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Drought analysis of African rivers: a study of non-stationary low-flow trends in the Volta and Nile

Desmond Yaw Manful[1], Charles Rodgers[2], Barnabas A. Amisigo[3]

Abstract

The Volta basin is a significant river system in West Africa. It drains approximately 400,000 km^2. Droughts continue to pose a threat to the economic development of six riparian states in the basin. In a region where food production and hydro-power generation are vulnerable to climatic risk, knowledge of drought patterns can prove indispensable in the effort towards the realization of the millennium Development Goals. The paper conducts a low-flow study in the Volta basin. Discharge proxies for drought conditions, consisting of annual minimum n-day flows obtained from gauging stations located in the Volta basin, are used to estimate drought quantiles. Weibull distribution is used for initial low-flow estimation. Simulated annealing is utilized as the optimization algorithm for Weibull parameter estimation towards an exploration of the maximum likelihood. Analysis of distribution fitting is then performed with L-Moment ratios which suggest the best fitted distribution function. The study is intended as a step toward the development of methodologies to evaluate impacts of extreme low-flow events on the design of reservoirs to suffice irrigation and hydropower in the Volta.

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Introduction

There is a growing awareness that many regions within Africa are currently vulnerable both to transient and to chronic water scarcity. The reasons are numerous, and include rapid population growth rates overlaid on low per capita incomes, relatively under-developed water storage and management infrastructure, and erratic and difficult climates – the majority of the African land mass (over 80%) is classified as semi-arid or arid. Vörösmarty et al. (2005) combined high-resolution geospatial data with digital river networks and concluded that roughly two out of three Africans rely on water resources that are limited and highly variable. Moreover, there is accumulating evidence that many regions within Africa are likely to become increasingly vulnerable to drought and water scarcity as a consequence of global and regional environmental change. Among recent studies, Nyong (2005) has estimated that if recent historical trends are extrapolated, rainfall in sub-Saharan Africa is likely to drop by 10%, and potential evapo-transpiration to increase substantially by 2050, leading to higher incidence of droughts and negative impacts on food production. Using drainage density analysis, De Wit and Stankiewicz (2006) conclude that availability of water resources will be highly sensitive to changes in precipitation, and decreases in perennial discharge may significantly affect surface water access across 25% of Africa by the end of the 21st century.

The Volta is a major West African transboundary river system, draining an area of 400,000 km^2. The Nile an even larger system drains an area of about 2, 3 million square kilometres. The Volta and the Nile are major African transboundary river systems, draining a combined area of 3,756,000 km2, roughly the size of the European Union. Droughts are already common occurrences in the basin, and pose a threat to food security, hydro-power generation and riverine ecosystems. The frequency and magnitude of drought occurrence may be undergoing changes influenced by global and regional climate change and landuse/landcover change.

Streamflow acts as an integrator of the regional climate signal, and low-flow statistics are often used to construct drought indices (Kroll & Vogel, 2002). A time series consisting of the minimum of observed annual values of successive n-day flows provides a proxy series from which drought quantiles can be estimated using fitted parametric distributions. This paper focuses on the development of methodologies to estimate distribution-based drought quantiles (magnitude of events having a specific frequency of exceedance). Analysis of distribution fit is then performed via L-Moment ratios, which provide evidence for the best-fit distribution function. The study is intended to serve as a step toward the development of methodologies to evaluate impacts of extreme low-flow events on the design of hydraulic structures.

Figure 1 The Volta Basin and the selected four gauges

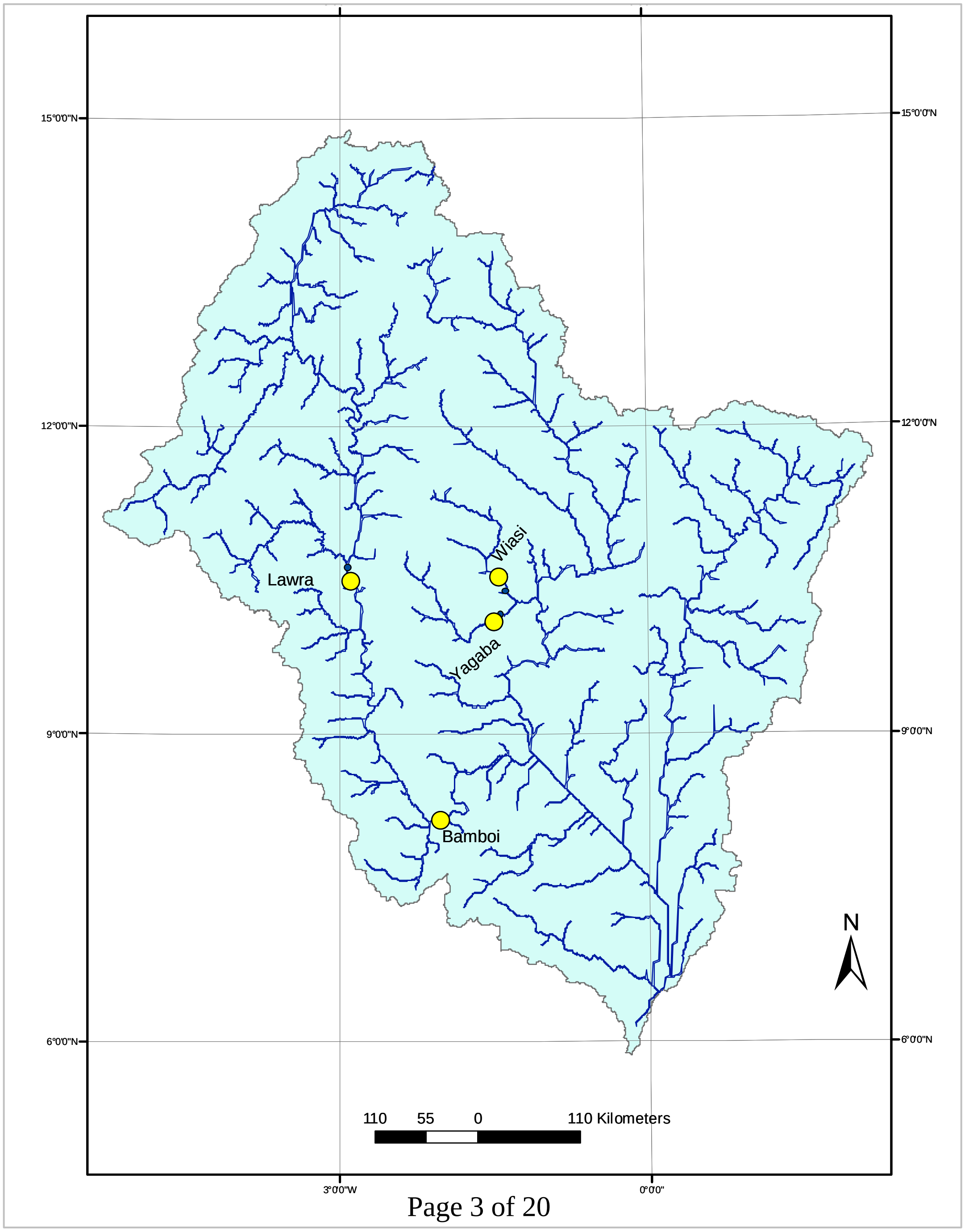
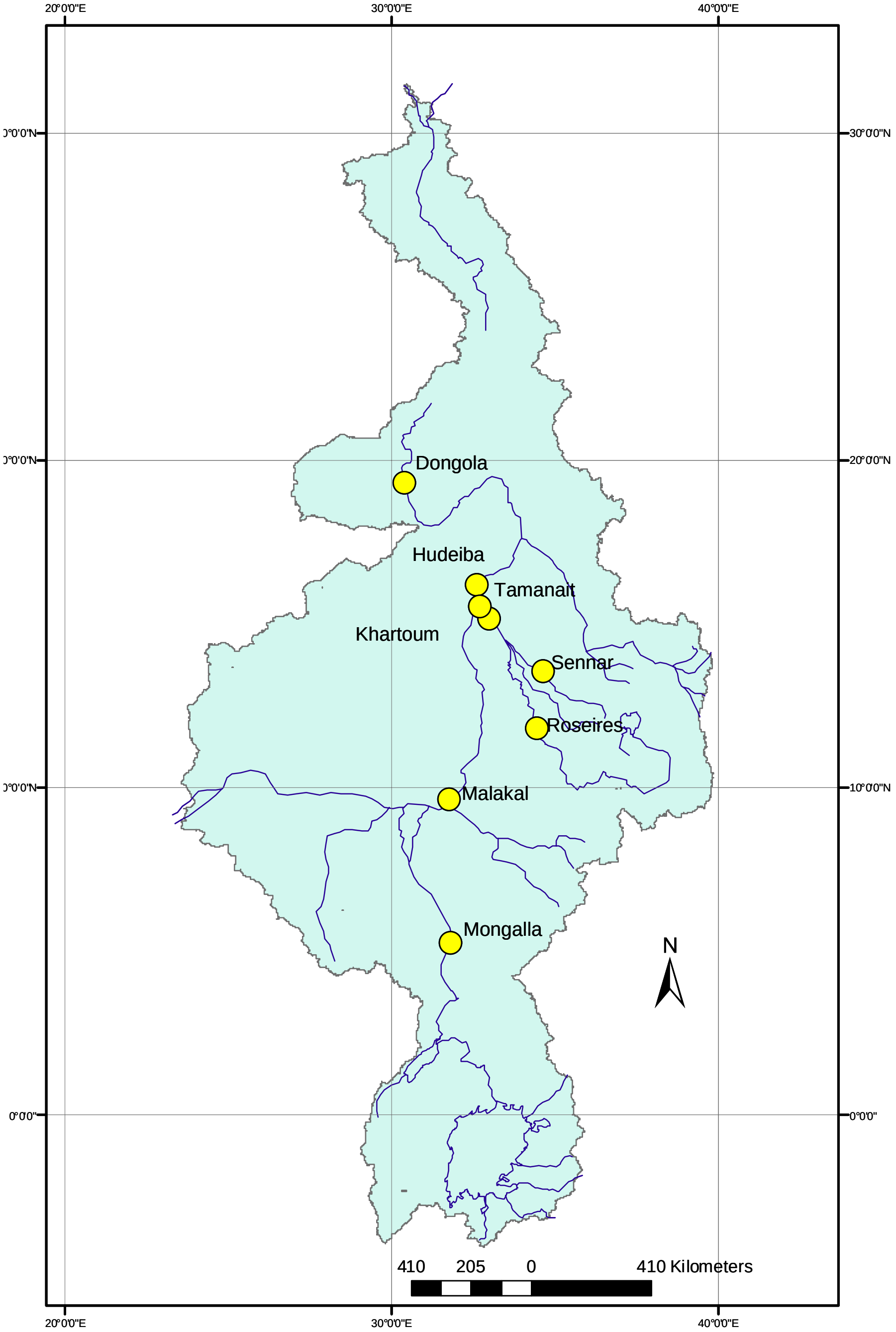


Figure 2 The Nile Basin and the selected eight gauges



The study area and datasets

The Volta River Basin (Figure 1) is the 9th largest in sub-Saharan Africa, with an area of roughly 400,000 km^2. The basin extends from latitude 5°45’ N in Ghana to 14°N in Mali, and encompasses parts of six West African countries, namely, Burkina Faso, Benin, Cote d’Ivoire, Ghana, Mali and Togo. The Volta river system comprises the Black Volta, White Volta, and Oti which converge to form Lake Volta, created by the Akosombo dam located in southern Ghana. Volta is one of the largest man-made lakes in the world, with a surface area of 8,500 square kilometres and a volume of 148 km^3. The energy generated at Akosombo plays a key role in supporting the Volta Aluminium Company, one of the pillar industries in Ghana.

The total basin population is expected to grow significantly from an estimated 18,600,000 in 2000 to approximately 33,900,000 in 2025 (UNEP 2002), an increase of 80% in a 25-year period. This in turn indicates a rapidly growing demand on the land and water resources in the basin. According to the World Bank (2004) classification of economies, all the countries in the Volta Basin are Low Income Counties (LICs) with 2002 Gross National Incomes (GNI) per capita of less than $735. The vast majority of the population is supported primarily by rainfed agriculture, but irrigation is becoming increasingly important in the basin (Amisigo 2006).

The annual mean temperature in the Volta basin ranges from about 27°C to 30°C, and humidity varies between 6% and 83% depending on the season and the location. Average annual rainfall varies across the basin from approximately 1600 mm in the south-east section within Ghana to about 400 mm in the northern part of Mali (UNEP 2002). Changes in precipitation patterns have apparently occurred, as rainfall and run-off reductions have been evident since the 1970s (Opoku-Ankomah, 2000). Some areas once characterized by bi-modal rainfall patterns now have only one mode, as the second (minor) rainy season has become weak or non-existent. This situation has a significant impact on rainfed agriculture, as it was possible previously to grow two rainfed crops, but now only a single crop can be grown. These trends have induced a new emphasis on irrigation, and on more efficient agricultural practice.

It has been estimated (UNEP 2002) that the catchment must receive approximately 340 km^3 of rain annually before significant run-off occurs. Once this threshold is reached, approximately half of precipitation is converted to run-off, indicating that even small changes in rainfall can have dramatic effects on run-off rates and hence on the availability of water resources. Although rainfall decreased by only 5% on average from 1936 to 1998, run-off decreased by 14% (Andreini *et al* 2000). Simulations of run-off using GCM-based climate scenarios developed by Minia (1998) showed 15.8% and 37% reduction in run-off of the White Volta Basin for the years 2020 and 2050, respectively (Opoku-Ankomah, 2000). These projections suggest that projects designed on the basis of historical records may perform poorly if climate continues to change adversely. The hydropower dam at Akosombo (Lake Volta) is an example of such a project - the dam, completed in the 1960's, has suffered from drought (dangerously low water level in the reservoir) several times in the last two decades.

Seasonal variation in rainfall leads to strongly seasonal runoff that exhibits a corresponding mono/bi-modal pattern (increasingly mono-modal as one moves northward). Figure 3, displaying typical annual hydrographs obtained at 7 Volta Basin gauges, provides an indication of temporal variability. Discharge series at each gauge shown in Figure 3 are normalized by the maximum daily discharge over the period 1951 to 2003. Most of the stations show a small peak in July or August and followed by a high-flow season starting in September and ending in November. The remaining 7 months between December and June are dry months. Critical dry periods occur in March and April with daily discharge as low as 0.01 m^3/s or occasionally no flow at all.

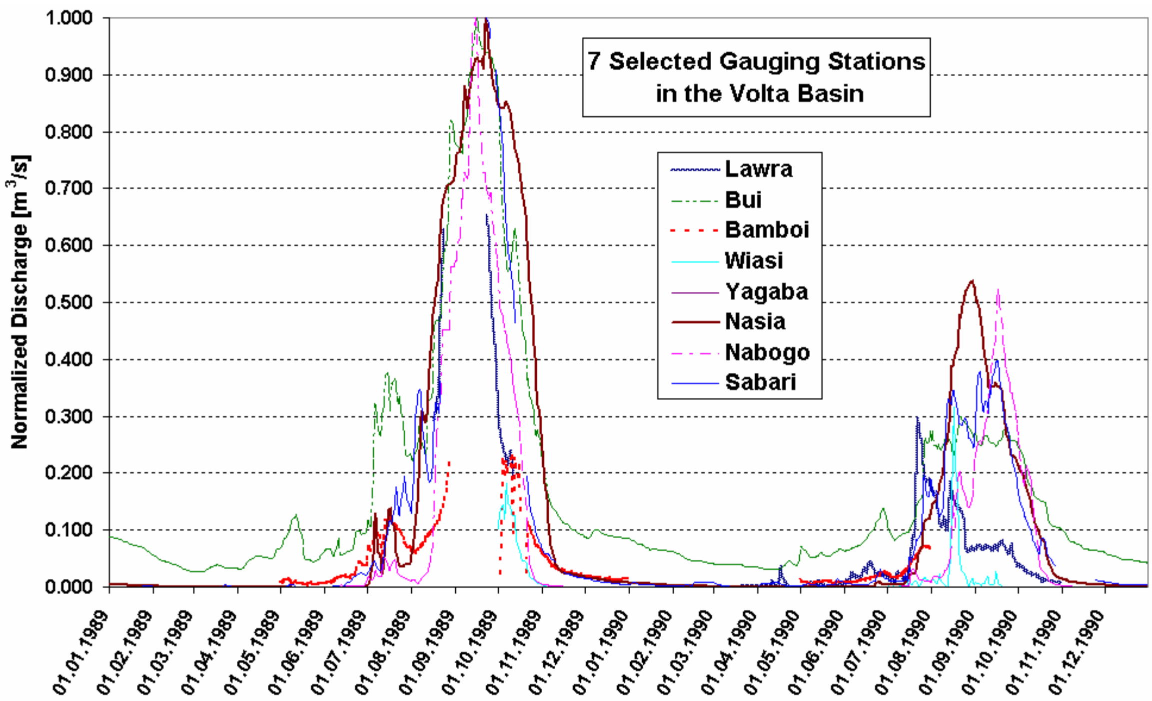


Figure 3 **Seasonal variability of the discharge at 7 gauging stations in the Volta Basin**

In general, discharge data in the Volta are limited -- there exist only a handful of gauging stations in the entire basin. Due to lack of maintenance and poor management, observed discharge series are typically short and full of irregular gaps of varying lengths. Apart from gaps, the available runoff series begin and end in different years, making it difficult to analyse spatial drought behaviour in the region within representative time periods. Figure 4 shows discharge data for the Black Volta Basin, containing missing data at irregular intervals. In present form, it would be difficult to extract the information required to perform a proper assessment of catchment response to rainfall inputs (Amisigo 2006). There have been a number of attempts to fill data gaps of various lengths in the daily run-off series by applying such methods such as auto-regression (Gyau-Boakye & Schultz, 1994), satellite imagery with non-linear modelling in stream flow generation (Papadakis *et al*, 1993), Thornthwaite-Mather (TM) method (Taylor 2003) and so forth. These methods however are not suitable for the Volta basin where the lengths of missing data are relatively long and neighbouring gauges are scarce. Amisigo (2006) provides a review and comparison of the available methods and proposes a spatio-temporal state space dynamic model approach. The method was tested for filling up short gaps of missing run-off data (a few days to a month). Although the utility of such methods can be improved using a more robust long-term regional water balance approach, however, they provide reasonably accurate interpolations of runoff during low-flow months suitable for use in the present drought study.

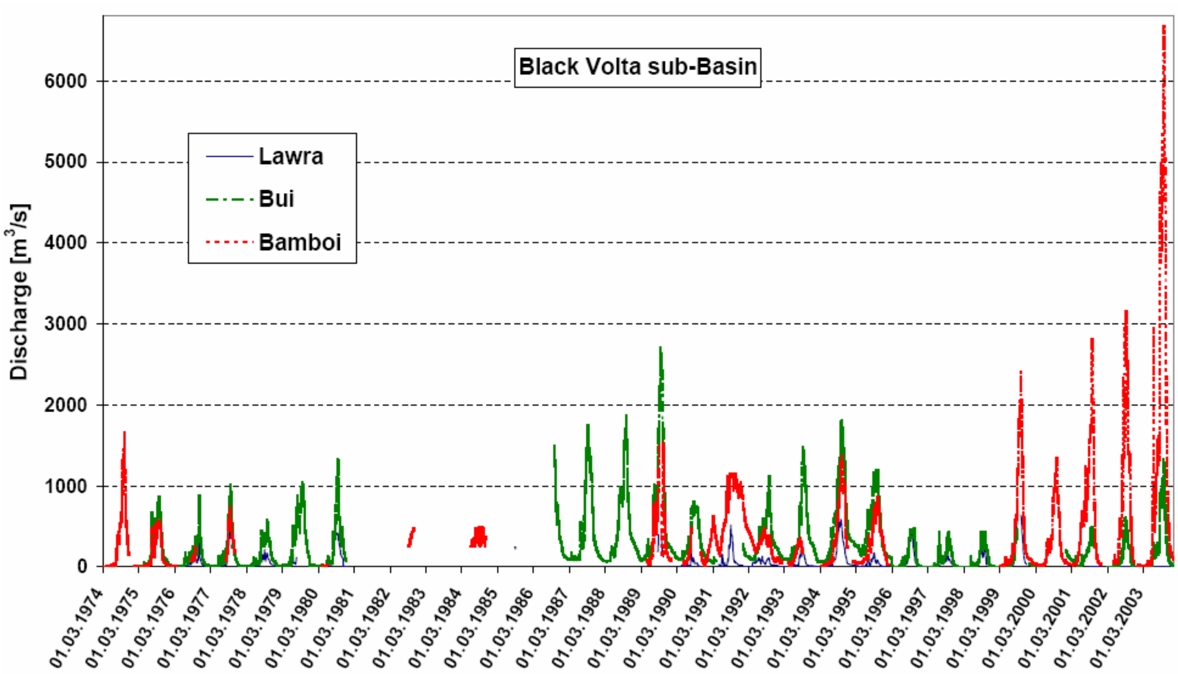


Figure 4 **Discharge data at the Black Volta sub-Basin (containing missing data at irregular intervals)**

For this study, 7 stations (see Table 1) were selected based on location and data coverage. Most of the data have been pre-screened using methods described in Amisigo (2006). The selected stations are from the northern section of the Ghanaian part of the Volta basin, located within a drier climatic zone due to proximity to the Sahel region, and experience a weak or imperceptible second (bi-modal) rainfall peak. This region is of interest due to the linkages between rainfall, runoff and food security; and with respect to hydro-power generation. Gauges are further selected based on quality of data, specifically, the number of missing data in the dry months of the year, and missing years. The selection procedure is described as follows:

1. count the number of missing days in a year, if more than 30 appear in the low-flow months (December, January, February, March, April, and May are considered here as critical low-flow months), reject the year record,
2. if there exists more than 3 consecutive years rejected due to (1), reject this gauging station;
3. for the accepted gauging stations, compute the average of 7 consecutive low-flows (7-day low flow) in the driest sequence of each year

This selection procedure yields only relatively short flow series, which unfortunately exclude several recent drought events. The four gauges selected are Lawra and Bamboi in the Black Volta sub-Basin and Wiasi and Yagaba in the White Volta sub-Basin.

Table 1 Selected characteristics of gauging stations used in the study (Data Source: Taylor, 2003)

Gauging Station	Volta tributary	Coordinates (decimal degrees)		Drainage area (km^2)	Available runoff series
		Longitude	Latitude		
Black Volta sub-Basin					
1. Lawra	Black Volta	2.90 W	10.60 N	96,000	1951-1973
2. Bui	Black Volta	2.10 W	8.20 N	111,853	1954-1971
3. Bamboi	Black Volta	1.90 W	8.15 N	134,200	1951-1975
White Volta sub-Basin					
4. Wiasi	Sissili	1.30 W	10.33 N	12,105	1962-1973
5. Yagaba	Kulpawn	1.2 W	10.10 N	9,100	1958-1972
6. Nasia	Nasia	0.75 W	10.10 N	6,070	1969-1975
7. Nabogo	Nabogo	0.80 W	9.70 N	3,040	1963-1974
Oti sub-Basin					
8. Sabari	Oti	0.20 E	9.28 N	72,775	1960-1973

Statistical Analysis of Drought

Extreme value statistics have been used to estimate the quantiles of many meteorological and hydrologic phenomena representing natural hazards, notably floods, extreme rainfall and droughts. The statistical analysis of drought poses particular challenges in that drought is a complex phenomenon, and unlike, e.g., floods, the quantitative assessment of drought does not rest on a single, measurable variable such as instantaneous discharge, but rather on a vector of characteristics that might encompass severity, duration, areal extent and sectoral impacts. Numerous definitions of drought have been developed to quantify the drought phenomenon with respect to particular phases of the hydrologic cycle. The American Meteorological Society (1997) has classified existing definitions into four categories: meteorological, hydrologic, agricultural and socio-economic drought, respectively. Recent reviews by Heim (2002), and by Smakhtin and Hughes (2004) document numerous drought definitions in use over the past century, including the Antecedent Precipitation Index (1954), Palmer Drought Severity Index (PDSI, 1965), Surface Water Supply Index (1981) and Vegetation Condition Index (1995). Most definitions make use of time series data on precipitation, and selectively, of temperature, soil moisture, streamflow, reservoir storage, snowpack and other available data relevant to the application of the index. Keyantash and Dracup (2004) combine a wide range of indicators to develop an aggregate drought index encompassing both the hydrologic cycle and the status of artificial storage.

Streamflow gauging records provide a convenient basis for the construction of drought indices, particularly where more detailed, spatially disaggregated climatic and hydrologic time series data are not available, since stream discharge is a spatio-temporal integrator of the climatic input to the drainage basin. The delineation of upstream catchment boundaries corresponding to a specific gauge location provides a readily available definition of the areal extent of drought, although heterogeneous drought conditions may prevail within larger basins that are difficult to assess through discharge alone. In this study, we utilize a standardized measure of annual low-flow discharge as a proxy of drought index, for several reasons. First, the assembly of internally consistent time series of precipitation and soil moisture for these regions would be difficult, if not impossible. Second, indices based on gauge discharge convey a spatial interpretation, as noted. Finally, the resulting series provides a general-purpose drought index, reflecting the basin’s hydrologic history and conditions and not limited to specific sectors or uses.

Having chosen discharge as a suitable metric for the quantification of the drought phenomenon, the appropriate time indices must be identified. It is widespread practice to use the lowest annual value of consecutive n-day discharge as a basis for hydrologic design, and for managing water resources (Smakhtin, 2001; Kroll and Vogel, 2002); and such an index is in many cases amenable to the fitting of parametric distributions. The appropriate number of days (n) will reflect, among other factors, the time resolution of available gauging records, size of the catchment, extent of seasonality in the pattern of discharge and the intended application or interpretation of the indicator. In most regions possessing well-defined rainy and dry seasons, there will be a corresponding seasonal pattern to discharge, suitably lagged to reflect basin size, topography, geomorphologic features and other factors controlling the behavior of respective flow components and flowpath times. In this study, we use annual minimum 7-day consecutive flows for Volta gauges, for which daily discharge records are available. The use of the annual n-day minimum is, however, inconvenient in certain other respects: Drought can be a multi-year phenomenon, and the use of annual minimum flow series may obscure this fact, and might thus understate the impacts on society. Furthermore, an assumption underlying the interpretation of distribution-based quantile estimates is that (annual) events are serially independent, an assumption that is violated in the case of multi-year droughts. In addition, the use of n-day flows does not permit an explicit examination of drought duration. However, for the purposes of evaluating the possibility of non-stationarity in climatic records, standardized measures can be useful in that they reduce the possibility that *ad hoc* judgments concerning the onset and termination of drought might influence the interpretation of long-term trends.

Methods of distribution screening and fitting

Extreme-value distributions commonly used to describe drought and low-flow quantiles include Weibull, Gumbel, Pearson type III and lognormal (Smakhtin, 2001; Vogel and Kroll, 1989; Kroll and Vogel, 2002). It is important to acknowledge the differences between extreme-value distribution fitting of meteorological and flood events, which are bounded below by 0 but unbounded above for increasingly rare events; and the modeling of drought events by stream discharge proxy measures, which are bounded asymptotically in the direction of increasing severity (lower frequency) at 0 discharge. Problems are encountered when fitting distributions to gauging records that contain multiple instances of 0-flow sequences in the annual n-day low flow series. In the absence of conditional assumptions concerning 0-flow sequences, a parametric distribution may assign negative-flows to low probability events. In this pilot study, we have attempted to avoid this issue by selecting gauges for which all annual minima were strictly positive. This does not eliminate the possibility that negative flows are assigned at recurrence intervals greater than the gauging record length, however. In this study, we evaluate the 2-parameter Weibull distribution (Equation 1) as a candidate for an appropriate model of low-flow series in the Volta. We will then use an alternative evaluation method, L-Moment ratio diagrams (Hosking and Wallis, 1997), to suggest alternative distribution choices.

$$F(t;\alpha,\beta) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right], t > 0 \qquad (1)$$

The method of moments is a simple and convenient procedure for estimating parameters from a sample of extreme value data. Alternatively, several other methods, including least squares and probability weighted moments, can also provide satisfactory parameter estimates. The maximum likelihood (ML) procedure yields asymptotically minimum variance and unbiased estimates, but it requires iterative computations (Kottegoda & Rosso 1997). The ML procedure is implemented here using a Simulated Annealing (SA) optimization algorithm for estimating Weibull parameters. SA was first proposed by N. Metropolis in 1953 (Metropolis et al. 1953) and modeled after a thermal equilibrium equation representing the metal annealing process. SA is classified as a derivative-free (Jang et al. 1997) and combinatorial optimization technique (Kirkpatrick et al. 1983).

Figure 5 shows the data and fitted distributions for the four selected gauges in Volta. Figures 6 & 7 show the fitted distributions for the two selected gauges in Nile. Weibull distribution shows satisfactory fitting for these records. Table 2 lists the estimated 7-day low-flow quantiles for the four selected gauges.

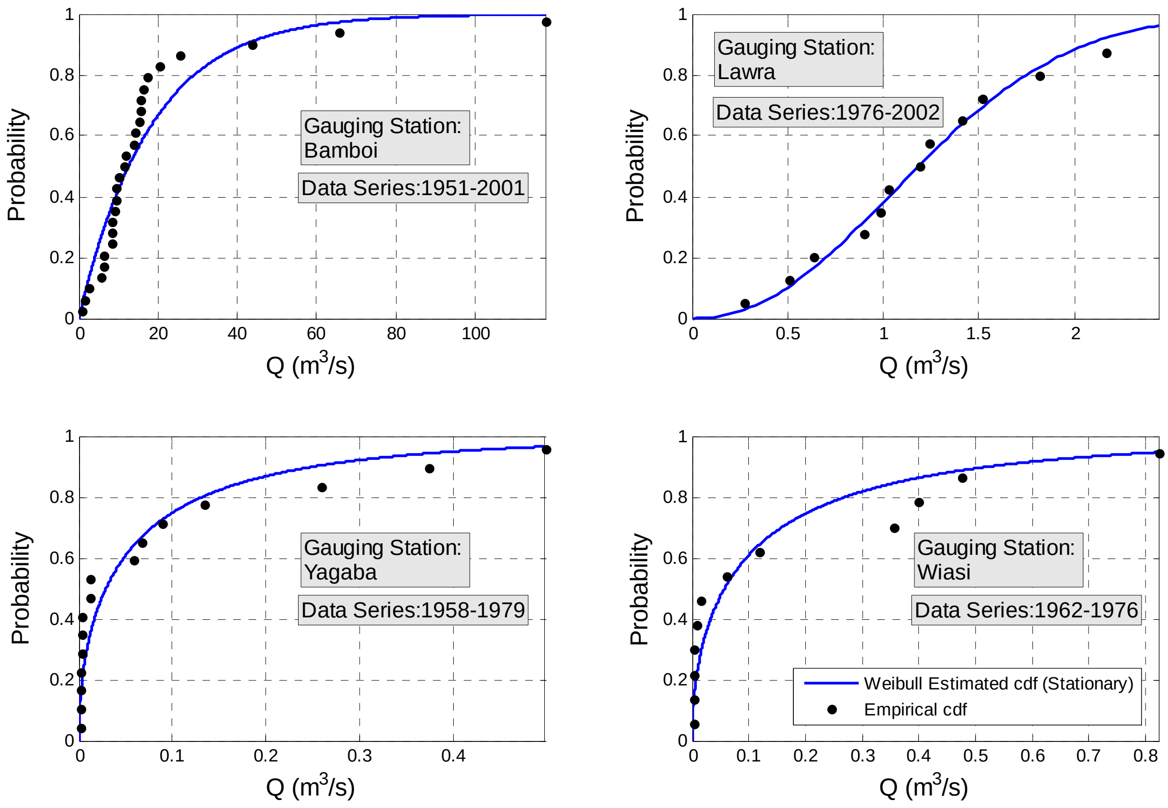


Figure 5 **Distribution fitting for the four selected gauges (Volta Basin)**

Table 2 **Estimated 7-day low-flow quantiles for the four selected gauges**

Return period [years]	**2**	**5**	**10**	**50**	**100**	**200**	**500**	**1000**
Bamboi	12.603	4.056	1.915	0.367	0.183	0.091	0.036	0.018
Lawra	1.185	0.701	0.495	0.230	0.166	0.121	0.079	0.057
Yagaba	0.029	0.004	0.001	0.000	0.000	0.000	0.000	0.000
Wiasi	0.057	0.007	0.002	0.000	0.000	0.000	0.000	0.000

The choice of an appropriate parametric distribution to describe the behavior of low-frequency drought should in general be based on some form of goodness-of-fit test. Overall goodness-of-fit can often be assessed visually, and formal tests, including Chi-square and Kolmogorov-Smirnov, are available for many distributions. Increasingly, Probability Plot Correlation Coefficient (PPCC) tests, generated via Monte Carlo simulation, are also used. An alternative is provided by L-Moment ratio diagrams. L-Moments are linear estimators less affected by bias than product moment estimators,

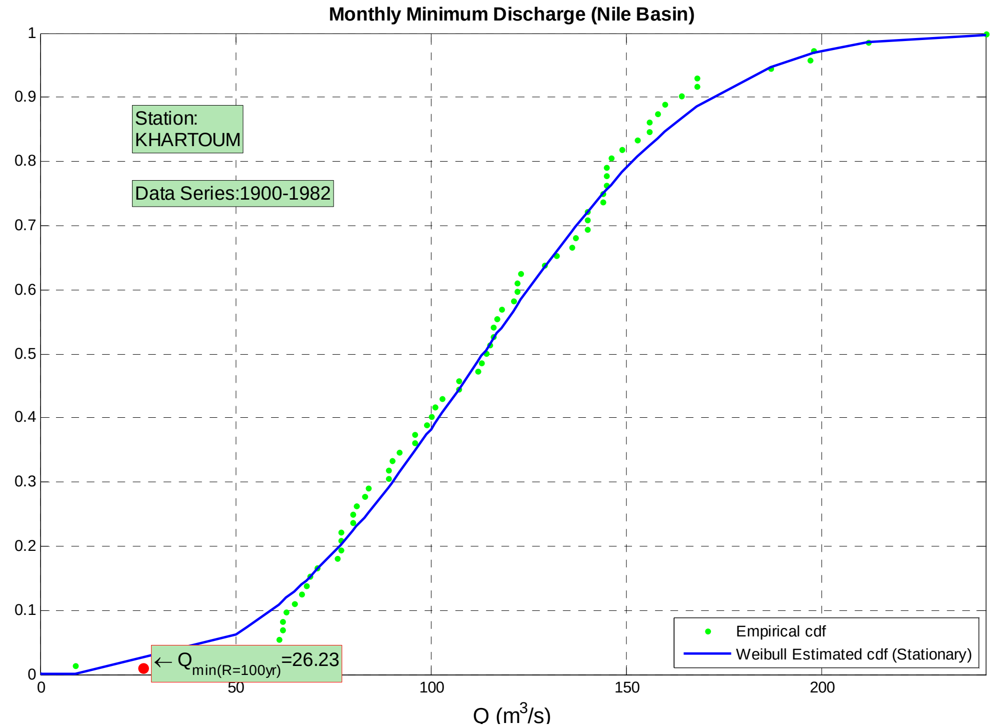


Figure 6 **Distribution fitting for the Gauge at Khartoum (Nile Basin)**

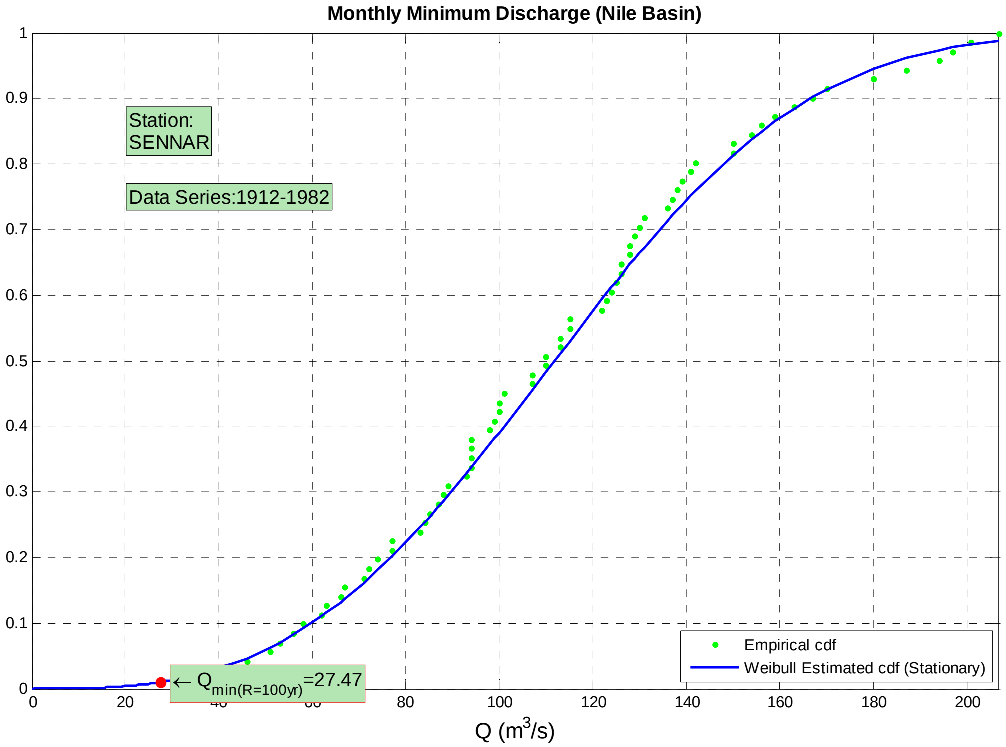


Figure 7 Distribution fitting for the Gauge at Sennar (Nile Basin)

particularly when used with small samples (Hosking & Wallis, 1997). L-Moments are used to construct ratios referred to as L-skewness and L-kurtosis that follow characteristic patterns for specific distributions, which have been identified for a range of 3-parameter distributions. A comparison of estimated sample L-moment ratios with theoretical ratios, in the form of an L-Moment diagram, provides insight into the underlying distribution.

L-Moment ratios were calculated for the Volta 7-day low flow annual series for each gauge location as well as for the Nile dataset; the results are plotted in Figure 8.

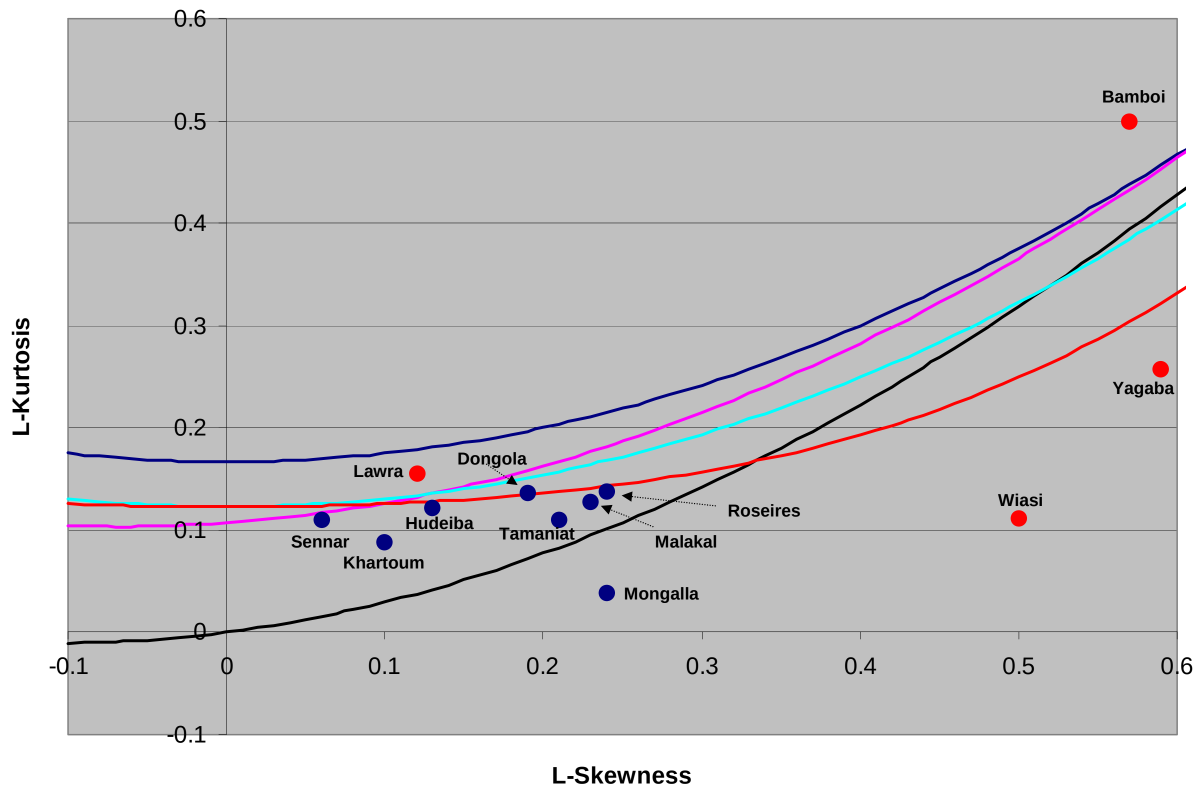


Figure 8 L-moment ratio for selected gauges

Individual Volta gauge low-flow data are not clearly associated with any specific 3-paremeter distribution type. As L-moment techniques are particularly well suited to regionalization procedures, efforts are underway to increase the number of suitable gauges in order to support a regionalized L-moment ration analysis of distribution type.

Discussion and Outlook

Conventional, parametric distribution-based methods for estimating natural hazard quantiles assume that annual maximum (minimum) events are independent, identically-distributed (iid) samples drawn from a population of stochastic events that is essentially stationary over time. If assumptions of independence and/or stationarity of the event-generating process are violated, the accuracy or unbiased nature of drought quantile estimates can be questioned. Non-stationarity in the annual minimum n-day flow series can arise from many sources, including changes in basin land use and land cover, construction of water storage and control infrastructure, increases in abstractive and consumptive use within the basin (e.g., expansion of irrigation), change in climate, or any combinations of the above. Although some research on statistical models that embody some forms of non-stationarity has been conducted (e.g., Sankarasubramanian and Lall, 2003), this work relates primarily to precipitation or flood quantile estimation. Little definitive work on modeling the statistical behavior of drought under assumptions of climatic non-stationarity currently appears in the literature.

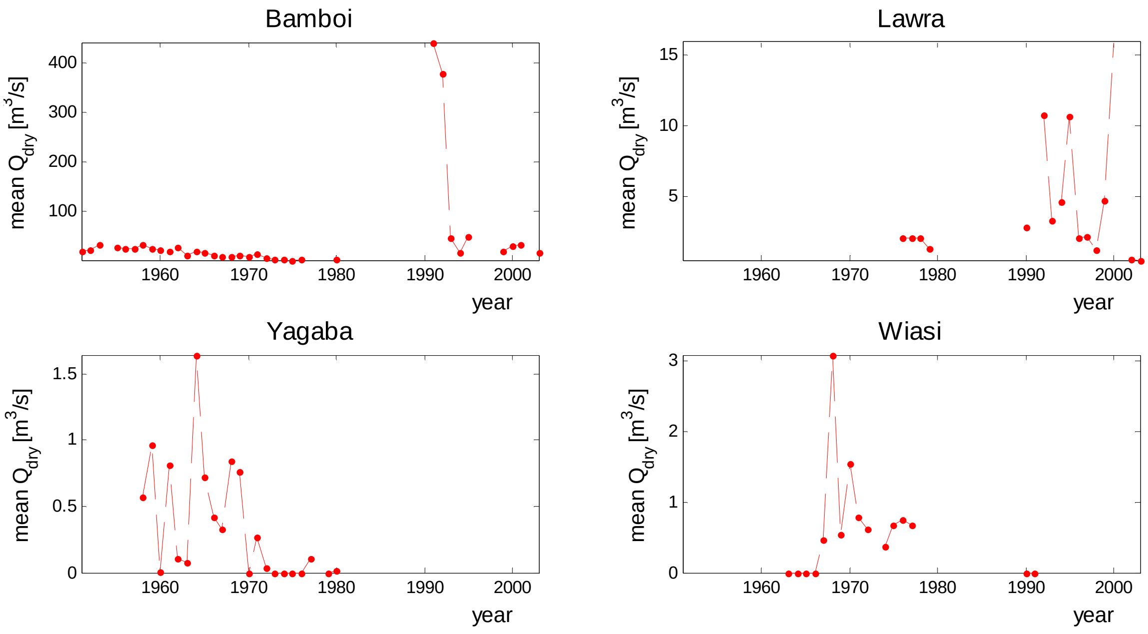
The challenge involved in modifying parametric distribution-based estimates to account for non-stationarity is particularly daunting. It is not enough to establish that a given series of events is not stationary; what is required in addition is an understanding of the structure (if any) of the non-stationarity, which is likely to be complex given the scope of potential interactions between climate, land use and water resources development trends.

The task of performing a comprehensive analysis of the drought phenomenon under potentially non-stationary conditions thus encompasses the following:

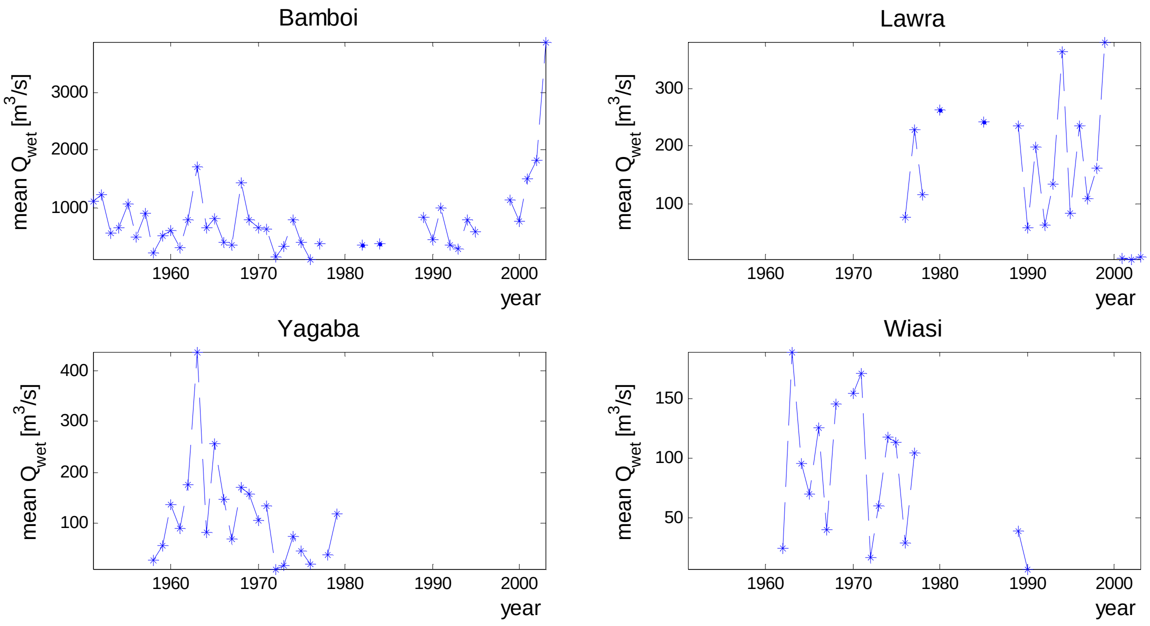
- to develop a conceptually valid and useful quantitative definition of the phenomenon;
- to identify a statistical model that provides a good fit to available data, to assign exceedance probabilities to events of a given magnitude (or vice versa);
- to evaluate the available time series of events in order to determine whether or not the assumptions of stationarity and serial independence are likely valid, and if so, to identify a model of the non-stationarity; and finally,

- to modify the statistical model of extreme values to reflect what is known about the non-stationarity.

Figure 9 shows annual mean runoff during critical dry (March and April) and wet (August, September and October) months for the Volta. For all the four gauging stations, apparent non-stationarity of the runoff series can be observed for both the dry and wet months. Yagaba station (Figure 6) shows, over the available timespan, that annual mean runoff can be as low as 10 m^3/s and as high 420 m^3/s. However, given short and irregular record periods, it is not clear whether observed variation indicates non-stationarity, or alternatively, *ad hoc* fluctuations. Currently available time series appear inadequate for making such judgments on the basis of formal statistical tests. This fact alone makes the development of non-stationary models of the drought process within the Volta Bain problematic. Research currently underway makes use of the remote sensing of moisture fields, in combination with mesoscale climate modeling (MM5) in developing more accurate and comprehensive drought specification indices. In parallel with such research efforts, however, the development of a regional historical database on precipitation and runoff should be considered a high priority in order to improve the understanding of the drought phenomenon within the Volta Basin, and to support a range of mathematical and statistical modeling approaches to droughts analysis.



(a) Annual mean runoff during March and April



(b) Annual mean runoff during August, September and October

Figure 9 **Annual mean runoff during critical dry and wet months**

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