 and finally the flow duration curve for the catchment was estimated by multiplying the dimensionless regional flow duration curve by the estimated of index flow. The validation was based on the comparison of the few available observed stream flow data (1980-1983) and the estimated flow duration curve. The plot of observed and estimated Flow duration curves is shown in Figure 4 and the Nash-Sutcliff efficiency (NSE) coefficient was found to be 0.91.

$$Y = 26.56 \times AREA + 12.17 \times ELEVATION + 18.23 \times MAP - 59499.02 \quad (14)$$

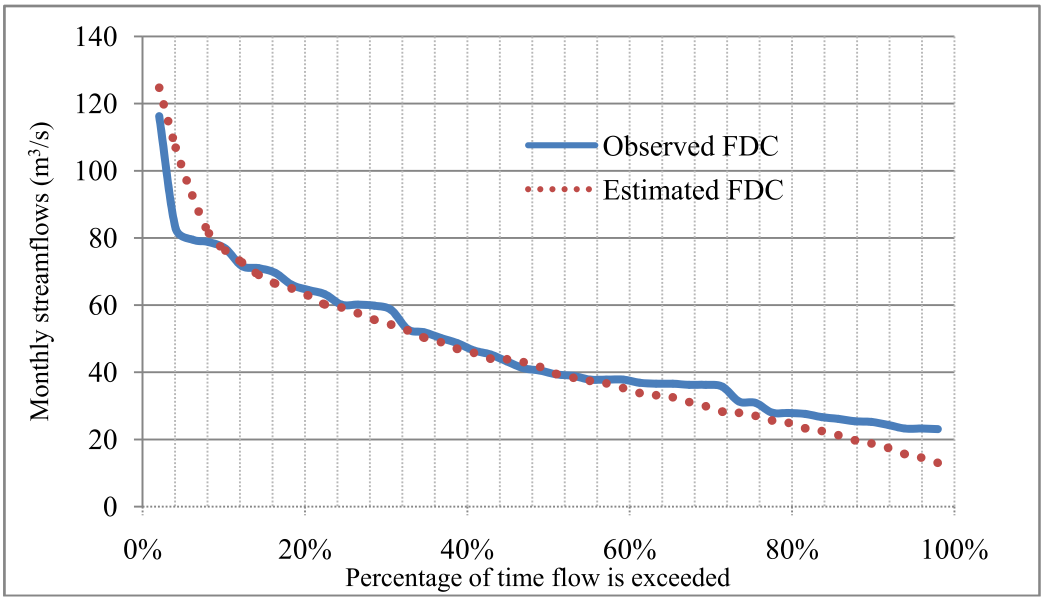

Figure 4: Observed and estimated flow duration curves for Rwegura catchment

Figure 5 illustrates the low flow characteristics of Rwegura gauging station. It can be observed that the flow corresponding to Q_{70} and Q_{90} are 26.7m^3/s and 16.8m^3/s, respectively.

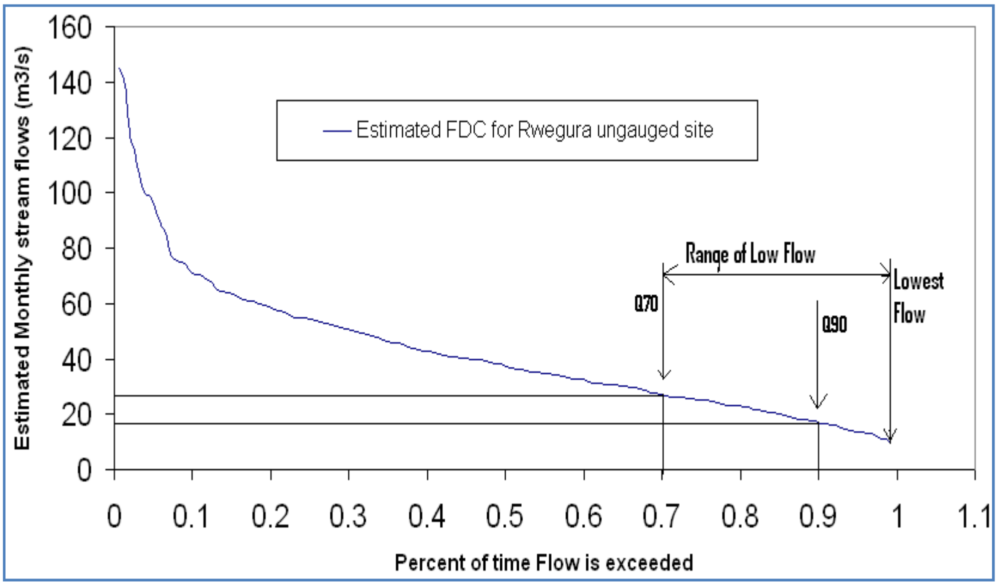

Figure 5: Estimated FDC for Rwegura ungauged site and Low flow indices

Table 4: Index flow, mean annual rainfall and derived catchment parameters

Gauged site	X_1 Catchment area (km^2)	X_2 Stream length (km)	X_3 Catchment elevation (m)	X_4 Mean annual rainfall (mm)	X_5 Stream slope (%)	Mean monthly flow (m^3/s)
11006	291.5	26.8	1416.0	1908	28	266.94
11032	432.5	26.6	1819.6	1427	17	153.23
11033	488.2	33.5	1783.6	1382	18	373.69

3 CONCLUSION

Flow duration curve and minimum flows for Rwegura ungauged site were successfully analyzed. From the estimated flow duration curve for Rwegura ungauged site, the monthly flow which is equalled or exceeded 90% of time (Q_{90}) is $16.8\, m^3/s$. This flow is known as the lowest flow for Rwegura ungauged catchment and therefore this value can be taken into consideration in assessing the reliability of Rwegura Power generation and environmental flow requirement in Rwegura ungauged Catchment.

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AUTHORS BIOGRAPHY

Joel Nobert: is a holder of PhD in Water Resources Engineering. He is currently a lecturer in the Department of Water Resources Engineering, University of Dar es Salaam, Tanzania. The author is also a member in GIS and modelling cluster of Nile Basin Capacity Building Network for River Engineering (NBCBN-RE).

Jackson Ndayizeye: is a holder of Masters in Water Resources Engineering and currently he is working as a Water Engineer with World Vision international organization in Burundi.

Simon Mkhandi: is a holder of PhD in hydrology and a senior lecturer at the University of Dar es Salaam, Water Resources Engineering Department.