Assessment of Low Flows Upstream of Nyumba ya Mungu Reservoir in Pangani River Basin, Tanzania.

TanzaniaのPangani川流域Nyumba ya Mungu貯水池上流の水位低下評価

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Knowledge of low flow characteristics is important in the Pangani river basin in Tanzania as this region has favourable conditions for agriculture as well as water for hydropower generation. During dry seasons when low flows are experienced, conflicting pressures on water distribution between irrigation projects upstream of Nyumba ya Mungu dam and hydropower generation occur. Of the two main rivers that provide inflow to the reservoir, the Ruvu river shows higher frequencies of low flows than the Kikuletwa river. Droughts assessed using Q70 threshold indicate larger deficit volumes and drought durations on Kikuletwa river than Ruvu river. The peak over threshold, (POT), method provides reasonable results on low flows and drought characteristics in the region. This is coupled with the quantile function plots approach and the mean excess plots for identifying the candidate model for fitting the distributions of the extreme values and the number of those extremes.

Key words : Low flows, drought, POT analysis, Tanzania, Africa

Pangani川流域の水位低下評価は、この地域が農業に適した条件ばかりか水力発電に適した条件をも備えているため、重要である。水位低下が経験される乾季に、Nyumba ya Munguダム上流域では、水資源を灌漑に用いるべきか、発電に用いるべきかというコンフリクトが発生する。貯水池に流入する2つの川、すなわちRuvu川とKikuletwa川の内、前者においてより高い水位低下頻度が経験される。Q70(日平均流量の累積分布で30%に当たる値)を閾値として用いた渇水評価においては、Kikuletwa川の渇水量及び、渇水持続期間の方がRuvu川のそれらよりも大きかった。POT解析(peaks over threshold analysis: 閾値超過ピーク解析)は、この流域の水位低下と渇水の特性を評価する上で信頼できる結果を提示した。この解析では、Q-Qプロットや平均超過値プロットが、POT解析で当てはめるべき極値分布の選択や、解析に用いる閾値の設定において有用であった。

キーワード: 水位低下, 渇水, POT解析, タンザニア, アフリカ

I. INTRODUCTION

1. General Introduction

Low flows occur naturally in dry seasons in Tanzania because during these periods there is no rainfall, also existing water use causes more frequent low flows with potentially adverse impacts on streams. Nine river basins for water resources administration have been defined. These basins include relatively small ones like the Ruvu/Wami,

which flows to the Indian ocean north of Dar es Salaam, to large ones like the Pangani basin.

2. Description of The Study Area

The 42,200km² Pangani river basin is located in the northeastern part of Tanzania reaching 450km from the southern slopes of Mt Kilimanjaro and Mt Meru in southeast to its outlet in the Indian ocean near Tanga (see Figs. 1 and 2).

About 90% of the population of 1.3 million in

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Fig. 1 The Pangani river basin in Tanzania, East Africa. Reservoir, rivers, power plants (pp), international borders and basin borders are shown

Fig. 2 Location of gauging stations upstream of Nyumba ya Mungu reservoir

the upstream part of the river basin depends direct on agriculture. The highlands above approximately 1000 m above sea level receive up to 2000 mm of precipitation annually and is heavily populated with up to 300 person/km². The distribution of rainfall within the year in the mountain is almost evenly distributed except the months of January to February and July to early October which becomes relatively dry. The lowland plains receive less than 500mm of precipitation annually and here irrigation is necessary for securing crops

against the uncertain rainfall and subsequent drought.

There is one major reservoir, Nyumba ya Mungu (NyM), located in the central part of the river basin. It has about 875 million m³ storage capacity and it feeds the hydropower stations downstream; at Nyumba ya Mungu (8MW), Hale (21 MW) and the New Pangani Falls (66MW). Most of the irrigated based agriculture in the basin are located upstream of this reservoir (Røhr *et al*, 2001). The catchment of Nyumba ya Mungu reservoir

occupies a total land and water area of about 8,433km².

3. Statement of The Problem and Study Objectives

According to a number of recent studies water scarcity in the Pangani basin has resulted in a severe deficit in water available for multiple uses. As a consequence, sectoral water demands are not being met, water levels in storage reservoir are low and competition for water between farmers and hydropower generators has intensified (Manganga *et al.*, 2001). It is estimated that a total area of 29,000ha (290km²) of the river basin is under irrigation of which some are big irrigation schemes of several thousand hectares. Most of the irrigation schemes are in the upstream of Nyumba ya Mungu dam.

The objective of this research is to undertake a regional study in the catchment of the Nyumba ya Mungu dam in order to aid estimation of extreme values of minimum flows and droughts including their corresponding drought durations. Once the analysis has been performed, the results can be applied to water management strategies. The results can be used to identify spatial compensation zones, areas which experience favorable conditions when there is low flow elsewhere, reservoir out-flow regulation for hydropower generation and water abstraction for irrigation projects.

II. MODELING OF EXTREME VALUES

Extreme value methods are applied to many areas of research, including hydrology, climatology, engineering, and finance. There are two principal distributions that are used: the generalized extreme value (GEV) distribution or some time called simply extreme value (EV) distribution and the generalized pareto (GP) distribution.

1. Modeling by Extreme Value (EV) Distributions

The actual distribution function of maxima is replaced by an extreme value (EV) distribution. The standard EV distribution functions $G_{i,\alpha}$ and G_γ

are subdivided within three submodels and a unified model, where α and γ are certain shape parameters (Reiss and Thomas, 2001).

A list of the three submodels by writing down the standard EV distributions with shape parameter α :

Gumbel (EV0) :

$$G_0(x) = \exp(-e^{-x}), \text{ for all } x \quad (1)$$

Fréchet (EV1), $\alpha > 0$:

$$G_{1,\alpha}(x) = \exp(-x^{-\alpha}), \quad x \geq 0 \quad (2)$$

Weibull (EV2), $\alpha < 0$:

$$G_{2,\alpha}(x) = \exp(-(-x)^{-\alpha}), \quad x \leq 0 \quad (3)$$

One must include location and scale parameters μ and σ in order to build the full statistical models. If a random variable X has the distribution function F then $\mu + \sigma X$ has the distribution function $F_{\mu,\sigma}(x) = F(x - \mu)/\sigma$ (Reiss and Thomas, 2001). By taking the reparameterization $\gamma = 1/\alpha$ of EV distribution functions $G_{i,\alpha}$ one obtains a continuous, unified model:

$$G_\gamma(x) = \exp(-(1 + \gamma x)^{-1/\gamma}), \\ \text{for } (1 + \gamma x) \geq 0. \quad (4)$$

Depending on the value of the extreme value index γ , G_γ reduces to the Fréchet ($\gamma > 0$), the Weibull (sometimes called reverse Weibull (Dougherty *et al.*, 2000)) ($\gamma < 0$) or the Gumbel ($\gamma = 0$ when the unified model is taken in the limiting sense i.e. it has to be interpreted as $\gamma \rightarrow 0$) distributions.

2. Modeling by Generalized Pareto (GP) Distributions

Representation of standard GP distribution functions within three submodels are given by (Reiss and Thomas, 2001) :

Exponential (GP0) :

$$W_0(x) = 1 - e^{-x}, \quad x \geq 0 \quad (5)$$

Pareto (GP1), $\alpha > 0$:

$$W_{1,\alpha}(x) = 1 - x^{-\alpha}, \quad x \geq 1 \quad (6)$$

Beta (GP2), $\alpha < 0$:

$$W_{2,\alpha}(x) = 1 - (-x)^{-\alpha}, \quad -1 \leq x \leq 0 \quad (7)$$

By taking reparameterization $\gamma = 1/\alpha$ of GP distribution functions $W_{i,\alpha}$ one obtains a unified model:

$$W_\gamma(x) = 1 - (1 + \gamma x)^{-1/\gamma}, \\ \text{for } (1 + \gamma x) \geq 0. \quad (8)$$

Depending on the shape parameter γ , W_γ reduces to Pareto ($\gamma > 0$), the Beta ($\gamma < 0$) and the Exponential ($\gamma = 0$, which has to be interpreted in the limiting sense i.e. $\gamma \rightarrow 0$) distributions.

III. BACKGROUND INFORMATION

1. Low Flow Frequencies

Work on assessment of low flows upstream of Nyumba ya Mungu reservoir was previously done in 1999 by Kazumba (Kazumba, 1999). The Weibull distribution was proposed to be a candidate distribution for modeling the low flow frequencies. The Weibull distribution has often been recommended and is extensively used as a statistical distribution in low flow frequency analysis (Clarke, 1994; Gustard *et al.*, 1992). The problem of whether the Weibull distribution globally could be fitted to all the data available and to all subcatchments in the region of study was not clearly defined. The work lacks the systematic way of choosing a distribution after extracting the extreme values[†] because a number of distributions have been proposed in literature for frequency analysis of low flows. Example of those distributions include the Gumbel distribution, lognormal distribution, Pearson type III distribution and the Weibull distribution.

This paper utilizes the recently proposed methods of choosing a distribution. The methods chosen are those which are based on graphical representation of data: the quantile plots (Quantile Quantile plots or simply QQ-plots) and the mean excess functions (Beirlant *et al.*, 1966; Reiss and Thomas, 2000; Bassi *et al.*, 1998). By applying a negative transformation to the minima, the methods used for maxima may be applicable by writing (Reiss and Thomas, 2000):

$$\min_{1 \leq n} (X_i) = -\max_{1 \leq n} (-X_i) \quad (9)$$

In order to utilize the data as much as possible, the peak over threshold (POT) method has been proposed.

2. Droughts

In analysing droughts for streams, two important low flow measures are considered: the length of period during which the flow is continuously below a given threshold value, known as drought duration, and the total volume of flow that would be required to maintain the flow at a given threshold, called the deficit volume. The threshold for analysing annual deficit volumes and drought durations in 1999 were considered up to 65% abstraction level of the mean flow of a given stream. In this research the threshold of $Q70^{††}$ of each gauging station is used. The graphical methods for choice of distributions are applied. In the previous work (Kazumba, 1999) only the Gumbel distribution was used to assess both the deficit volumes and drought durations.

IV. DATA DESCRIPTION

For this study, data of 17 gauging stations were collected from the Ministry of Water (Ubungu Maji) and the University of Dar es Salaam, Water Resources Engineering Section. The period of record varies from 2 year to 36 years. Stations with period of record less than 10 years are excluded in the analysis, as a result only 10 gauging stations are used. Many stations were opened in 1950s and 1960s in the upstream of Nyumba ya Mungu dam but due to operational problems including financial constraints, the Ministry of Water decided to close some of the stations.

The need for water management forced some of the stations to be re-opened since more hydrological data were required. This has led to some stations to have large gaps of missing data for analysis, as shown in Table 1. Stations 1DC6, 1DC3A, 1DC11A and 1DC33 have large gaps of more than a year. To simplify the matter, the gaps were filled by a seasonal mean and smoothed by Fourier series if consecutive number of days with missing data were less than 100 days, otherwise the gaps were not considered in the analysis. The

[†] The extreme values used for analysis were the mean annual 10 day minimum, MAM (10), flow data.

^{††} $Q70$ is the flow which is equalled or exceeded for 70% of the period of record.

Table 1 Gaps of missing data at gauging stations

Main river	Station	Period of record	No. of years	No. of gaps of missing data ≥ 1 year
Kikuletwa	1DD6A	1969/01-1987/07	19	0
	1DD54	1967/01-1993/12	27	0
	1DD1	1952/01-1987/07	36	0
Ruvu	1DC6	1952/01-1987/07	36	1
	1DC2A	1952/01-1987/06	36	0
	1DC1	1952/01-1968/10	17	0
	1DC3A	1953/01-1983/12	31	1
	1DC11A	1952/01-1985/09	34	1
	1DC33	1958/01-1971/01	14	1
	1DC35	1959/01-1977/09	19	0

existence of trend in the time series at 1DD1, 1DD54 and 1DC33 was another problem encountered in the analysis. Of the two main rivers; station 1DD1, 1DD6A and 1DD54 belong to the Kikuletwa river, the rest belong to Ruvu river.

V. METHODOLOGY

1. Low Flow Frequencies

Data analysis in this research was done by using the *XTREMES* software and *FORTRAN* programs. The 10 day moving average was applied to the data for smoothing. All the data were multiplied by -1 in order to rearrange the order of the data, then at a given threshold value the extreme values were extracted. For this study, two events are considered to be independent if they are separated in time by a minimum of 60 days. This is due to the fact that if the extreme value of low flow was experienced in the long dry season by the end of October then after short rains there might be another event in the short dry season of January to February. The average of 1 to 2 extremes per year was considered reasonable for the analysis. The extremes extracted in the long dry season showed no correlation with the events of the short dry season.

Quantile plot (QQ-plot) is important tool among the graphical data exploration techniques which has been used to distinguish visually different dis-

tribution functions. Let us consider a sample distribution function $\hat{F}(x_i)$ which, for a set of n observations given in increasing order $x_1, \leq, \dots, \leq x_n$, is defined as:

$$\hat{F}(x_i) = \frac{i}{n+1}, \quad i=1, \dots, n. \quad (10)$$

Thus, the sample quantile function is written as:

$$\hat{F}^{-1}(q_i) = x_i; \quad q_i = \frac{i}{n+1} \quad (11)$$

Formally the QQ-plot is defined by the points:

$$(\hat{F}^{-1}(q_i), F^{-1}(q_i)), \quad i=1, \dots, n \quad (12)$$

where $F^{-1}(q_i)$ is the quantile function of a given distribution. If the sample data come from the family of distributions F , the plot will be close to a straight line. If the deviation from the straight line is too strong we conclude that the sample comes from a different distribution.

Another graphical tool which is helpful for selection of distribution is the sample mean excess plot. Theoretically the mean excess function $e(u)$ of a distribution F of a random variable X at a given threshold u , is given by the conditional expectation of $X-u$ given $X>u$. We have

$$e(u) = E(X-u|X>u) \quad (13)$$

The theoretical mean excess function for three submodels (Exponential, Pareto and Beta distribution) of the generalized Pareto distribution (GP) are as follows:

Exponential(GP0) :

$$e_{w0}(u) = 1 \quad u > 0 \quad (14)$$

Pareto(GP1), $\alpha > 1$:

$$e_{w1,\alpha}(u) = \frac{u}{\alpha - 1}, \quad u > 1 \quad (15)$$

Beta(GP2), $\alpha < 0$:

$$e_{w2,\alpha}(u) = \frac{u}{\alpha - 1}, \quad -1 \leq u \leq 0 \quad (16)$$

Based on representative sample $x_1, \leq, \dots, \leq x_n$, the sample mean excess function $\hat{e}_n$ at threshold $u = x_{n-k}$ where k is the number of $x_i > u$, is given by:

$$\hat{e}_n(x_{n-k}) = \frac{1}{k} \sum_{j=1}^k x_{n-j+1} - x_{n-k} \quad (k=1, 2, \dots, n-1) \quad (17)$$

The sample mean excess plot is defined by the point $(x_{n-k}, \hat{e}_n(x_{n-k}))$.

2. Deficit Volumes and Drought Durations

The aim of drought analysis is often to try to find a probability distribution of drought duration and deficit volume to be able to predict the risk of future droughts. The two most common extreme value analysis models are the annual maximum series (AMS) model and the peak over threshold (POT) model. An AMS consists of the largest event within each year, whereas a POT contains all events above a threshold. POT model is the most consistent definition of the extreme value region considering not only the largest annual events but all events which exceed the threshold value, therefore, this method is employed.

The use of daily flow discharge introduces two special problems; dependency among droughts and the presence of minor droughts. To avoid

these problems, three procedures for grouping dependent and minor droughts are proposed in literature; the moving average procedure (MA), the sequent peak algorithm (SPA) and the inter-event time and volume criterion (IC). Hisdal and Tallaksen (2000) described the procedures that the IC method is inferior to the MA and SPA. The moving average simply smoothes the time series by applying the moving average filter, the SPA has the advantage over other methods since it has straightforward interpretation as the observed data are used directly.

To analyze deficit volumes and drought durations the sequent of peak algorithm (SPA) method is used. The maximum deficit volume is equivalent to the required storage w_t at time t . Analogous to design of reservoir, let q_t denote the daily inflow to a reservoir and q_0 the desired yield, then the storage w_t required at the beginning of the period t is (Hisdal and Tallaksen, 2000):

$$w_t = w_{t-1} + q_0 - q_t, \quad \text{if positive, otherwise is 0.} \quad (18)$$

An uninterrupted sequence of positive w_t , $\{w_t, t = \tau_0, \dots, \tau_e\}$ defines a period with storage depletion and a subsequent filling up (Fig. 3). The required storage in that period, $\max \{w_t\}$, defines the drought deficit volume (s_i) and the time interval from the beginning of the depletion period, τ_0 , to the time of the maximum depletion, $\tau_{\max}$, defines the drought duration ($\tau_{\max} - \tau_0 + 1 = d_i$). Based on this method two droughts are combined if the reservoir has not totally recovered from the first drought when the second drought begins. The Q

Fig. 3 Definition of drought events by SPA method

70 at each gauging station is taken to be the threshold level (q_0) for characterizing the drought deficit volumes and drought durations.

VI. RESULTS OF ANALYSIS

1. Low flow Frequencies

In order to extract the extremes of minima of daily flows, the values were multiplied by -1 to rearrange the order of the data, as shown in Fig. 4 for the data at 1DC2A. The maximum values above a threshold value, (-6), were taken (Fig. 5). The sample autocorrelation model was used to test independence of the extracted extremes and showed no correlation in the data.

To determine the model which may be used to fit the distribution of minima and the number of extreme values to be used for quantile estimation,

the sample mean excess plot (Fig. 6) and the QQ-plot (Fig. 7) are used. The sample mean excess function has a negative slope of the Beta model. From the Beta distribution QQ-plot it can be clearly seen that there is a need to reduce the number of extremes by increasing the threshold value from -6 to -5 so that we have the extreme values which provide good fit to the QQ-plot (Fig. 8).

The maximum likelihood estimate (MLE) method provides the parameters $\gamma = -0.50$, $\mu = -4.99$ and $\sigma = 1.76$. Moreover the right endpoint of the estimated Beta distribution is -1.44 . The 50 and 100-year return minima are $1.95\text{m}^3/\text{s}$ and $1.80\text{m}^3/\text{s}$ respectively (Fig. 9). The same procedure was carried out to the remaining gauging stations. Problem was encountered in estimating

Fig. 4 Time series at station 1DC2A, 1952–1987, threshold at -6

Fig. 5 Extracted extremes (68) at station 1DC2A

Fig. 6 Sample mean excess function at station 1DC2A

Fig. 7 Beta distribution QQ-plot of 68 extremes at station 1DC2A

Fig. 8 Beta distribution QQ-plot of 54 extremes at station 1DC2A

Fig. 9 Low flow frequency curve at station 1DC2A

Fig. 10 Extracted extremes (52) at station 1DD1

minima when the model detected from the sample mean excess plot does not fit well on the QQ-plot. Example is seen for the extremes extracted at 1DD1 (Fig. 10). The sample mean excess function follows

Fig. 11 Sample mean excess function at station 1DD1

Fig. 12 Beta distribution QQ-plot at station 1DD1

the Beta model (Fig. 11) but the curvature of the Beta distribution QQ-plot shows that the Beta model overestimates the size of the right tail of this distribution (Fig. 12). The results for all ten gauging stations are presented in Table 2.

2. Deficit Volumes and Drought Durations

In order to extract the extremes of deficit volumes and drought durations, a threshold value of Q_{70} was determined to characterise the droughts. At 1DC2A the $Q_{70}=4.58\text{m}^3/\text{s}$ (Fig. 13). By using the SPA model, the deficit volumes were analyzed. Some years could not show any deficit (Fig. 14). A threshold of 1.5 million m^3 was used to pick the extremes. The extracted data (Fig. 15) were tested for independence using the sample autocorrelation function and showed no dependence. The

Table 2 Quantiles of low flow (m^3/s) frequency for 10 gauging stations

Main river	Station	Mean flow (m^3/s)	Return period (years)					
			2	5	10	20	50	100
Kikuletwa	1DD6A	1.89	1.039	0.759	0.712	0.698	0.694	0.693
	1DD54	14.36	11.370	10.711	10.303	9.960	9.588	9.359
	1DD1	23.49	13.203	8.660	6.151	4.234	2.375	1.349
Ruvu	1DC2A	6.39	3.955	3.034	2.569	2.239	1.945	1.797
	1DC6	3.00	1.719	0.970	0.670	0.495	0.370	0.320
	1DC1	26.22	1.511	0.276	0.150	0.126	0.121	0.120
	1DC11A	2.01	0.231	0.062	0.040	0.036	0.034	0.034
	1DC3A	0.71	0.067	0.018	0.015	0.015	0.015	0.015
	1DC33	3.77	3.638	3.212	2.890	2.568	2.142	1.820
	1DC35	0.92	0.643	0.363	0.227	0.133	0.053	0.015

Units: m^3/s

Fig. 13 Time series at station 1DC2A, 1952–1987, threshold at $4.58\text{m}^3/\text{s}$

Fig. 15 Extracted extremes (27) at station 1DC2A, 1952–1987

Fig. 14 Deficit volumes at station 1DC2A, 1952–1987

Fig. 16 Sample mean excess function at station 1DC2A

Fig. 17 Pareto distribution QQ-plot at station 1DC2A

Fig. 18 Deficit volume frequency curve at station 1DC2A

Table 3 Quantiles of deficit volume (million m³) for 8 gauging stations

Main river	Station	Threshold: Q70 (% mean flow)	Return period (years)					
			2	5	10	20	50	100
Kikuletwa	1DD6A	63.48	0.868	2.218	3.776	6.027	10.603	15.884
	1DD54	80.06	3.284	8.856	16.634	29.922	62.924	109.001
	1DD1	56.32	48.403	89.169	109.254	123.185	135.278	141.237
Ruvu	1DC2A	71.60	5.601	11.639	16.776	22.412	30.794	37.902
	1DC6	57.60	6.481	12.487	17.030	21.574	27.580	32.123
	1DC1	13.35	9.499	23.531	37.314	54.599	84.362	113.597
	1DC11A	21.88	2.207	4.315	5.910	7.504	9.612	11.206
	1DC3A	26.79	0.720	1.540	2.290	3.176	4.594	5.893

Units: million m³

sample mean excess plot suggests a positive slope of Pareto model (Fig. 16) and most of the data lie on a straight line of the Pareto distribution QQ-plot (Fig. 17).

The maximum likelihood estimate (MLE) method provides the parameters $\gamma = 0.14$, $\mu = 1529360$ and $\sigma = 5589070$. The 50 and 100-year return deficit volumes are 30.8 million m³ and 37.9 million m³ respectively (Fig. 18). The same procedure was carried out for the drought duration distributions and to the remaining gauging stations. The results for deficit volumes and drought durations are provided in Table 3 and Table 4 respectively. Most of the years in the period of records at station 1DC33 and 1DC35 did not show droughts except in 1960–1962 at 1DC33 and in

Table 4 Quantiles of drought duration (days) for 8 gauging stations

Main river	Station	Return period (years)					
		2	5	10	20	50	100
Kikuletwa	1DD6A	58	124	173	222	288	337
	1DD54	127	292	416	541	705	830
	1DD1	160	340	477	613	794	930
Ruvu	1DC2A	97	201	299	417	611	794
	1DC6	213	370	464	542	624	674
	1DC1	68	154	225	301	412	503
	1DC11A	148	231	270	295	315	325
	1DC3A	84	149	189	222	257	278

Units: days

1961–1964 at 1DC35. Due to few droughts the data were discarded from the analysis.

VII. CONCLUDING REMARKS

1. The peak over threshold, (POT), method provides reasonable results on low flows and drought characteristics in the upstream of Nyumba ya Mungu reservoir. This is coupled with the quantile function plots approach and the mean excess plots for indentifying the candidate model for fitting the distributions of the extreme values and the number of those extremes.
2. Of the two main rivers that discharge water in the Nyumba ya Mungu dam, higher frequencies of low flows are experienced in the Ruvu river than that of the Kikuletwa river. Droughts assessed by using Q70 threshold indicate larger deficit volume and drought durations on Kikuletwa river than Ruvu river.
3. Under good water management, water from Kikuletwa river may serve some part of the region in the Ruvu river catchment during dry seasons because it has less low flow frequencies than those on Ruvu river.

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