Drought frequency analysis of annual rainfall series in central and western Sudan

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Abstract Rainfall is the most important water resource in central and western Sudan, a region affected by the recent drought in Africa. A general methodology for studying the annual rainfall process is presented and applied to data from central and western Sudan. It is assumed that certain time series models adequately describe the annual rainfall process in the region. Based on this assumption, the drought frequencies are calculated in the subregions with stationary series. The theory of runs is applied in calculating drought frequencies using a data generation method.

Analyse de la fréquence des sécheresses des précipitations annuelles dans les parties centrale et occidentale du Soudan

Résumé Les précipitations constituant la plus importante ressource en eau dans les parties centrale et occidentale du Soudan, ces régions ont été affectées par la récente sécheresse africaine. Une méthodologie générale pour l'étude des précipitations annuelles est présentée, puis appliquée aux données des régions centrale et occidentale du Soudan. Nous avons supposé que certains modèles de séries temporelles dérivent d'une façon adéquate les précipitations annuelles dans ces régions. A partir de cette hypothèse, les fréquences des sécheresses ont été calculées dans les différentes parties de ces régions qui avaient des séries statistiques stationnaires. La théorie des "runs" a été appliquée a des précipitations générées par des simulations pour calculer les fréquences des sécheresses.

INTRODUCTION

Hydrological drought is defined as a deficit of water supply in time, in area or in both, with deficit magnitude and deficit duration taken into account (Yevjevich, 1967). A water supply deficit is defined relative to a specified water demand level. In the following is described a drought study in the Sudan.

Sudan is the largest country in Africa, with an area of about 2.5 m km^2. It extends from the Sahara region of Africa to the Equator. The population of Sudan is about 16 million and the main water resource is the surface water of the Nile and its tributaries. Other important water resources are rainfall and groundwater. Rainfall amounts decrease from the south to the north. Sudan is an agricultural country with more than 75% of the population working in agriculture. The region of central and western Sudan is part of the African belt which is affected by the recent continental drought known as the Sahel and

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Sudano-Sahel regions, (see Fig. 1). The population of the region is around 30% of the total Sudan population and its area is about 35% of the total area.

Rainfall is the main water resource in the region. It is a vital water source for human and animal consumption as well as for agriculture and natural vegetation. Agriculture and grazing are the main economic activities. Another activity which depends on rainfall is the production of gum Arabic and the region is the main producer in the world of this crop.

The rainy season in this region extends for around six months, starting in April or May and ending in October or November. Some of the rainfall is stored in small reservoirs ("hafir") mainly for human and animal consumption.

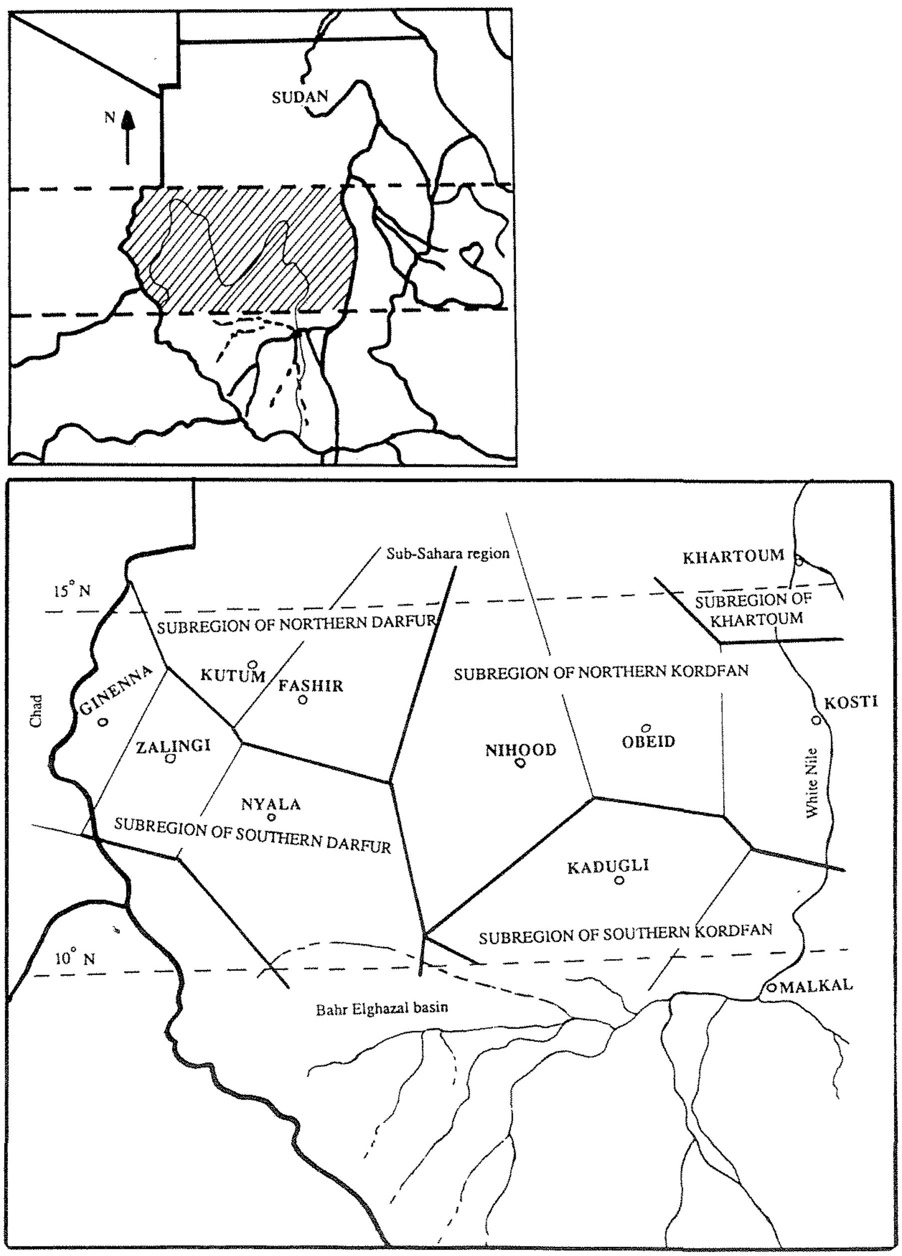

Fig. 1 Regions of central and western Sudan.

The normal levels of effective rainfall in the region (rainfall minus evaporation) are not enough for creating permanent surface runoff in the form of streams. In recent years, low levels of rainfall have affected the region and resulted in a severe drought. The years 1983 and 1984 were the most difficult years for the region in recent history.

The present study focusses on the annual rainfall process in central and western Sudan with the objective of estimating drought frequencies. In the following, the data set used in the study and the models considered are described and the methodology suggested for studying the annual rainfall process is outlined. The results of applying such a methodology to data from the region are then discussed. A drought frequency analysis is presented followed by some brief conclusions.

DATA

The data used in the study consist of two sets: a monthly set and an annual set. The monthly data set was supplied by the National Centre for Atmospheric Research (NCAR), Boulder, Colorado. The annual data set was supplied by the Meteorological Office, Khartoum, Sudan. The latter extends the records up to and including the year 1986 in contrast to the monthly data set which extends, for most of the stations, only to 1973 or 1975.

The percentage of data available covers more than 96.5% of the entire records. Compared with that of other African stations, it can be concluded that the records of the Sudanese stations are more complete. They are sufficiently complete for the purposes of this study. Different models were tried for filling in missing data points. The Nash & Sutcliffe (1970) efficiency criterion, used in river flow forecasting, was found useful in comparing the efficiency of different models. Most of the missing data points were filled by multiple linear regression using available data at three nearby stations.

The number of stations studied was eleven. The area covered is about 795 000 km^2 with a station density of approximately one station per 72 000 km^2. It is clear that the station density in the region is very poor and this fact was observed in deciding how to use the records available, viz. either adopting a regional average or treating each station record separately. A reasonable compromise was achieved by treating each station record separately and then generalizing the conclusions from the results obtained from more than one station. Double mass analysis was carried out for the eleven records and the results showed at least relative homogeneity of the records.

SELECTION OF MODELS

It is widely accepted that, while certain climatic conditions dominate in any region of the world, annual rainfall amounts in a region fluctuate randomly about a well-defined mean that is characteristic of those climatic conditions. It is observed that the annual rainfalls in many parts of the world are independent. The annual rainfall amount in any year does not depend on the annual rainfall amount in the previous year (Yevjevich, 1964). Some of the features observed in the annual rainfall series in the region of central and western Africa are not consistent with the independence assumption. Some studies suggest that certain feedback mechanisms are responsible for the persistence observed in the annual rainfall series for that region. Charney (1975) suggested that the change in albedo, being a function of the previous year's rainfall amount, is a possible carry-over mechanism in the Sahel region of Africa. Eltahir (1987) concluded that the evaporating water from the neighbouring swampy region of Bahr Elghazal provides a possible feedback mechanism.

Two models were selected for describing the annual rainfall process in the region, viz. the normal frequency model and the first order autoregressive model, AR(1). If the normal frequency model did not describe a series adequately, a gamma distribution model was a possible skewed alternative.

METHODOLOGY FOR STUDYING THE ANNUAL RAINFALL PROCESS

The procedure for identifying a model suitable for describing the annual rainfall series in the region consisted of five groups of tests, two of which were applied before assuming the form of the model, viz. first order stationarity tests and independence tests. Those tests were conducted according to the flow chart of Fig. 2. Based on the results of the two tests, one of the two models was assumed and three groups of tests applied to confirm the choice of model. Depending on the model, those tests follow the flow chart in Fig. 3 or the one in Fig. 4.

The parameters of the normal distribution were estimated by the method of moments. If AR(1) was selected, the parameters were estimated by the method of moments and the population autocorrelation coefficient at lag one was estimated from the observed sample. The autocorrelation coefficient at lag one was corrected for bias using methods suggested by Wallis & O'Connell (1972).

Some of the tests applied for checking the assumption of an AR(1) model were performed on the residuals derived from the series according to the model structure. Testing the residual series for being a random sample from an independent normally distributed population is equivalent to testing the original series for being a sample from a population described by an AR(1) process.

The conclusions are based on the results of the statistical tests with a 5% level of significance. WMO (1966) specifies the 5% level of significance for most of the tests which are recommended as checks for climatic changes.

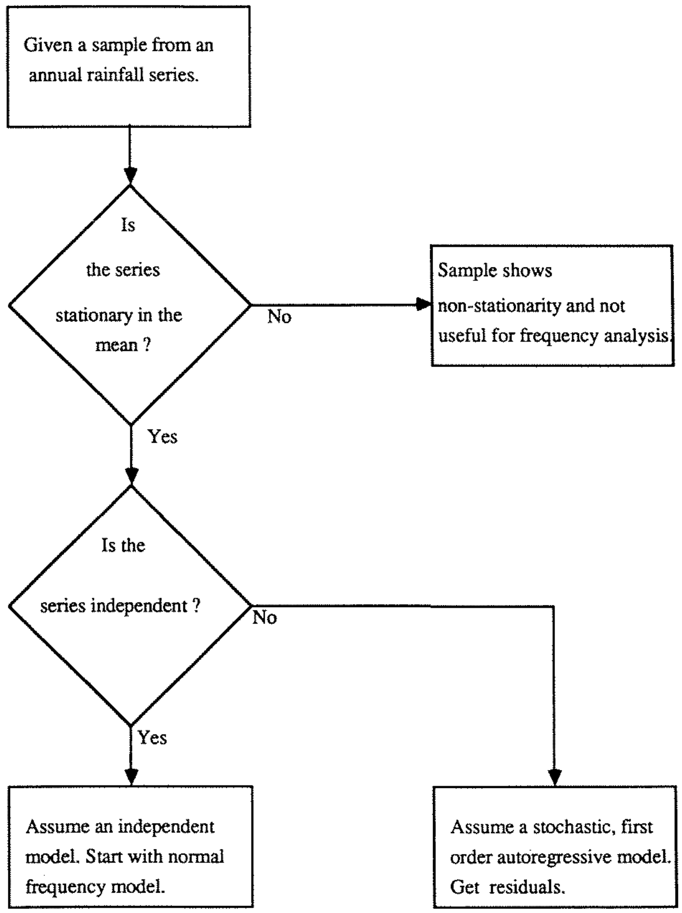

Fig. 2 Methodology for studying the annual rainfall series.

SIMULATION TESTS

Simulation tests were applied for assessing the adequacy of the models in describing some of the features observed in the annual rainfall series. The features studied were the persistence within the extremes and the drop in the mean of the series. The persistence within the extremes is the tendency for dry years to follow dry years and wet years to follow wet years. The drop in the mean is a measure of the decline in rainfall amounts in the last few decades.

Persistence within the extremes

Eltahir (1987) reviewed previous studies which focussed on the annual rainfall process in the region and concluded that persistence within the extremes is a genuine feature of the process. Therefore models assumed for describing the annual rainfall process in this region should reproduce this feature.

The test for persistence within the extremes is as follows: the ratio R_o of the number of years with observed persistence in extremes to the total number

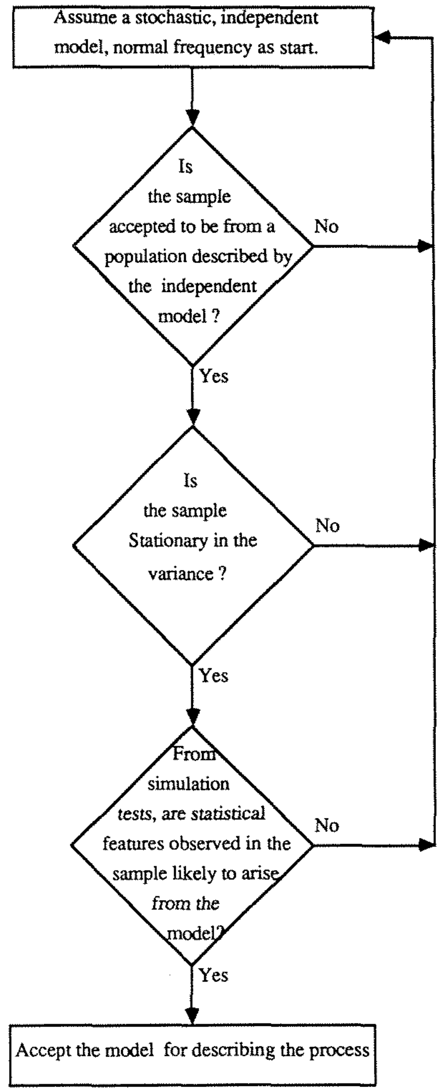

***Fig. 3** Methodology for studying independence series*

of years of record is a numerical measure of the persistence within extremes. The extremes are defined arbitrarily but are a function of the mean and standard deviation of the series, e.g. a wet year is defined as a year in which the total rainfall exceeds the mean of the series by an amount which is a function of the standard deviation. Twenty thousand samples were generated according to the assumed model. Each sample had the same number of years as the number of years in the observed series. In a procedure similar to the calculation of R_o, the ratio R was estimated for each sample. Let the number of times R exceeded R_o in the 20 000 samples be M. The probability P that a value of R greater than R_o can possibly arise from a process described by the assumed model is the ratio of M to 20 000. If that probability was larger than the selected level of significance for a one-sided test, the model was accepted as adequately tolerating this feature.

Drop in the mean

It has been observed that the annual rainfall amounts in the region of central and western Africa have declined significantly in the last few decades. Simulation experiments provide a possibility for constructing a test to focus directly on this drop in the mean as an observed feature of the annual rainfall series in the region.

The test is as follows: the mean of the observed series, *MS*, and the mean of the last 30 years of the observed series, *MLS*, were estimated. The observed drop in the mean, *DS*, is the difference between *MS* and *MLS*. From the same 20 000 samples of the previous test, the mean of each entire sample, *XM*, and the mean of the last thirty years of the sample, *XML*, were estimated from each sample. The drop in the mean for any sample, *XD*, is the difference

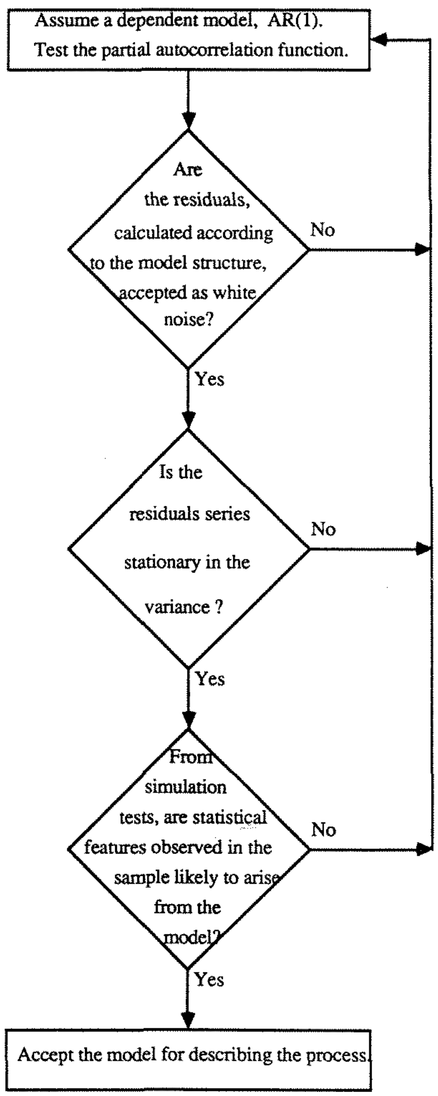

Fig. 4 *Methodology for studying dependent series.*

between *XM* and *XML*. Let the number of times *XD* exceeded *DS* be *M*. The probability that a drop in the mean greater than *DS* can possibly arise from a process described by the model is the ratio of *M* to 20 000. If that probability was larger than the selected level of significance for a two-sided test, the model was accepted.

GROUPING OF THE STATIONS

A grouping of the stations was required in order to decide which station's results to consider while deriving conclusions about the time series structure of annual rainfall in the different subregions. In grouping the stations four parameters were considered: the mean of the series, the coefficient of variation, the length of the rainy season and the autocorrelation coefficient at lag one. According to the values of those parameters the region was divided into five subregions, viz. Khartoum, northern Kordfan, southern Kordfan, northern Darfur and southern Darfur. Table 1 shows the grouping of the stations and describes the annual rainfall series for each station.

Table 1 *Description of annual rainfall series*

Sub-regions and stations	Period of record	Mean (mm)	Coefficient of variation	Autocorrelation coefficient at lag one	Length of rainy season (months)
Khartoum:					
Khartoum	(1899-1986)	155.7	0.48	0.21	5
Northern Kordfan:					
Kosti	(1909-1986)	387.6	0.29	0.34	6
Obeid	(1902-1986)	363.9	0.30	0.29	6
Nihood	(1912-1986)	393.7	0.29	0.19	6
Southern Kordfan:					
Kadugli	(1910-1986)	728.2	0.19	0.04	7
Malkal	(1909-1986)	777.0	0.20	0.18	8
Northern Darfur:					
Fashir	(1918-1986)	267.7	0.43	0.32	5
Kutum	(1929-1986)	297.3	0.36	0.27	5
Southern Darfur:					
Nyala	(1920-1986)	457.4	0.26	0.42	6
Ginena	(1929-1986)	505.3	0.29	0.51	6
Zalingi	(1929-1986)	603.6	0.23	0.57	6

RESULTS OF THE TESTS OF STATIONARITY

As shown in Fig. 2, checking the stationarity in the mean of the observed series was the first step in studying the annual rainfall process. The Kendall test and student's *t* test (WMO, 1966) were applied to the 11 annual rainfall series. The two tests were applied as two-sided tests with the null hypothesis that the series was a sample from a population stationary in the mean. The results of the two tests are shown in Table 2. From those results it was concluded that

Table 2 *Results of the stationarity in the mean test*

Subregion	Station	Kendall test	Student's *t* test
Khartoum	Khartoum	A*	A
Northern Kordfan	Kosti	A	A
	Obeid	A	A
	Nihood	A	A
Southern Kordfan	Kadugli	R*	A
	Malkal	R	A
Northern Darfur	Fashir	R	R
	Kutum	R	R
Southern Darfur	Nyala	R	R
	Ginena	R	R
	Zalingi	R	R

*A: the null hypothesis was accepted at the 5% level of significance; and R: the null hypothesis was rejected at the 5% level of significance.

the annual rainfall series in northern and southern Kordfan and in Khartoum are stationary in the mean. The only exception arose from the results of the Kendall test for southern Kordfan, but results from a slightly weaker test suggested that the annual rainfall series in southern Kordfan is stationary at the 2% level of significance. As indicated by the results of the two tests, the hypothesis that the annual rainfall series in northern and southern Darfur are stationary in the mean was rejected.

RESULTS OF THE INDEPENDENCE TESTS

As shown in Fig. 2, independence tests were the second step in the procedure. Only stationary series were subjected to the independence tests. Based on the results of the previous section only the stations from the sub-regions of Khartoum, northern Kordfan and southern Kordfan were subjected to the independence tests.

Two independence tests were applied: the Wald & Wolfwitz (1943) test and the runs test (Saldarriaga & Yevjevich, 1970). They were applied as two-sided tests with the null hypothesis that the series was a sample from a stationary independent population. The results of the two tests are shown in Table 3. Only those series which passed the two tests were accepted as independent, viz. the annual rainfall series in southern Kordfan. The two annual rainfall series in southern Kordfan were subjected to more powerful tests. They both passed the tests at the 10% level of significance and it was concluded that both the annual rainfall series in the sub-region of southern Kordfan were independent.

The annual rainfall series from the sub-regions of Khartoum and northern Kordfan were tested with the same null hypothesis that the series was a sample from a stationary independent population, against the alternative hypothesis that the series was a sample from a stationary positively dependent population. The results of those tests are shown in Table 4. From those results it was concluded that the annual rainfall series in the sub-regions of Khartoum and northern Kordfan were positively dependent.

Table 3 *Results of the independence tests*

Subregion	Station	Wald & Wolfwitz test	Runs test
Khartoum	Khartoum	R*	A*
Northern Kordfan	Kosti	R	R
	Obeid	R	A
	Nihood	A	R
Southern Kordfan	Kadugli	A	A
	Malkal	A	A

*A: The null hypothesis was accepted at the 5% level of significance; and R: the null hypothesis was rejected at the 5% level of significance.

Table 4 *Results of independence against positive dependence tests*

Subregion	Station	Wald & Wolfwitz test	Runs test
Khartoum	Khartoum	R*	A*
Northern Kordfan	Kosti	R	R
	Obeid	R	A
	Nihood	A	R

*A: The null hypothesis was accepted at the 5% level of significance; and R: the null hypothesis was rejected at the 5% level of significance (the alternative hypothesis was accepted).

ANNUAL RAINFALL SERIES IN SOUTHERN KORDFAN

The annual rainfall process in southern Kordfan was found to be stationary in the mean and independent. Following the procedure described by the flow chart of Fig. 2, the normal frequency model was assumed to describe the annual rainfall process in the sub-region. The parameters of the normal distribution were estimated by the method of moments.

The normality assumption was tested using different statistical tests following the flow chart of Fig. 3. The tests, in their order of application, were normality tests, a stationarity in the variance test and simulation tests. Two normality tests were applied: the Anderson (1942) test and the Kolmogorov-Smirnov test. They were applied with the null hypothesis that the series was a sample from a stationary independent normal population. The null hypothesis was accepted for the two series at the 20% level of significance. The only exception was the result of the Anderson test for the Malkal annual rainfall series, since the null hypothesis was accepted at the 5% level of significance. The Kolmogorov-Smirnov statistic was calculated as 0.077 for Kadugli and 0.074 for Kalkal. From those results it was concluded that the annual rainfall in southern Kordfan was a stationary independent normal process.

In the above tests, the critical values for the Kolmogorov-Smirnov statistic were corrected since the normal distribution parameters were estimated from the sample (Crutcher, 1975). The skewness of the annual rainfall series in Kadugli was 0.3 and in Malkal 0.4. Both values were not significantly different from zero at the 5% level.

The Bartlett test (WMO, 1966) for stationarity in the variance was applied to the annual rainfall series in the sub-region. It was applied as a one-sided test with the null hypothesis that the series was a sample from a normal population stationary in the variance. The null hypothesis was accepted at the 5% level of significance. From those results it was concluded that the annual rainfall series in the sub-region was stationary in the variance.

For investigating the persistence within the extremes a simulation test was designed as a one-sided test with the null hypothesis that the ratio of observed number of years with persistence within the extremes to the total number of years was likely to arise from a process described by the normal frequency model. The results of this test are shown in Table 5. The ratio of the number of years with persistence within extremes in the annual rainfall series in Kadugli was below the mean ratio for the normal process, while the ratio obtained for Malkal was above the mean. The slight dependence in the Malkal annual rainfall series is the reason for that high ratio.

Table 5 *Results of the tests for persistence within the extremes*

Subregion	Station	Ratio obtained from series	Mean ratio obtained from the samples	Probability of exceedance of the series ratio	Result of the test
Southern Kordfan	Kadugli	0.289	0.318	0.77	A*
	Malkal	0.403	0.310	0.02	R*
Northern Kordfan	Kosti	0.390	0.410	0.62	A
	Obeid	0.381	0.400	0.62	A
	Nihood	0.405	0.369	0.24	A
Khartoum	Khartoum	0.368	0.351	0.31	A

*A: The null hypothesis was accepted at the 5% level of significance; and R: the null hypothesis was rejected at the 5% level of significance.

For investigating the drop in the mean of the last 30 years, a simulation test was designed as a two-sided test with the null hypothesis that the drop in the mean of the last 30 years from the mean of the entire series was likely to arise from a process described by the normal frequency model. The results of this test are shown in Table 6. From those results it was concluded that the drop in the mean of the last 30 years from the mean of the entire series, as observed in annual rainfall in the sub-region, was likely to arise from a process described by the normal frequency model.

ANNUAL RAINFALL SERIES IN KHARTOUM AND NORTHERN KORDFAN

The results of the stationarity and independence tests indicated that the annual rainfall series in Khartoum and northern Kordfan were stationary in the mean

Table 6 Results of tests for drop in mean

Subregion	Station	Drop observed (mm)	Probability of exceedance	Results of the test
Southern Kordfan	Kadugli	45.8	0.08	A*
	Malkal	54.0	0.06	A
Northern Kordfan	Kosti	15.7	0.59	A
	Obeid	41.9	0.12	A
	Nihood	29.2	0.27	A
Khartoum	Khartoum	8.3	0.63	A

*A: The null hypothesis was accepted at the 5% level of significance.

and positively dependent. An AR(1) process was assumed to describe the annual rainfall process in the two sub-regions with its parameters estimated by the method of moments. The model assumption was subjected to a series of tests according to the flow chart of Fig. 3.

The partial autocorrelation function (PAF) was calculated for each of the annual rainfall series in the two sub-regions. Since for an AR(1) process the PAF is zero for all lags greater than one, the calculated values of the PAF at lags greater than one were tested for being not significantly different from zero. It was concluded that AR(1) was a valid model for describing the annual rainfall process in the two sub-regions. The residuals were calculated according to the model structure and were subjected to independence and normality tests. Two independence tests were applied, viz. the Wald & Wolfwitz test and the runs test. They were applied as two-sided tests with the null hypothesis that the residuals series was a sample from a stationary independent population. For the four series from the two subregions the null hypothesis was accepted at the 10% level of significance. The Anderson test and the Kolmogorov-Smirnov test were applied with the null hypothesis that the residuals series was a sample from a stationary independent normal population. The null hypothesis was accepted at the 20% level of significance. The only exception was the result of the Kolmogorov-Smirnov test for Khartoum, since the null hypothesis was accepted at the 1% level of significance. The Kolmogorov-Smirnov statistic was calculated as 0.071, 0.061, 0.064 and 0.104 for Kosti, Obeid, Nihood and Khartoum respectively. From those results it was concluded that the residuals series were white noise. Accepting the residuals as white noise indicated that an AR(1) process is a suitable model for describing annual rainfall series in the two sub-regions.

The residuals were further subjected to the stationarity in the variance test. The Bartlett test was applied as a one-sided test with the null hypothesis that the residuals series was a sample from a normal population which is stationary in the variance. For the four series the null hypothesis was accepted at the 5% level of significance. Since the variance of the residuals was linearly related to the variance of the series, it was accepted that the annual rainfall series in the two sub-regions were stationary in the variance.

For investigating the persistence within the extremes, a simulation test was designed as a one-sided test with the null hypothesis that the ratio of observed number of years with persistence within the extremes to the total number of years was likely to arise from a process described by an AR(1) process. The results of the test are shown in Table 5. From those results it was concluded that the ratio of the number of years with persistence in extremes in the observed annual rainfall series in the two sub-regions was likely to arise from a process described by an AR(1) process.

For investigating the drop in the mean of the last 30 years, a simulation test was designed as a two-sided test with the null hypothesis that the drop in the mean of the last 30 years from the mean of the entire series was likely to arise from a process described by an AR(1) process. The results of the test are shown in Table 6. From those results it was concluded that the drop in the mean of the last 30 years from the mean of the entire series, as observed in annual rainfall in the two subregions, was likely to arise from a process described by an AR(1) process.

DROUGHT FREQUENCY ANALYSIS

Yevjevich (1967) introduced the application of the statistical theory of runs into the hydrological investigation of droughts. In studying drought frequency by runs theory, three methods can be applied: an empirical distribution-free method, a data generation method and an analytical method. The data method was applied for calculating the drought frequencies in the region.

For southern Kordfan the samples were generated from the normal distribution. For northern Kordfan and Khartoum the samples were generated from an AR(1) process. For each of the six stations a very large sample was generated. The size of the sample was such that it had 30 000 drought events relative to the specified demand level. The demand level was assumed to vary between 0.6 times the mean to 1.0 times the mean. For each demand level the 30 000 drought events were studied and the following questions answered:

(a) given that there is a drought in the region, what is the probability that it will be of duration (run-length) more than N years;

(b) given that there is a drought in the region, what is the probability that it will have a total deficiency (run-sum) of water more than D; and

(c) given that there is a drought in the region, what is the probability that it will be of average severity (run-intensity) of more than R?

The same samples were used, and for each demand level, in calculating the return period of having a drought event with different properties in answering the following three questions:

(d) what is the return period for having a drought event of duration more than N years;

(e) what is the return period for having a drought event with total deficiency of water more than D; and

(f) what is the return period for having a drought event with average severity of more than *R*?

As an example, Appendix A shows graphically the answers to the six questions for the Obeid station.

CONCLUSIONS

The methodology presented in this paper provides an appropriate framework for studying the annual rainfall process in any region. The statistical tests applied in the study are the only objective means for identification of the time series structure in the annual rainfall process, which is the first step in any drought frequency analysis.

The annual rainfall process in central and western Sudan has different characteristics in the different sub-regions. Non-stationarity of the relatively short records in Darfur makes it impossible to come to a conclusion about the structure of the annual rainfall process in that sub-region. Annual rainfall in southern Kordfan is an independent normal process. The annual rainfall in northern Kordfan has a significant dependence structure: an AR(1) process with a weak dependence structure describes the process adequately. The annual rainfall in Khartoum has a significant dependence structure, and an AR(1) process is a suitable model to describe the weak dependence observed in the series, although it does not fit the series as well as in the sub-region of northern Kordfan.

Drought frequency can only be calculated for a stationary rainfall process. The records from Darfur are not stationary, hence they are not useful for frequency calculation. The records from Kordfan and Khartoum are stationary and are used for calculating the drought frequencies. The drought frequency charts produced in this study can be easily utilized in water resources planning in central and western Sudan.

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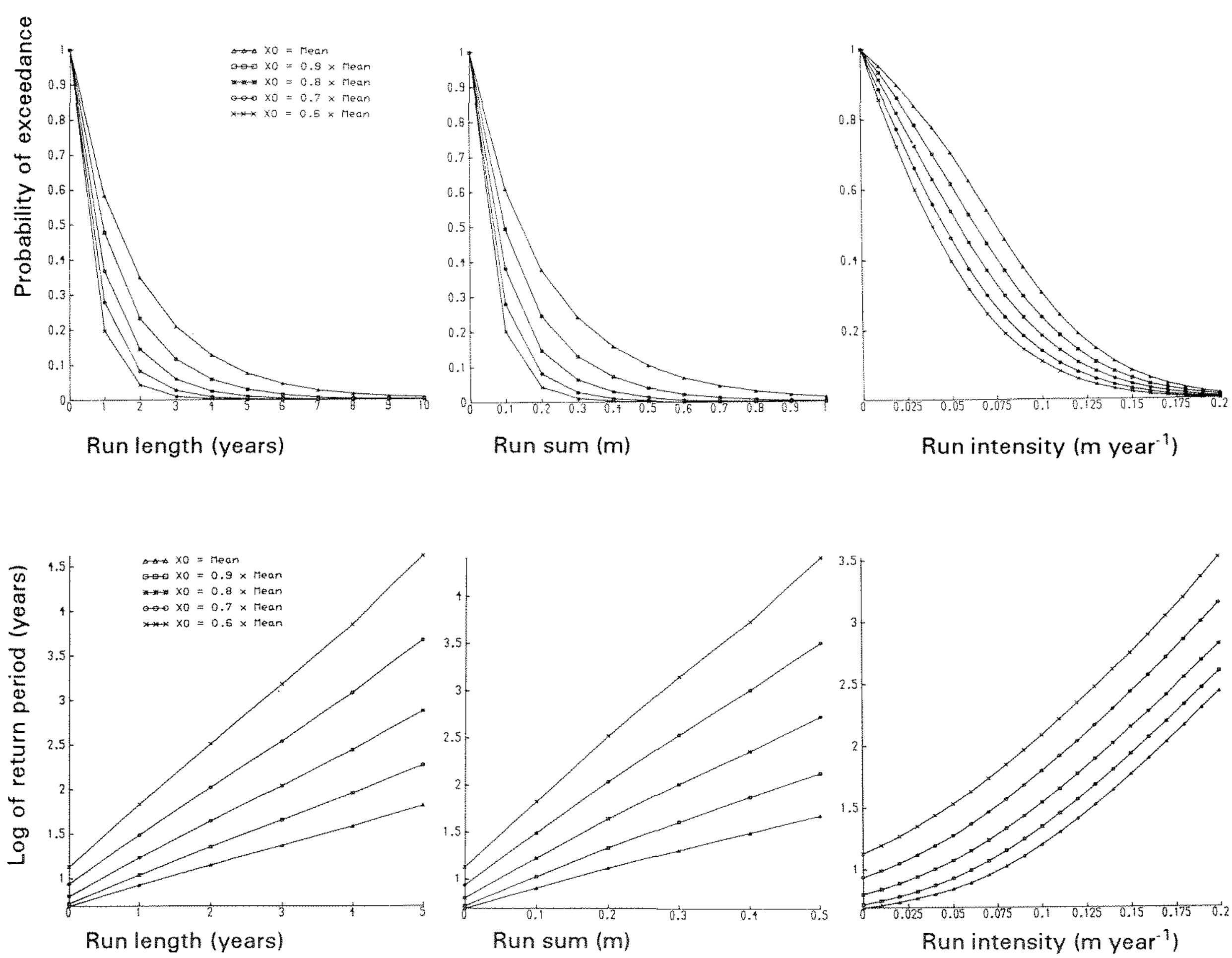
APPENDIX: DROUGHT FREQUENCY GRAPHS FOR OBEID



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