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Low Flow Duration Frequency Relationships of Selected Catchments in the Blue Nile Basin

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ABSTRACT

Low flow extremes are natural phenomena that have amplitudes lower than the average low flow on a river basin brought about by severe droughts that hamper sustainable development in the basin (e.g. agricultural damage, water supply shortage). The study aimed to establish a probabilistic picture of extreme Low flow-Duration-Frequency (QDF) relationships in the Blue Nile basin. A 3-arc seconds (approximately 90m at the equator) digital elevation model (DEM) that covers the Blue Nile basin from CGIAR-CSI SRTM 90m database were downloaded and used in the delineations. The distribution parameters and aggregation levels were calibrated in a combined manner in deriving the QDF relationships accounting for their return period. Hence, the QDF relationship comprises the multi-duration and multi-frequency characterisation of observed extreme values. The amplitude of low flow discharge in Blue Nile basin is phenomenally varying with catchment area, hence, accurate and representative design of QDF curves should be created in order to prevent over and under estimation of design

discharge values. Low-flow-duration-frequency models represent the watershed drought regime which can be used to predetermine low-flow characteristics of a catchment. The QDF models developed in this study can be a useful tool in terms of amount and duration of water abstraction during dry period in an area.

Keywords – Hydrology, Low Flow Extremes, QDF, Blue Nile Basin, Experimental Design, Cebu, Philippines

INTRODUCTION

The focus of this paper is on hydrological drought that is described as a "period of abnormally dry weather sufficiently prolonged to give rise to a shortage of water as evidenced by below normal streamflow" (UNESCO-OMM, 2002) in the Blue Nile basin of which Ethiopia, source of Blue Nile, has been hit by years of acute drought (Zaroug, Eltahir & Giorgi, 2014). The Nile is one the most complex and sensitive hydrological basin in the world as it is shared by 10 countries (Burundi, Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda) with 250 million people of different culture, language, religion, and cultural background, thus, "water is a hot political issue in the Nile region" (NBCBN, 2011). According to NBCBN (2011), "the Nile Basin countries are experiencing a number of problems such as rapid population growth, limited water resources, environmental degradation and poverty". Blue Nile, which originates at Lake Tana in Ethiopia, contributes for 59% of the water in the Nile (Shamseldin & O'Connor, 2003).

However, droughts or low flows at the Blue Nile likewise cause difficulties both upstream and downstream of the Nile basin. Egypt, with minimal rain and 97% desert, particularly depends on the Nile River for irrigation, electric power, and drinking water. Likewise, Ethiopia has to face such problem of desertification, drought, and soil erosion (Demeke, 2003). The climate of the Blue Nile basin changes from humid to semiarid conditions from southeast to northwest. Rainfall, as the main factor of river discharge, in the Blue Nile significantly decreases such that from 2000 mm/yr to less than 200 mm/yr (Awulachew, McCartney, Steenhuis & Ahmed, 2008) as elevation descends from the highlands of Ethiopia to the plains of Sudan at Khartoum. On the other hand, temperature varies inversely with altitude as highest occur in plains of Sudan, while lowest in the highlands of Ethiopia. Sudan daily temperature can range from 14 ^{0}C to 44 ^{0}C, while a mean monthly temperature between 3 ^{0}C and 21 ^{0}C in Ethiopia (Awulachew et al., 2008). Thus, there is a need to statistically analyze low flow extremes in the Blue Nile to account for its variability as the results can be considered in practical works for water resources planning and management. QDF (Quantity-Duration-Frequency) or IDF (Intensity-Duration-Frequency) curves are useful information for design of hydraulic structures both in small and big catchments that are supervised by local authorities in establishment of plans for water resources in terms of usage. This study contributes in assessing drought impact on the Blue Nile flow applying lowflow-duration-frequency (QDF) relationships.

OBJECTIVE OF THE STUDY

The study was conducted to establish a probabilistic picture of extreme low flow regimes in flow-time dimensions for different aggregation levels (duration) at 1, 10, 30, 90, 120, 180, 240, and 300 days accounting for their return period (frequency) specifically for river gauging stations at Megech, Ribb, Gumera, Koga, Gilgel Abay, Bahir Dar, El Diem, Sennar, and Khartoum.

MATERIALS & METHODS

Digital elevation model (DEM) and stream flow daily records of the study site

A 3-arc seconds (approximately 90m at the equator) digital elevation model (DEM) that covers the Blue Nile basin from CGIAR-CSI SRTM 90m database by Jarvis, Reuter, Nelson and Guevara (2008) were downloaded and used in the delineations (Fig. 1). The datasets were projected in a geographic (Latitude/Longitude) projection with WGS84 horizontal datum and EGM96 vertical datum (Jarvis et al., 2008). Streamflow daily records were obtained from the Ministry of Water Resources and the National Meteorological Services Agency in Ethiopia. In this study, it is assumed that streamflow data obtained are stationary, consistent and homogeneous to make use in simulating hydrological extremes. Missing data were replaced by its respective day of the year average to make possible that the time series were long enough.

The Blue Nile River basin is situated between two African countries, the Ethiopia and Sudan (Fig. 1). The upper Blue Nile (known as Abbay in Ethiopia), located at Ethiopia, begins at Lake Tana and ends at the Ethiopia-Sudan border. The lower part of the study area is situated in Sudan and eventually meets the

White Nile River at Khartoum{Formatting Citation}.

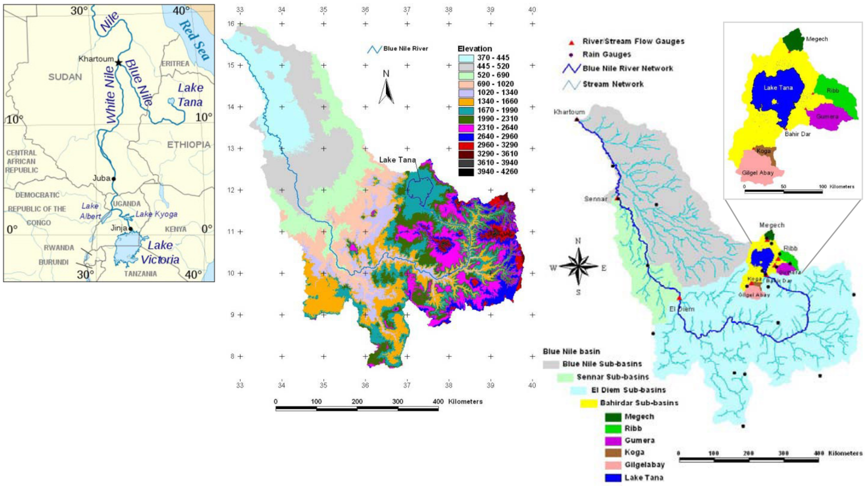

Figure 1. (left-right) Location of Blue Nile basin
in Ethiopia and Sudan, Africa (Source: Nile-en.svg), DEM,
and Delineated Blue Nile Basin and its Sub-Basins.

DEM of Blue Nile basin located between Sudan and Ethiopia lies within to East longitude and to North latitude. Lake Tana lies within to East longitude and to North latitude with an elevation of 1786 meters above sea level. Blue Nile elevation changes considerably from the highlands of Ethiopia to the plains in Sudan. The streams and watersheds of the upper Blue Nile basin descend from 4000 to 1000 meter above sea level and enters Sudan at El Diem station, approximately, at 530 meter above sea level. From El Diem station, the elevation of lower Blue Nile descends further to 380 meters above sea level at Khartoum station. From Bahirdar station to El Diem station, the upper Blue Nile River stretches to a distance of 926 kilometers, while from El Diem station to Khartoum station, the lower Blue Nile River extends to a distance of 827 kilometers. Thus, the long and winding Blue Nile River is calculated to be approximately 1753 kilometers (1090 miles).

Table 1. Coordinates of river flow gauges and its catchment area

Station	Longitude	Latitude	Catchment Area [km^2]
	Upper Blue Nile in Ethiopia		
Koga	37.0337	11.3762	330
Megech	37.4462	12.4846	529
Gumera	37.6329	11.8338	1303
Ribb	37.7162	12.0071	1445
Gilgel Abay	37.0337	11.3754	1699
Bahirdar	37.4104	11.5979	15489
Eldiem	35.1854	10.9879	176910
	Lower Blue Nile in Ethiopia		
Sennar	33.5829	13.5671	206488
Khartoum	35.5496	15.6179	314835

Blue Nile Watershed Delineation

Watershed delineations were useful in this study in knowing the catchment areas and boundaries that allow in determining what physical (e.g. elevation, slope, landuse, soil type) and climatic (e.g. rainfall, temperature, PET) characteristics within the watershed that influence river discharge. Locations of the river flow gauging stations are shown in Table 1. Delineations of the Blue Nile basin and its sub-basins were successful from the 3-arc seconds DEM (Fig. 1). Blue Nile basin is basically divided into lower (in Sudan) and upper (in Ethiopia) Blue Nile. Lake Tana, source of the Blue Nile, is located at the north-eastern part of the upper Blue Nile. Blue Nile basin has a drainage area of about 314835 km2 at Khartoum where it unites with the White Nile to form the Nile River.

General Steps Applied in Constructing Low-flow QDF

1) Extraction of nearly independent low-flow extreme values;
2) Steps 1 was repeated for eight durations D at 1, 10, 30, 90, 120, 180, 240, and 300 days aggregation levels;
3) Examination of distribution's tail and selection of a corresponding probability distribution;
4) Calibration of distribution parameters $\theta\left(\hat{\beta}(D),\ \hat{t}(D), \text{and}\, \hat{x}_t\,(D)\right)$ of equation (8) by optimizing parameters c, w, H, z and a in a combined manner; and

5) Establishment of relationships of different discharge *Q*, at different aggregation level *D*, with different return periods *F*.

Extraction of nearly independent low-flow extreme values

Nearly independent low-flow extreme values were determined using WETSPRO by inverse 1/Q transformation applying Peaks-Over-Threshold (POT) independency criteria proposed by Willems (2009) where peak flows are selected based on inter-event time, inter-event low flow discharge and peak height (Fig. 2).

$$\frac{q_{min} - q_{base}}{q_{max}} < f$$

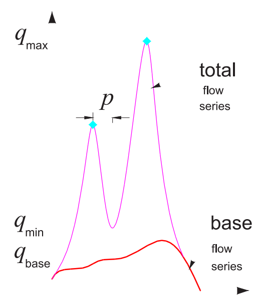

Figure 2. Parameters used in the criteria to select nearly independent extremes from the discharge series (Source: Willems, 2009).

Low flow tail distribution analysis

As the nearly independent 1/Q peaks were extracted, the extracted extreme low flows (as the empirical quantiles) were arranged in descending order. A corresponding empirical probabilities of exceedance were then calculated to each value, where and denotes the total number of observed extracted peaks for the extreme value analysis. The tail of the distribution was tested in the Q-Q plot according to exponential Q-Q plot, Pareto Q-Q plot, Weibull Q-Q plot, etc. With the aid of a hydrological extreme value analysis tool called ECQ, developed by Willems (1998), graphically fitting a distribution to the tail of the extracted extreme low flows were simplified visually without knowledge of the parameter values.

Pickands (1975) has investigated that if only values of above a sufficiently high threshold are considered, the distribution's tail becomes the Generalized Pareto Distribution (GPD):

$$G(x) = 1 - \left(1 + \gamma \frac{x - x_t}{\beta}\right)^{-1/\gamma} \qquad \text{if } \gamma \neq 0 \qquad (1)$$

$$G(x) = 1 - exp\left(-\frac{x - x_t}{\beta}\right) \qquad \text{if } \gamma \neq 0 \qquad (2)$$

where x_t is threshold value or the location parameter, β is the scale parameter or slope of the distribution's tail in a QQ plot, and γ is the shape parameter. Considering $X = 1/Q$ and as the tail of distribution appears normal as in this study, the GDP matches the exponential distribution. The distribution was calibrated to series of $X = 1/Q$ above a sufficiently high threshold x_t :

$$F(x) = P[X \leq x | X \geq x_t] = 1 - exp\left(-\frac{x - x_t}{\beta}\right) \qquad (3)$$

Where such equation can be expressed towards a distribution for Q (using $q = 1/x_t$ as follows:

$$P[Q \leq q | Q \leq q_t] = P[X \geq x | X \geq x_t]$$
$$= 1 - P[X \leq x | X \geq x_t] = exp\left(-\frac{x - x_t}{ß}\right) = exp\left(-\frac{q^{-1} - q_t{}^{-1}}{ß}\right) \qquad (4)$$

or:

$$F(q) = P[Q \leq q | Q \leq q_t] = exp\left(-\frac{q^{-1} - q_t{}^{-1}}{\beta}\right) = \frac{exp\left(-\frac{q^{-1}}{\beta}\right)}{exp\left(-\frac{q_t^{-1}}{\beta}\right)} \qquad (5)$$

The last equation matches the Fréchet distribution $\left(exp\left(-\frac{q^{-\tau}}{\beta}\right)\right)$ for $\tau = 1$, when considered for flow values lower than q_t (threshold discharge).

Hence, the return period *T*, for low flow minima, is calculated based on the probability distribution *F(q)*:

$$T[\text{years}] = \frac{n}{t}\frac{1}{F(q)} = \frac{n}{t}\frac{exp\left(-\frac{q_t^{-1}}{\beta}\right)}{exp\left(-\frac{q^{-1}}{\beta}\right)} \qquad (6)$$

This return period equation is valid when minima are considered below the threshold during n years (Mirghani et al., 2005).

Low flow Duration Frequency (QDF) relationship

The POT low flow extremes were extracted based on the moving average of river discharge at the time scale that are relevant for hydrological applications. The time span of low flow period is the aggregation level from 1, 10, 30, 90, 120,180, 240, and 300 days that are suitable for river hydrology in designing reservoir for water storage. For the different aggregation levels, the independency period parameter p was set constant, while fraction f and q_{lim} were given an increasing and decreasing magnitude in order to extract reasonable number of peaks from the flow series after inverse (1/Q) transformation. Hence, the distribution parameters $\theta[\hat{\beta}(D),\ \hat{t}(D), \text{and}\ \hat{x}_t\ (D)]$ were calibrated to derive the QDF relationships for several range of aggregation-levels (durations) in a combined manner accounting for their return period (frequency).

For the calibration of the distribution parameters $\theta[\hat{\beta}(D),\ \hat{t}(D), \text{and}\ \hat{x}_t\ (D)]$, equation (1) is calibrated by optimizing parameters c, w, H, z and a such that the fit curves produced by this equation and the threshold values (β, t, x_t) were having minimal errors.

$$\theta(D) = cD^{-H/a}\left(1 + w\left(\frac{A}{D^{1/z}}\right)^{a}\right)^{-\left(\frac{Hz}{a^2}\right)} + \bar{q} \qquad (7)$$

A good fit were accomplished among the nine (9) river discharge gauging stations where threshold results are plotted together with the calibrated (fit) curves. After calibrating the relationships between the model parameters and the aggregation level $\theta[\hat{\beta}(D),\ \hat{t}(D), \text{and}\ \hat{x}_t\ (D)]$, the 'calibrated QDF-relationships' (relationships between) for extreme low flows were calculated, based on linear regression in the exponential Q-Q plot (for $\gamma = 0$) and noting that Q was transformed into 1/Q, as follows:

$$Q = \frac{1}{\hat{x}_t(D) + \hat{\beta}(D)\left(\ln(T) - \ln\left(\frac{n}{\hat{t}(D)}\right)\right)} \qquad (8)$$

RESULTS AND DISCUSSION

Shown in figures 2 to 5 are an example analysis for the Blue Nile basin at Khartoum station. The data starts from 1st January 1965 to 30th September 2005. The daily discharge values were transformed into 1/Q so that the low-flows became maxima and were extracted by POT approach using WETSPRO. Prior to the extraction of independent peak events, parameter and were estimated, as shown in Fig. 4, and were found to be about 30 days and the fraction is 0.4, respectively. For this application, the estimated value of provides an insight to ascertain high degree of independency between two peak events. POT extraction was then carried out as the independency criteria were specified as (1) p = 100 days, (2) f = 0.4 , and (3) q_lim = 0.002 . As a result, 58 independent peak events were extracted that corresponds to independent low-flow events after back transformation (See Figure 5).

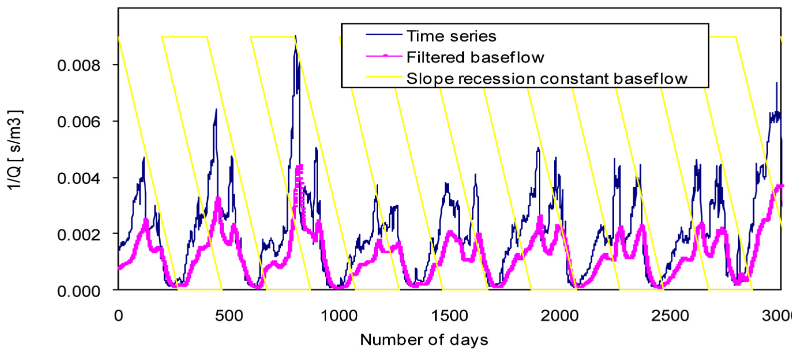

Figure 2. Baseflow filtering of Blue Nile Basin at Khartoum Station

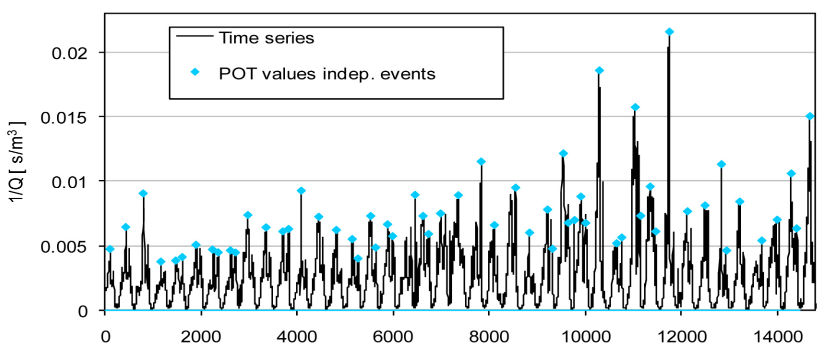

Figure 3. Extracted independent peak events for Blue Nile basin at Khartoum station for 1 day duration

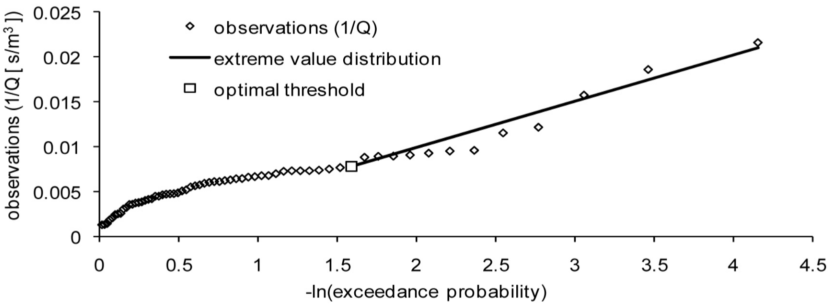

Figure 4. Exponential Q-Q plot showing normal tail distribution for 1/Q at Khartoum station for 1 day duration

The daily flow data were aggregated by moving average for 10, 30, 90, 120, 180, 240, and 300 days in which the same approach were done in extracting their corresponding independent events. The extracted POT, ranked in descending order, were brought into a hydrological extreme value analysis tool called ECQ in order to determine the type of tail-distribution, input parameter β, rank t , and threshold values x_t for the eight different aggregation levels (e.g. Fig. 6). A function for censoring threshold rank in ECQ is an additional feature in modifying slope β. The threshold levels (β, t, x_t) where the distribution is calibrated were considered as the parameters of the distribution's tail. As the shape parameter γ being the most important (Willems, 2010), the distribution's tail of nine (9) catchments were found the same as being exponential (normal tail) with $\gamma = 0$.

Table 2. Threshold inputs for calibration of distribution parameters for Khartoum [1965-2005]

Aggregation level [days]		Threshold	
	Rank,	Slope,	Value,
1	13	0.0052	0.0078
10	13	0.0041	0.0073
30	13	0.0030	0.0070
90	13	0.0022	0.0054
120	13	0.0018	0.0050
180	13	0.0018	0.0044
240	13	0.0015	0.0039
300	9	0.0013	0.0035

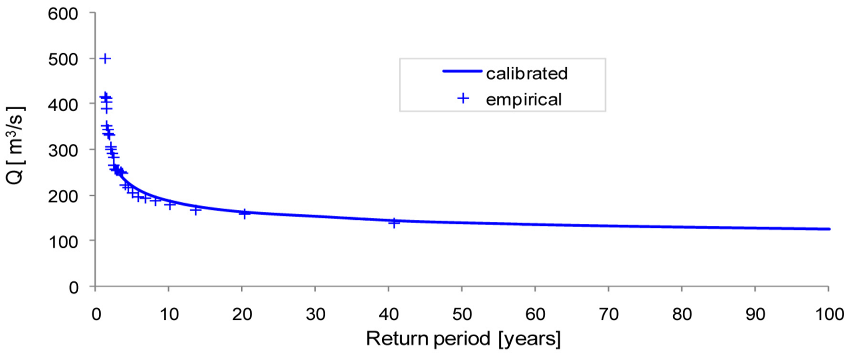

Figure 5. Return period of low-flow extremes at Khartoum station for 240 days duration

QDF models

Consequently, a goodness of fit between the distribution parameters $\theta[\hat{\beta}(D), \hat{t}(D), \text{and}\, \widehat{x}_t\,(D)]$ and threshold inputs for slope β, rank t, and value x_t should produce a low flow duration frequency (QDF) model with minimal differences between the empirical values and the calibrated QDF curve at different durations and return periods as shown in Figures 8 to 10. Thus, a good combined fit between empirical values and calibrated QDF curves were also examined in parallel with a good fit of observed values and calibrated extreme value distributions at different aggregation periods produced based on the calibrated QDF curve. Hence, a good combination of threshold inputs for slope, rank , and value was the crucial gauge in creating a representative QDF models that will consequently generate a satisfactory graphical fit of the observed extreme tail distribution.

Overall, in cases where empirical values appear distant from the theoretical curves are driven by randomness in the occurrence of low-flow extreme events (Mirghani et al., 2005) or inherent uncertainties of hydrological data (Chbab et al., 2000).

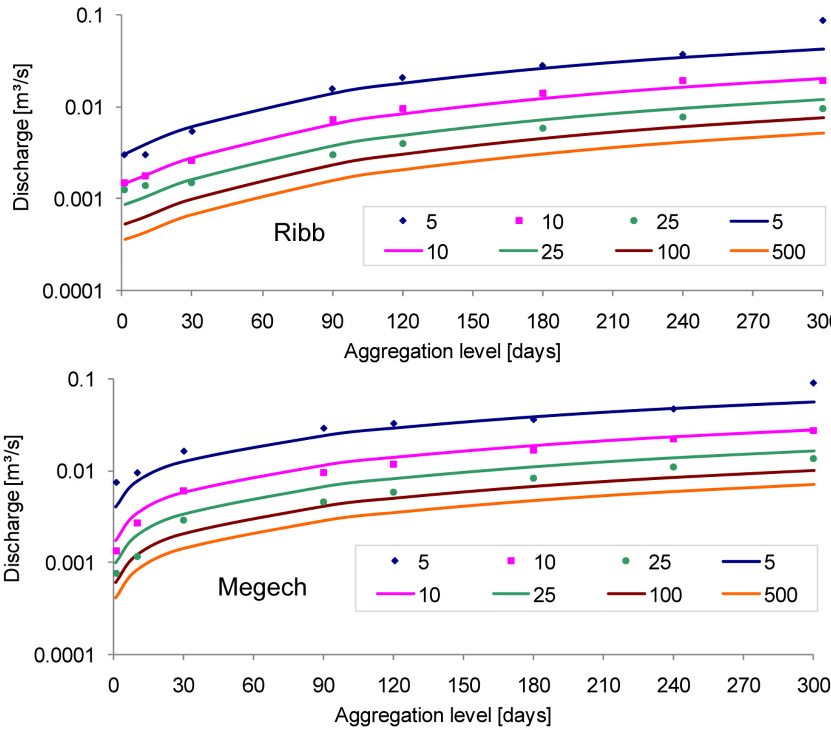

Figure 6. Probabilistic QDF models of Ribb [1961-2004]
and Megech (1980-2006)

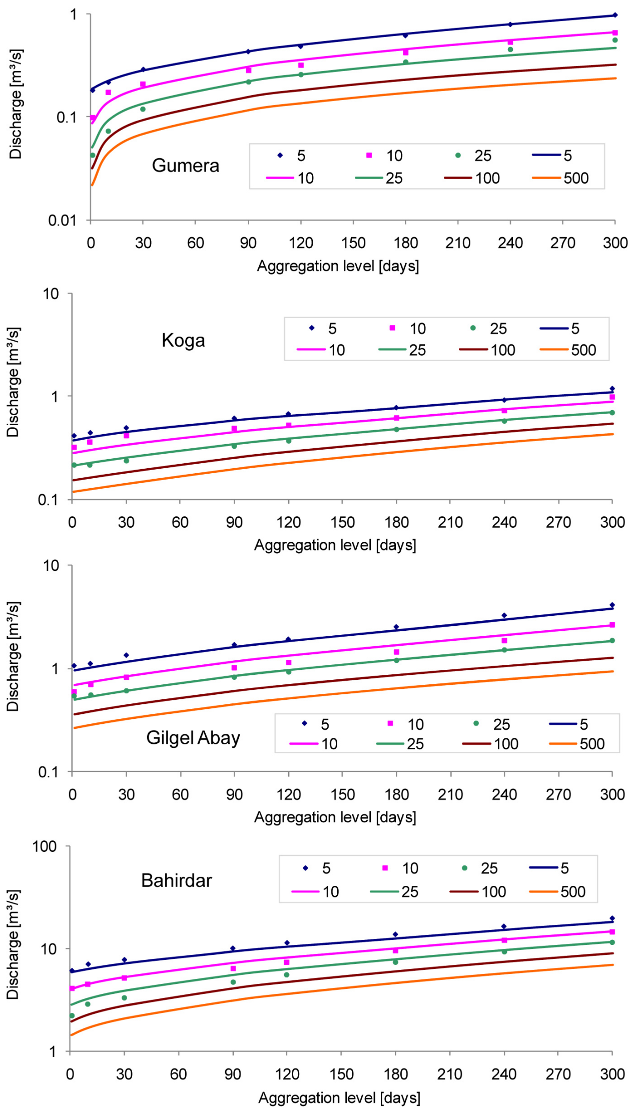

Figure 7. Probabilistic QDF models of Gumera [1971-2006], Koga [1983-2006], Gilgel Abay [1973-2006] and Bahirdar [1973-1999]

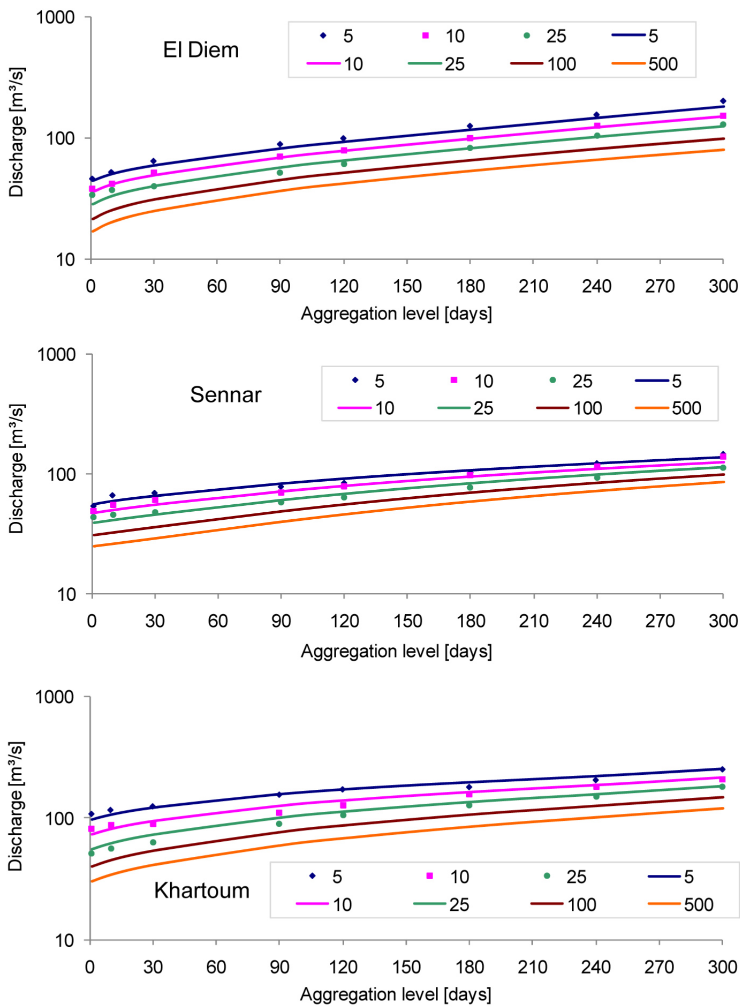

Figure 8. Probabilistic QDF models of El Diem [1965-1996], Sennar [1968-2001], and Khartoum [1965-2005].

QDF models, in this study, represent pictorially the condition of low flow extreme values and its recurrence rate in the time series for a specified duration. For low flow extremes, the higher the aggregation period the higher the discharge since it increases with duration. The models presented in Figures 6 to 8 are arranged in ascending magnitude that is Ribb catchment has the lowest while Khartoum has the highest magnitude of low flows. The longer the duration of recorded daily discharge time series, the better it can present a QDF curve with higher return period.

CONCLUSIONS

This study is an experimental work on an attempt to establish a probabilistic picture of extreme Lowflow-Duration-Frequency (QDF) relationships in the Blue Nile basin. The distribution parameters and aggregation levels were calibrated in a combined manner in deriving the QDF relationships accounting for their return period. Hence, the QDF relationship comprises the multi-duration and multi-frequency characterisation of observed extreme values. The 1/Q distribution's tail of the catchments considered in this study were having a normal distribution in an exponential Q-Q plot, with , when values of 1/Q above a sufficiently high threshold are considered. Consequently, QDF models were calibrated successfully for the nine (9) catchments wherein these provide a good understanding of their behaviour.

The amplitude of low flow discharge in Blue Nile basin is phenomenally varying with catchment area, hence, accurate and representative design of QDF curves should be created in order to prevent over and under estimation of design discharge values. Future studies are required to investigate QDF of more sub-catchments of a very huge and important Blue Nile basin.

TRANSLATIONAL RESEARCH

The findings of the study are useful information to water resource engineers and to other stakeholders engaged with riparian rights in predetermining low-flow characteristics of a catchment. The QDF models developed in this study can be translated into a useful tool in terms of amount and duration of water abstraction during dry period in an area. The output of this paper can be valuable to stakeholders in assessing the threat of not satisfying the required storage volume of a dam at present as well as future conditions.

These QDF curves is important for assessment of extreme quantiles which can be translated to different water resources applications (Taye and Willems, 2011) such as planning water supplies and impact assessment of prolonged period dry weather on agriculture and aquatic ecosystems (Kankam-Yeboah et al., 2013), among others.

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