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DROUGHTS, RAINFALL AND RURAL WATER SUPPLY IN NORTHERN NIGERIA

BY

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A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree
Doctor of Philosophy

McMaster University

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DROUGHTS, RAINFALL AND RURAL WATER SUPPLY IN NORTHERN NIGERIA

DOCTOR OF PHILOSOPHY (1997) McMASTER UNIVERSITY

(Geography) Hamilton, Ontario

TITLE : **DROUGHTS, RAINFALL AND RURAL WATER SUPPLY IN NORTHERN NIGERIA**

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ABSTRACT

Knowledge concerning various aspects of drought and water scarcity is required to predict, and to articulate strategies to minimize the effects of future events. This thesis investigated different aspects of droughts and rainfall variability at several time scales and described the dynamics of water supply and use in a rural village in northeastern Nigeria.

The parallel existence of measured climatic records and information on famine/folklore events is utilized to calibrate the historical information against the measured data. It is shown that famines or historical droughts occurred when the cumulative deficit of rainfall fell below 1.3 times the standard deviation of the long-term mean rainfall. The study demonstrated that famine chronologies are adequate proxy for drought events, providing a means for the reconstruction of the drought/climatic history of the region.

Analysis of recent changes in annual rainfall characteristics show that the series of annual rainfall and number of rain days experienced a discontinuity during the 1960's, caused largely by the decrease in the frequency of moderate to high intensity rain events. The periods prior to and after the change point are homogenous and provide an objective basis for the estimation of changes in rainfall characteristics, drought parameters and for demarcating the region into sub-zones. Rainfall variability was unaffected by the abrupt change. Furthermore, the variability is independently distributed and adequately described by the normal distribution. This allows estimates of the probability of various magnitudes or thresholds of variability.

The effects of droughts and rainfall variability are most strongly felt in rural areas. Analysis of the patterns of water supply and use in a typical rural village revealed that the hydrologic system is driven by the local rainfall. Perturbations in the rains propagate through the system with short lag time between the various components. Where fadama aquifers occur, they offer a major supplement of water for six to seven months during the dry season. Under traditional systems, the pattern of water withdrawal from the fadama aquifers is designed to accommodate the diverse interests of different groups and to minimize the potential for conflict.

The results contribute to our understanding of drought and water scarcity and are useful in various practical applications.

ACKNOWLEDGEMENTS

I am indebted to my supervisor, Dr. Ming-Ko Woo who guided the research along from his hospital bed for much of the time. For his constructive criticisms and support beyond the call of duty, I am extremely grateful. I am also grateful to the members of my supervisory committee, Dr. John Drake and Dr. Pavlos Kanaroglou for their very useful suggestions and debates. I shall also be forever grateful to Dr. D.C. Ford for his advice, understanding and support. I would like to extend a special thank you to Dr. Gary and Joy Warner for lending their listening ears all the time and for their willingness to help, and to Father K. Kennedy for his confidence in me.

Funding for my study and for this research was provided by the Canadian International Development Agency (CIDA) and by the Rockefeller Foundation (African Dissertation Internships Awards). I thank the University of Jos for granting me study leave during the period of this research. To the wonderful people in the Department of Geography: Joan, Jude, Darlene, Medy, Rick and Bob, I say, keep up the good work and thank you very much. I am especially thankful for my lab mates who have all been very friendly, providing a comfortable atmosphere for study: Sharon, Bob, Kathy, Ron, Shannon, Sean and Mark.

I thank my parents and my brother, Vitalis, for the support and the sacrifices they have made over the years that I might pursue my dreams. I am deeply grateful to my parents in-law, Margareta and Frits, and my sister in-law, Marjoleine for their

encouragement, trust and financial support.

Many friends have been helpful in various ways. Deserving special mention are Dabi, Gire, Tony, Jasper, all the field assistants, the Bulama and the friendly people at Katarko.

Finally but not the least, I thank from the bottom of my heart, my wife Roos whose love, tender prodding and editorial skills kept me going, and my son Sesugh whose arrival makes the whole world a little bit brighter.

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PREFACE

The thesis is made up of a collection of papers which have been published or submitted for publication. The study problem, objectives and the relationship among the various papers are described in the introduction. The research papers include the following:

Chapter Two: Aondover Tarhule and M-K. Woo, 1997, accepted: Towards An Interpretation of Historical Droughts in Northern Nigeria, *Climatic Change.*

Chapter Three: Aondover Tarhule and M-K. Woo, 1997: Rainfall Trends in Northern Nigeria, *International Journal of Climatology*, Submitted.

Chapter Four: Aondover Tarhule and M-K. Woo, 1997: Variability in Rainfall Characteristics in Northern Nigeria, *Theoretical and Applied Climatology*, Submitted.

Chapter Five: Aondover Tarhule and M-K. Woo, 1997: Sources of Rural Water Supply for semi-Arid Nigeria: A Village Example, *Applied Geography*, Submitted.

Chapter Six: Aondover Tarhule and M-K. Woo, 1997: Characteristics and Use of Shallow Wells in a Stream Fadama: A Case Study in Northern Nigeria, *Applied Geography*, **17**(1), 29-42.

While all the papers were co-authored with the research supervisor Dr. M-K. Woo, the first author and candidate conducted the actual research involving problem formulation, literature review, data collection, field work and writing. Dr. Woo provided guidance on the direction of the research, critiqued all the papers and provided editorial advice.

Variations in symbols and style were necessary to satisfy the different journals. In some cases these variations were maintained in the thesis

CHAPTER ONE

INTRODUCTION

1.1.0 Background

Droughts and anomalous periods of dryness are regular features of the climate of the arid and semi-arid regions of West Africa. During the past five centuries, periods of extreme rainfall fluctuation ranging from a few years to several decades occurred over the area (Nicholson, 1978). More recently in this century, severe droughts which affected all or large parts of Sahelian Africa occurred in 1913, 1942, 1973 and 1983. However, it was the drought of 1968-73 with its maxima in 1972-73 that focused the attention of the world and the scientific community on the existence of the problem. Since then, droughts as well as the associated phenomenon of rainfall variability have been studied from a number of different perspectives. On the one hand are the physically based studies which seek to explain the dynamic causal mechanisms in terms of large scale atmospheric circulation processes (e.g. Druyan, 1991; El Tahir and Gong, 1996; Janicot, 1992; Lamb and Peppler, 1992; Semazzi et al, 1996; Ward, 1992). The major theories and models in this category are reviewed in Druyan (1989), Hastenranth (1995) and Nicholson (1989). On the other hand are the empirical studies which emphasize the characteristics and manifestations of droughts and rainfall variability (e.g. Demaree and Nicholis, 1990; Hulme, 1992; Nicholson and Palao, 1993; Oladikpo, 1995). Most of the investigations in northern Nigeria fall into this category.

Northern Nigeria (10^{0}30'N-14^{0}N; 3^{0}40'E-14^{0}30'E) comprises the semi-arid Sahel and Sudan savanna bioclimatic belts of West Africa which are prone to droughts and large rainfall fluctuations. During the drought of 1973, approximately 250 000 people died in the six worst affected Sahelian countries and agricultural productivity dropped to 70% of the pre-drought levels (Oyebande, 1990). In northern Nigeria, 10.3 million people faced starvation and an estimated 600 000 heads of cattle perished. In 1987, 5 million metric tons of grain, mainly millet and sorghum, valued at over US$400 million were lost to drought (Oladikpo, 1995). In addition to the devastating economic losses, recurrent droughts impose severe constraints on the biological productivity as well as the regenerative capacity of the ecological systems, mass migrations leading to social dislocations, refugee crises and a perpetration or reinforcement of rural poverty (e.g., Anyadike, 1987; van Apeldoorn, 1981; Watts, 1983, 1989). In fact, many researchers have argued that droughts and water scarcity constitute the major constraint to the attainment of self-sufficiency in food production and the development of the semi-arid regions of sub-Saharan Africa (Falkenmark, 1987; Glantz, 1987; 1994). This view is not generally shared. The opposing argument is that drought prevails in other parts of the world and, in affluent societies, need not be more than a nuisance (Hulme, 1992; Morse, 1987). However, due to overwhelming poverty and the fact that subsistence agriculture is almost entirely rain-fed, the effects of reduced rainfall are often the loss of agricultural productivity, decimation of livestock herds and other effects which are woven in the economic and social fabric of the region (Morgan and Solarz, 1994; Sivakumar, 1992). As an illustration, Figure 1.1 presents the much quoted Lamb index and the trends in per capita food production in sub-Saharan Africa and other developing parts of the world. It is striking that the sharp decline in per capita food production is coincident with the downward trend in the rainfall index. While this does not prove that the agrarian crises in the region is the result of climatic misfortunes, it strongly suggests that climatic influences may have played an important role. Hence, the need to study droughts and rainfall fluctuations cannot be over emphasized.

The literature on drought distinguishes between meteorological or climatic drought, agricultural drought, hydrological drought and economic drought. Dracup et al., (1980) discussed the major differences among the various types. In practice, the distinctions are blurred because, for example, a deficiency in precipitation (climatic drought) could lead to a depletion of stream discharge and reservoir storage (hydrologic drought), inability of soil moisture to satisfy field crop water requirements (agricultural drought) and economic losses (economic drought). However, it has not been possible to articulate a definition of drought which is universally applicable to the various forms in which water scarcity may occur (see, for example, Wilhite and Glantz, 1987). In this study, the term is used in the climatic sense to refer to the deficiency of precipitation with respect to some expected value and/or a delay in the onset or timing of precipitation.

Previous studies investigated the periodicity or the frequency with which episodes of rainfall deficiency of particular magnitudes may be expected to recur (e.g. Anyadike, 1993; Olaniran, 1991; Olaniran and Sumner, 1991). However, owing to significant non-stationarity in the time series of climatic variables at many Sahelian locations, it has been questioned whether the mechanisms responsible for the cycles in the past are at present operating in the same way and with the same effects (Demaree, 1990; Snijders, 1986). Other studies attempted to quantify the severity or magnitude of drought through the analysis of indices of rainfall departure or variability from an expected norm (Ojo, 1987; Oladikpo, 1985). Furthermore, in the aftermath of the 1968-73 drought, total annual rainfall in the Sahel consistently declined leading to the view that the drought persisted for 17 years (Lamb, 1985; Sivakumar, 1992) or that the climate of the region could be changing (Demaree; 1990; Dennett et al.,, 1985; Olaniran, 1991). The latter notion prompted a large number of studies on the trends and changing characteristics of rainfall in northern Nigeria. Hess et al., (1995), Anyadike (1993) and Adejuwon et al., (1990) calculated the magnitude of trends using regression methods. All the studies ignored the possibility of non-stationarity in the records of rainfall. Characteristics of the rainy season investigated include the number of rain days, dates of onset, termination and duration of the rainy season as well as rainfall of various daily intensities (Bello, 1996; Hess et al.,, 1995; Olaniran and Sumner, 1989).

Despite the large number of studies, several aspects of droughts and rainfall characteristics remain unanalyzed or poorly understood. For example, despite frequent mention of the increasing intensity and frequency of droughts (Oyebande, 1990), there has been little or no attempt to establish the long-term climatic experience of the region against which to compare recent events. The measured climatic data on which the analysis are based are too short climatically speaking, to yield useful results on the long-term trends. For most of northern Nigeria synoptic weather stations were not established until the 1930's. In the sequel, various studies incorporate different assumptions which lead to inconsistent conclusions. A better understanding of the history of droughts prior to the instrumental period could significantly increase the confidence in identifying sequences of climatic variations.

A second problem is the uncertainty associated with the period on which to base the analysis of drought and rainfall characteristics. The base period controls the statistical parameters through which droughts are distinguished from other events as well as the magnitude of trends and rainfall fluctuations. Over short intervals, rainfall sequences may constitute significant trends (e.g. the 1950-61 annual rainfall in the Sahel), but the same sequences may represent mere fluctuations when viewed from a longer time perspective such as a century. These considerations require homogeneity of the series to be analyzed. Elsewhere in French West Africa, studies based on various change point techniques show that the series of rainfall records contain significant inhomogeneities (Demaree, 1990;

Hurbert and Carbonel, 1987). Such change point methods have not been applied to the rainfall series of northern Nigeria. Consequently, researchers use arbitrary periods, often determined solely by the availability of records (Adejuwon et al.,; 1990; Anyadike, 1993; Olaniran, 1991) or the equally arbitrary demarcated series defined by the so called climatic normal periods (Hess et al., 1995; Hulme, 1992).

Closely associated with the trends is the variability around the trend lines. Variability is "the most critical characteristic of African rainfall for resource applications. Failure to appreciate fully the greater and more complex temporal (and spatial) variability of African rainfall has in the past led to misjudgments being made about the viability of hydrological and agricultural schemes" (Hulme, 1992, p.685). Yet, in many studies variability is treated as a mere constraint which reduces the reliability of model results, rather than as a bona fide climatic feature which requires comprehensive treatment. Furthermore, because of such variability, it is important to understand the operational processes at various scales including both regional and local scales.

Ultimately, the role of droughts, rainfall fluctuations and variability are of greatest concern in agricultural productivity, particularly small scale subsistence agriculture which is especially vulnerable. Small scale agriculture is the main mode of employment in semi-arid Nigeria, employing over 90% of the workforce in rural areas and producing most of the cereal requirements for the country. Despite previous failures, it is still seen as the best hope for the attainment of food security for the region (Kimmage and Adams, 1990; Morgan and Solarz, 1994). Thus, there is a need to translate results of analysis of droughts and rainfall fluctuations to policy measures at the rural level where agricultural productivity occurs. This requires information on the hydro-climatic processes at the rural level and their relation to the sources, timing and magnitude of water supply and use. Presently, information on such processes pertains almost exclusively to specific irrigation and other water-related development projects.

Among other reasons, investigations of hydro-climatic processes in the rural areas are hampered by the paucity of gauging sites in the data gathering network. Most of the existing climatic gauging stations were planned for aviation purposes and are thus located in large urban centers. Similarly, the hydrologic gauging network was designed to provide information for dam construction and other large-scale river control projects. It was not until the late 1970's that a conscious effort was made in some areas to design a network that would cater to the needs of the rural areas. However, in many areas, large expanses remain uncovered. Such areas could benefit from an ability to relate short-term measured data to long-term records at other locations.

The investigation of these issues constitute the main objectives of the present research.

1.1.1 Objectives

Specifically the objectives of the study include the following:

1. To attempt a quantitative interpretation of historical or folklore droughts in northern Nigeria utilizing chronicled information and other proxy data. Presently, very little is known about the droughts apart from when they occurred and some qualitative indication of their magnitude. Such an interpretation will enhance the utility of the historical information, contribute towards the reconstruction of the drought history, and allow recent drought events to be assessed in the context of the long-term climatic experience of the region.
2. To determine an objective and statistically supportable base period for the estimation of droughts, rainfall trends and fluctuations, and other changes in rainfall characteristics. This would allow for more consistent and reliable estimates and reduce the contradictions inherent in the use of arbitrary base periods.

3. To examine the variability in rainfall characteristics in northern Nigeria using the base periods identified in (2) above and to test the feasibility of using rainfall variability to estimate the risk of droughts for various activities.
4. To describe the dynamics of water supply and availability at the rural level and to indicate qualitative relation among the sources of water using a representative village. This would facilitate an integrated approach to water resources investigations and also highlight the connection between such resources and the regional climatic processes.

These objectives are addressed in a series of papers either published or submitted for publication.

1.1.2 Conceptual relation among research objectives and organization of dissertation.

Figure 1.2 presents a conceptual relation among the research objectives and indicates the areal extent and time period covered by each of the papers. At the base is the long-term historical drought study covering the period 1600-1965. The parallel existence of historical information and measured climatic data allows comparison between both times of droughts and the calibration of historical information against the climatic data in Chapter 2. In addition to northern Nigeria, information on historical or chronicled drought events from the Niger Bend (Mali) and the present day Republics of Chad and Niger are also utilized.

Chapter 3 deals with the second objective. The influence of base period on the magnitude of trends of annual rainfall and number of rain days as well as other characteristics including the dates of onset, termination and duration of the rainy season are examined. Trends based on periods determined by a statistical method are compared with those based on the widely used climatic normal periods.

Subsequently, in Chapter 4, the variability in rainfall based on the periods identified in Chapter 3 are analyzed. The known normal distribution is used to describe the fluctuations around the trend lines in the various rainfall characteristics. Illustrative examples of the use of the method to estimate the probabilities of drought risk are presented. In terms of areal extent, Chapters 3 and 4 cover the drought prone region of northern Nigeria.

Chapters 5 addresses the fourth objective and describes the various sources of water at the rural level as well as the timing and magnitude of water supply from each source. Because the analysis is based on short-term local data, it is compared to long-term records within the region as a test of representativeness.

Chapter 6 focuses on the occurrence, exploitation and use of shallow groundwater for various activities. The chapter includes a brief description of the mechanisms adopted by rural inhabitants to safeguard against conflict arising from competing demands for water.

The major findings and contributions of the research are summarized in Chapter 7.

As previously mentioned, all the chapters have been submitted to various journals for publication. Thus, a certain amount of information necessary as background material for the individual papers shows up as repetitive once the papers are collated. This, however, is unavoidable.

Finally, all the papers are co-authored with Dr. Ming-ko Woo, my research supervisor. However, the fieldwork, analysis and writing were all done by the candidate and first author with Dr. Woo providing guidance on research direction, critiquing the various papers and providing editorial advice.

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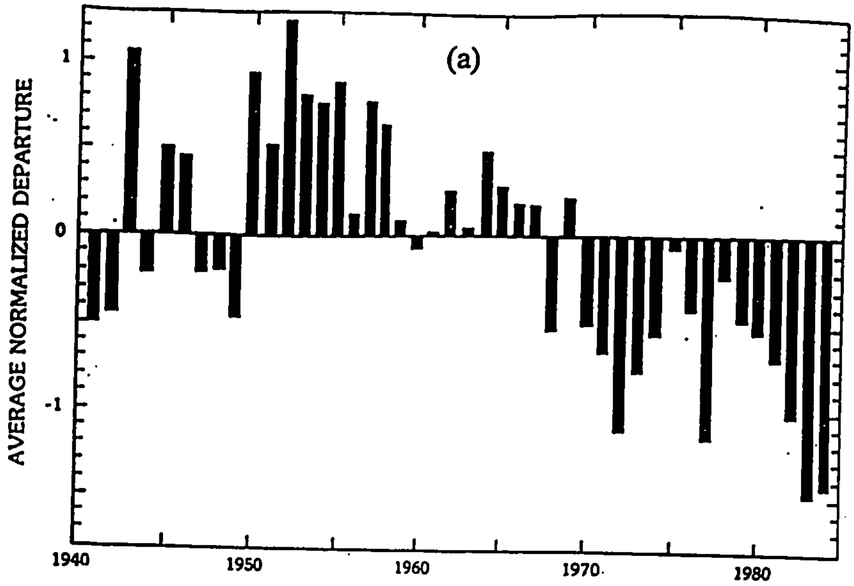

Rainfall index for 20 sub-Saharan stations in West Africa west of the 10° E between 11° N–19° N developed by Lamb (1985).

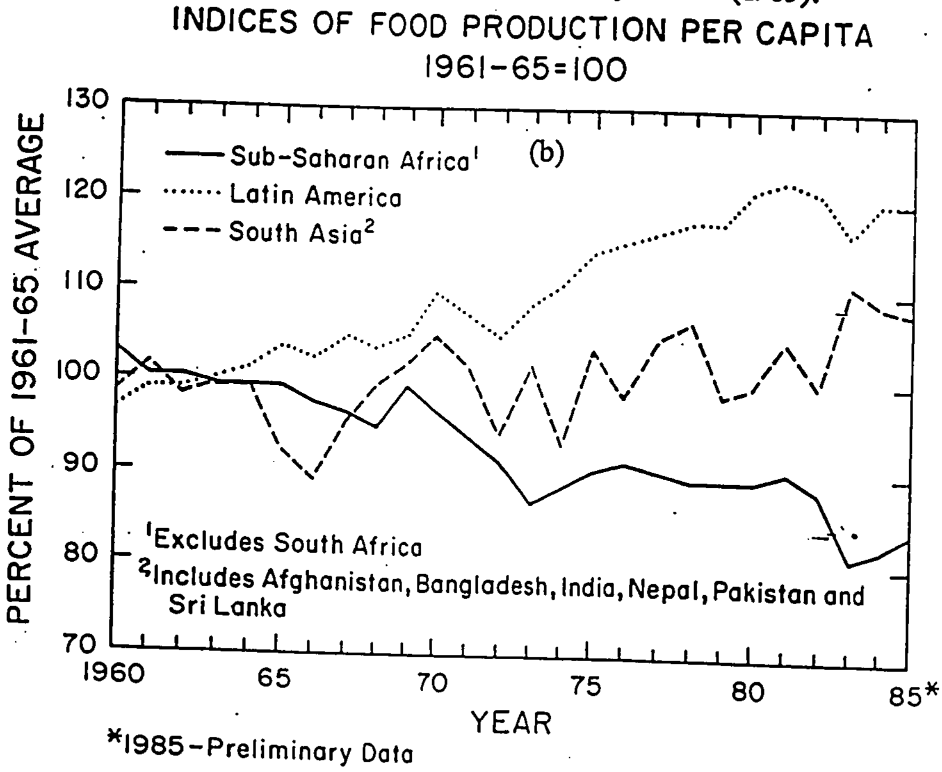
INDICES OF FOOD PRODUCTION PER CAPITA
1961–65=100

Figure 1.1 (a) Lambs (1985) index of rainfall variability in the Sahel; (b) trends in per capita food production in Sub-Saharan Africa and other developing regions.

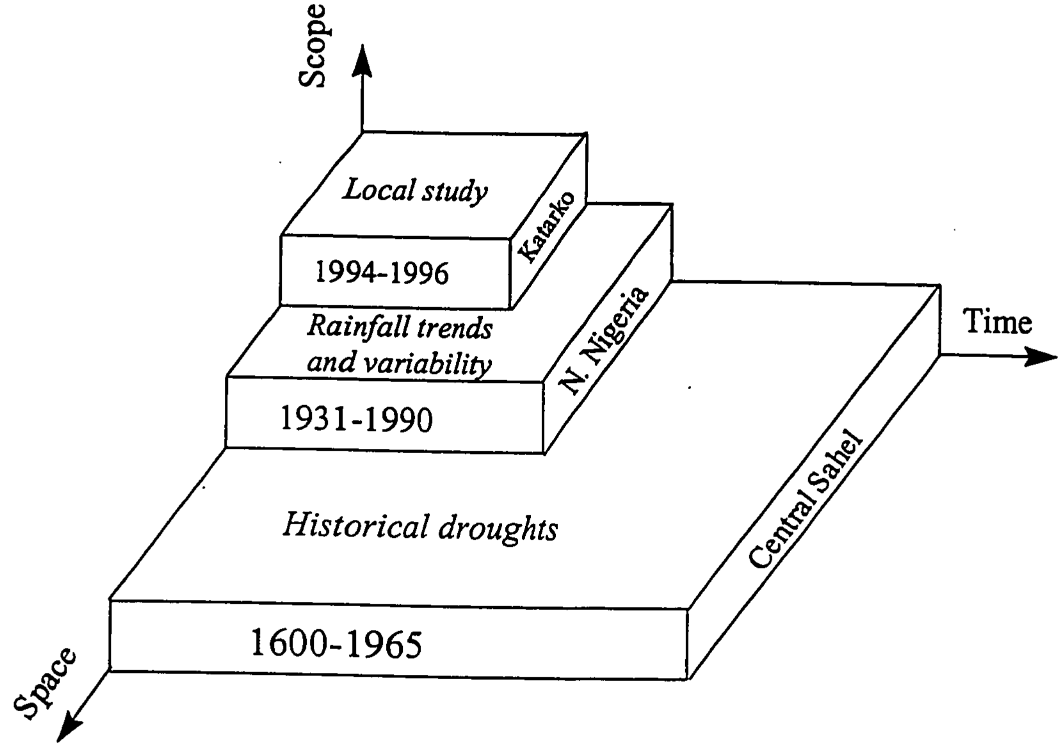

Figure 1.2 Conceptual view of the thesis.

CHAPTER TWO

Towards An Interpretation of Historical Droughts in Northern Nigeria

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Accepted for Publication in *Climatic Change*

Abstract

Both historical information on sub-Saharan droughts/famines and measured rainfall data from northern Nigeria were analyzed. Their parallel existence since 1905 allows famine chronologies to be quantified from the rainfall series. It is found that the most disruptive historical famines occurred when the cumulative deficit of rainfall fell below 1.3 times the standard deviation of long-term mean annual rainfall for a particular place. Thus defined, rainfall droughts matched approximately 90% of the famine events chronicled for northern Nigeria. An attempt is made to utilize information obtained from this matching of events to interpret droughts which occurred before scientific measurements. Difficulties inherent in such interpretation are discussed.

2.1.0 Introduction

2.1.1 Background

Interpretation and quantification of historical droughts which occurred in the Soudano-sahel belt of Africa is useful in understanding the long-term climatic experience of the region. Here, the term "historical"refers to the period predating the beginning of scientific measurements of climatic variables (Koslowski and Glaser, 1995). In the central and western Sahel, instrumental records for most climatic processes date back to only the beginning of this century. For large areas, synoptic weather stations were not established until the 1930's. Such series are not long enough, in the climatic sense, to provide information on long-term trends.

The usefulness of historical information and other proxy data in extending the length of available records has been demonstrated in many disciplines. In hydrology, paleo-flood records and other evidence of high water marks (physical, verbal, written archaeological and geomorphological) have been used to augment measured flow records (Guo, 1990; Sutcliffe, 1987). Despite inherent uncertainties, it is generally acknowledged that the information contained in such records, when used in conjunction with the systematic data, can increase the accuracy in estimating flood quantiles at a given site (Cohn and Stedinger, 1987; Hosking and Wallis, 1986; Salas et al., 1994; Stedinger and Baker, 1987). In climatology, Koslowski and Glaser (1995) used various sources of documentary historical data to reconstruct the ice winter severity in the western Baltic from about 1700. Rodrigo et al., (1994,1995) reconstructed the total annual rainfall in Andalusia during the 16th and 17th centuries using annals and chronicles of cities, ecclesiastic archives and other documentary evidence. Similarly, Oliver (1991) compared monthly precipitation distribution and wind direction during the period 100 BC-100 AD to present day conditions for many cities based on translations from aL-Biruni's *"The Chronology of Ancient Nations"*.

The Sahel has a long history of droughts and information on many of these droughts exists in various forms from the days of the great empires and kingdoms. However, there has been no attempt to utilize historical information in articulating various attributes of drought such as their intensity or duration. This is somewhat surprising since drought analysis has often been constrained by shortness of record sample and can clearly benefit from extension of the effective record length (Woo and Tarhule, 1994). The situation is particularly acute in arid and semi-arid environments where for example, several years of record might yield only one sample drought event.

In northern Nigeria where rain-fed agriculture is practised, periods of severe famines often inflicted by droughts were given specific names by the people and preserved in songs, oral folklore and myth (Watts, 1983). Van Apeldoorn (1981) compiled such folklore events between 1835 to 1954. Eight drought periods were identified, six by their names. These events were subsequently collaborated by other historic evidence including reports of colonial administrators such as the Colonial Blue

Books and Annual Report on Northern Nigeria. Unfortunately, apart from the names which hint at the approximate time when they occurred, not much else is known about such characteristics as their spatial extent, their severity or intensity, their durations or even what qualified them for such honours.

The parallel existence of record on historical or folklore droughts and measured scientific data since 1905 allows historical drought events to be defined from the rainfall series. The objective of this study is to decipher the information contained in historical or folklore droughts by comparing them with droughts defined by climatic data for a period when both sets of information are available. Unravelling the climatic causes of droughts is beyond the scope of this paper. Our goal is to interpret in quantitative terms those events already identified in the chronicles rather than to reconstruct the past climate. This will provide answers to the following problems: What is the rainfall threshold below which a historical/folklore drought is deemed to have occurred? What is the areal extent and spatial characteristics of such events? What are the durations and relative severity of historical droughts? Knowledge thus obtained may then be extended to the interpretation of historical droughts which predate scientific measurements.

1.2 Droughts in historical records

The perception of drought is inextricably inter-woven in the social and political fabric of societies. Hence, considerations other than climate frequently influence whether an event is recorded or not. For example, a drought which coincides with an important socio-political event such as the death or coronation of a new king is more likely to be remembered and therefore recorded and preserved in some way. In addition, drought concepts vary between cultures and evolve in response to changing environmental and social conditions. This implies that similar evidence or records of historical droughts in different cultures could potentially refer to quite different phenomena.

For an economy based on rain-fed agriculture, the reconstruction of historical drought is facilitated by its close relationship with famine. However, there is no inevitable predetermined relationship between the two phenomena (Watts, 1983). Several factors other than rainfall deficit may cause famine including wars, incidence of pests and diseases, failure of the economy and other administrative measures. Excessive rainfall may also lead to famine by destroying field crops through flooding. Torry (1986, p.8) distinguished between underlying (ultimate) and catalytic (proximate) causes of famine. The latter are "situational and originate shortly prior to or during an emergency"; the former are "predisposing conditions transforming proximate causes into famine distresses...In fact proximate causes (e.g. drought) can land a household in the clutches of famine with or without the involvement of ultimate causes". Hence, "while a specific drought may be considered a proximate cause of famine droughts (in general) can be considered an underlying cause" (Glantz, 1987, p.56). Similarly, Watts (1983, p. 104) observed that in Hausaland (northern Nigeria), "the great hungers of the past were the almost inevitable outcome of excessively poor rainfall (*fari*), either because seasonal totals were greatly inadequate, or the rains terminated abruptly prior to maturity (*Kumshi*) of the upland grain crops". While such considerations allow famine chronologies to be used as proxy for droughts, they nevertheless require that both the input information and the ensuing results be interpreted with caution.

2.2 Sources of Data

Two types of data were collected for this study: daily rainfall records, data on folklore or famine chronologies and historical droughts. Strictly speaking, all droughts extracted from historical records, gauged or otherwise, are historical. However, in this paper, the term is reserved for events predating scientific measurements. Folklore droughts refer to events appearing in oral folklore (*tsatsunyoyi* in Hausa), songs or stories many of which have names. Statistical droughts or simply droughts will be applied to events which have been calculated from the recorded data.

2.2.1 Rainfall data (1905-1994)

Annual rainfall data for various locations in northern Nigeria were obtained from the archives of the Federal Department of Aviation and Meteorological Services Oshodi, Lagos. For this study, annual series for eight stations north of latitude 9° were utilised. The sample stations are well distributed over northern Nigeria and the length of their records varies from 54 years at Birnin Kebbi (1919-1973) to 90 years at Kano (1905-1994). Missing data were handled in one of two ways: where only one year of data was missing, it was replaced by the average value of the previous five years. Where two or more consecutive years of data were missing, they were estimated using Bradley's (1976) median of ratios method. From the series of rainfall data P_i^x and P_i^y , i=1,2,...,n at two

$$Z_1 = P_1^x / P_1^y, Z_2 = P_2^x / P_2^y, ..., Z_n = P_n^x / P_n^y \qquad (2.1a)$$

adjacent gauging stations x and y, a series of ratios Z_i is formed so that

Because Z_i is often positively skewed, the median ratio is used to estimate the missing

$$P_i^x = P_i^y * Z(\text{median}) \qquad (2.1b)$$

values (say, P_i^x) in either series.

The nearest stations with the highest inter-station correlation were used in calculating the ratios.

2.2.2 Famine/drought chronologies in northern Nigeria (1835-1954)

After the great droughts of 1968-73, a survey was conducted in northern Nigeria to determine famines/drought events which could be remembered. Many of these events were discussed in folklore and subsequently verified by critical analysis of other supporting evidence (Van Apeldoorn, 1981). This study utilizes the series of folklore droughts identified from these sources (Table 2.1). The names given to these droughts often provide some insight about their location and time of occurrence or which agricultural activities were most adversely affected. For example, in northeastern Nigeria, the famine of 1913/14 was referred to as *Kankala Kori* (short stalks), an apt description for the stunted growth of field crops. Similarly, the famine of 1953/54 which affected areas from Bedde to Sokoto in northern Nigeria was known as *Dan Mubi,* possibly because the people were saved from starvation by grains brought from Mubi (northeastern Nigeria). It may be inferred further that northeastern Nigeria was unaffected by this drought.

2.2.3 FAMINE/DROUGHT CHRONOLOGIES IN THE CENTRAL SAHEL (1600-1920)

Nicholson (1976) compiled famine/drought chronologies from various sources for this period, covering many parts of Africa. For our study, the chronologies for three areas closest to northern Nigeria were selected including Niger Bend, Nigeria, Chad and Borno (Fig.1). Periods described as "normal", "prosperous" or as having experienced a flood have been omitted. The chronologies for Chad and Chad and Borno were merged into one regional chronology (Appendix 1). Concerning the reliability of the information, Nicholson (1976, p.100) noted that "the chronicles from certain regions are surprisingly long and detailed. Those from Borno begin well before 1500; from at least 1500 the events during the reign of each king are described in great detail. A major problem involved with this particular chronology was specifying the year in which events occurred. Famines can always be dated to a particular reign but there is little agreement among historians concerning reign dates". In western Africa where the Arab calendar was used by chroniclers, the dates are more reliable.

2.3 Definition of Droughts

A major assumption of this study is that famine chronologies are suitable proxy for rain deficits. This assumption allows quantification of historical or folklore droughts using gauged rainfall records for the period when both sets of information are available.

Agricultural and ecological systems in semi-arid environments are adapted to sporadic periods of rainfall deficit. Deficits refer to deviation below some expected norm or threshold and do not necessarily lead to stress; in fact, they may even go unnoticed. A drought occurs when rainfall deficit exceeds some critical level beyond which the prevailing adaptive mechanisms fail to cope. If deficit is defined as annual rainfall falling below a threshold value, P_c, the annual deficit for year t (d_t) will be

$$d_t = P_t - P_c , \qquad d_t < 0 \tag{2.2}$$

where P_t is annual rainfall for year t. Water surplus, instead of deficit, is attained when $P_t > P_c$. When deficit reaches a critical level so that certain agricultural activities are curtailed, a drought occurs. It is argued that annual deficits are cumulative. In other words, a spell of dry years each with a rainfall deficit will lead to a worsening drought situation. On the other hand, a drought is broken when annual rainfall shows a surplus again. This follows from the definition of drought in terms of rain-fed agricultural activities. It is not necessary to satisfy previous annual deficits in order to begin a new planting season.Thus, the cumulative deficit reached on the ith year after the deficit began

$$D_i = \sum_{k=1}^{i} d_k \tag{2.3}$$

(D_i) is

and drought occurs when $D_i < X_0$, with X_0 being the stage at which drought commences. Since droughts are a slowly worsening phenomenon, their arrival cannot be determined with precision. In this study, the duration of drought is considered to be the continuous period during which cumulative rainfall deficit exceeds the drought threshold.

Deficits can be obtained from the rainfall record once the expected threshold, P_c, is determined. Droughts can be defined when the critical threshold, X_0, is decided upon. These threshold values are probably related to some measure of the expected rainfall and a critical departure from this expected level for a particular site because the local agricultural practices are likely to have adapted to the long-term water supply conditions. To determine P_c and X_0 therefore, calibration of the recorded data against folklore drought events is required.

2.4 Calibration for the thresholds

Kano provides the longest and most complete annual rainfall record (1905-1994). This city also has been of strategic importance in historical times and, as such, has a long chronicle of drought events. Hence rainfall data for Kano is used to illustrate the determination of P_c and X_0 .It is argued that agricultural activities within a region are usually adapted to a norm which may be approximated by the long-term average rainfall. However, "average" or "normal"rainfall in the Sahel is sensitive to the period used in their calculation. Lamb (1982) suggested that the current downward trend in Sahelian rainfall began in the mid 1960's. As an experiment, the means calculated using sub-samples for various periods within the 1905-1965 record were found to be not significantly different. Consequently, 1905-1965 was decided upon as a suitable base period for the computation of the long-term mean. Using 1965 as a cut off point allowed most northern Nigerian stations to yield a significant length of record (>30 years) for spatial comparisons.

Through a crude optimization procedure, several values for P_c and X_o were tried on the Kano (1905-1965) rainfall series using the mean, $\overline{P}$, and the standard deviation, S, as indicators. The criterion for optimising these parameters is that they would reproduce the drought events indicated by the chronicles for Kano. An optimum solution was obtained at

$$P_c = \overline{P} \qquad (2.4a)$$

and

$$D_i / S < -1.3 \qquad (2.4b)$$

when all the recent folklore events in Kano (Table 2.1) were successfully matched (Fig. 2.2). Of significance, the famines of the late 1910's which were described as mild at Kano show up as deficits rather than droughts. Furthermore, prior to 1960, no deficits other than those indicated in the famine chronology crosses the "drought" threshold.

2.5 Results

The above procedure was applied to eight locations well distributed across the major climatic belts in the Soudan and Sahel savanna regions of northern Nigeria. In figure 2.3, the famine events cited in historical sources are indicated and those matched by the rainfall records are labelled. A total of 19 folklore "station events" were cited at the four extreme northern locations with long rainfall records viz. Sokoto, Katsina, Kano, Maiduguri (Table 2.1). Of these, seventeen (17) or approximately 89% are successfully matched by our drought analysis. Considered that the starting date of rainfall records varies from 1905 at Kano to 1922 at Katsina, the matching is considered to be satisfactory and suggests that despite the complexity of the relationship, famine chronologies can be used as a suitable proxy for drought occurrence.

Figure 2.3 shows that while droughts may end abruptly, their beginning is more likely to be preceded by a series of deficit years. For example, the drought of the early 1940's (Yar Balange) is preceded by three and two years of deficit respectively at Kano and Zaria. In the context of famines, it implies a gradual diminishing of stored food until the critical threshold is exceeded. Then the event is recorded as a folklore drought. Such analogy justifies the use of cumulative deficits to define droughts. Furthermore, the name of a drought may refer to a particular year but this does not mean that it is a one year event. Based on the rainfall analysis, figure 2.3 shows that the duration of the Yar

Balange (1942) drought ranged from two years at Bauchi to over seven years at Birnin Kebbi. The name may refer to the starting year, the year when the deficit reached the critical stage or a year with some significant non-climatic event such as war or pestilence. Watt (1979) stated that in Katsina, this drought was locally known as Yar Dikko in apparent reference to the role played by the Emir of Katsina (Dikko) who was reported to have confiscated foodstuff from around Katsina emirate to meet the target requisitions set by the colonial government.

Both the starting date and duration of drought are variable over space. The inter-station correlation of annual rainfall at Sokoto. Katsina, Kano and Maiduguri is very low, ranging from only 16 to 31%. Such high spatial variability implies that a drought could occur at one location but not at other northern Nigerian sites (see also Oladipo, 1995).This accounts for variations in chronicled events at the different locations. Further complication to the matching of rainfall and historical drought events is due to local variations in drought names, such that different folklore names at two locations may refer to the same event, though this is not always made clear in the chronicles. For example, between 1926 and 1930, the famine which occurred west of Kano was known as Shudde Mu Gaisa to the north of Sokoto and Mai Buhu elsewhere. In this study, events at two locations whose duration overlaps by less than 50% are considered as distinct events.

Since droughts are calculated on the basis of cumulative rainfall deficits, longer drought duration implies a worsening of the deficit. Defining drought magnitude as max(D), or the maximum cumulative deficit of an event, a relationship between drought duration and drought magnitude is presented in figure 2.4. This result indicates that drought magnitude may be inferred from the duration of a famine despite the absence of historical information on magnitudes.

Further examination of the rainfall deficit records (Fig. 2.3) allows two groups of droughts to be distinguished. Short events lasting less than three years tend to be patchy in occurrence. None of these droughts shown in figure 2.3 occurred simultaneously at all eight locations and the range of their influence varied considerably. These events are caused by local scale, short-lived atmospheric forcing which disrupts the delivery of rainfall. Because they are localized, they are prone to go unrecorded in the chronicles and hence may be missed by our matching procedure. Several droughts detected from the rainfall record, notably those of the early 1930's and the late 1940's, fall under this category. Another possibility is that such short events were considered as part of other events (e.g. the drought of 1949 at Katsina and Zaria could have been merged with the 1950/51 drought).

A second type of drought event are those lasting longer than three years. They are more regionally extensive and reach larger magnitudes than the short ones. For example, the droughts of the early 1940's affected all of northern Nigeria. Although the paucity of rainfall record makes the determination of the spatial extent of the 1912-14 drought difficult, it is known (Van Apeldoorn, 1981; Watts, 1983) that much of the western and central Soudan were affected. More than any other event, this drought has been compared to the drought of 1972-73 both in terms of areal coverage and severity (Van Apeldoorn, 1981). A third category, droughts of extreme duration and large deficits, may be added for events which last longer than seven years. These three drought categories will be used in the interpretation of historical droughts which predate scientific measurements.

2.6 Interpretation of historical events (1600-1900)

Figure 2.5 summarizes the historical droughts from three regions in Sahelian Africa. Events known to have been caused by non-climatic reasons (i.e. wars, pests and epidemics) have been eliminated. Furthermore, since duration is the criterion for our drought classification, events of unknown duration have also been eliminated. Finally, when the precise date of occurrence of an event is unknown but there is general agreement on its duration, the event is included. Based on the definitions established above, we propose that the periods shown in figure 2.5 suffered rainfall deficits in excess of 1.3 standard deviation of the long-term mean.

The duration of drought should be interpreted broadly as a "period of drought" rather than as absolute duration. This interpretation allows for the possibility that the droughts may have been interrupted by brief interludes of surfeits but that overall, the periods may be considered years of deficits. Even so, historians and chroniclers are not always agreed on the interpretation of certain information. For example, the frequent reference to "seven year" drought at many locations may simply connote a long and severe drought which is metaphorically compared to the biblical drought rather than offering a specification of duration (Nicholson, 1976).

Most droughts recorded since 1600 were events of short duration which did not extend over all three regions from which the information was derived. The longest drought on record was approximately ten years and the longest period of contemporaneous droughts at all three locations was between 1740 and 1750. The beginning of this century also saw widespread, severe droughts. Information presented in the chronicles for northern Nigeria in the 18th century is very detailed. The scarcity of recorded droughts for this period may indicate that the region was relatively unaffected by large scale atmospheric anomalies. Apart from the droughts of 1831-37 at Chad and Borno, events during the 19th century appeared to be generally short and spatially variable.

2.7 Conclusions

Parallel existence of historical information on famines and rainfall data in the sub-Saharan environment allows the matching of drought events and the interpretation of chronicled records. This study demonstrates such an application to northern Nigeria.

(1) In a rain-fed agricultural society, drought represents the cumulative effect of annual rainfall deficit as it reaches some critical level that cripples crop yield. In this regard, deficit arises when rainfall is below an expected norm represented by the long term mean and drought commences when cumulative deficit crosses a threshold represented by 1.3 times the standard deviation of annual rainfall. Thus defined, rainfall droughts matched approximately 90% of the famine events chronicled for northern

Nigeria, verifying the feasibility of interpreting proxy information using scientifically measured data.

(2) Drought duration is related to magnitude, considered here as the maximum cumulative rainfall deficit. This relationship confirms that longer droughts recorded in the chronicles are more severe than the shorter ones.

(3) Both chronicles and rainfall records show that droughts of short duration (<3 years) tend to be less severe, more frequent and spatially more variable than long droughts. Droughts lasting over three years are regional in extent and are separated by long intervals between occurrences.

(4) In the historical records for the Sahel dating back to 1600 AD, there were chronicled droughts lasting ten years or more. These are inferred to be of extreme severity. The paucity of droughts mentioned in the chronicles for the 18th century suggests that this was a relatively wet period while the droughts in the following century were mostly short and localized.

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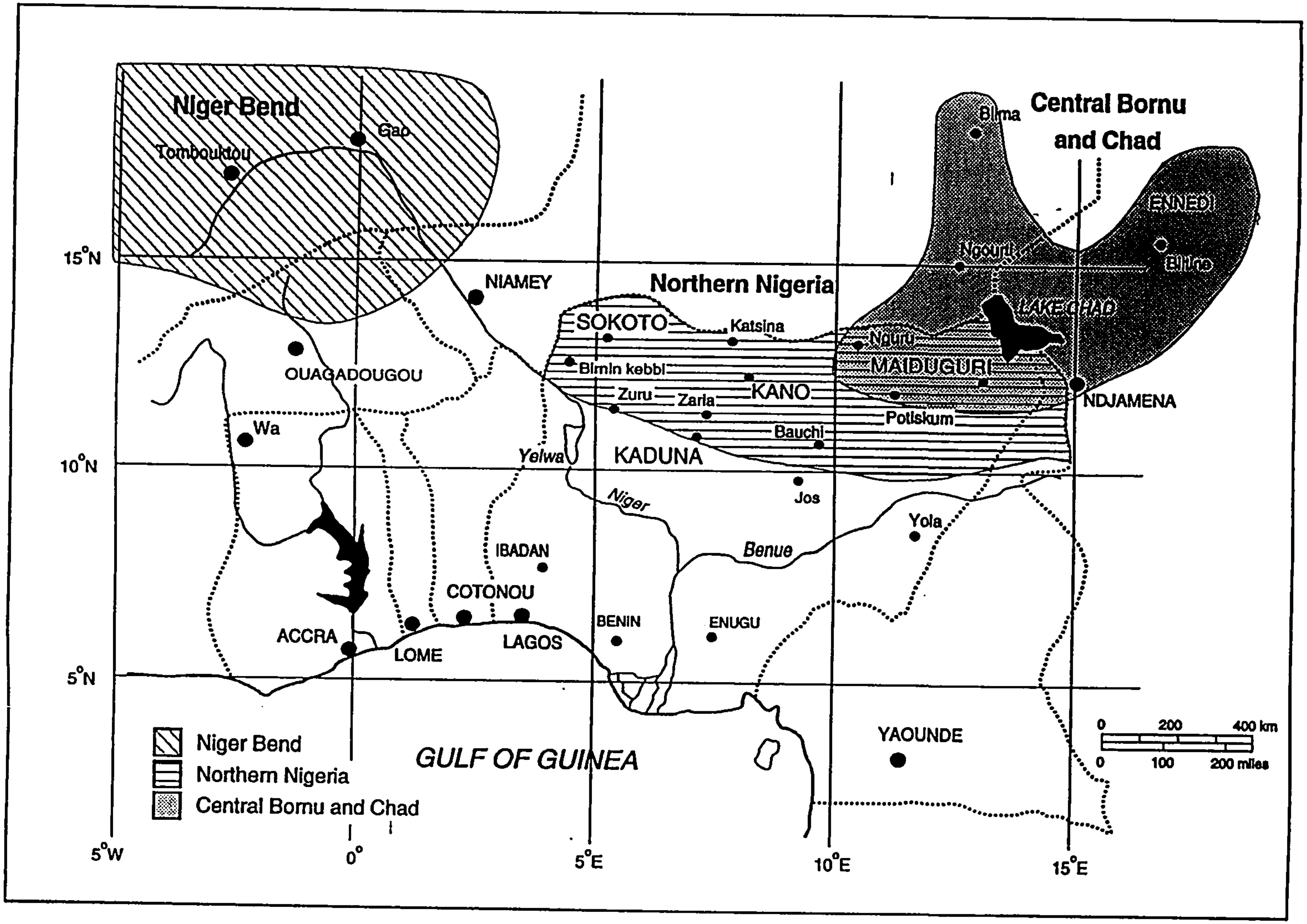


Fig. 2.1 Rainfall gauging stations in northern Nigeria and areas from which famine chronologies were analyzed.

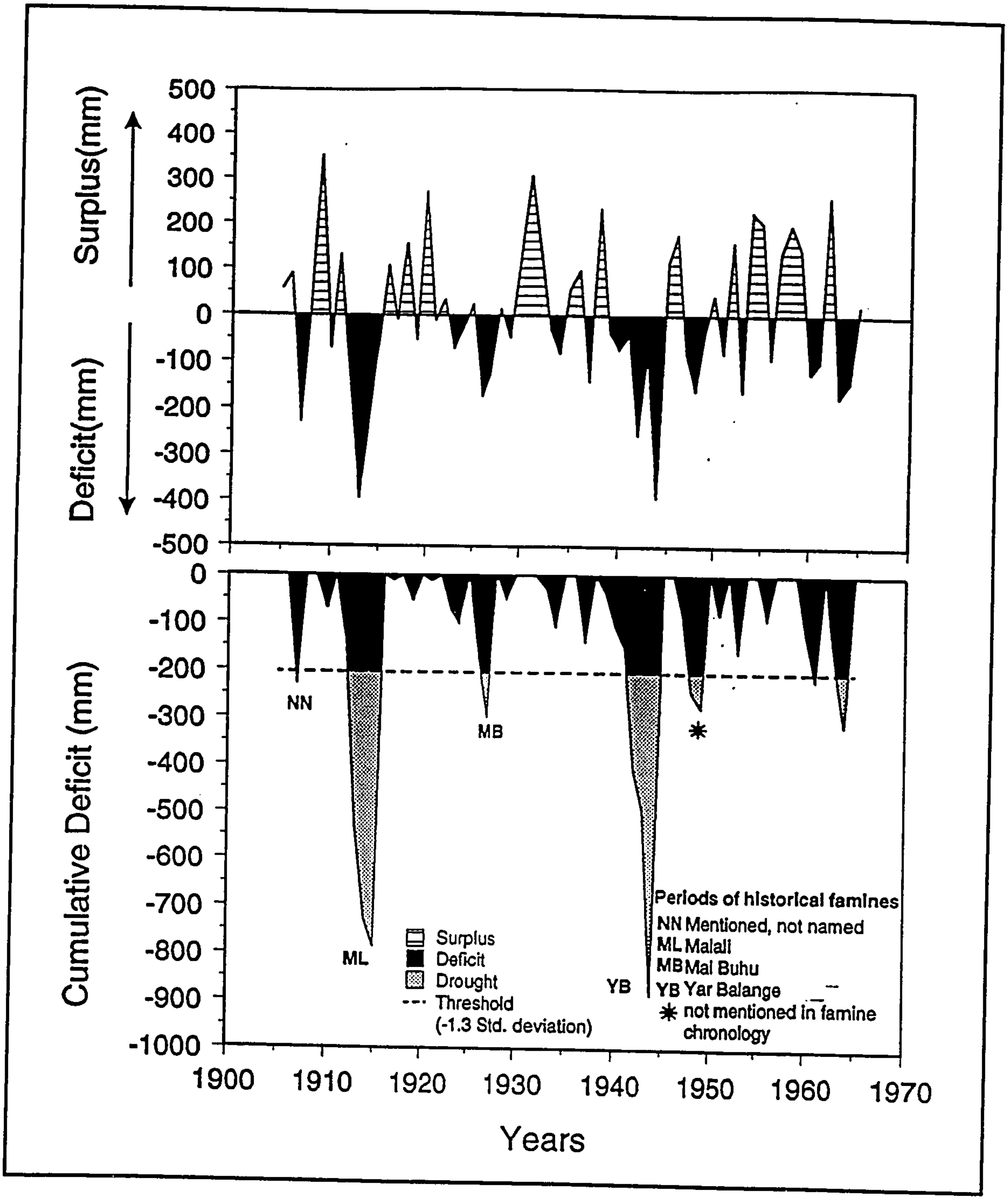
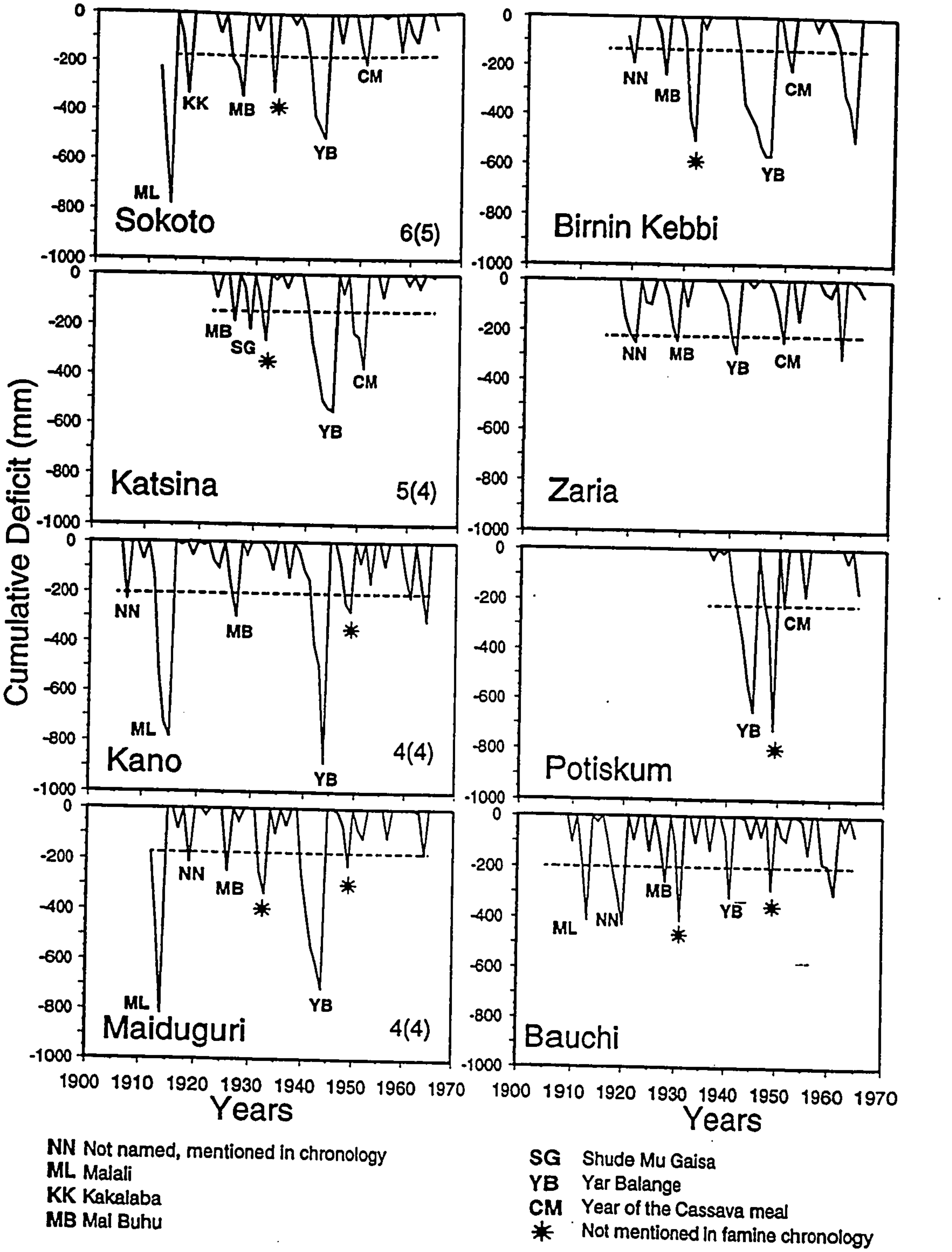


Fig. 2.2 Definition of annual surplus, deficits and droughts using rainfall data for Kano. To obtain deficits (upper panel), the annual precipitation is first plotted and the threshold (the mean of 1905-65) is superimposed. Values that fall below this threshold are considered as deficits. In lower panel, the deficits are accumulated, but the cumulative values are terminated once a subsequent year shows a surplus. The -1.3 times standard deviation (of 1905-65) line is added and the period when the cumulative deficit falls below this line defines the drought duration.



6(5) represents the number of historical famines and number of events(in brackets) matched by the rainfall records.

Fig. 2.3 Matching rainfall droughts and historical famines in northern Nigeria. Dashed lines represent critical levels defined at 1.3 times the standard deviation below the mean.

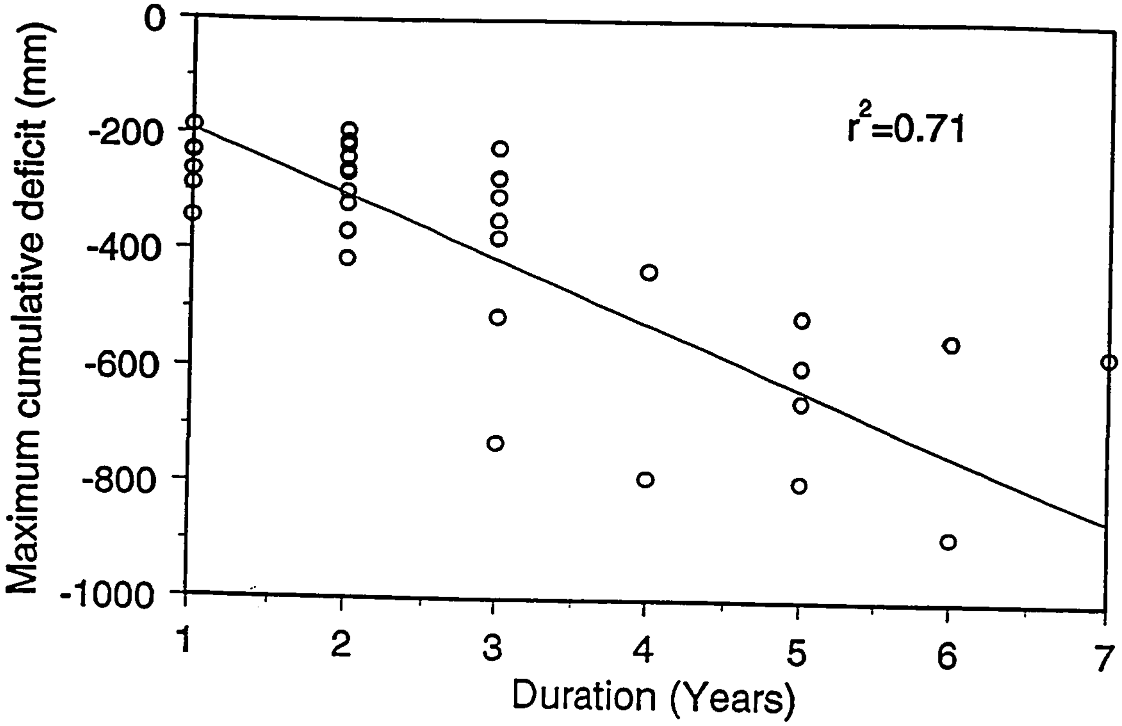


Fig. 2.4 Relationship between drought duration and magnitude (maximum cumulative rainfall deficit) based on events from 13 stations in northern Nigeria.

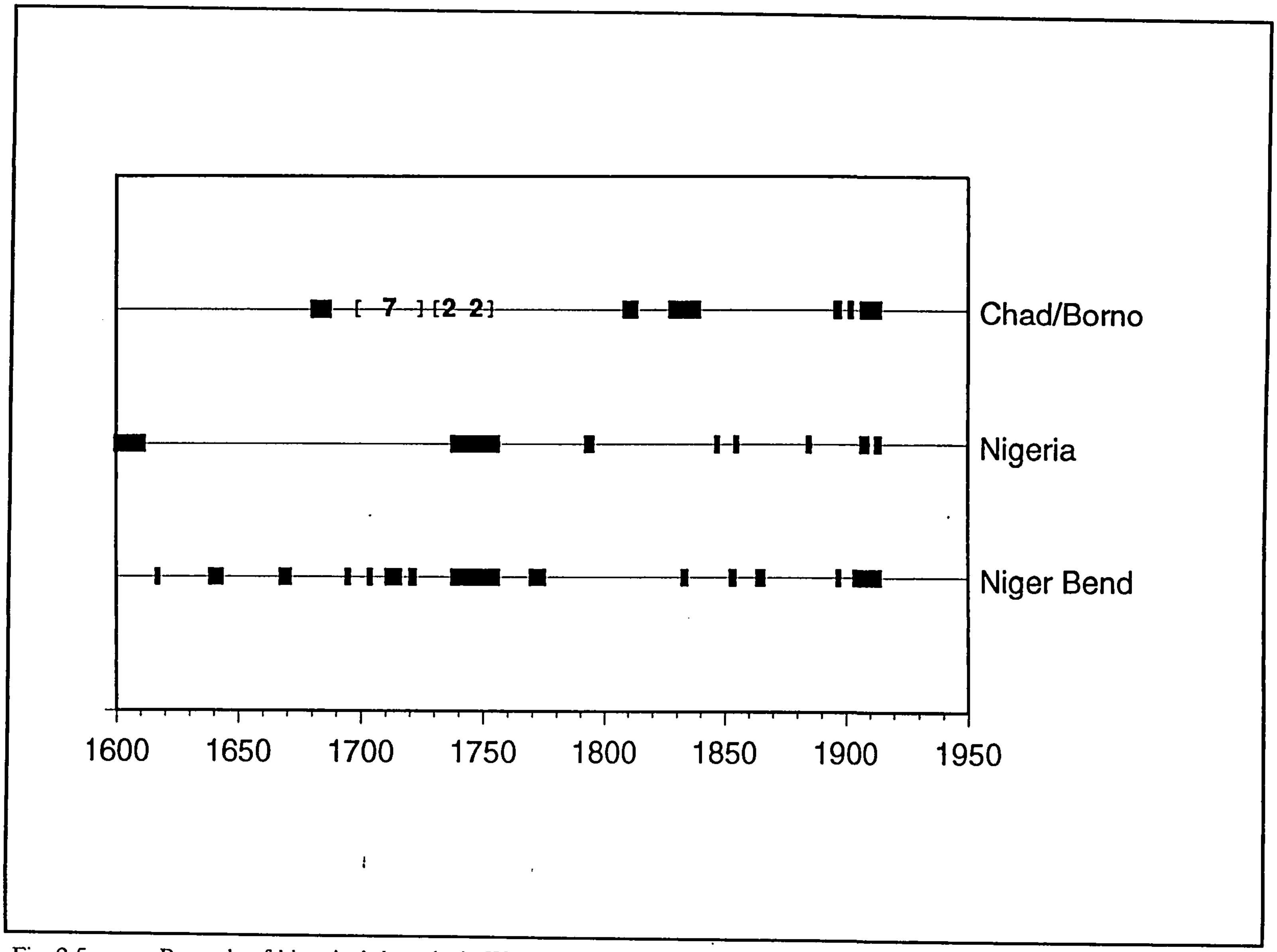


Fig. 2.5 Records of historical drought in West Africa since 1600. The numbers for Chad/Borno indicate the durations of drought whose exact date of occurrence cannot be ascertained.

Table 2.1. Famine Chronologies in Northern Nigeria 1900-1960, based on compilation by van Apeldoorn (1981)

Period	Name of famine	Area affected	Source	Comments
1907-1908	-	Sokoto-Borno	Hill, 1972; 1977, Watts and Shenton, 1978	Described as mild to severe
1913-1915	Kankala Kori Kakalaba	Bedde & Borno Hausaland	Kura, 1976 Laya, 1975; U.Ahmed, 1976	Considered one of the most severe and widespread drought
1918-1921	-	Patchy	Watts and Shenton, 1978 Laya, 1975	Generally described as mild
1926-1930	Mai Buhu Shude Mu Gaisa	Western Kano Northern Sokoto	Watts and Shenton, 1978; Mortimore, 1973; Abdu, 1976; Hassan,1976	Poorly documented, worst drought N.W. of Sokoto
1941-1944	Yar Gusau Yar Balange	Sokoto, Katsina Kano	Ndaks, 1976; Ahmed, 1976 Poncet, 1974 Watts and Shenton, 1978	Inadequate rains aggravated by wartime economy
1950-1951 1953-1954	"Year of Cassava meal" Dan Mubi	Rep. of Niger, Kano Bedde-Sokoto	Salifou, 1975 Kura, 1975; Watts and Shenton, 1978	-

APPENDIX 1

HISTORICAL DROUGHTS AND FAMINES IN NIGERIA.

Compiled By Nicholson (1976), Watts (1983)

1600-1610	Eleven years of famine near Kano; may have been caused partly by war of the last century
18th Century	Frequent famines in Borno during the second half of the eighteenth century
1738-1756	Famine ravaged Tombouctoo and the Niger Bend during this period and probably affected all of the western Soudan, from Hausaland to Wolof (i.e. western Nigeria to Senegal). Similarly, Kano also suffered a severe drought of ten or more years' duration in the 1740s and early 1750s.
1793-95	Rainfall drought in northwestern Nigeria.
1790's	Kano hit by serious drought which depleted grain reserves and caused emigration.
1805-1810	Mild and patchy famines
1847	Famine in Hausaland, known as *Darwara*
1855	Very severe famine in Hausaland, known as *Banga-Banga*
1863	Slight famine or inadequate rainfall.
1864	Slight famine in Hausa country.
1873	Slight famine in Hausa country.
1879	Famine, known as *Malali.*
1884	Slight famine in Hausa country.
1888-1890	Mild and localized famines in Katsina; *Yar mani* (1888), *Ci Kworiya* (1890).
1898	Localized famine, known as *El Commanda* in Daura

1902-1910	Patchy, moderate to severe famines in northern Nigeria. In 1905, a localized famine occurred in Katsina referred to locally as *ci abinki ta rimin gora*. In 1908, famine (known as *Yunwar Kanawa*) afflicted Kano and its surrounding areas.
1912-1914	Severe famine, probably the most severe one in Hausaland since 1855, most of the African Soudan was affected.

(For details concerning these events, the reader is referred to Nicholson (1976) and Watts (1983).

CHAPTER THREE

Rainfall Trends in Northern Nigeria

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Abstract

Two base intervals for the estimation of rainfall trends are compared: Climatic Normal Periods (CNP) and periods separated by a step jump based on Statistical Change Point (SCP) method. Several characteristics of the seasonal rainfall, including annual and monthly total rainfall and frequency of rain days as well as the onset, termination and duration of rainy season, were tested for the presence of an abrupt change. The jump is found only in the total rainfall and frequency of rain days during the 1960's and affected areas north of 11^{0}N. Trends based on CNP's are spuriously high and blur regional variations in rainfall characteristics. Conversely, trends based on SCP highlight regional variations which may be used to divide the region into sub-areas. Trends of monthly rainfall showed maximum decreases of between 1 to 2 mm a^{-1} in August and September while maximum decrease in rainfall intensity occurred in the range of 25 to 35 mm d^{-1}. The fact that high intensity rainfall does not contribute significantly to agriculture may explain the continuation of agricultural activities in the Sahel despite massive reductions in total rainfall.

3.1.0 Introduction

Reliable estimates of the magnitude of trends are needed to assess the severity of droughts and changes in rainfall characteristics in semi-arid West Africa. Rainfall trends in this region are sensitive to the time interval on which they are evaluated, hence there is a need for specifying an appropriate base period. In Nigeria, several recent studies (Hess., 1995; Anyadike, 1993) estimated trends based on Climatic Normal Periods (CNP) defined by the World Meteorological Organization as 1931-1960 and 1961-1990 for sub-Saharan Africa (WMO, 1971). Others (e.g. Adejuwon et al., 1990) used the entire period of available data which, in some cases, began in 1922. Both approaches ignore the possibility of significant inhomogeneities within the arbitrarily demarcated segments of the rainfall series. Indices presented by Jones and Hulme (1996), Nicholson (1993) and Lamb (1985) suggest that in addition to trends, annual rainfall in the Sahel experienced a discontinuity (also referred to as a shift or abrupt jump) during the mid-1960's. It is important to examine such a discontinuity in inhomogeneous series to avoid erroneous inferences from the rainfall data.

Elsewhere in West Africa, particularly in the Francophone areas, Statistical Change Point (SCP) methods have been used to identify this discontinuity. In Mauritania, for example, Demaree (1990) identified its occurrence in 1967-68 based on application of the

Pettitt change point test. Using a similar technique, Snijder (1986) located the discontinuity in 1969 for Burkina Faso rainfall. The SCP methods have not been applied to Nigerian rainfall data. The objective of this study is to determine the occurrence of a step jump in the time series of Nigerian rainfall variables, compare the magnitudes of trends in time series which have been segmented based on CNP's and SCP and to seek a more meaningful approach to examine the trends. Both annual and monthly rainfall and frequency of rain days as well as dates of onset/termination and duration of the rainy season will be analysed. Conspicuously neglected in previous studies is the assessment of trends in different categories of rainfall intensity. Olaniran's (1988, 1991) studies of rain days of different amounts remains an exception in this regard. In the present study, ten categories of rainfall intensity (i.e. 5, 10,..., 50 mm) are analysed.

3.2.0 Methods

It is hypothesised that the rainfall variables in Nigeria consist of a step jump which partitions the series into two segments and each may or may not exhibit a trend (Fig. 3.1). To test for the occurrence of a step jump or abrupt change, the non-parametric Pettitt change point test is particularly useful when no hypothesis can be made about the location of the change point. The test is given as (Pettitt, 1979)

$$K = \max_{1 \le k \le N} |U_k| \tag{3.1}$$

where U_k is calculated from

$$U_k = 2\sum_{i=1}^{k} M_i - k(N+1) \tag{3.2}$$

and M_i is the rank of the i^{th} observation when the $X_1, X_2 \ldots X_N$ series are arranged in ascending order. A change point occurs at the location K in the series where U_k attains a maximum. The significance of the change point is determined by comparing the calculated value of K with its theoretical value at probability level α given as

$$K_\alpha = \sqrt{\frac{-\ln\alpha\ (N^3+N^2)}{6}} \tag{3.3}$$

Figure 3.2 shows an example of the application of the procedure. A clearly defined peak indicates a sharp change point (Fig. 3.2a,b) whereas a truncated peak (Fig. 3.2c,d) suggests a more gradual transition. No assumption is made about the homogeneity of the series before or after the change point.

Two features are of interest in assessing the changes in a series containing an abrupt jump:

(1) the magnitude of the jump expressed as the difference in mean ($\overline{X}_A$ - $\overline{X}_P$), in which the subscripts refer to the period after (A) and prior to (P) the change point. When used in connection with CNP's, P and A will refer to the first and second climatic

normals respectively. Expressing the means as a ratio ($\bar{X}_A / \bar{X}_P$) is also useful standardization for comparing variables especially where their magnitudes vary considerably from station to station;

(2) the sign (direction) and magnitude of trend in consecutive periods.

Once a change point is established to be significant, the series is segmented at the location of the change point and the magnitude of the trend at time T, X(T), in the sub-periods estimated by bT where b is the slope obtained from the regression of the variable against time. The significance of b is tested against the null hypothesis of no linear slope ($\beta=0$) using the t test

$$t = \frac{|b-\beta|}{\sigma_b} \qquad (3.4)$$

where σ_b is the standard error of b. The slope is significant if the calculated value of t exceeds the theoretical value of the t distribution for appropriate degrees of freedom at a specified probability level α.

3.3.0 Data and analytic procedures

The data set consists of daily rainfall records for 25 locations in Nigeria obtained from the Federal Department of Meteorological Services, Oshodi. To keep the length of record approximately equal for all stations, the base period of analysis is taken as the two successive CNP's: 1931-1960 and 1961-90. Five of the 25 locations have incomplete records during the first period with two stations starting in the late 1930's (Potiskum, 1936; Kaduna, 1939) and three in the early 1940's (Nguru, 1942; Mokwa, 1943; Yelwa, 1943). A few missing values during the base period were estimated using Bradley's (1976) median ratio approach from the nearest station with the highest inter-station correlation. Where only one year of record was missing, it was estimated as the mean of the adjacent four years.

For this analysis, a rain day is any day receiving at least 1 mm of rainfall. Specification of this lower limit avoids uncertainties associated with small rainfall totals (<1.0 mm). The onset of the rainy season is considered to be the first rainy day after which there are no dry spells longer than 14 days during the subsequent four rain-events. Similarly, the season is considered terminated on any rain day followed by a dry spell longer than 14 days during the last four rain days. The duration is the number of days between the termination date and the onset of the rainy season.

In the first instance, annual variables - total rainfall (R_a), number or rain days (D_a), starting date, ending date and duration of the rainy season - at all locations were tested for presence of a change point. Subsequent analysis was confined to the region where abrupt changes were identified. The magnitude of jump (ratio of means) and trends were computed for the sub-periods and compared to the corresponding values based on Climatic Normals. A similar procedure is applied to the total monthly rainfall (R_m) and monthly number of rain days (D_m). Trends in different classes of rain events are analysed only for periods segmented by the Pettitt test. To obtain the cumulative values for a specified threshold, only those events less than or equal to the threshold are considered.

3.4.0 Results

4.1 Trends and change point periods: Annual series

The distribution of the stations analysed and the major climatic belts in Nigeria are shown in Figure 3.3. The locations and years in which step jumps occurred in R_a and D_a are also shown (Fig. 3.3). The figure shows that the occurrence of jumps in both R_a and D_a is limited to the area north of latitude 11^0 N with a slight dip towards the east. This region comprises the Sahel, most of Soudan Savanna and a small part of the northern Guinea Savanna belt or about 35% of the total land mass of the country (Fig. 3.3). It is noteworthy that in the aftermath of the 1968-74 drought, the Geological Survey of Nigeria designated the region north of latitude 11^0 N as a high risk drought region. This designation was based primarily on the severity and areal extent of previous droughts and its coincidence with the area affected by abrupt changes in R_a and D_a is therefore significant. For both R_a and D_a, the jump occurred between 1960 and 1970 but was not generally coincident at the same location. However, the interval between the change point in R_a and D_a is of the order of 1 to 2 years except in the northeast where it reaches 4 and 5 years at Potiskum and Maiduguri respectively. Furthermore, there is no preferred order of occurrence (i.e. the change point in R_a is not necessarily preceded by a change in D_a.) reflecting the low correlation ($0.42 \leq r^2 \leq$

0.68) between R_a and D_a . Such correlation may also account for the fact that at some locations (e.g. Kaduna) a step change in the number of rain days is not accompanied by a corresponding change in total annual rainfall or vice-versa (e.g. Yelwa).

No significant jumps were identified in the series of variables related to the length of the rainy season, i.e. the dates of onset, termination or duration. In a study of rainfall trends in the northeast arid zone of Nigeria, Hess et al., (1995) concluded that the trends in the starting and ending dates of the season are generally not significant. This suggests that the explanation for recent observed changes in rainfall over the region lies in the frequency and distribution of rainfall *within* the season.

3.4.2 *Comparison of periods: CNP and SCP*

Trends and step jumps in the sub-series defined by CNP and SCP for annual rainfall and frequency of rain days are shown in Figures 3.4 and 3.5. Table 3.1 presents the magnitude of trends in R_a and D_a. Both CNP and SCP produce comparable trends during the first period. In most cases, there is close alignment in the trend line defined by either method despite differences in the length of records analysed. Rainfall totals show positive annual increases of up to 3.5 mm a^{-1}. The anomalously high value of 12.5 mm a^{-1} at Yelwa is probably due to undocumented changes in gauge location or measurement procedures. Positive trends during this period are most likely the result of terminating the series on a "high note", i.e. the higher than average rainfall experienced during the 1950's and early

1960's at some locations. During the second period, there is a sharp difference in the rate of decline under SCP and CNP. While generally negative in both cases, the slopes obtained using SCP, or b(SCP), are lower than those for CNP, b(CNP), by about 2-6 mm a^{-1}. At Sokoto and Katsina, b(SCP) is approximately 50% and 30% respectively of b(CNP). Potiskum presents an extreme case in which b(SCP) for annual rainfall is positive (0.4 mm a^{-1}) as opposed to a decrease of 7.6 mm a^{-1} for b(CNP). Such differences highlight the need for an appropriate base period for analysis.

The magnitude of trends in the series of rain days reveals a slightly different pattern. The rate of decrease ranges from 0.41 to nearly 1.0 d a^{-1} in the Sahel. The negative trends based on the second CNP are significant at the 1% probability level for 8 of the 10 locations while those estimated from SCP are significant at 5% only within the Sahel region.

3.4.3 Magnitude of jump: annual series

The mean of the sub-period after the occurrence of a jump was expressed as a ratio of the period prior to the jump (Table 3.2). The use of CNP's does not explicitly assume that a step change occurred. Nevertheless, a difference in means analogous to an abrupt change is introduced by the truncation of the series into two separate periods. Let $W = \overline{X}_A / \overline{X}_P$. Then W is unity if there is no difference in means between the periods; it is less than unity if $\overline{X}_A < \overline{X}_P$ and vice-versa. Table 3.2 shows that W(CNP) is consistently higher than W(SCP), being up to 8% for R_a. The stations in Table 3.2 are arranged approximately along two west to east transects so that the first six (Sokoto, Katsina, Kano, Nguru, Potiskum and Maiduguri) are located roughly on 12^0N and the subsequent four (Yelwa, Zaria, Kaduna and Bauchi) on 11^0 N. There is a noticeable difference in $W(R_a)$ values between the two transects. For example, at 12^0N mean annual rainfall during the second (SCP) period is ≈ 77% of the mean of the first period. This increases to 88% at 11^0N, reflecting the severity of the decrease in rainfall over the Sahel. A similar pattern in observed for CNP. In terms of the number of rain days, there is less obvious difference between the transects, suggesting that the decrease in this variable was relatively uniform over the region.

The ratios for dates of onset and termination and duration of rainy season are virtually identical for CNP and SCP, ranging from 0.94 to 1.02 with no coherent spatial pattern. This indirectly confirms the stationarity of the entire length of record for these variables.

3.4.4 Trends in monthly rainfall

During the months of June, July, August and September (JJAS), the Inter-Tropical Convergence Zone which is responsible for rainfall in West Africa is fully entrenched over Northern Nigeria. Consequently, rainfall in these months accounts for between 77% (Kaduna) to 94% (Nguru) of the annual total so that changes in rainfall during these months are more likely to produce a noticeable effect on the annual total. Table 3.3 shows the occurrence of step jumps in total rainfall and number of rain days in JJAS. Some observations are noteworthy. One is that the JJ rainfall contains no step jumps. This is in agreement with other studies (Anyadike, 1993; Hulme, 1992) which found either positive or negligible negative trends for these months. Another observation is that the step jumps in August occurred only at those locations along 12^0N while the jump in September was more widespread. In Mauritania, Demaree (1990) obtained a significant step jump only for August. Finally, the change point in monthly series occurred over a longer time period, spilling into the 1970's in many cases and preceded or lagged the annual jump by several years. August and September contribute about 36% and 25% respectively to total annual rainfall. Hence, an early decline during these months at some locations noticeably reduced the annual total, raising the possibility (Nicholson, 1989; Olaniran, 1991) that the decline in rainfall in the Sahel may have began as early as the 1940's.

The magnitudes of jumps and trends in August and September for the sub-series segmented by SCP and CNP are examined further. Table 3.4 indicates that W(CNP) are, on average, about 5% higher than W(SCP) although differences up to 31% and 14% exist at Maiduguri and Sokoto (D_m). Comparing the months, the ratios for September are consistently lower than for August, implying that the decline in R_m and D_m is proportionately more severe for September. As was found in the annual series, CNP's yielded larger slopes, many of which are statistically significant (Table 3.5). However, trends based on SCP are generally non-significant, suggesting that the slopes based on CNP are probably spurious.

3.4.5 Trends in Rainfall of various intensities

Abrupt changes in the annual amount of rainfall below several intensity thresholds are restricted largely to the Sahel Savanna region. However, the entire area experienced jumps in the corresponding number of rain days per year. Figure 3.6 shows the magnitude of trends before and after the occurrence of a change point for each category. The pattern mirrors the annual series. Of particular interest are the trends after the change points. Figure 3.6b suggests that the rate of decrease in total rainfall is about 2 mm a^{-1} for rainfall intensity < 20 mm d^{-1}. At higher intensities, there are larger decreases, attaining a maximum in the range of 25-35 mm d^{-1}, followed by a "flattening" out or "recovery". This may be due to the rarity of events higher than 35 mm d^{-1} so that the cumulative totals do not change with increasing threshold. Frequency of rain days (Fig. 3.6d) show a similar if more muted pattern.

3.5.0 Discussion and Conclusion

Both Climatic Normal Periods and periods based on the Pettitt test have been used to assess trends in Nigerian rainfall series. The results presented reinforce earlier findings that the recent drying phase affected most of the country although more severely in the region north of 11^0 N. Even so, the drought prone region is not homogeneous, with significant local variations which become more pronounced when the occurrence of a change point is taken into account. Thus, both the ratio of means and the magnitude of trends show different responses in the Sahel compared with the Soudan and northern Guinea savanna regions. Previous attempts to derive regional patterns employed ambiguous or poorly defined criteria such as "northern belt" and computed a single index of variability for the whole region (e.g. Anyadike, 1993). Our results suggest that sub-regions may be more meaningfully defined on the basis of their response to rainfall variations. These differences are masked when the analysis is based on CNP. Moreover, our finding does not support the assumption that a single trend is applicable over the entire period of rainfall record (e.g. Adejuwon et al., 1990), nor do we find the Climatic Normal Periods suitable as base periods for trend estimation. By ignoring the existence of a change point, CNP's yield trends which are spuriously high and may lack statistical validity.

Total annual rainfall received at a place is determined by the frequency of rain events as well as the duration of the rainy season. Total rainfall may be considered dependent upon the length of the rainy season and the number of rain days. Since there are no statistically significant changes in the starting, ending or duration of rainy season, the frequency of rain events is a driving factor behind recent observed changes in rainfall characteristics over northern Nigeria. Other researchers (e.g. Hess et al., 1995) reached a similar conclusion. The present study further illustrates the changes in rain days over time and space. At a monthly scale, the reduction in total rainfall and number of rain days over northern Nigeria is concentrated in the months of August and September but the change in the number of rain days is more regionally pervasive. Furthermore, the magnitude of jump in September suggests that the decline during this month was more severe than previously acknowledged.

Regression coefficients of rain intensity below different thresholds show that the largest decrease occurred in the range of 25-35 mm d^{-1} for both total rainfall and number of rain days. This supports Olaniran's (1991) observation that the recent drought in the Sahel region of West Africa is "associated with a large decline in the frequency of moderate and heavy rainfall events during the wet season". A practical implication is that activities which rely on rainfall within this range may be affected adversely. Conversely, Lamb (1983) and Nicholson (1983) noted a relative lack of suffering during the dry years between 1975 and 1981. Dennett et al., (1985) commented that this may be attributed to the stability of the early season rainfall among other factors. The relative stability in low intensity rainfall ($\leq$ 20 mm d^{-1}) revealed by our study may also have played an important role. This is because low to moderate rain intensities contribute most to rain-fed agriculture while higher intensity rainfall merely induces erosion and fast runoff.

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List of Figures

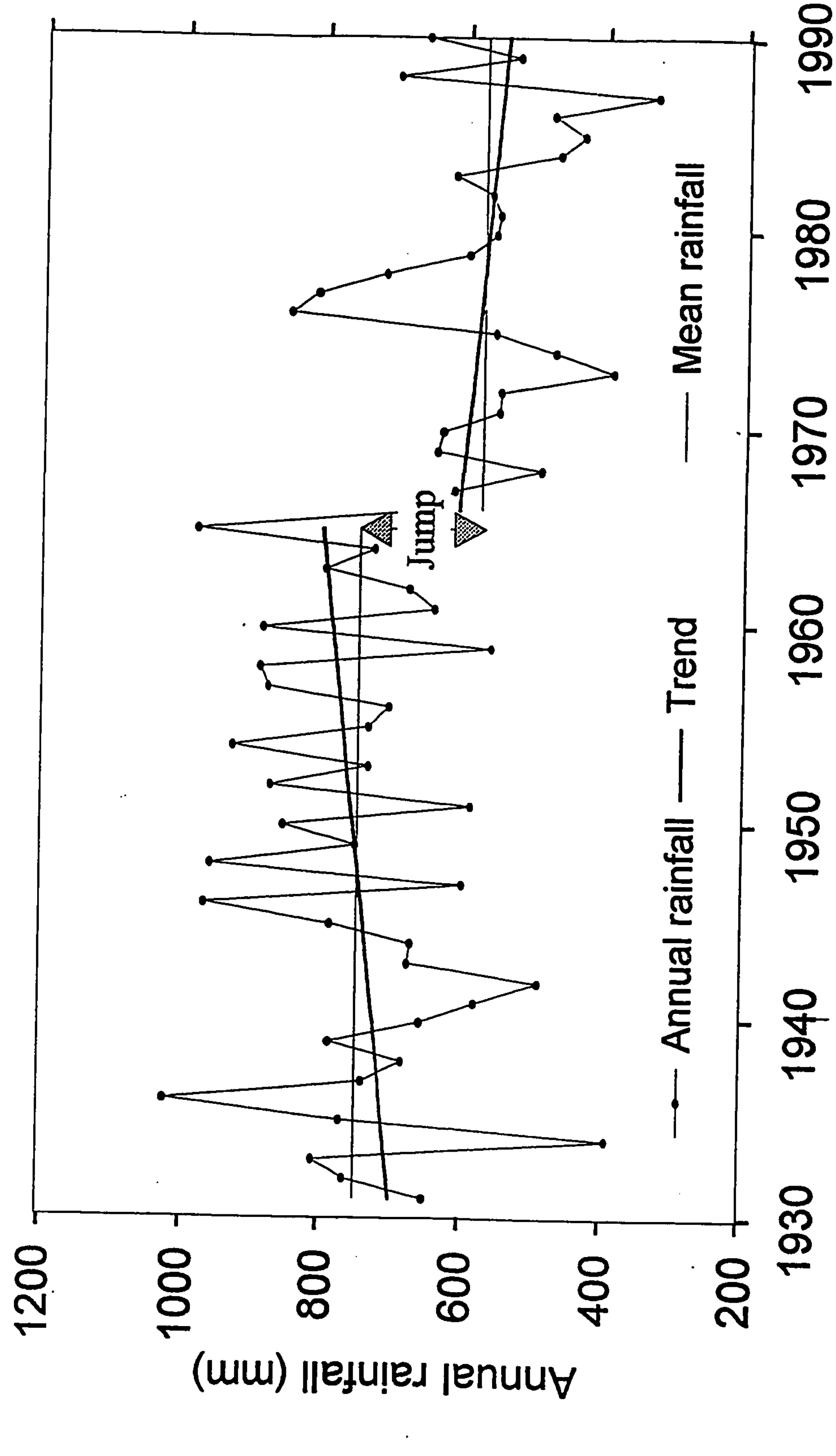


Fig. 3.1. Graphical illustration of a step jump and trends, based on rainfall at Sokoto

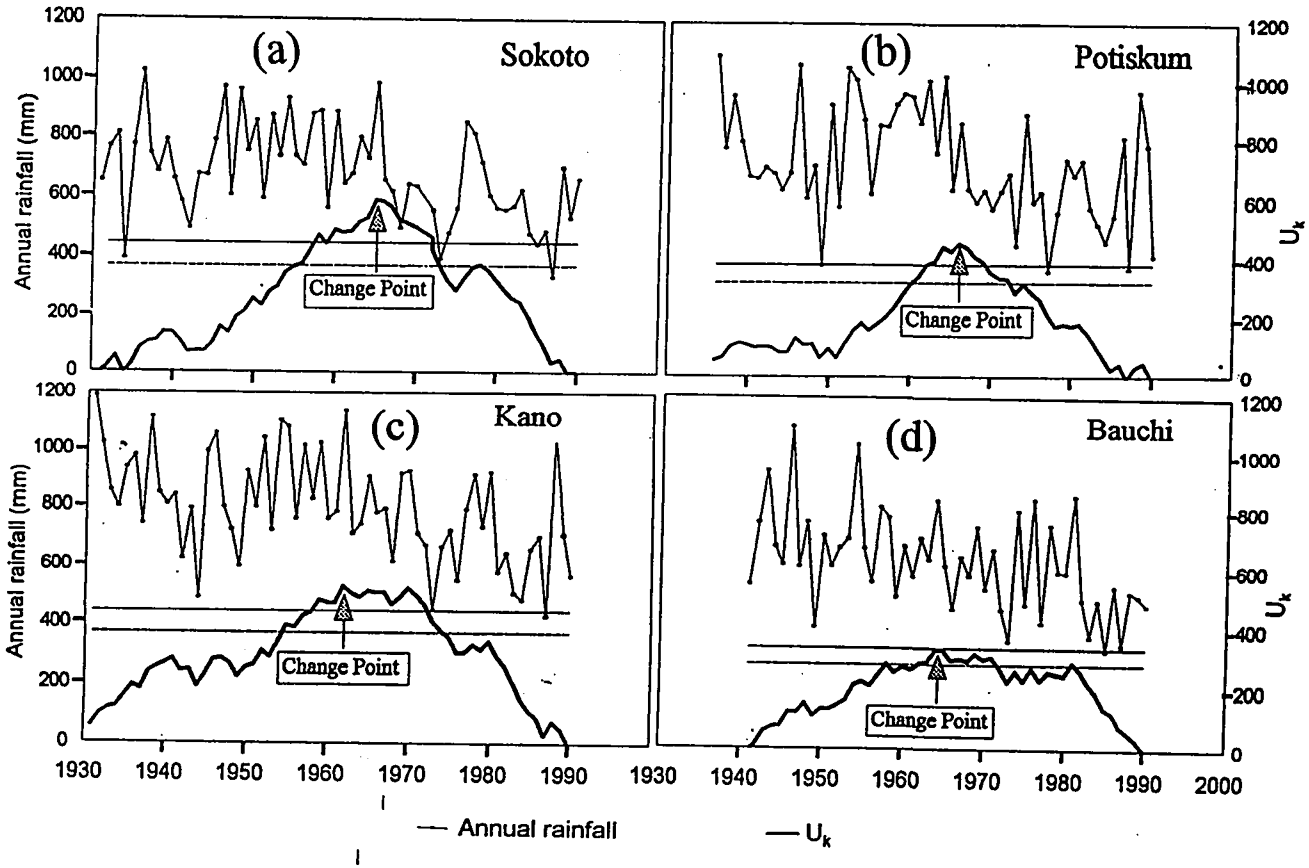


Fig. 3.2. Application of the Pettitt test to several northern Nigerian annual rainfall series. The dashed and solid lines indicate the confidence limits at 5% and 1% probability. Thick lines are the calculated U_k statistics (see text) and the change points are located at max(U_k)

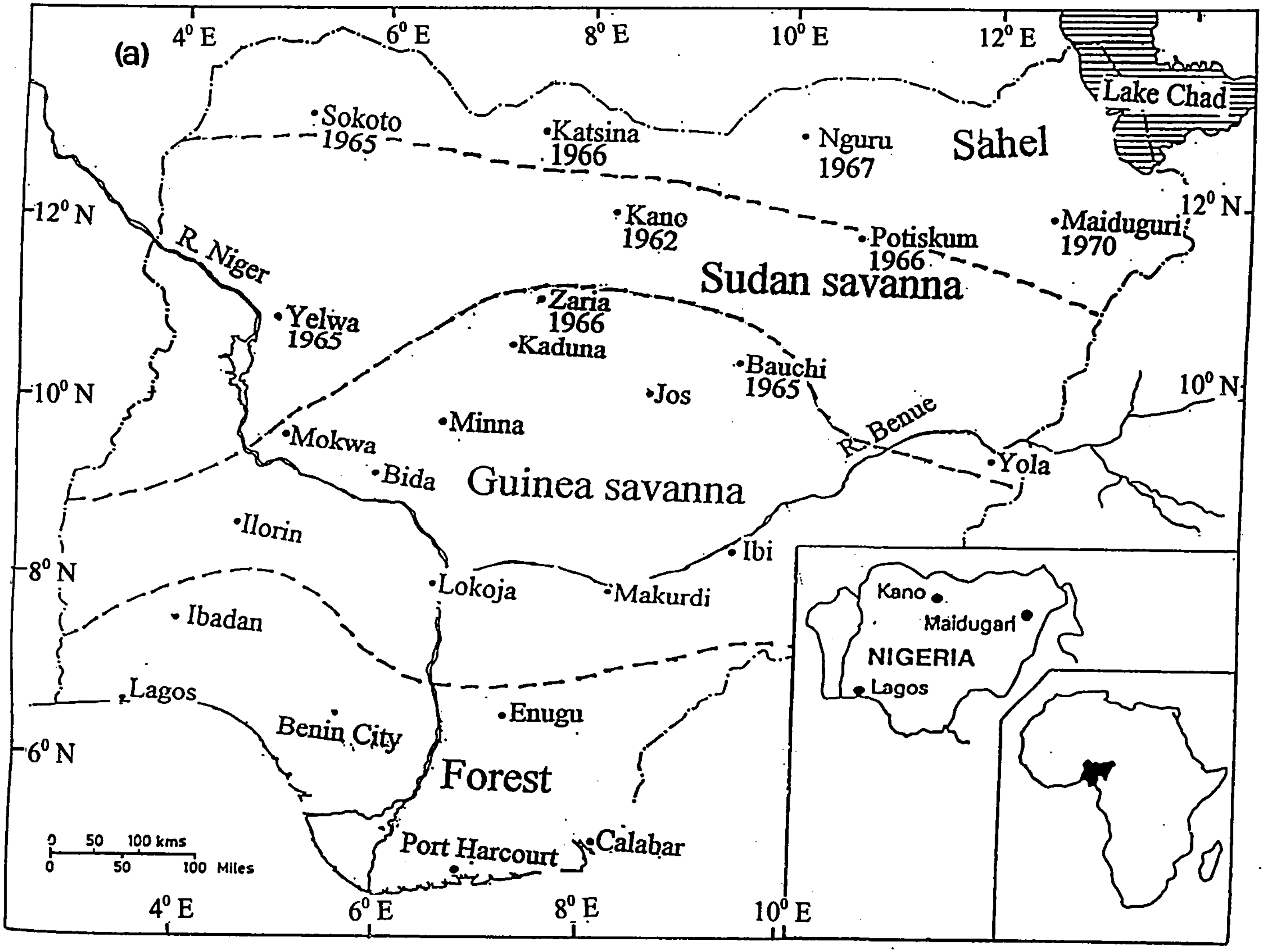
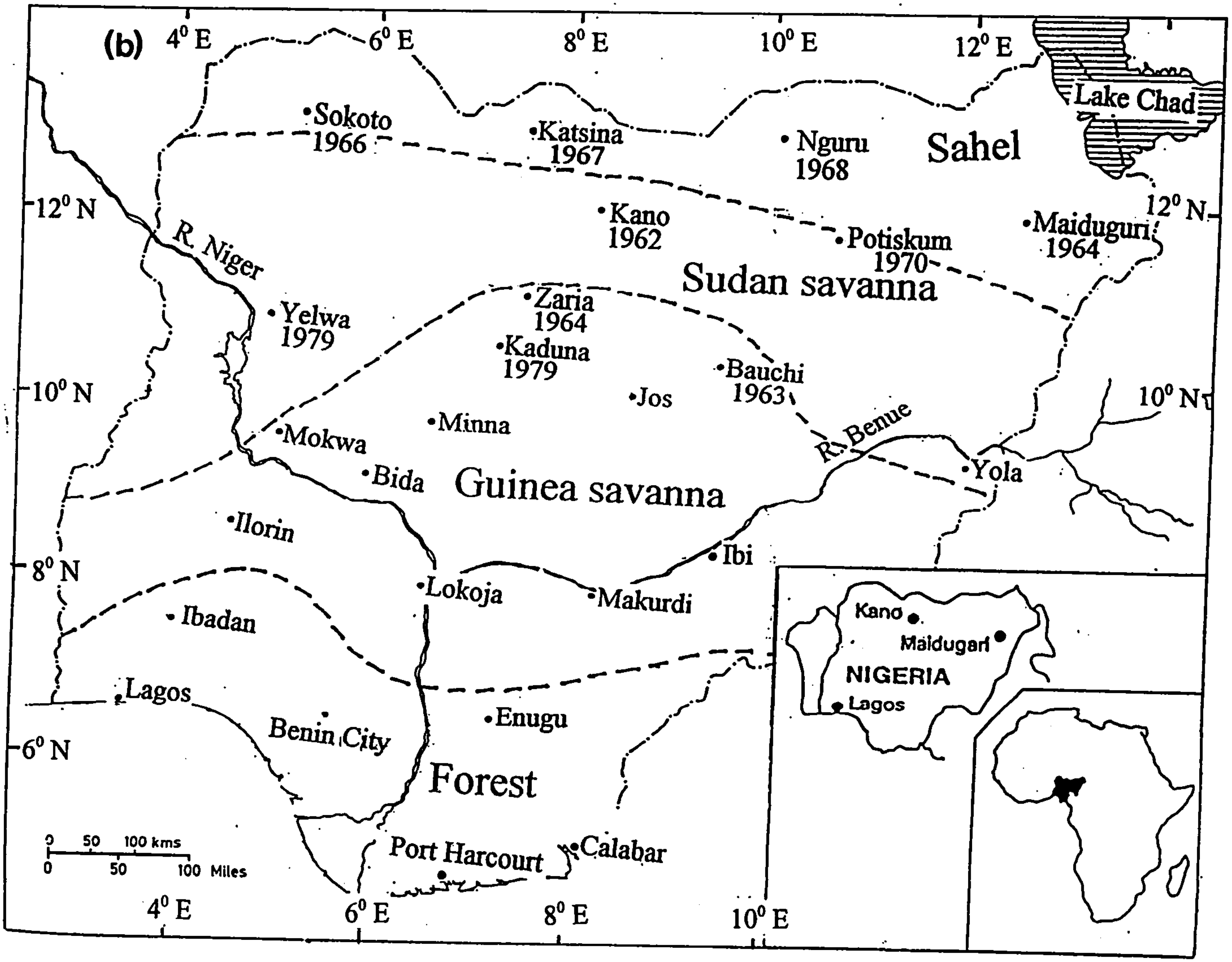


Fig. 3.3. The location of sample stations analysed and the occurrence of change point in (a) annual rainfall and (b) number of rain days. Locations unaccompanied by a year indicate no change point.


(b)
4° E
6° E
8° E
10° E
12° E
12° N
10° N
8° N
6° N
Lake Chad
Sahel
Sudan savanna
Guinea savanna
Forest
Sokoto 1966
Katsina 1967
Nguru 1968
Kano 1962
Potiskum 1970
Maiduguri 1964
Yelwa 1979
Zaria 1964
Kaduna 1979
Bauchi 1963
Jos
Minna
Mokwa
Bida
Yola
R. Niger
R. Benue
Ilorin
Ibi
Lokoja
Makurdi
Ibadan
Lagos
Benin City
Enugu
Port Harcourt
Calabar
0 50 100 kms
0 50 100 Miles
Kano
Maiduguri
NIGERIA
Lagos

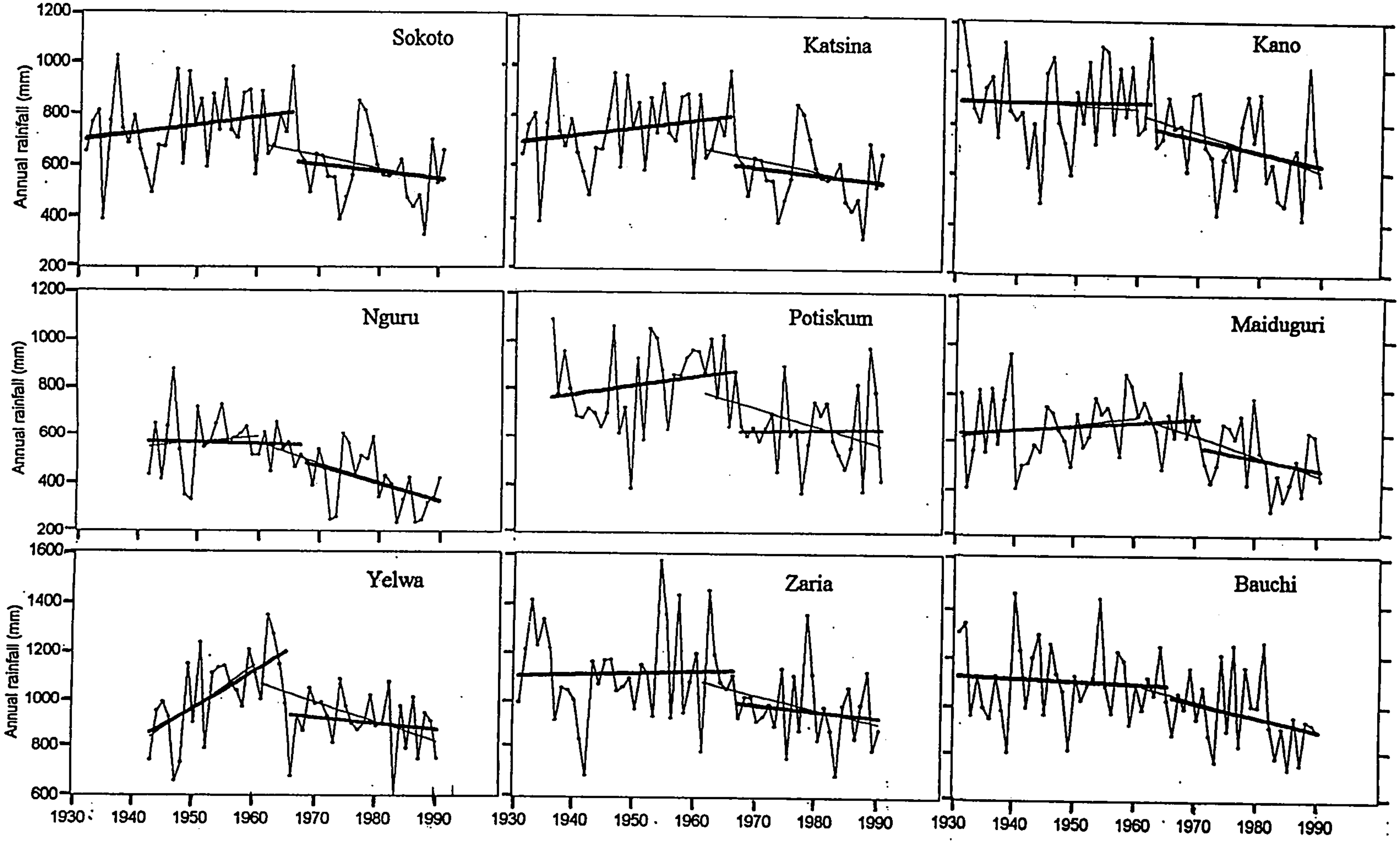


Fig. 3.4. Annual rainfall (thin marked line), trends and step jumps defined by Statistical Change point (thick line) and Climatic Normal Periods (thin line) for selected stations in northern Nigeria.

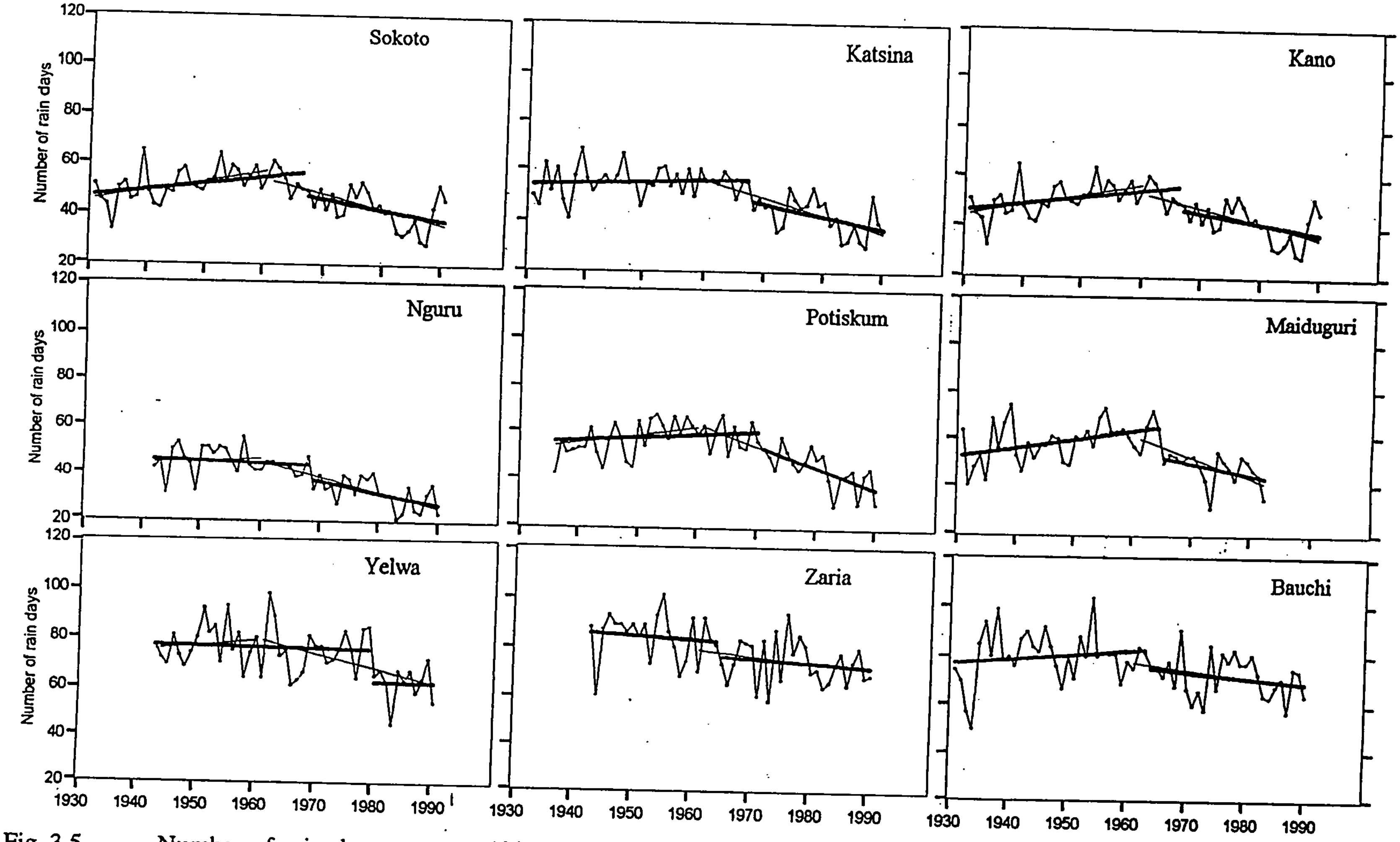


Fig. 3.5. Number of rain days per year (thin marked line), trends and step jumps defined by Statistical Change Point (thick line) and Climatic Normal Periods (thin line) for selected stations in northern Nigeria

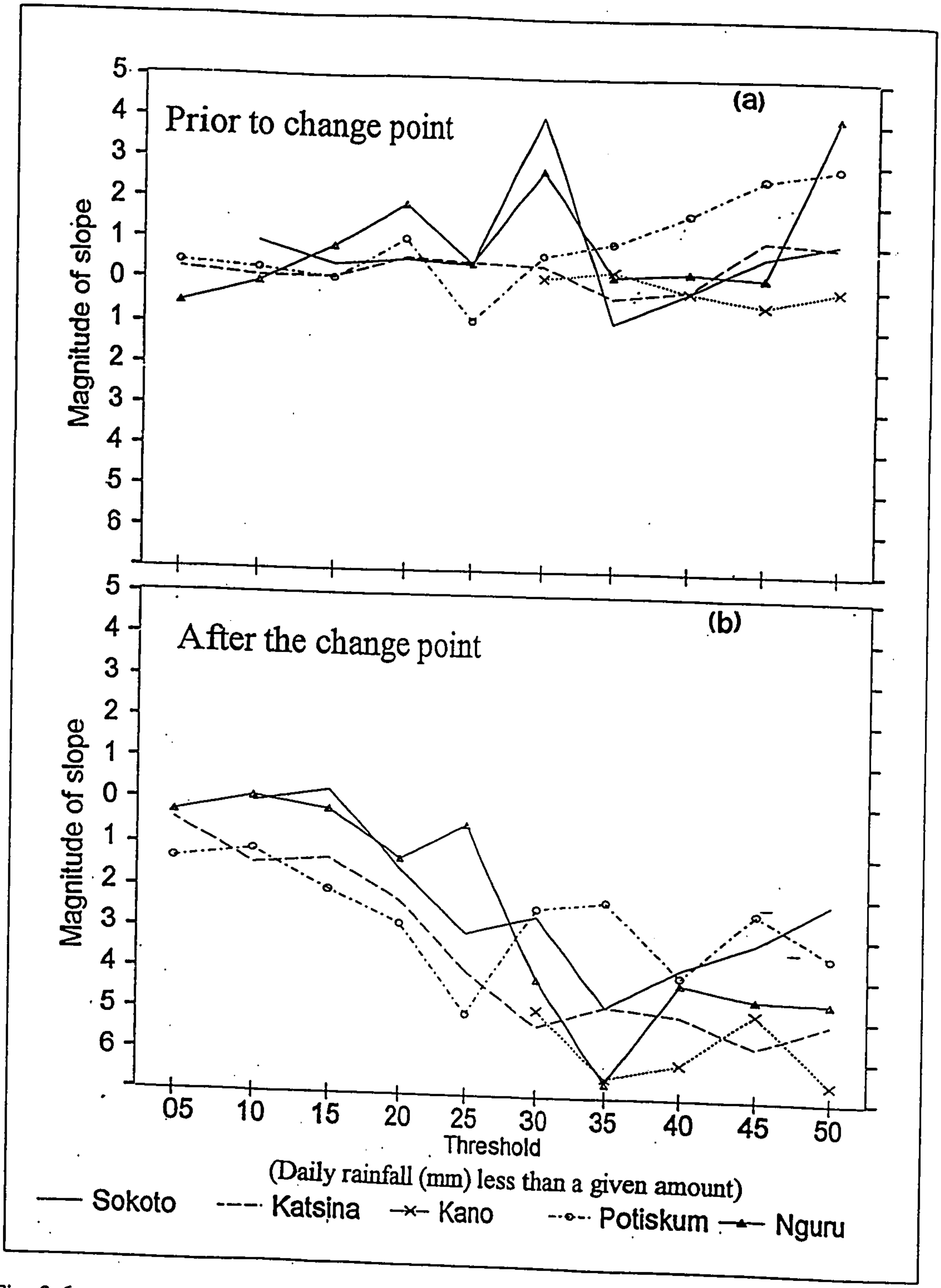


Fig. 3.6. The magnitude of trends in daily rainfall below various thresholds: (a,b) total rainfall and (c,d) frequency of rain days before and after the occurrence of a change point

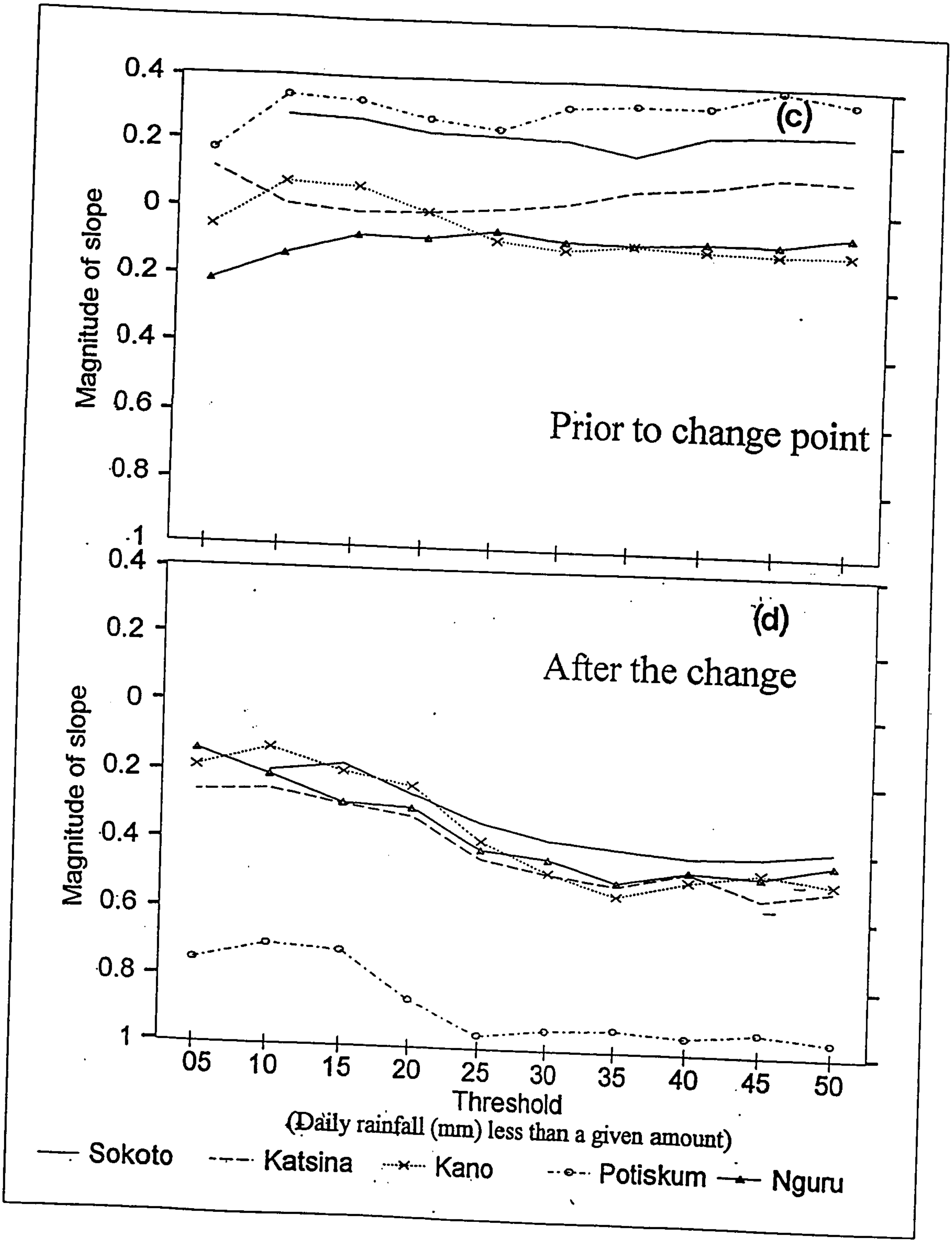

(c)
Prior to change point
(d)
After the change
Magnitude of slope
0.4
0.2
0
0.2
0.4
0.6
0.8
1
05
10
15
20
25
30
35
40
45
50
Threshold
(Daily rainfall (mm) less than a given amount)
Sokoto
Katsina
Kano
Potiskum
Nguru

Table 3.1 The magnitude of trends in annual rainfall and number of rain days for sub periods defined by SCP and CNP

		Annual rainfall		Number of raindays	
Location	Period(1)	SCP	CNP	SCP	CNP
Sokoto	P	3.10	2.63	0.28 **	0.41 **
	A	-2.27	-4.78 *	-0.41 *	-0.58 **
Katsina	P	2.55	2.22	0.06	0.12
	A	-2.51	-8.59 **	-0.48 *	-0.68 **
Kano	P	-0.09	-1.35	-0.07	-0.07
	A	-5.15	-7.30 *	-0.47	-0.49 **
Nguru	P	-0.55	2.37	-0.09	0.10
	A	-5.01*	-8.18 **	-0.48 **	-0.63 **
Potiskum	P	3.56	3.90	0.12	0.31
	A	0.38	-7.62 *	-0.91 **	-0.87 **
Maiduguri	P	1.62	2.88	0.36 **	0.37 *
	A	-5.00	-8.18 **	-0.51 *	-0.90 **
Yelwa	P	12.49 **	18.08 **	-0.04	0.21
	A	-2.62	-8.58 **	-0.03	-0.6 **
Zaria	P	0.65	1.13	-0.14	-0.07
	A	-2.81	-6.21 *	-0.16	-0.27
Kaduna	P	(2)	2.49	-0.15	-0.18
	A	(2)	-5.37 *	-0.33	-0.67 **
Bauchi	P	-1.06	-0.98	0.18	0.23
	A	-6.12	-6.76 *	-0.23	-0.31 *

Note: (1) P and A refer to the period prior to and after the jump
(2) No significant change point
* Significant at 0.05, ** Significant at 0.01

Table 3.2 The magnitude of jump in rainfall variables

	Total rainfall		No. Of Rain days		Starting date		Ending date		Duration	
Station	SCP	CNP	SCP	CNP	SCP	CNP(1)	SCP	CNP(1)	SCP	CNP(1)
Sokoto	0.79	0.81	0.82	0.87	1.02	1.00	1.00	1.00	0.98	1.00
Katsina	0.75	0.82	0.77	0.82	0.99	1.03	1.01	1.01	1.02	0.98
Kano	0.80	0.83	0.85	0.85	0.98	0.99	0.99	0.99	1.00	0.98
Nguru	0.72	0.77	0.71	0.76	0.99	1.00	0.99	0.98	0.99	0.96
Potiskum	0.76	0.83	0.77	0.85	1.00	1.02	0.99	0.99	0.97	0.95
Maiduguri	0.79	0.87	0.75	0.88	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Yelwa	0.88	0.95	0.81	0.91	1.05	1.00	0.95	0.97	0.96	0.94
Zaria	0.86	0.89	0.88	0.89	1.01	1.02	0.98	0.98	0.96	0.95
Kaduna	(2)	0.95	0.84	0.92	1.06	1.03	0.98	0.99	0.94	0.97
Bauchi	0.87	0.89	0.90	0.91	1.03	1.01	0.98	0.99	0.96	0.97

Note: n.d. No data

(1) The year when a change point occurred in the "no. of rain days" is used to segment the series of starting, ending date and duration of rainy season.

(2) No significant change point

Table 3.3 Occurrence of change point in (a) total monthly rainfall and (b) monthly number of rain days

(a)

	Sokoto	Katsina	Kano	Nguru	Pot	Maid	Yelwa	Zaria	Kaduna	Bauchi
Jun	-	-	-	-	-	+	-	-	-	-
Jul	-	-	-	-	-	-	+	+	-	-
Aug	- 1967	- 1971	- 1966	- 1967/8	- 1964	- 1961	-	-	+	-
Sep	- 1967	- 1967	- 1962	- 1964	- 1964	- 1967	- 1972	- 1967	-	-

(b)

	Sokoto	Katsina	Kano	Nguru	Pot	Maid	Yelwa	Zaria	Kaduna	Bauchi
Jun	-	-	-	-	- 1969	-	-	-	- 1969	-
Jul	-	- 1970	-	-	-	-	-	-	-	-
Aug	- 1965	- 1971	- 1959	- 1968	- 1972	- 1971	-	-	-	-
Sep	- 1967	- 1962	- 1967	- 1970	- 1976	- 1967	- 1971	- 1967	- 1975	-

Note: Negative or positive signs indicate the direction of trend. The years indicate that the change point is significant at 5% probability level.

Table 3.4 Relative magnitude of jumps in total rainfall and number of rain days for August and September expressed as a ratio of the mean after the jump to the mean prior to the jump.

Station	Total rainfall				Number of rain days			
	August		September		August		September	
	SCP	CNP	SCP	CNP	SCP	CNP	SCP	CNP
Sokoto	0.72	0.72	0.60	0.65	0.75	0.83	0.64	0.78
Katsina	0.71	0.84	0.74	0.75	0.81	0.87	0.67	0.68
Kano	0.75	0.80	0.71	0.74	0.83	0.84	0.73	0.73
Nguru	0.65	0.72	0.55	0.58	0.79	0.81	0.63	0.63
Potiskum	0.77	0.84	0.67	0.71	0.76	0.91	0.60	0.75
Maiduguri	0.75	0.95	0.84	0.81	0.71	1.02	0.70	0.57
Yelwa	n.s.	n.s.	0.73	0.83	n.s.	n.s.	0.78	0.87
Zaria	n.s.	n.s.	0.62	0.69	n.s.	n.s.	0.71	0.77
Kaduna	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.81	0.89
Bauchi	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Note: n.s. indicates no change point occurred in SCP and no ratio is calculated

Table 3.5 Magnitude of trend in total rainfall (mm/yr) and number of rain days (d/yr) in August and September prior to and after the occurrence of a change point.

Station		Total rainfall				Number of rain days			
		August		September		August		September	
	Period$^{(1)}$	SCP	CNP	SCP	CNP	SCP	CNP	SCP	CNP
Sokoto	P	-0.09	1.86	-0.46	-0.08	0.09	0.09	0.04	0.05
	A	-1.87	-2.05	0.18	-1.27	-0.05	-0.17**	-0.02	-0.14*
Katsina	P	1.48	2.98	-0.65	-0.50	0.03	0.05	0.03	0.04
	A	-0.67	-4.48**	-0.65	-1.03	-0.03	-0.20**	-0.13**	-0.16**
Kano	P	-0.19	-0.21	-0.74	-1.20	-0.02	-0.04	-0.03	-0.04
	A	0.98	-2.10	-0.84	-1.42	-0.10	-0.11	-0.10	-0.16*
Nguru	P	-2.34*	-3.37	-1.16	-1.23	-0.03	-0.08	-0.08	0.02
	A	-1.66	-3.20*	-0.78	-1.28	-0.07	-0.19**	-0.13	-0.13**
Potiskum	P	3.52*	3.52	0.09	0.02	0.15*	0.33*	-0.01	0.09
	A	-1.86	-3.58	-1.07	-1.87*	-0.16	-0.26**	-0.10	-0.17*
Maiduguri	P	0.77	1.10	-0.28	-1.85	0.04	0.10	0.04	0.08
	A	-1.89	-5.32**	-5.78	-2.50*	-0.14	-0.25**	-0.11	-0.18**
Yelwa	P	n.s.	n.s.	-0.07	3.05	n.s.	n.s.	0.02	0.04
	A	n.s.	n.s.	2.09	-3.67	n.s.	n.s.	-0.23	-0.28**
Zaria	P	n.s.	n.s.	2.66	6.33	n.s.	n.s.	-0.07	-0.05
	A	n.s.	n.s.	0.63	-3.98	n.s.	n.s.	-0.01	-0.13
Kaduna	P	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	-0.02	0.02
	A	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	-0.05	-0.15**
Bauchi	P	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	A	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Note: (1) P and A refer to the period prior to and after the jump

n.s. indicates that no change point occurred in SCP and no trends were calculated. The trend value for CNP is also omitted.

* Significant at 0.05, ** Significant at 0.01

CHAPTER FOUR

Variability in rainfall characteristics in northern Nigeria

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Abstract

Variability in the characteristics of rainfall in semi-arid West Africa can amplify the risk of droughts and impose constraints on the reliability of rainfall. This paper examines the temporal distribution of the variations in seven series of rainfall variables in northern Nigeria. The series include total rainfall, number of rain days, the dates of onset, termination and duration of the rainy season as well as five thresholds of daily rainfall amounts (5 mm, 10 mm, ..., 25 mm). Variables showing statistically significant change points are segmented into two sub-series, representing the periods before and after the change point. The detrended variables for both periods are found to be independent and normally distributed. Kolmogorov-Smirnov tests show no significant differences in the distributions before and after the change points. Illustrative practical applications of the results are presented.

4.1.0 Introduction

A large part of northern Nigeria is semi-arid and subject to year to year fluctuations in rainfall characteristics. High variability implies uncertainty in the timing and availability of water and is a major concern particularly in the Sudan and Sahel savanna where natural and agricultural systems are sensitive to small variations (Oladipo, 1995). These areas are economically important, being the principal cereal, groundnuts, cotton and livestock producing zone for the country. However, the brevity of the rainy season, together with inflexibility of the agricultural practices leave little room for remedial measures should deviations from an expected rainfall norm occur. Thus, there is a need to study the variability of rainfall characteristics as a contribution towards the assessment of drought risks.

Apart from practical applications, this study is timely in light of the improving rainfall situation in the Sahel. By the close of the last decade many researchers believed that the observed changes in the Sahelian rainfall were irreversible and marked a major change in the climate. The continuing recovery of the rainfall highlights the dominance of short and sustained variability on the rainfall characteristics and suggests the need for more information at different scales (Tarhule and Woo, 1997).

In a companion paper, Tarhule and Woo (submitted) identified points of step change in the various rainfall variables and showed that the periods preceding, and following, the occurrence of the change points are homogenous. Comparable results were obtained by Demaree (1990) in Mauritania. However, the distribution of the variations in the sub-periods is unknown. This paper has two objectives: to describe and compare the variability in sub-periods of several rainfall characteristics using suitable probability distributions and to demonstrate a simple method for estimating the probabilities associated with fluctuations of given magnitudes.

Previous studies of rainfall variability and fluctuations in Nigeria tended to emphasize periodicities or the occurrence of cycles (e.g. Adejuwon et al., 1990; Anyadike, 1993; Olaniran, 1991; Olaniran and Sumner, 1990). On the other hand, due to the occurrence of change points in rainfall series, Demaree (1990) and Snijders (1986) questioned whether the mechanisms responsible for the cycles in the past are at present operating in the same way and with the same effect. Moreover, knowledge concerning periodicities is of limited practical use for farmers and planners who face day to day management decisions.

4.2.0 Methods

Tarhule and Woo (submitted) described the procedures for the determination of change points and the magnitude of trends in the series of several rainfall variables, viz. annual rainfall, number of rain days, starting, ending, and duration of rainy season as well as cumulative rainfall totals at various truncation levels (5, 10, ..., 25 mm/d of rainfall) in northern Nigeria. The present paper focuses on the determination of the distribution of the variations. Where a change point occurs, the sub-periods are first analyzed separately. For each series y_i, i=1,2,..N with N being the length of record, the estimated values, $\hat{y}_i$, are obtained from simple linear regression and subtracted from the observed values to yield a series of residuals y'_i or variations around the trend line. The residuals with mean and slope both equal to zero are tested for autocorelation (Matalas, 1967) and for normality using both non-parametric (Lilliefors) and parametric (Chi-squared) tests. To apply the Lilliefors test, the $y_1, y_2 ... y_N$ values are standardized as $z_i = (y_i - \bar{y}) / s$ where $\bar{y}$ is mean and s is standard deviation. The distribution of Z is compared to the standardized normal distribution by means of a Kolmogorov-type statistic defined as:

$$L = \max\left|P(Z < z_i) - \hat{P}(Z < z_i)\right| \tag{4.1}$$

where $\hat{P}$ denotes the cumulative probability of the standardized normal distribution and P is the cumulative relative frequency for the observed distribution. The hypothesis of normality is rejected if $L > L_{N:1-\alpha}$, where α is the desired level of significance.

The magnitude of variability is expressed as the absolute value of the residuals ($x_i = |y_i'|$) and the X series is examined for trends using the non-parametric Mann-Kendall τ statistic. Thus transformed, significant positive or negative trends would indicate increasing or decreasing variability. For each x_i, the number of subsequent terms in the series $x_{i+1} ... x_N$ whose values exceed x_i are counted and denoted as n_i. Then, the τ statistic is obtained by

$$\tau = \frac{4\sum_{i=1}^{N-1} n_i}{N(N-1)} - 1 \tag{4.2}$$

and compared with the theoretical value of the t-distribution for any desired probability level α:

$$(\tau)_t = \pm t_\alpha \sqrt{\frac{4N+10}{9N(N-1)}} \tag{4.3}$$

The mean and range of variation are also calculated.

Differences in the residuals between the period prior to, Pc, and after, Ac, the change point are tested using the F-test. The Kolmogorov-Smirnov test is applied again with the null hypothesis that the distributions of residuals in the sub-periods are identical. The critical value for the test is :

$$KS_{N_1,N_2:\alpha} > C_\alpha \sqrt{\frac{N_1+N_2}{N_1N_2}} \tag{4.4}$$

where N_1 and N_2 are the lengths of Pc and Ac. The constant C is a large sample approximation which is related to the desired probability level α. For $\alpha = 0.05$, C=1.36 (Marascuilo and McSweeney, 1977). Where the null hypothesis is not rejected, the two sub-periods are combined and the normal distribution is again applied to the series. The pertinent parameters are estimated by the method of probability weighted moments and the root mean squared error for the goodness of fit is calculated.

4.3.0 Data and study area

Daily rainfall records at 10 gauging stations (record length 48-60 years) located north of 10.5°N in Nigeria (Fig. 4.1) were obtained from the Federal Department of Meteorological Services, Oshodi. The region encompasses the Sahel and Sudan savanna belts as well as a small part of the Guinea savanna. It has been shown by various authors to be highly susceptible to droughts and wide fluctuations in rainfall (Anyadike, 1993; Oladipo, 1995; Olaniran, 1991). Like the rest of West Africa, the rainfall patterns over the region are controlled by the seasonal migration of the Inter Tropical Discontinuity (ITD), itself driven by the pressure gradient between the Sahara and the St. Helena subtropical high in the South Atlantic. The arrival of the ITD in the Sudan savanna at about April/May heralds the beginning of the rainy season. Initially, the rain which comes in short, intense bursts is highly irregular, giving rise to high variability in the onset of the season. By July/August, the ITD is fully entrenched over the region and the rain producing synoptic processes (notably line squalls, easterly waves and vortices) become more organized to yield higher and relatively more regular rainfall. The rainy season ends abruptly in September/October as the ITD retreats southwards.

4.4.0 Results

Annual rainfall and number of rain days exhibit step changes (Fig. 4.2), with the jumps occurring between 1962 and 1970. Although not generally coincident, the difference is of the order of one to two years at each station except at Potiskum and Maiduguri where it reaches four and six years respectively (Fig. 4.1). The detrended series in Figure 4.2 are composites of the sub-periods Pc and Ac which were detrended separately. For annual rainfall and number of rain days, the variations range from -400 to +400 mm and from -20 to +20 days. The extremal values occur during periods of extreme wetness or dryness, such as the above-average rainfall during the 1950's and the droughts of 1941-44, 1973 and 1982/83. On the other hand, the ranges of variations for starting and ending days and the duration of the rainy season are, respectively, -36 to +43, -29 to +35 and -43 to +41 days. At 9 of the 10 locations, the range in starting day exceeds the ending day by between 7 and 28 days, indicating greater variability in the starting date of the rainy season (see also Hess et al., 1995).

The absolute values of the residuals show no statistically significant trends at the 1% probability level, suggesting that the variations around the trend lines are stationary. Sample values of the τ statistic at four representative locations are given in Table 4.1. τ-values for the absolute annual rainfall and rain day residuals are calculated separately for the sub-periods as well as for the combined periods. Only the results for the combined periods are provided in Table 4.1. The mean and range of variation in the rainfall and number of rain days for sub-period Ac and the dates of onset, termination as well as the duration of rainy season appear in Figure 4.3. The variations in total annual rainfall over northern Nigeria is about 100 mm. The apparent uniformity of the mean is deceiving; when expressed as a ratio of the mean of the raw values, there is some differentiation between the five Sahelian locations (Sokoto, Katsina, Nguru, Potiskum and Maiduguri) and the locations in the Sudan and Guinea savanna belts (Kano, Yelwa, Zaria, Kaduna and Bauchi). In the former, the ratio for the means is approximately 0.19 compared to 0.10 in the Sudan savanna. Similarly, the ratios for the range are generally > 0.50 in the Sahel compared to about 0.37 in the Sudan. Such spatial differentiation was also noted by

Tarhule and Woo (submitted) who observed that rainfall variability can be used as an index to define sub-regions for agricultural planning and drought risk assessment. Considering the rain days, mean variation over northern Nigeria is remarkably uniform at about nine days while the range varies from 29 to 44 days. The uniformity is maintained even when the values are standardized, indicating that the changes in the number of rain days are more uniform and widespread over the region. The variations in aspects of the season (onset, termination and duration) are also similar. Deserving special mention is the mean variation in the starting date which is exactly 12 days at all locations except at Sokoto where it is 13 days.

The first-order autocorrelation test on the residuals for sub-periods Pc, Ac and the combined series shows no significant correlation at the 5% probability level and examination of the correlograms reveals no cyclic tendencies (Fig. 4.4). Similarly, the F-test finds no significant differences in the variance of the residuals of periods Pc and Ac. The hypothesis of normality cannot be rejected at the 5% probability level for all series based on the results of both the Chi-square and the Lilliefors tests. Thus, the residuals may be considered to be random, independent, and identically distributed. Summary statistics of the residuals at Kano are shown in Table 4.2.

The observed and theoretical distribution of the variations for sub-periods Pc, Ac, and for the combined periods are shown in Figure 4.5, as are the parameters of the distributions and the regression coefficients of the trend lines for the raw series. There are no regression coefficients for the combined series since a single trend line is not acceptable. There is excellent agreement between the fitted and the observed distributions, with the combined series offering the least root mean square errors (and therefore the best fit) followed by the Ac period. Conversely, period Pc provides the largest standard deviations and root mean square errors. The reason is that the period prior to the change point comprised three distinct decades in terms of total rainfall: average rainfall (1931-1940), below average (1941-1950) and above average (1951-60), giving rise to larger deviations from linearity. In contrast, the period after the change point was characterized by generally low annual rainfall hence the lower variations. The fitted and observed distributions of the date of onset, termination and duration of the rainy season are presented in Figure 4.6.

Several levels of daily rainfall are critical for different agricultural activities. Hence, the variations in five rainfall thresholds (5 mm/d, 10 mm/d, ..., 25 mm/d) were analyzed. According to Tarhule and Woo (submitted), the assumption of homogeneity in sub-series Pc and Ac is no longer valid at thresholds greater than 25 mm/d. The parameters of the normal distributions fitted to the variations at the various thresholds are presented in Table 4.3. Again, period Pc provides the largest standard deviations and root mean square errors although all the fits are considered excellent.

4.5.0 Application of results

Utilizing the information obtained and the coefficients of the linear trends, it is possible to estimate the probabilities associated with various magnitudes of variability in the different rainfall characteristics. As an illustration, it is desired to estimate the probability that the annual rainfall at Sokoto for 1991 will be (1) $\leq$ 500 mm, (2) > 800 mm and (3) between 500 and 800 mm. To do so, one first evaluates the value of the trend line at time T (1991) using the linear relationship

$$\hat{y}(t) = a + bT \tag{4.5}$$

For Sokoto, this yields 561 mm (see Fig 4.5; Sokoto, Ac). Then $P(R \leq 500 \text{ mm})$ is equivalent to $P(R' \leq -61 \text{ mm})$ which can be read directly from Figure 4.5 as 0.31. Alternatively, the parameters in Figure 4.5 (Sokoto, Ac) can be used to calculate the standardized variation as -0.492 and the cumulative probability is 0.31. Similarly, $P(R>800 \text{ mm}) \cong P(R'>+239 \text{ mm})$ or $1-P(R' \leq +239 \text{ mm})$ which is found from Figure 4.5 to be 0.023. Finally, $P(500\text{mm} \geq R \leq 800 \text{ mm}) = 0.67$. The measured annual rainfall was 793 mm.

As another example, a similar procedure yields the probability that the rainy season at Sokoto starting on or before Julian day 120 (April 30) is 0.15 and the probability that it starts after Julian day 150 (May 30) is 0.21. Thus, the probability that it will begin in May is 0.64. For 1991, the rainy season started on Julian day 133 (May 13).

Similar analysis may be performed on monthly rainfall series or other suitable time scale provided that the residuals are independent and normally distributed. It should be noted that because the residuals are obtained as variations around the trend lines, failure to identify a change point in the trends could lead to erroneous assumptions regarding their distribution.

4.6.0 Discussion and conclusion

Variability is an important attribute of rainfall in semi-arid West Africa because of the risk of droughts and the constraint it imposes on rainfall reliability. The foregoing analysis indicates that despite the dramatic changes in rainfall characteristics (notably total rainfall and number of rain days) in northern Nigeria between 1931-1990, the variations around the general trend lines remained unchanged. The results therefore suggest homogeneity of the detrended residual series when the occurrence of a change point is taken into account, further supporting the need for proper identification of change points. Evidence from several studies (Hess at al, 1995; Olaniran, 1991) suggests that the changes in the rainfall over the region have been driven largely by a reduction in the number of rain days of moderate to high daily intensity during the peak rainy period (July, August, September). Other aspects of the rainy season such as the onset, termination and duration remained unchanged. Since the changes affected a certain rainfall category each year, the effect was, perhaps, akin to the removal of a constant from each years' total rainfall so that the variation over time remained unchanged.

The study demonstrates that the variations in all the residuals are adequately described by the normal distribution. The method of fitting distributions has often been criticized for the lack of theoretical support. However, the approach is easy to use and has strong practical applications.

Our findings contribute to the status of knowledge concerning recent changes in rainfall over northern Nigeria and indicates that simple analysis of the variability can provide important preliminary information for agriculture and water resources planning. The approach proposed may be applied to other regions in the West African Sahel with similar climatic experience. While the processes generating such changes remain unclear, increased information on the empirical manifestations such as presented in this and other studies may better prepare the region for future occurrences.

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List of Figures

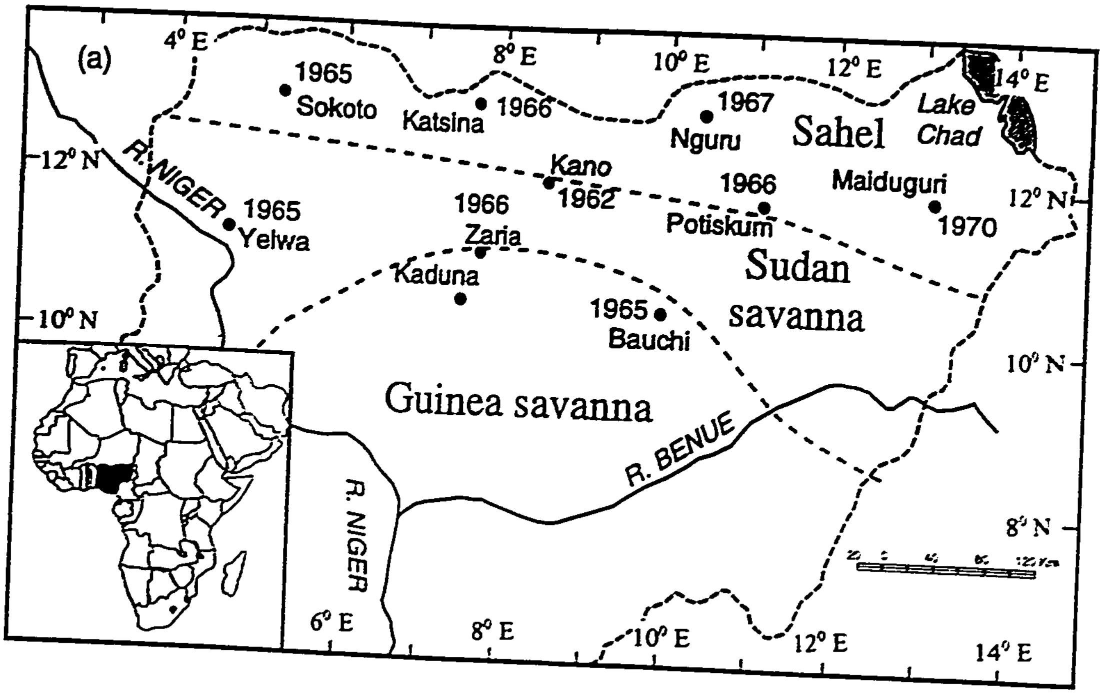
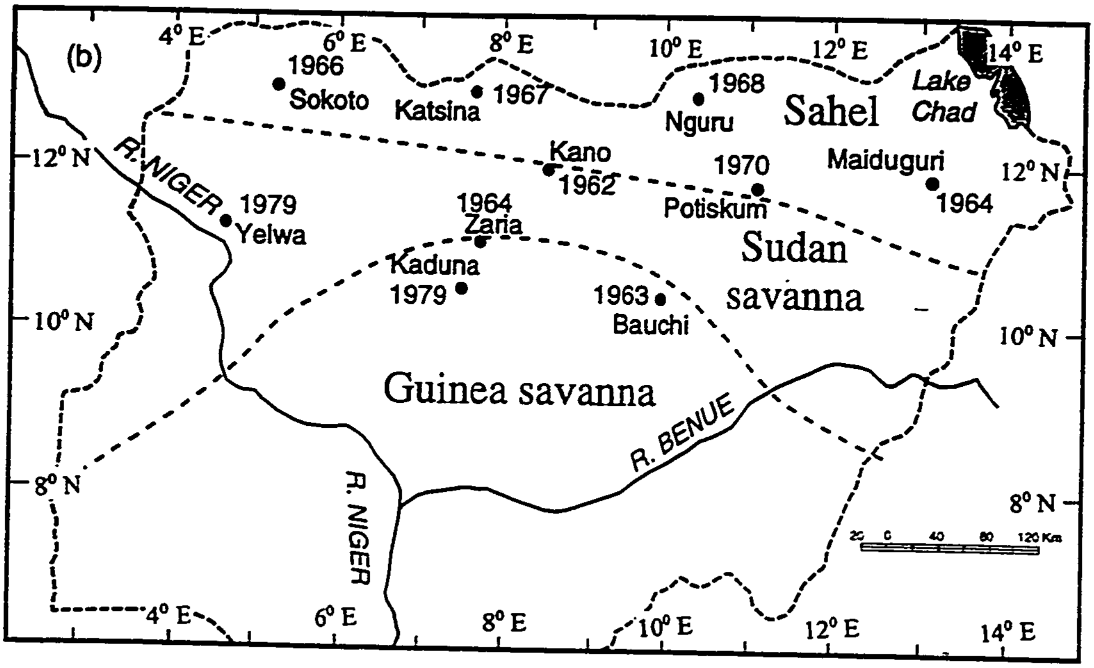


Figure 4.1 Study area in northern Nigeria showing the major climatic belts and the years when change points occurred in (a) annual rainfall and (b) number of rain days.


(b)
4° E
6° E
8° E
10° E
12° E
14° E
1966
Sokoto
Katsina
1967
1968
Nguru
Sahel
Lake Chad
12° N
R. NIGER
Kano
1962
1970
Maiduguri
1979
Yelwa
1964
Zaria
Potiskum
1964
Sudan savanna
Kaduna
1979
1963
Bauchi
10° N
Guinea savanna
R. BENUE
8° N
R. NIGER
20 0 40 80 120 Km

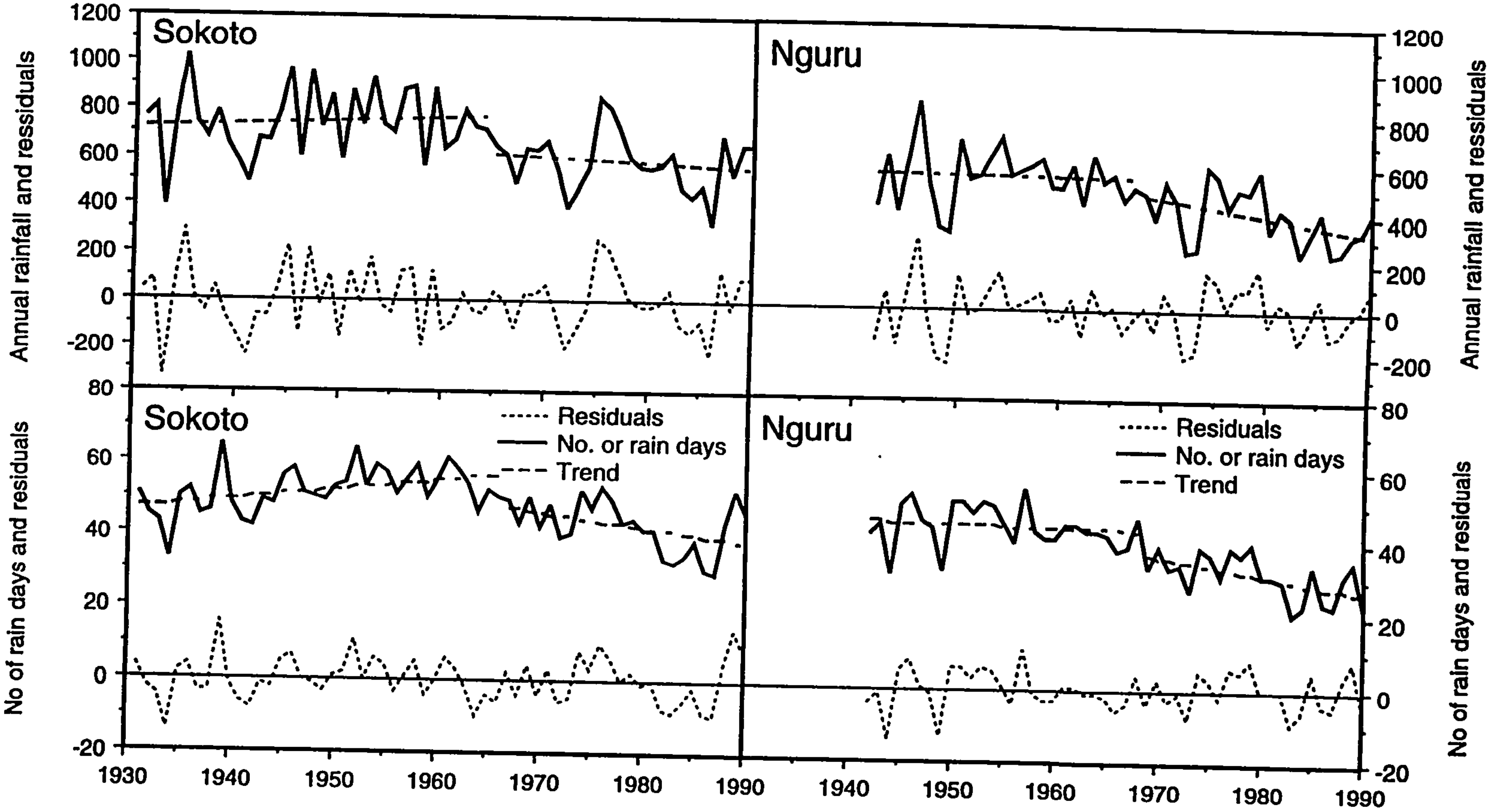
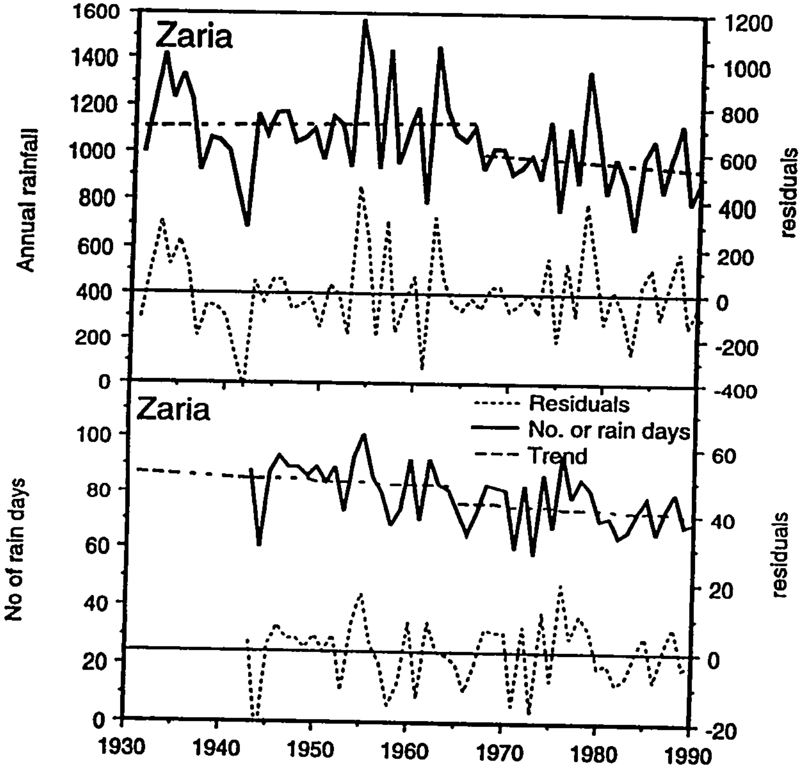
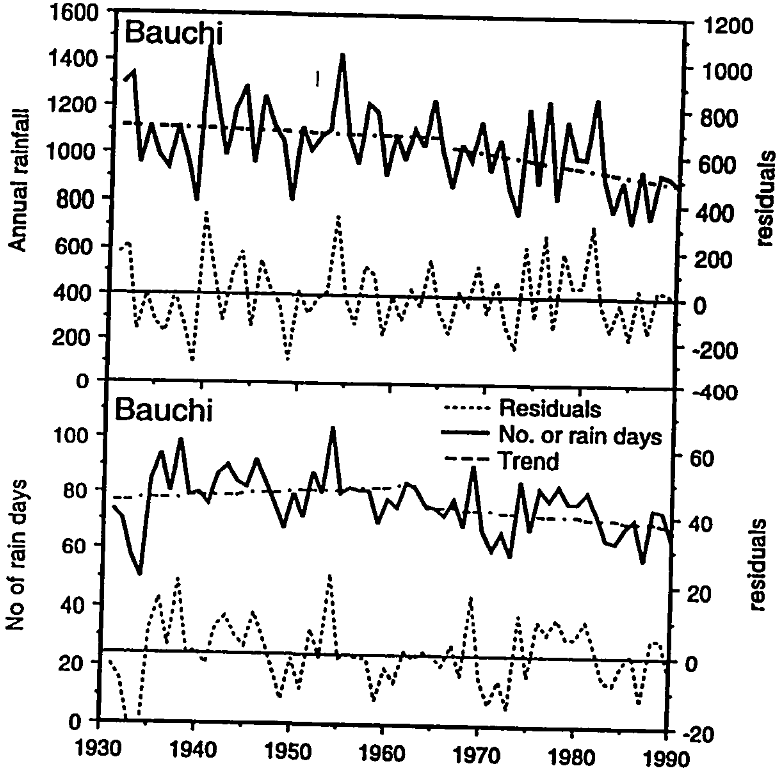


Figure 4.2 Raw and detrended series of annual rainfall and number of rain days at Sokoto, Nguru, Zaria and Bauchi. Thick lines represent the fitted linear trends.


Zaria
Annual rainfall
1600
1400
1200
1000
800
600
400
200
0
residuals
1200
1000
800
600
400
200
0
-200
-400
Zaria
Residuals
No. or rain days
Trend
No of rain days
100
80
60
40
20
0
residuals
60
40
20
0
-20
1930
1940
1950
1960
1970
1980
1990


Bauchi
Annual rainfall
1600
1400
1200
1000
800
600
400
200
0
residuals
1200
1000
800
600
400
200
0
-200
-400
Bauchi
Residuals
No. or rain days
Trend
No of rain days
100
80
60
40
20
0
residuals
60
40
20
0
-20
1930
1940
1950
1960
1970
1980
1990

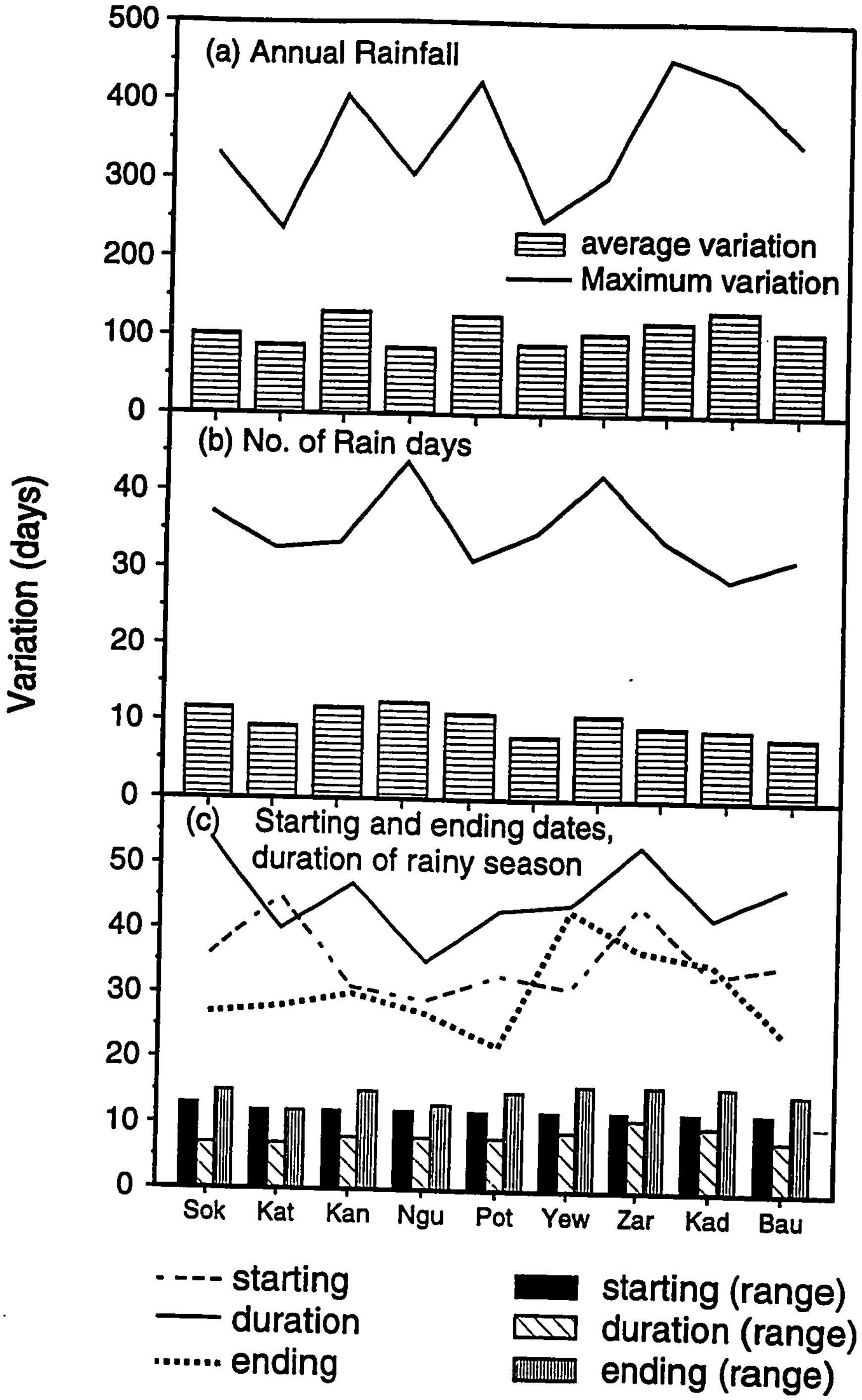


Figure 4.3 Mean and range of absolute variations for the period after the change point: (a) annual rainfall, (b) number of rain days and (c) starting, ending and duration of rainy season. Sok=Sokoto, Kat=Katsina, Kan=Kano, Ngu=Nguru, Pot=Potiskum, Mad=Maiduguri, Yew=Yelwa, Zar=Zaria, Kad=Kaduna, Bau=Bauchi

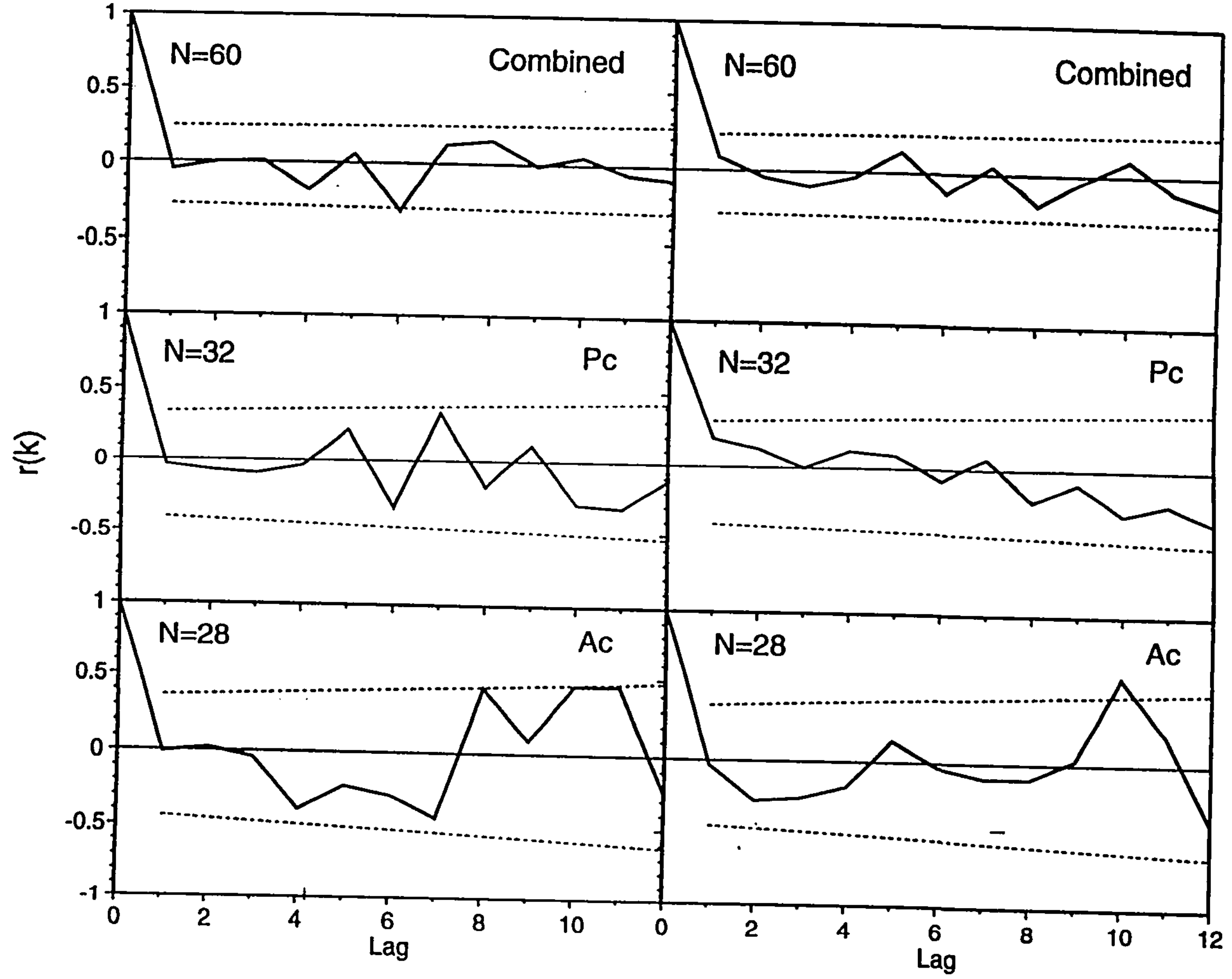


Figure 4.4 Correlograms of variations in annual rainfall (left panel) and the number of rain days (right panel) at Kano for Pc, Ac and the combined series. The dotted lines show confidence limits at 5% probability level.

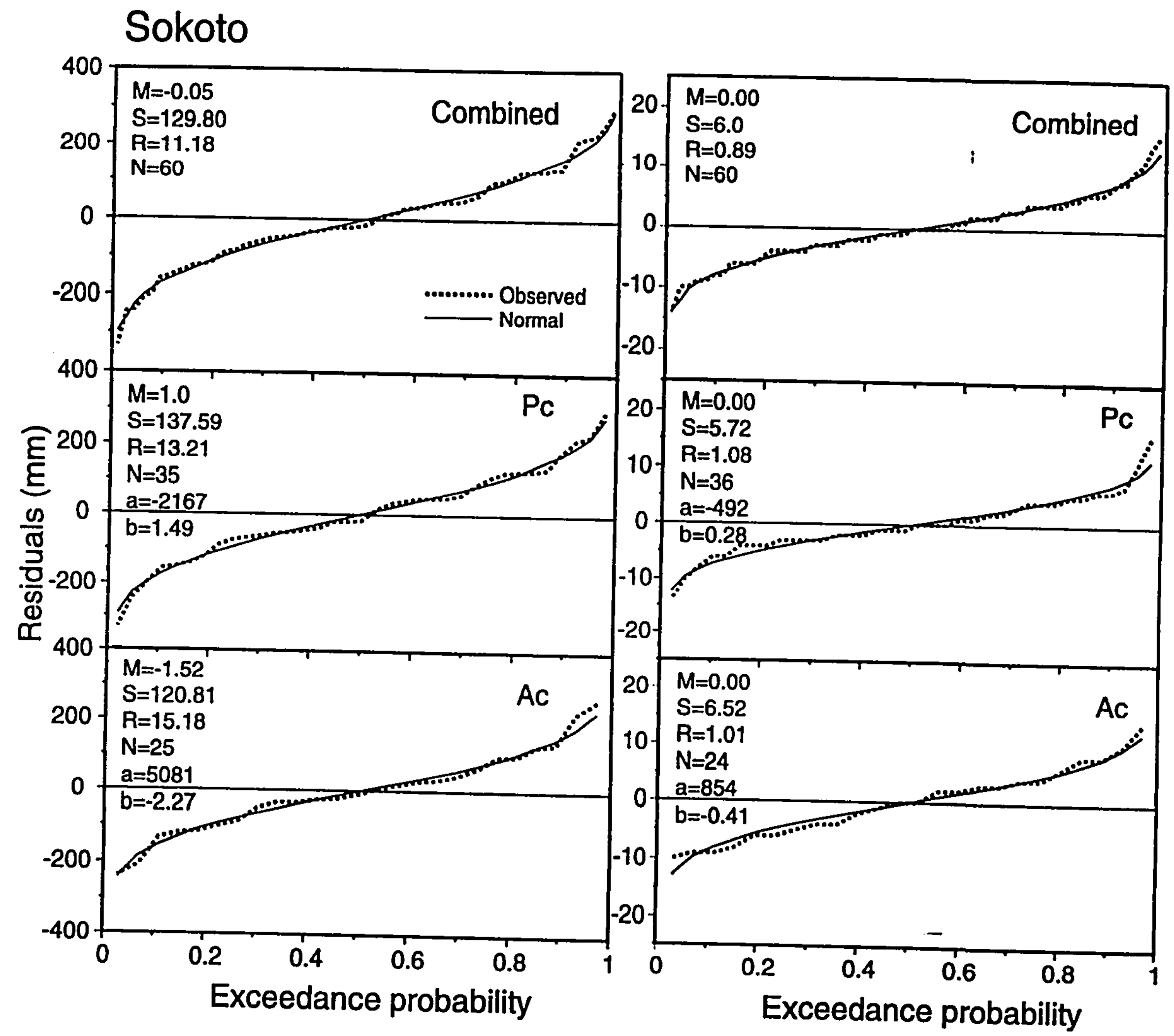
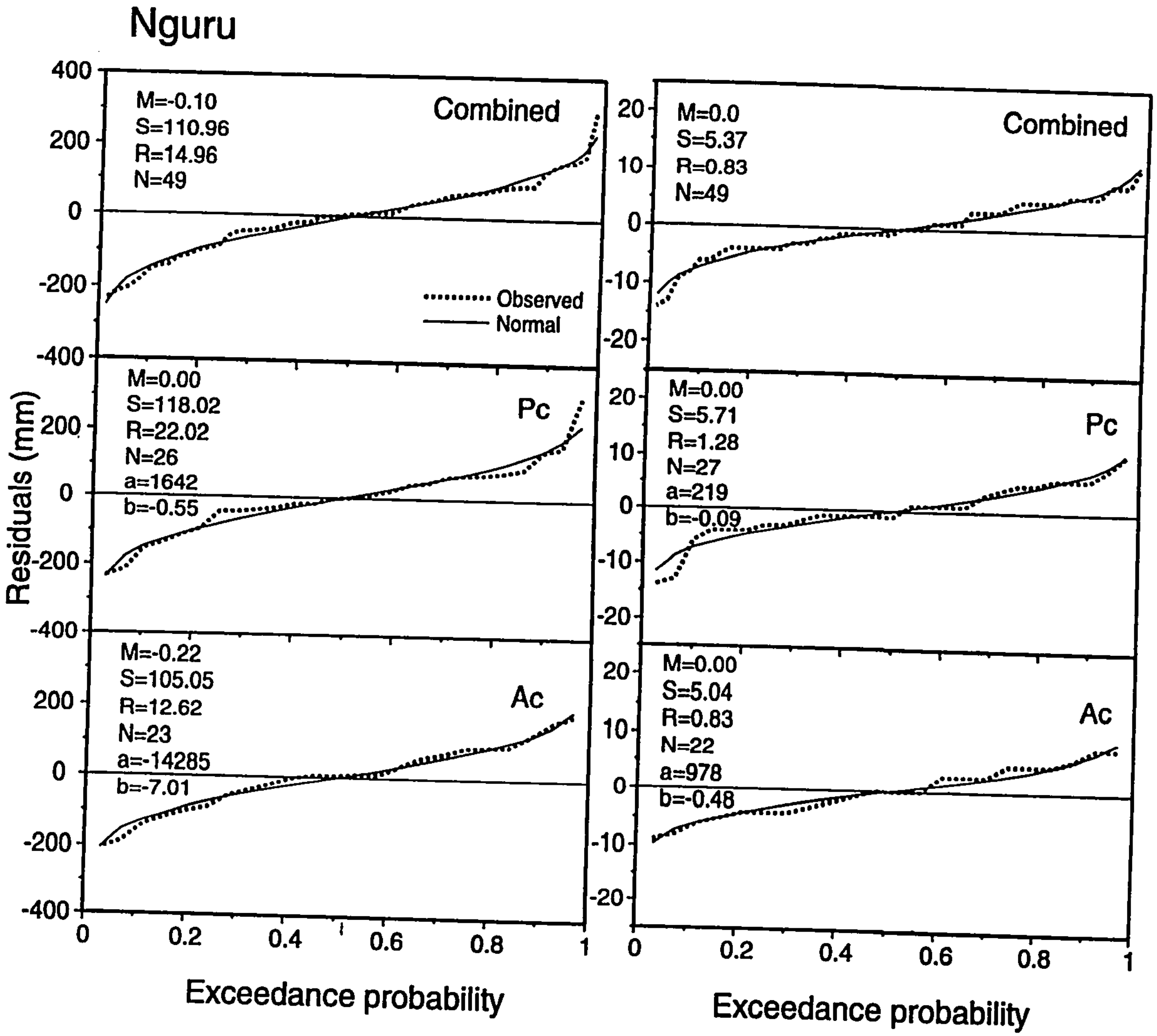
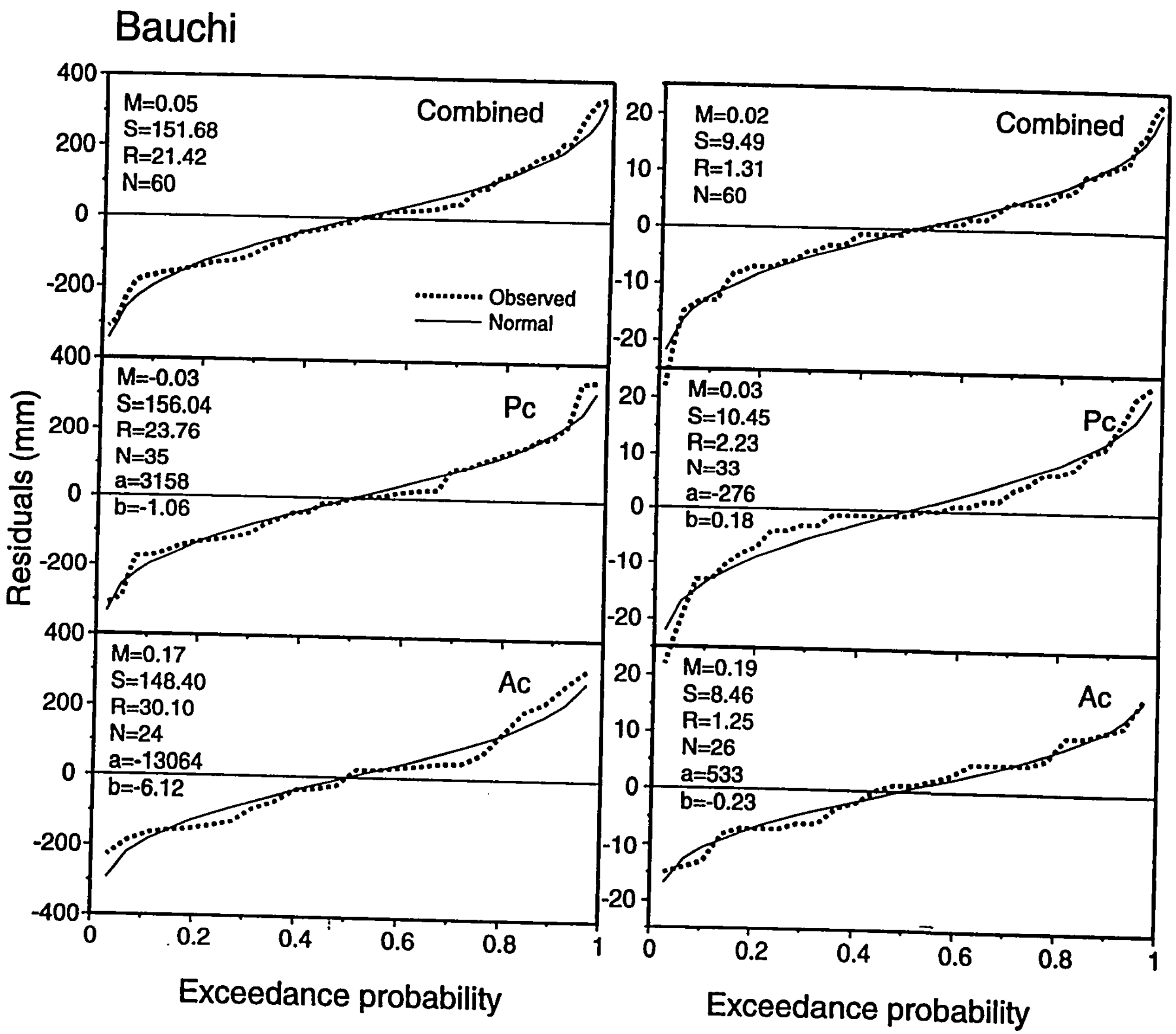


Figure 4.5 Observed and theoretical normal distribution of the variations in annual rainfall and number of rain days at Sokoto, Nguru, and Bauchi for Pc, Ac and the combined series. M=Mean, S=Standard deviation, R=Root mean square error, N=length of record, a,b = intercept and slope of the fitted linear trends (see eq. 5).


Nguru
Combined
M=-0.10
S=110.96
R=14.96
N=49
Observed
Normal
Pc
M=0.00
S=118.02
R=22.02
N=26
a=1642
b=-0.55
Ac
M=-0.22
S=105.05
R=12.62
N=23
a=-14285
b=-7.01
Residuals (mm)
400
200
0
-200
-400
0
0.2
0.4
0.6
0.8
1
Exceedance probability
Combined
M=0.0
S=5.37
R=0.83
N=49
Pc
M=0.00
S=5.71
R=1.28
N=27
a=219
b=-0.09
Ac
M=0.00
S=5.04
R=0.83
N=22
a=978
b=-0.48
20
10
0
-10
-20
Exceedance probability


Bauchi
Residuals (mm)
M=0.05
S=151.68
R=21.42
N=60
Combined
Observed
Normal
M=-0.03
S=156.04
R=23.76
N=35
a=3158
b=-1.06
Pc
M=0.17
S=148.40
R=30.10
N=24
a=-13064
b=-6.12
Ac
400
200
0
-200
400
200
0
-200
400
200
0
-200
-400
0
0.2
0.4
0.6
0.8
1
Exceedance probability
M=0.02
S=9.49
R=1.31
N=60
Combined
M=0.03
S=10.45
R=2.23
N=33
a=-276
b=0.18
Pc
M=0.19
S=8.46
R=1.25
N=26
a=533
b=-0.23
Ac
20
10
0
-10
-20
20
10
0
-10
-20
20
10
0
-10
-20
0
0.2
0.4
0.6
0.8
1
Exceedance probability

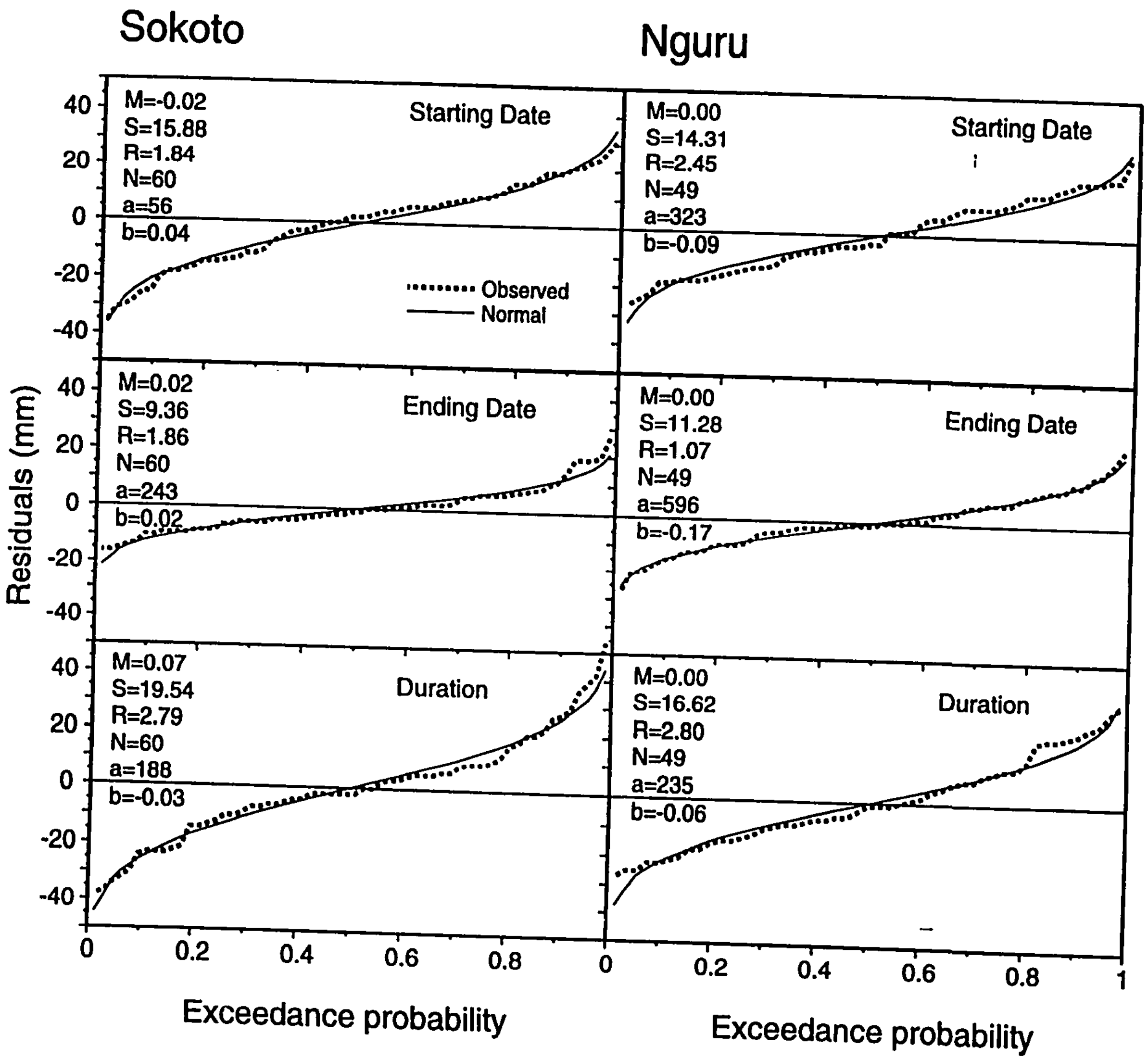


Figure 4.6 Observed and theoretical normal distribution of the variations in the starting, ending and duration of season at Sokoto, Nguru, Zaria and Bauchi. M=Mean, S=Standard deviation, R=Root mean square error, N=length of record, a,b = intercept and slope of the fitted linear trends

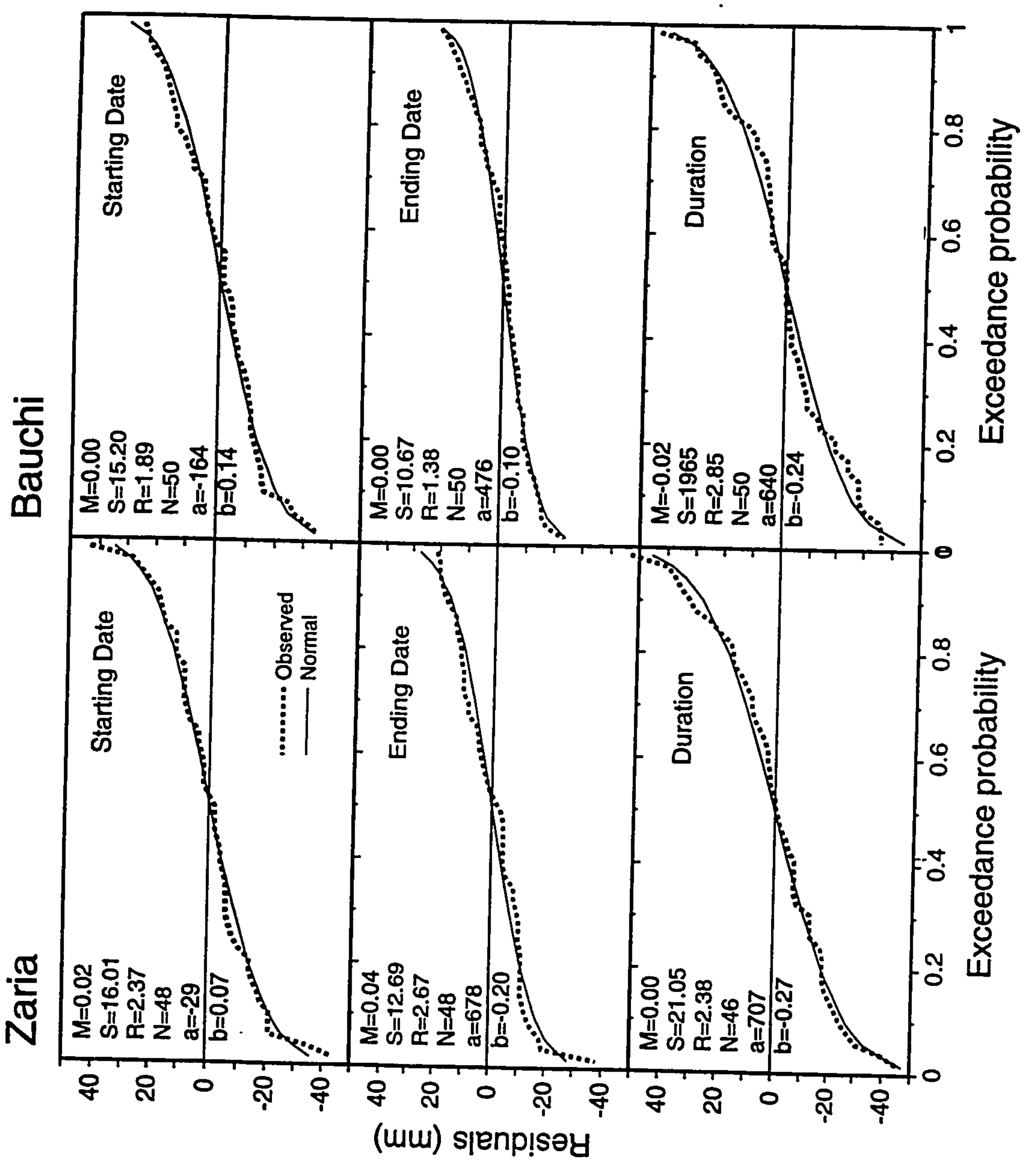

Zaria
Bauchi
Residuals (mm)
40
20
0
-20
-40
Starting Date
Ending Date
Duration
M=0.02
S=16.01
R=2.37
N=48
a=-29
b=0.07
M=0.04
S=12.69
R=2.67
N=48
a=678
b=-0.20
M=0.00
S=21.05
R=2.38
N=46
a=707
b=-0.27
M=0.00
S=15.20
R=1.89
N=50
a=-164
b=0.14
M=0.00
S=10.67
R=1.38
N=50
a=476
b=-0.10
M=-0.02
S=19.65
R=2.85
N=50
a=640
b=-0.24
Observed
Normal
0
0.2
0.4
0.6
0.8
1
Exceedance probability
Exceedance probability

Table 4.1 τ-values for absolute residuals at four representative locations.

	Rainfall	No. of rain days	Starting date	Ending date	Duration
Sokoto	-0.092	0.033	-0.025	-0.025	0.058
Nguru	-0.109	-0.119	-0.072	0.059	0.000
Zaria	0.116	-0.031	-0.077	-0.042	-0.086
Bauchi	0.018	-0.009	-0.017	-0.100	-0.017

Table 4.2 Summary statistics of residuals of rainfall characteristics at Kano.

	Rainfall (mm/a)		No. of rain days		Starting date	Ending date	Duratio
	Pc	Ac	Pc	Ac			
Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Standard error	30.23	28.82	1.32	1.38	1.88	1.38	2.40
Median	-40.04	-17.27	-1.96	-0.58	-2.25	-0.18	-0.08
Standard deviation	171.03	152.50	7.47	7.28	14.59	10.71	18.58
Variance	29252	23257	56	53	213	115	345
Kurtosis	-0.50	0.58	-0.31	-1.09	-0.72	0.48	-0.29
Skewness	-0.13	0.56	0.49	-0.12	0.25	-0.08	-0.48
Slope	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Range	701	683	29	25	57	59	79
Minimum	-394	-278	-12	-12	-26	-29	-36
Maximum	307	405	17	13	31	30	32
Sum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Count	32	28	32	28	60	60	60

Pc = Period prior to change point
Ac = Period after change point

Table 4.3 Parameters for residuals of rainfall series at five thresholds at Nguru.

Threshold		Pc	Ac	Combined
5 mm	M	0.00	0.00	0.00
	S	11.74	9.26	10.75
	R	1.82	1.88	1.55
	N	29	20	49
10 mm	M	0.00	0.00	0.00
	S	23.52	18.57	22.36
	R	4.51	4.38	3.92
	N	28	21	49
15 mm	M	0.00	0.00	0.00
	S	33.74	27.56	34.64
	R	5.50	3.94	5.18
	N	27	22	49
20 mm	M	0.00	0.00	0.00
	S	49.73	34.91	46.18
	R	9.11	5.70	8.60
	N	24	25	49
25 mm	M	0.00	0.00	0.00
	S	65.28	30.82	61.58
	R	14.45	8.94	14.86
	N	34	15	49

Note: M = mean, S = standard deviation, R = root mean square error, N = length of record, Pc = period prior to change point, Ac = period after the change point, Combined = entire period of record

CHAPTER FIVE

Sources of rural water supply for semi-arid Nigeria: a village example

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Abstract

Rural areas in the Sahel and Sudan savanna region of Nigeria rely almost exclusively on natural water sources for their domestic and economic activities. These sources include rainfall, streamflow, shallow and deep groundwater. Such water supply systems are subject to considerable seasonal and inter-annual variabilities. The dynamics of the water sources for a village in northeastern Nigeria provide an example that demonstrates linkages among these sources. Long-term records on the various hydrological components are rarely available at the rural level. However, it is shown that short-term data can be interpreted in the context of the long-term climatic experience of the region. The hydrologic system is driven by the local rainfall and any perturbations in the rains propagate through the system with short lag time between the components. Deep groundwater circulation plays a minor role in the water supply for the area but it is sufficient to sustain withdrawals during the dry season. The integrated approach discussed can contribute significantly to the development of strategies to efficiently utilize and manage the water resources of the region.

5.1.0 Introduction

The rural areas of the drought-prone northern Nigeria are the home to an estimated 30 million people or about 30% of the nation's population. Most of the foodstuff, especially cereals, are produced in small farm holdings of one to two hectares. The region supplies over 90% of the beef and red meat for the country and supports the associated leather and tanning industries. The domestic and agro-pastoral activities rely almost entirely on natural supplies of water through rainfall, streams and groundwater. Being unregulated, these water sources are prone to wide fluctuations due to climatic variability. Frequently, the interaction among these systems determines whether the effects of a drought are moderated or amplified. For example, riparian locations offer supplementary water sources from the streams which may compensate for rainfall deficits during some dry years.

Despite such interactions, there is a lack of literature that provides an integrative treatment of the rural water supplies which encompass the various sources. It is the purpose of this paper to (a) provide information on the sources and timing of natural water supply as well as the magnitudes and spatial distribution in a rural setting, and (b) describe the interaction among the different sources of water supply utilizing information obtained from a two year study in a village in northeastern Nigeria.

The use of short-term data carries the risk that the samples may not be representative of the average or 'normal' pattern and they do not indicate the range of variability. In northeastern Nigeria, only rainfall data have been collected for long periods. The two-year data obtained in our field study will be compared with the long-term rainfall series from adjacent locations to establish the representativeness of our results.

5.2.0 Study Area

A two-year study (1994-95) was carried out in Katarko (11^0 34'N, 11^{0}55'E), a rural village of over 4000 inhabitants located 20 km southeast of Damaturu, on the southern fringe of the Sahel in northeastern Nigeria (Fig. 5.1). Despite its proximity to an emerging urban centre, the village has few modern amenities. There is no electric power supply, piped water or storage facilities and the people rely entirely on natural water supply systems to satisfy their water needs. Nearly every household is engaged in some form of farming although about 65% of the working population are also involved in secondary occupations such as petty trading and craft. Both rain-fed and irrigation agriculture are practiced and the range and scale of economic activities are typical for rural settlements within the Sudan savanna. Etuks' (1978) description of rural agriculture in Nigeria is apt for the village. The level of technology is low, with land and labor as the main inputs; the use of fertilizers and other modern inputs such as herbicides and pesticides is extremely limited. The implements used in farming include hoes, cutlasses and other simple manually operated tools; apart from the recent introduction of petrol-driven irrigation pumps, the use of power equipment and machinery is almost nil.

The village is located within the Sahel savanna belt which refers to the zone lying between the 250 mm and 750 mm mean rainfall isohyets (Glantz, 1994). The rainfall is markedly seasonal, with the seasonality determined by the atmospheric circulation patterns over West Africa (Bello, 1996). The rainy season falls between May and October. Most of the rainfall is generated by the storms associated with the Inter Tropical Discontinuity which lingers over the region at this time (Omotosho, 1990).

Most of northeastern Nigeria is underlain by the Chad Formation, an extensive deposit of lacustrine origin which has been dated to be Pleistocene (Bumba et al., 1991). It is covered by superficial deposits of sands and clays. Exploitable aquifers occur at depth up to 650 m and comprise the upper, middle and lower zones. The upper aquifer system is composed of three aquiferous sub-zones termed A,B and C. The A sub-zone has a thickness which varies from 10 m to 40 m but locally reaches a maximum thickness of 96 m where it merges with the underlying.B and C sub-systems (Ezeigbo and Ogbukagu, 1991). The A sub-zone constitutes the main groundwater source in the Katarko area.

The area around Katarko has low relief; mean elevation above sea level is about 160 m. The lack of relief and low rainfall give rise to a low drainage density in which the rivers are few and widely spaced. The river beds are generally flat and shallow so that a broad area is flooded during the rainy season. None of the rivers are truly perennial but their floodplains, locally called fadamas (Adams and Carter, 1987; Kimmage and Adams, 1990; Turner, 1985), provide some of the best irrigated land in the region. The yield from the fadama aquifer is generally reliable during the dry season. Consequently, most of the large settlements are located along the main rivers. The region has been inhabited for centuries and the vegetation is greatly affected by cultivation, cuttings, indiscriminate burning and grazing. Presently, it consists of scrub, thorny species and patches of woodland, except in river valleys where dense riparian vegetation occurs.

5.3.0 Water Sources

Like most other villages in northern Nigeria, Katarko utilizes water from rainfall, surface water (streamflow and ponds) and groundwater (deep and shallow groundwater). The time when the various sources are available during the year is described by Tarhule and Woo (1997). Rainfall begins in May and ends in October while the stream flows from June/July to October. Wells tapping the deep aquifer (village wells) provide water throughout the year although several may dry up towards the end of the dry season. The fadama aquifer on the other hand offers a major supplement for about six to seven months each year, starting about two months after the end of the rainy season. Ponds usually occur on the river bed during the transitions from one season to another. At the beginning of the rainy season, the ponds are formed in depressions which collects the runoff and, at the end of the rainy season, the cessation of flow leaves disjointed pools of water in the stream channel.

5.3.1 Rainfall

The characteristics of rainfall at Katarko during the study period are summarized in Table 5.1. A rain day is any day receiving at least 1 mm of rain and the duration of the rainy season is the interval between the onset and termination of rains. For the two years when measurements were made, rainfall was 677 mm (1994) and 587 mm (1995). This difference reflects the large inter annual variability common to this region and can be attributed to the decrease in the number of rain days from 46 (1994) to 35 (1995). This is consistent with studies of the long-term rainfall variations in the Sahel which found that the decrease in the number of rain days is a major factor influencing the variations (Hess et al., 1995; Olaniran, 1991; Tarhule and Woo, submitted). However, in terms of rainfall intensity, the decrease is most pronounced in the category of moderate (11-25 mm d^{-1}) intensities rather than the high (>25 mm d^{-1}) intensity events.

To test the representativeness of the data, the monthly rainfall at Katarko was compared to that at the surrounding stations for comparable periods. The stations include Damaturu (20 km northwest), Potiskum (100 km southwest), and Maiduguri (100 km northeast). Biu (100 km south), was not included because its mean annual rainfall (790 mm yr^{-1}) is significantly higher than the annual rainfall at Katarko (632 mm yr^{-1}). Total monthly rainfall and the monthly number of rain days between May to October at the four locations were tested for correlation. For total rainfall, the highest correlation ($r^2 = 0.96$) was obtained between Katarko and Potiskum, followed by Katarko-Damaturu, 0.80 and Katarko-Maiduguri, 0.66. However, for the number of rain days, the highest r^2 was obtained with Damaturu (0.83), followed by Potiskum (0.81) and Maiduguri (0.63). Thus, Maiduguri (11°58' N, 13° 10' E) is the least correlated in both cases, suggesting that rainfall at Katarko is more representative of the southern margin of the Chad formation. It is noteworthy that Damaturu, the closest station to Katarko is not the most strongly correlated in terms of total rainfall. This is probably due to measurement error. On the other hand, the correlation between Katarko and Potiskum is high for this region and may be due to chance (i.e. the short length of record used). The r^2 values for Damaturu-Potiskum and Damaturu-Maiduguri were 0.75 and 0.67 for total rainfall; 0.78 and 0.55 for the number of rain days. The average monthly rainfall at Katarko, Damaturu and Potiskum for 1994-95 is presented in Figure 5.2. The average rainfall at Damaturu was significantly higher than the rainfall at Katarko and Potiskum in July and August. Conversely, it was much lower in September, resulting in the low correlation between Damaturu and Katarko.

Since 1990, the amount of rainfall at many locations in the Sahel increased appreciably, ending the downward trends prevalent in the previous two decades. However, at some locations, (e.g. Katsina and Nguru), the improvements have been minimal and drought conditions still prevail. To test whether the two year measurements at Katarko indicate drought or 'normal' conditions, the probability of exceedance based on the long-term record of total rainfall and number of rain days at Potiskum was analyzed (Fig. 5.3). Whereas Damaturu provided the strongest correlation with Katarko in terms of the number of rain days, the total length of record (10 years) is too short to yield satisfactory probabilities. On the other hand, Potiskum has both long records and strong correlation with Katarko. Hence, the homogenous period of record (or data without significant trend, see Tarhule and Woo, Submitted) at Potiskum was utilized. Figure 5.3 indicates that the exceedance probabilities of the two year data from Katarko range from 0.46 (1994) to 0.84 (1995) for total rainfall; and 0.39 to 0.54 for the number of rain days. Similarly, the exceedances for the duration of the season are 0.58 (1995) and 0.78 (1994). Such probability ranges lie within the relatively 'normal' conditions for this part of the Sahel savanna.

5.3.2. Streamflow

The Annuma River, a tributary of River Gongola, is a seasonal, water losing stream with poorly defined channel near Katarko. It drains an area approximately 1790 km^2 and flows between July and September, frequently overflowing its shallow banks onto the floodplain. Figure 5.4 shows the river channel during the dry season (19 February, 1995) and during the peak of the rainy season (15 August, 1995). Locally, the width of the flooded section exceeded 250 m in places. Daily water level or stage measurements during the flow period were taken under the bridge. Maximum flood stage recorded was about 2.5 m and occurred in the middle of September of both years. Comparison of the exceedance probability of the mean daily water levels for River Annuma and Gaya, another river of comparable basin size (1708 km^2) shows similar trends. However, mean basin precipitation for Gaya is 735 mm a^{-1}, often giving rise to higher stream levels.

There are 140 flow days, representing a probability of 0.82 of yielding flow between May 1 to October 10 which encompasses the rainy season. Nearly all the days with no flow occurred at the beginning of the rainy season. Once flow commences, the probability of zero flow is low unless there is a false start in the rains. Considering differences in channel morphology and their effect on the stage, the similarities between River Gaya and River Annuma are notable and suggest that the observed flow characteristics at Katarko are typical for the region.

Figure 5.5 presents the exceedance probabilities of daily rainfall and daily stream stage. The probability of obtaining rainfall (≥ 1 mm d^{-1}) on any given day is 0.25 and about 0.05 for high intensity rainfall (≥ 25 mm d^{-1}). For streamflow, the mean bankfull stage is about 1 m. Thus, The probability of flooding is about 0.35. Rainfall being a discrete phenomenon is more variable, with mean interval between rain events of about 4 days (Table 5.1).

5.3.3 Groundwater

Groundwater exists in two types of aquifers: deep groundwater and fadama (alluvial) aquifer. The latter is found at shallow depths (3-4 m below ground surface) and is recharged annually by downward and lateral seepage from the stream. The fadama at Katarko may be classified as Type IIbS or a streamside fadama (Turner, 1985). Elsewhere in the Sudan and Sahel savanna, large depressions which are ponded annually may also create and sustain local aquifers at shallow depths without the benefit of a stream (Turner, 1985). Exploitation of the shallow aquifer begins in December when the flood plain is dry enough for well construction. At first, the wells are used mainly for irrigated agriculture but withdrawals for domestic uses increase as the dry season progresses and some of the village wells begin to fail. Tarhule and Woo (1997) describe the occurrence and use of the shallow aquifer at Katarko.

Deep groundwater occurs at depths exceeding 8 m. This is the aquifer tapped by wells located within the village. The water is in phreatic condition and constitutes part of the "A" sub-zone of the upper aquifer system of the Chad Basin (Ezeigbo and Ogbukagu, 1991). There are 21 private and 12 public wells in the village. Six of the public wells are lined with concrete rings to prevent periodic collapse but none of the private wells are lined. Depth to water table is, on average, 10 m and 15 m on either side of a highway which divides the village into northeastern and southwestern sectors. The deepest well (W29) measures 29 m and the cost of constructing hand-dug wells beyond this depth exceeds the means of many rural inhabitants.

5.4.0 Hydrological events and water supply

The beginning of the rainy season in May or June is usually characterized by intense, showery outbursts lasting about 15-30 minutes and depositing between 5 to 20 mm of rain. Coming at the end of a protracted dry period during which the soil surface is compacted by grazing animals and the soil pores plugged by wind blown particles, such high intensities exceed the infiltration capacity of the soil, generating overland flow and significant erosion of the loose sandy deposits. Figure 5.6 presents an example of the sheet flow produced by the first rain event of 1993 (May 30th). Soil profiles observed at the end of this storm showed that the wetted depth was only about 3 cm. Evaporation pan measurements for May during the previous season indicated a value of 388 mm. Due to such high values, the meager soil moisture is lost to evaporation unless other rain events quickly follow the first. Runoff accumulated in shallow depressions is also subject to evaporation loss. Large depressions along stream beds may produce ponding which represents localized points of concentrated infiltration for the recharge of fadama aquifers. On the other hand, flooding of the riparian zone renders many of the fadama wells unusable (Tarhule and Woo, 1997).

These events indicate that while the beginning of the rainy season is usually a sign of welcome relief, it still presents considerable risks for water supply both for domestic and agricultural purposes. Rainfall is irregular and infiltration in upland areas is negligible. The amount of soil moisture may be adequate for cultivation but insufficient for seed germination or sustained growth, presenting a dilemma for the farmers. The ponds contain little more than muddy, polluted water rich in sediments and debris. In terms of domestic water supply, this is the period when direct rain harvesting is most needed since in other forms, the water is of minimal utility. Unfortunately, observations revealed that the use of direct rain harvesting techniques is limited to a few small (4 l) to medium sized (14 l) containers scattered in the open or beneath the edges of roofs.

If the rainy season experiences a false start (i.e. one or few rain events followed by a long dry spell) as happened in 1995, both domestic water supply and agricultural activities are placed at peril. In the case of the former, viable sources of water (e.g. fadama wells) are destroyed but alternative sources such as village wells are not yet recharged. Towards the end of the dry season, farmers often plant seedlings in anticipation of the rain. An early rain event may induce germination of the seedlings which subsequently die out as the soil desiccates. While the practice may appear risky, it is anchored in generations of experimentation and trial and error. Due to high rainfall intensities and low organic content, the soils are prone to leaching and early sown crop takes advantage of the flux of mineralized nutrients which would otherwise be leached out of the root zone (Kassam and Kowal, 1975). Future planning of water resources and agricultural activities in the region needs to pay particular attention to the beginning of the rainy season.

Streamflow commences about one or two months after the onset of rains (Fig. 5.7). Most of the flood peaks are generated by local rainfall although several events may be attributed to upstream sources. The headwaters of the Annuma River are located on the Biu Plateau which, due to orographic effects, receives higher amounts of rainfall than the low-lying regions. This explains the maximum observed flood stages (Sept. 20, 1994; Sept. 18, 1995) which are out of phase with the local rainfall events. The amount of discharge appears to be significant only in so far as it demarcates the extent of the flooded area, since this influences the useful limits of the flood plain during the dry season. The stream water is used for bathing, washing, animal watering and fishing. From the third week of September, river stage falls rapidly and the flow ceases altogether by the end of October, leaving behind disjointed strings of stagnant ponds. Pond water is used for the same activities as stream water although brick making may be important where suitable clayey sediments are available.

A cross-section of the water table from the village to the floodplain revealed a pronounced gradient towards the village. However, it is uncertain whether the alluvial and the deep aquifers are hydraulically connected. Further analysis, perhaps including the isotopic compositions of both sources, is needed to resolve the question and to ascertain their interaction.

Water levels in two selected wells in the village and daily rainfall are presented in Fig. 5.8. Daily fluctuations in well levels are on the order of 0.2 m and reflect day to day variations in demand plus measurement error estimated at ± 0.05 m. Similar diurnal variations in water level have been observed at Nguru (Hadejia-Nguru Wetlands Project, unpublished data).

There appears to be little relationship between individual rain events and water table rises in the wells. However, the well levels rose steadily from about Julian day 190 (early July) when cumulative total precipitation reached one-quarter of its annual total in both years. The duration of rise varied at different wells, ranging from a few days (W29) to about two months (W31). Maximum annual elevations are on the order of 0.5 m - 0.8 m and may be attributed to direct rainfall recharge since it predates, in some cases, the rise in stream stage (Fig. 5.7) but may also reflect decreased reliance on the wells. Because water is generally available during the rainy season, the wells are used only for drinking and cooking. For example, estimated average daily water withdrawal at W14 between 16 and 19 May, 1995 (dry season) was 1020 l. Between 9 and 11 August, 1995 (rainy season), average daily withdrawal was 708 l or 69% of the dry season value. Nevertheless, The modest rise in well levels reflects relatively low recharge from rainfall. From a 10-year study in the Maiduguri area using a soil moisture deficit model, Odigie and Anyaeche (1991) estimated recharge at about 20% of average rainfall. They found that groundwater recharge occurred between July and September; August accounted for 50% of the annual recharge.

Some wells receive additional recharge input other than the direct rainfall and their levels show much higher rises. Well W21 (250 m from the stream talweg) is one such example (Fig. 5.9). Prior to mid-August, stream stage was < 1 m and the change in the well level was small although an upward trend has already begun. By mid-August, when mean stream stage exceeded 1 m and flood peaks approaching 2 m were common, well level rose sharply (approximately 0.8 m over 3 days), confirming that the well received recharge input from the river. However, the maximum water level rise in the well lagged the maximum flood peak by about 10 days.

The recession of well levels generally commences in mid-October and continues to December. The recession phase appears to be shorter for public wells (e.g. W29) than for private wells (e.g. W31), reflecting greater intensity of water withdrawal (Fig. 5.8). By January, the dry season water level is stabilized but cumulative effect of differential water withdrawal produces greater drawdown in the public wells than in the private wells. In perennial wells which include many village wells, the level changes little until the onset of the rainy season. Wells which are not perennial begin to fail towards the end of January.

In the fadama, shallow wells are usually ruined when they become in-filled by sediments and debris transported by surface runoff, or they may be flooded when streamflow begins. Unlined village wells may also fail structurally when the weaker underlying sediment layers are preferentially eroded. In any given year, 30-40% of all unlined wells may collapse. Figure 5.10 presents water level measurements in W14 which collapsed on 11 December, 1994. Usually it is possible to get water from the collapsed wells for a few days but the water soon becomes polluted or seeps through the fallen debris.

Apart from the sources discussed above, regional groundwater flow is an important source of recharge for many areas. In the Katarko area, rainfall is the primary source of water recharge and the slow, deep regional component is secondary but allows dry season withdrawals to be sustained. Furthermore, because both stream discharge and groundwater recharge are strongly related to local rainfall, water availability may be affected by land use practices in the immediate vicinity of the village which change the interaction among the various systems. For example, activities which enhance the runoff potential and reduce infiltration capacity may inhibit direct groundwater recharge, leading to increased stress during the dry season. Decrease in the amount and extent of recharge to the fadama aquifer (e.g. an upstream dam, sediment loading due to increased erosion, or over exploitation for irrigation purposes) can also adversely affect the natural water supply system for the village.

5.5.0 Conclusion

Comprehensive information on hydrological processes and their interactions is needed to understand the dynamics of the rural water supply systems. This paper demonstrates that short-term measured data and observations may be interpreted in the context of the long-term hydro-climatic experience of the region. Rural water supply is dependent on various sources with each source being dominant at different times of the year.

Our results show that rainfall is the immediate or indirect source of water supply to the stream and the groundwater. Although additional inputs such as lateral inflow from upstream sources are observable, the local rain source dominates. Thus, any perturbations in the local rainfall propagate through the hydrologic system with short lag time between the components. Possible interaction between the alluvial and the deep aquifer requires further study because there may be implications of river regulation and control on the viability of hand-dug wells in the riparian zone.

The occurrence of droughts and periods of water shortage will continue to be integral components of the climatic experience in semi-arid environments. However, an integrated approach to water resources investigations at the rural level along the lines discussed in this paper could lead to more efficient utilization of the available water, potentially mitigating against mild drought episodes.

Acknowledgments

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List of Figures

Table 5.1: Summary of rainfall characteristics at Katarko

	1994	1995
Total rainfall (mm)	677	587
No. of rain days	46	35
Days between rainfall events:		
Mean	3	4
Range	7	11
Rainy season:		
Starting date	May 28	May 7
Ending date	Oct. 7	Oct. 5
Duration (days)	132	151
Rainfall intensity ≤ 10 mm/d:		
No. of events	22	19
% of total rainfall	14	21
Rainfall intensity 11 - 25 mm/d:		
No. of events	17	9
% of total rainfall	44	29
Rainfall intensity > 25 mm/d:		
No. of events	8	7
% of total rainfall	41	50

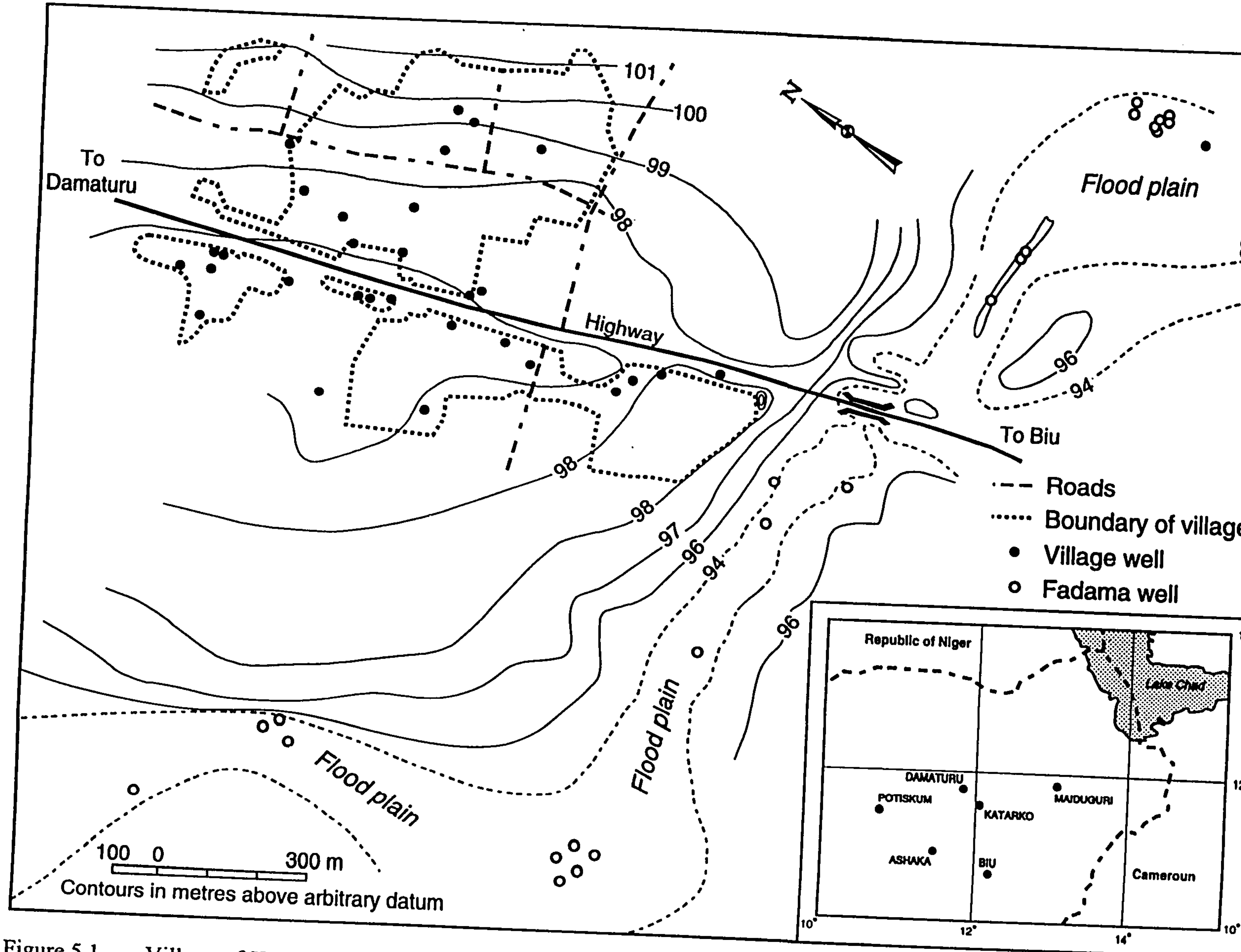

Figure 5.1 Village of Katarko and location of Katarko, Biu, Damaturu, Maiduguri and Potiskum in northeastern Nigeria.

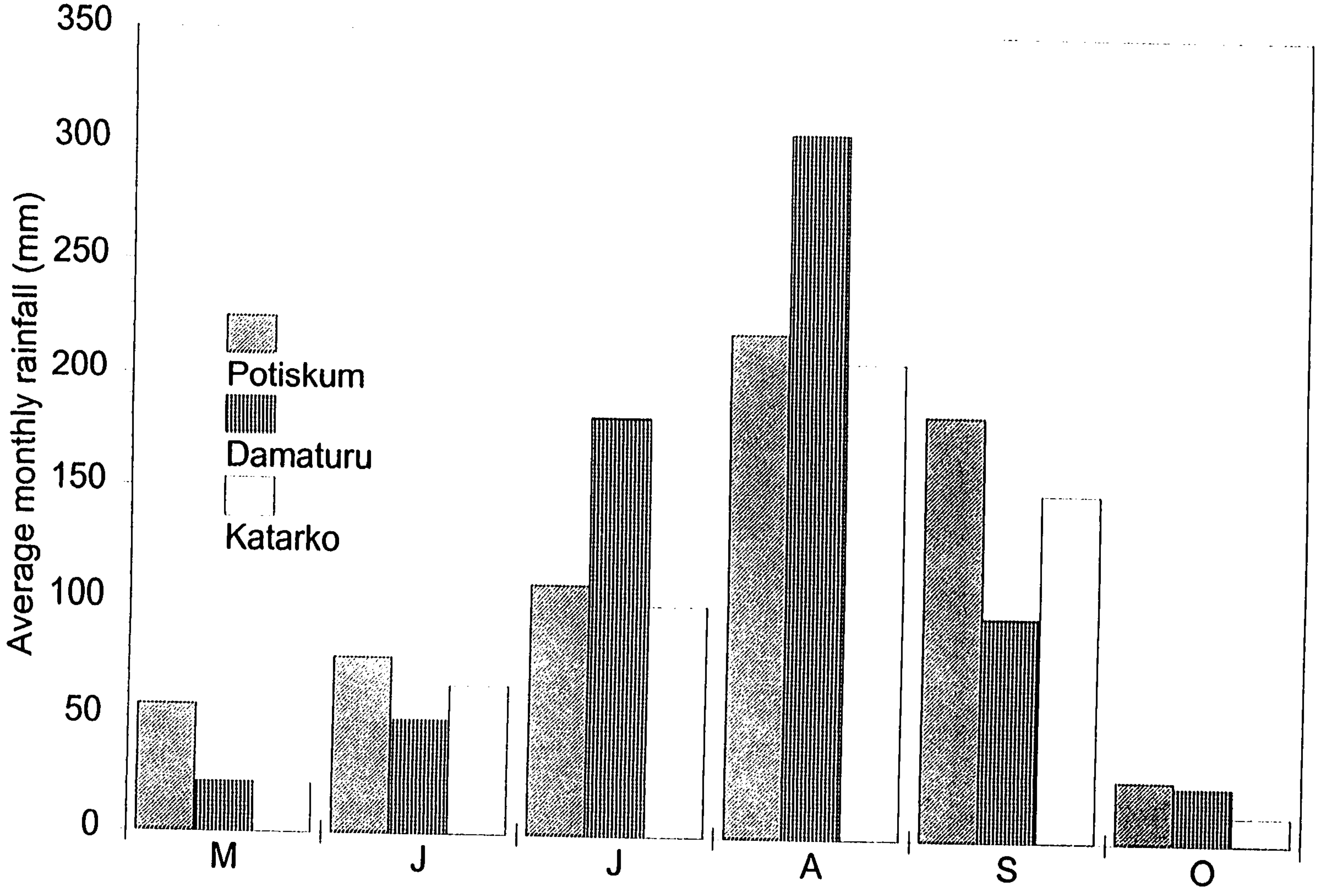

Figure 5.2 Average monthly rainfall at Katarko, Damaturu and Potiskum

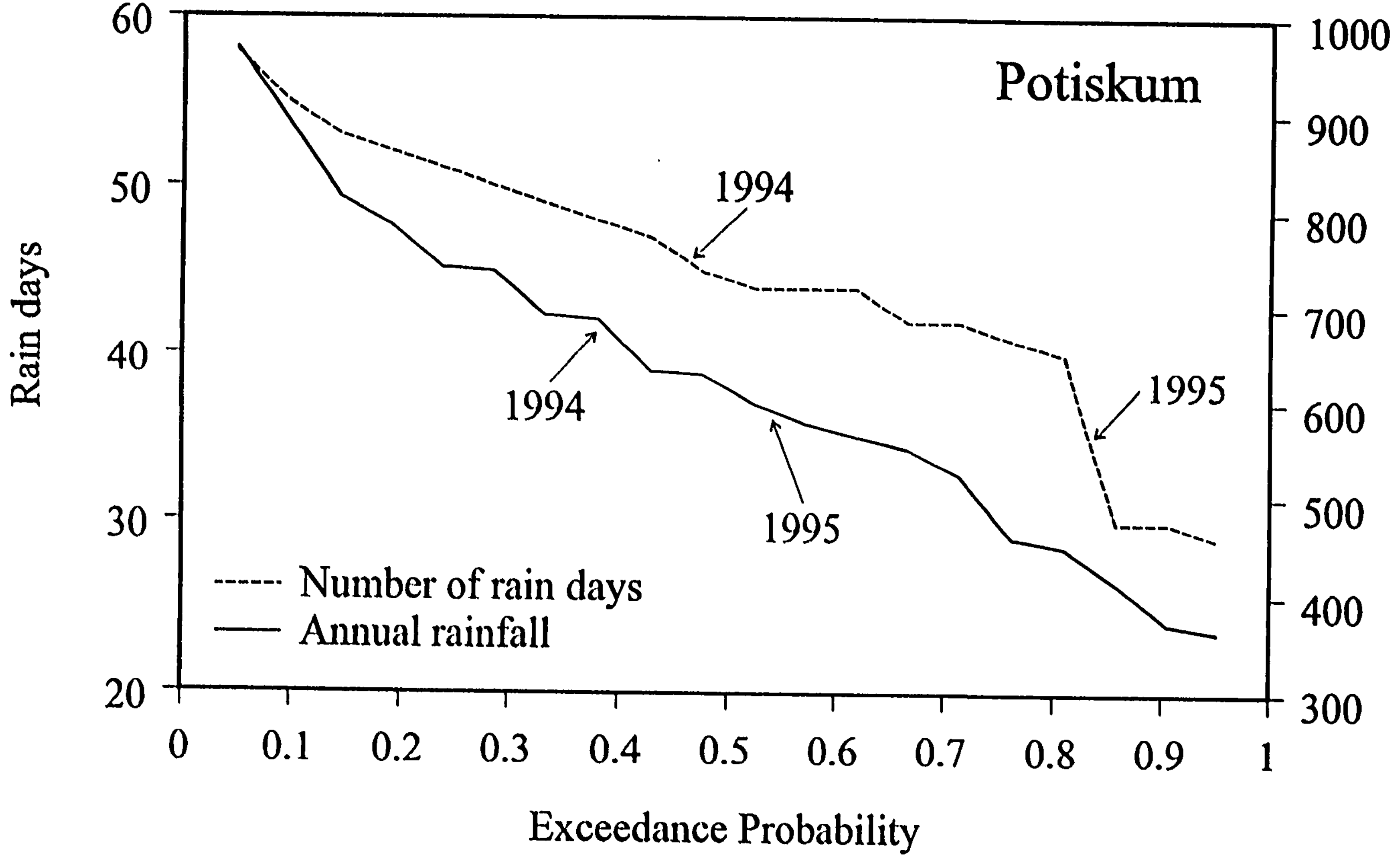

Figure 5.3 Exceedance probability plots of the total rainfall and the number of rain days at Potiskum. Arrows point to the annual rainfall and the number of rain days observed at Katarko during the study period.

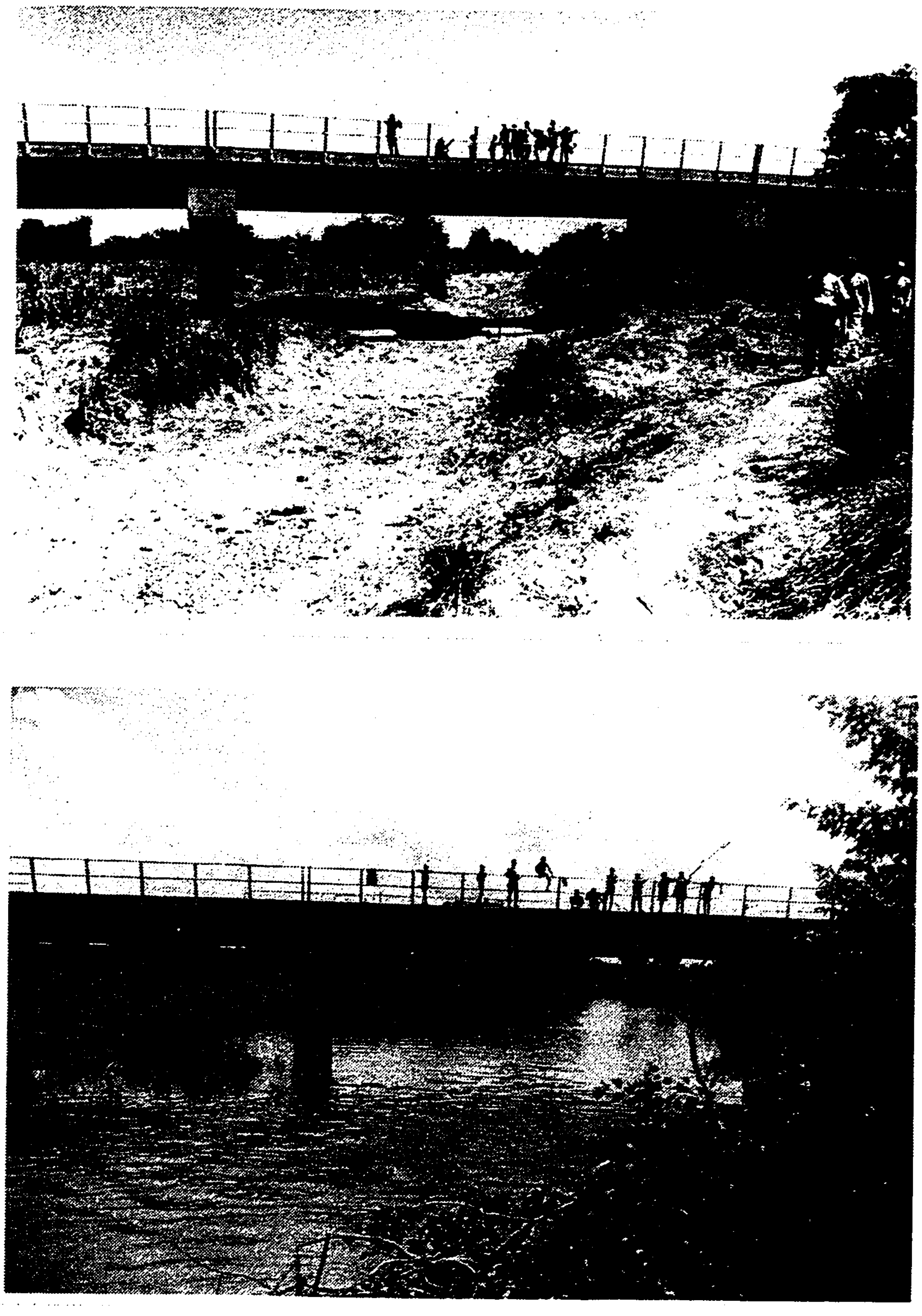

Figure 5.4 River Annuma at Katarko (a) dry stream bed on 19 February, 1995 (b) Flood condition on 15 August, 1995.

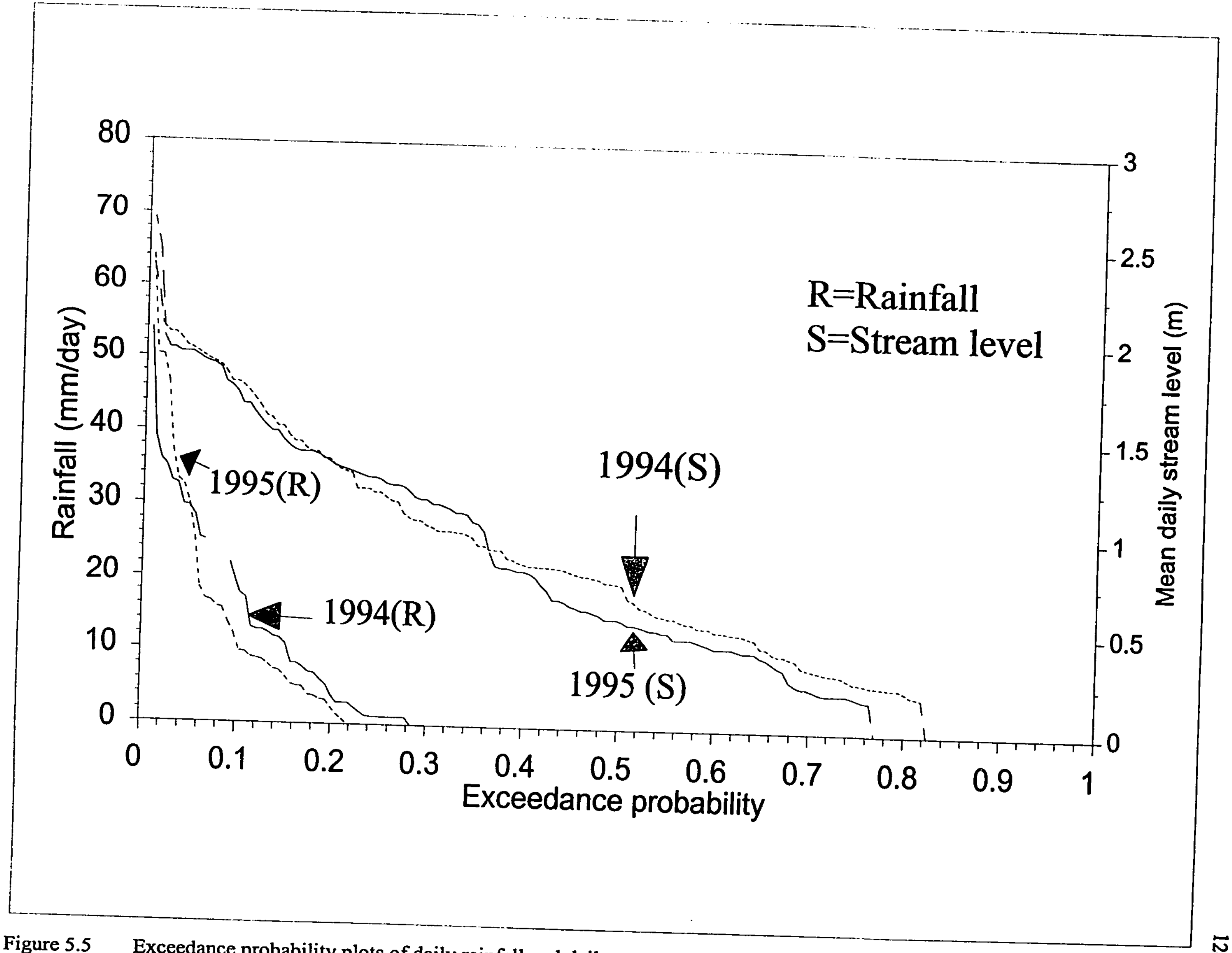

Figure 5.5 Exceedance probability plots of daily rainfall and daily stream level of Annuma River at Katarko (1994-95).

Figure 5.6 Overland flow generated by heavy rain at the beginning of the rainy season of 1993 (May 30th) near Potiskum.

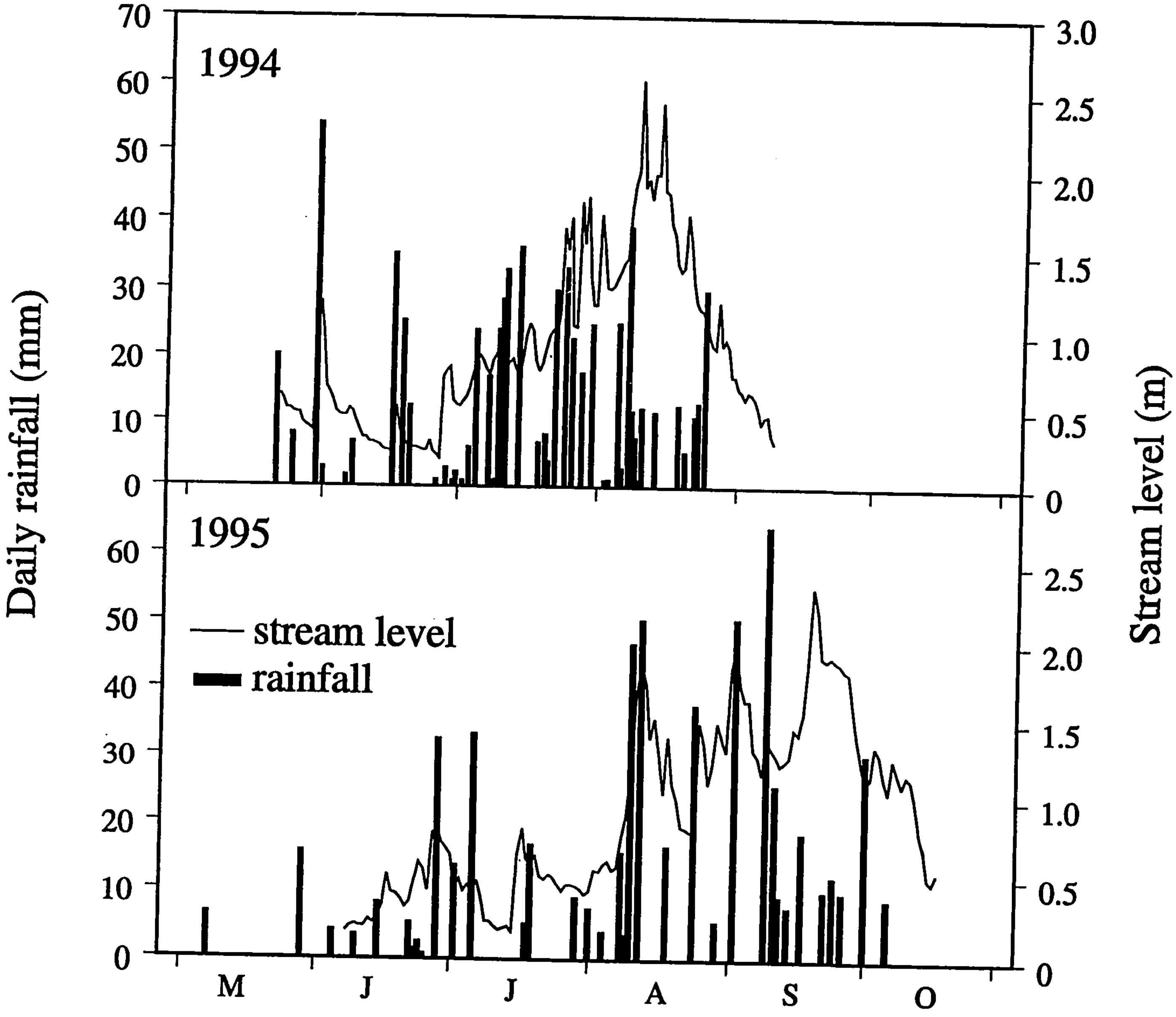

Figure 5.7 Daily rainfall and stream level hydrograph of Annuma river at Katarko during the rainy season.

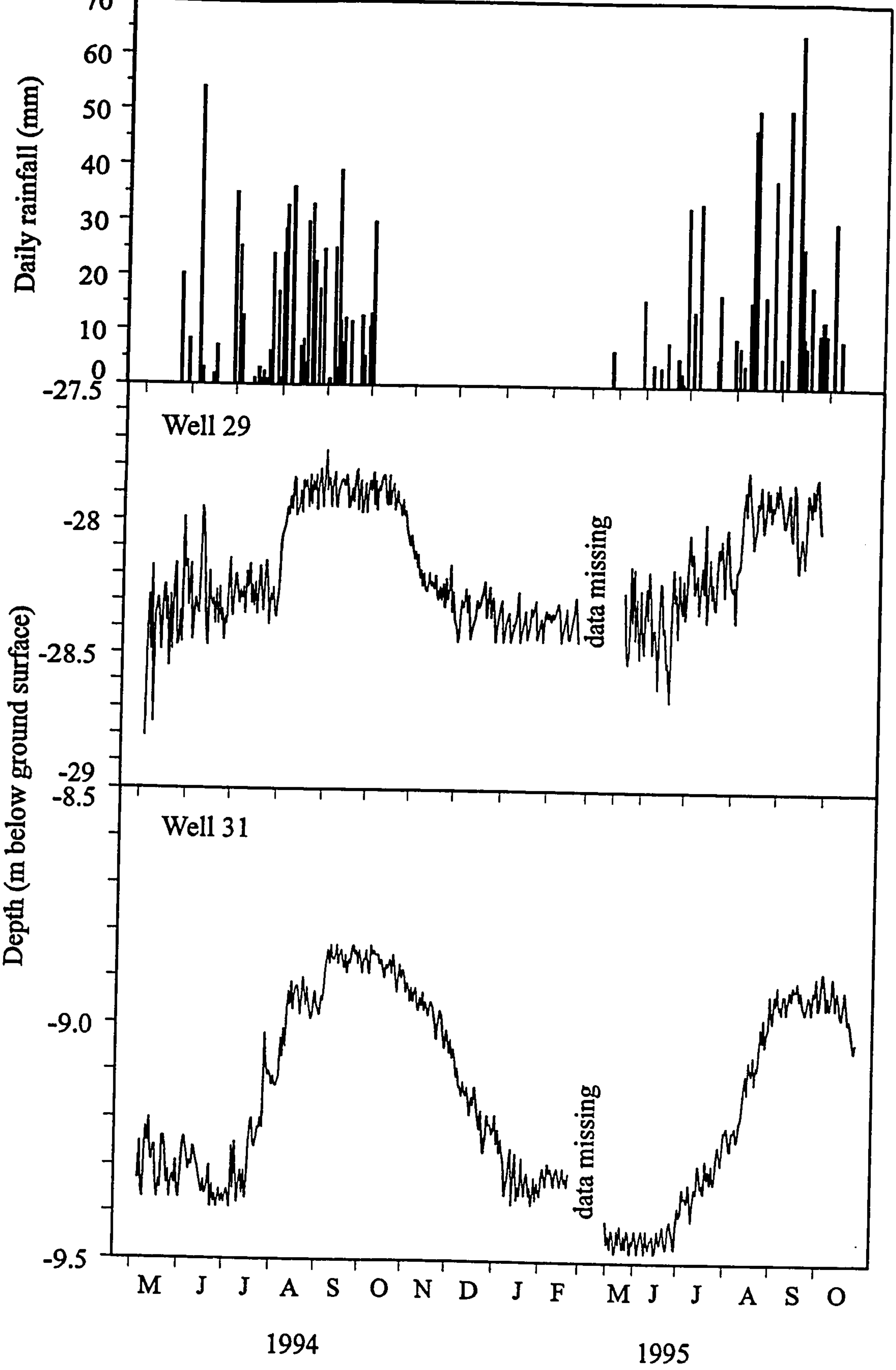

Figure 5.8 Fluctuation of levels in two village wells during the rainy season.

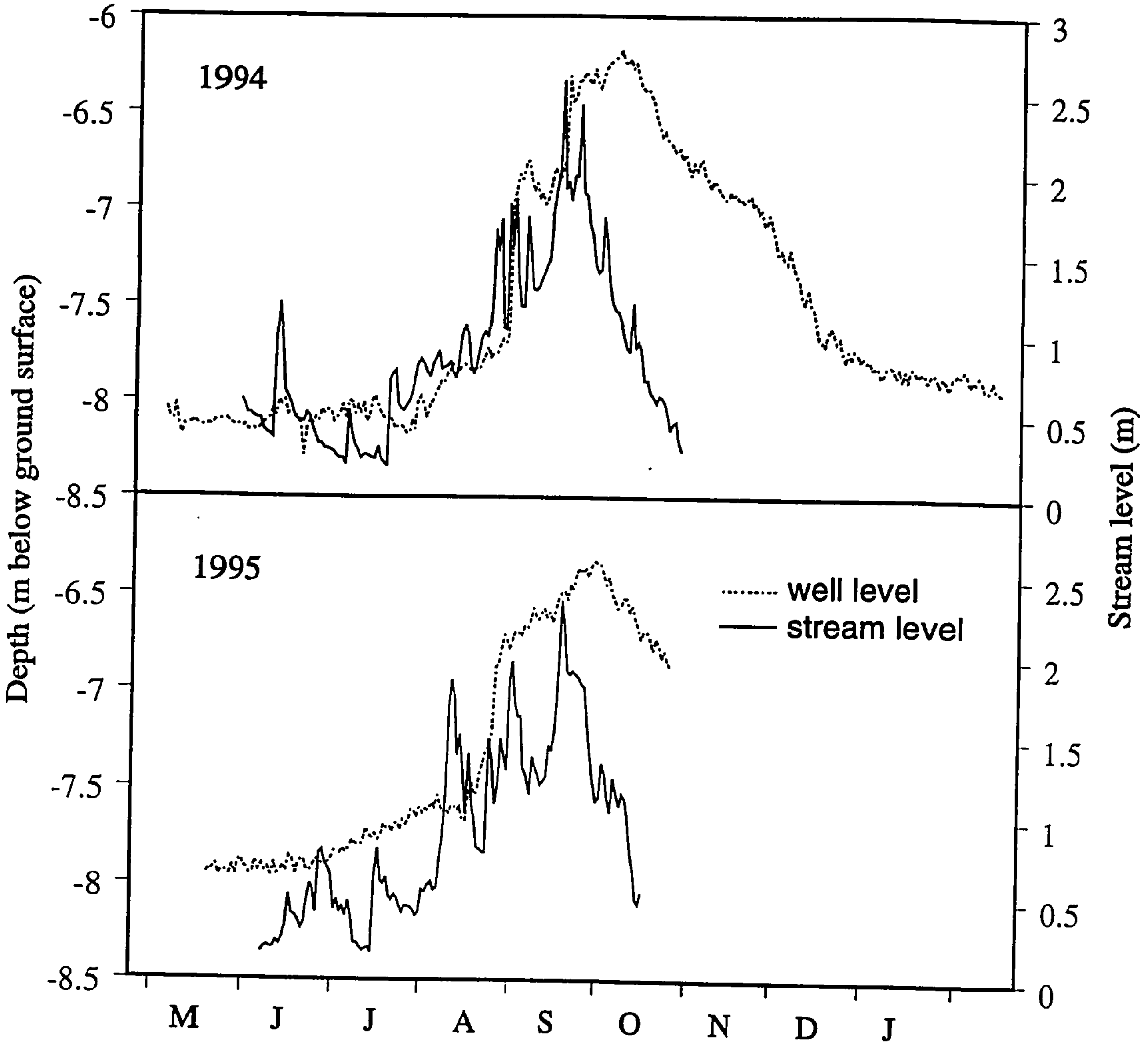

Figure 5.9 Daily stream level and water elevation in Well 21

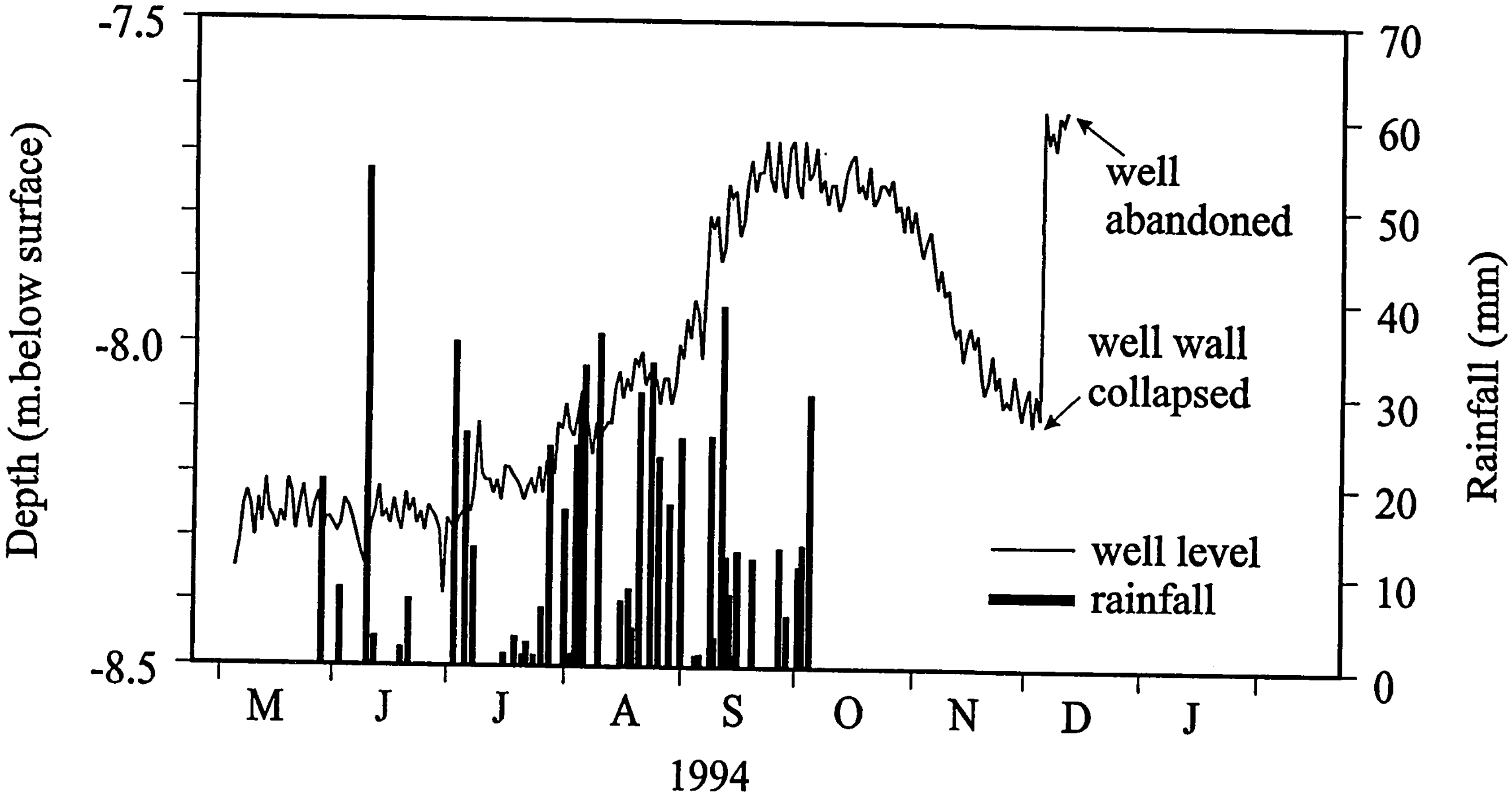

Figure 5.10 Water level in a village well that collapsed during the dry season.

CHAPTER SIX

Characteristics and use of shallow wells in a stream fadama: A case study in Northern Nigeria

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Abstract

This paper examines the occurrence and use of shallow wells in a typical streamside fadama (seasonally flooded land) in northern Nigeria. The interplay of hydrologic and social considerations which govern the location and use of seasonal, hand-dug wells in the fadama are also examined. Contrary to popular conception, children, women and men were found to be equally involved in the search for water although large differences exist between ethnic and religious groups. It is shown that traditional patterns of water withdrawal are designed to accommodate the diverse interests of different groups and minimize the possibility for conflict. New technologies and policies which strengthen the water abstraction capacity of one group over others disrupt existing patterns and intensify discord between groups. Information obtained in this study can assist policy makers in articulating more equitable water development policies.

6.1 Introduction

In many Sahelian areas, shallow ground water occurs in alluvial aquifers at depths of 3-4 m in flood plains or stream beds. This physiographic environment belongs to a feature called the fadama, defined as "land which is seasonally flooded or water-logged" (Turner, 1985, p.18). The term fadama (plural - fadamuni) is the singular form of the Hausa word for this class of features which vary from small shallow depressions to the flood plains of major rivers but does not include marshes or swamps which are permanently flooded or water-logged. Owing to the failure of large scale irrigation schemes in sub-Saharan Africa, fadamas and similar environments elsewhere (e.g. the Dambo's of east Africa or the Mbuga's of southern Africa) have been extensively studied as potential sites for small scale irrigation projects (Adams and Carter, 1987; Carter, 1984). Fadamas are important not only for their irrigation potential, they are a major source of water for domestic consumption and livestock grazing and watering in these regions. Exploitation of these water sources for sustenance probably dates back to the earliest episodes of water scarcity. Historically, abstraction involved digging wells in the fadama to intercept the water table, a practice that has continued largely unchanged.

Despite a long history, there has been very little research on the hydrological characteristics of these shallow wells and the factors which govern their location and use. Furthermore, because of the availability of water, fadamas tend to support high concentrations of populations. However, under traditional farming or grazing systems, rarely did water use conflicts arise. Recent reports of conflict among users are largely the effects of water development projects (Kimmage, 1991) which offset the fabrics of community balance. The objectives of this paper are two-fold: (i) to study the shallow ground water wells in a typical fadama, (ii) to examine the patterns of fadama aquifer use under the traditional system. The information provided will be useful for future investigations of shallow groundwater potential and for developing water resource strategies in semi-arid environments.

6.2 Study area

The village of Katarko (11° 34' N, 11° 55' E) is located 20 km southeast of Damaturu, the capital of Yobe State (Fig. 6.1). The area lies on the southern fringe of the Chad formation within the drought prone region of northern Nigeria described as semi-arid or dry savanna (Owonubi et al, 1991). The vegetation is sudan savanna and comprises scrub, acacia, thorny trees and the boabab. The climate is semi-arid tropical and, like the rest of West Africa, dominated by two main air masses: the south-westerly rain-bearing Tropical Maritime and the dry, northeasterly Tropical Continental air masses. These air masses converge to form an unstable boundary known as the Inter Tropical Discontinuity (ITD) which often bears rain. In general, the rainy season begins in June and ends in September. Average annual rainfall is about 700 mm and the mean number of rain days per year is 29.

August is the rainiest month with 10 rain days accounting for 36% of total annual precipitation.

Daytime temperatures are high year round, generally above 25° C and frequently exceeding 40° C during the hot season (March - May). For part of the dry season (October to March) dry, cold and dusty winds known locally as harmattan persist. Drainage network is dendritic, sparse and none of the rivers are truly perennial.

River Anumma, a tributary of River Gongola, begins from the Biu hills southeast of Katarko. At Katarko, the river bends southwards to create a wide, flood plain which may be classified as a Type IIbS or a seasonal streamside fadama (Turner, 1985, p.92). At this stretch, it is an influent (water-losing) stream with poorly developed channel and flows periodically between July and September. For seven months of the year (December - June), the fadama aquifer is tapped by shallow wells for domestic water supply, irrigation and livestock watering.

6.3 Fadama and shallow wells

Fadama aquifers are depositional environments. A combination of low gradient and poorly defined channels leads to the deposition of clay, organic material and debris washed off from areas of higher relief. Silt and other material suspended in stagnant ponds of water also settle to the bottom. This process is particularly pronounced at the beginning, and towards the end of the rainy season when the stream channel contains isolated pools of water.

Over time, these accretions form inter-bedded layers of silt, clay, sand and silty loam overlying the original sandy material. Figure 6.2 illustrates this layering and the heterogeneity of the floodplain material. There is no obvious order of succession. The low water transmission and storage properties of the deposited material and its uneven distribution (due to natural irregularities in surface features) result in the occurrence of pockets of aquifers throughout the floodplain. These aquifers may be overlain by a layer of aquitard or they may be perched above such layers. Through experience and trial and error, the villagers identify and dig wells where aquifers occur. Hence, shallow wells are often clustered in groups along the fadama (Fig. 6.1). Areas of local occurrence of clay may be revealed by abortive wells and are the preferred sites for brick making.

Hydraulic conductivities of the aquifers in the fadama of Katarko village were determined at three shallow wells (marked As, Bs and Cs in Fig. 6.1) using the single hole pumping test technique described by Luthin (1966). The results showed that the conductivities are in the order of 10^0 to 10^1 m/d. The lowest hydraulic conductivity occurs in the well cluster marked Bs (wells located within 10 m of each other comprise a cluster). The stratigraphic profiles in Figure 6.2 indicate that substantial layers of clay occur at a depth of about one meter at this location. On the other hand, the highest conductivity occurs at Cs which has relatively thick sandy beds (> 0.9 m) at depths of about 1.6 m. In general, however, the values obtained are comparable to the average hydraulic conductivities for the A sub-zone of the Upper aquifer system within the Chad Formation (Ezeigbo and Ogbukagu, 1991). Provided that the aquifer is sufficiently extensive, such high yield is able to sustain water withdrawal at 5000 l/d/m^2 without seriously lowering the water table.

Shallow wells in the study area are circular in shape, with an average diameter of 0.85 m and a depth that seldom exceeds 4 m. There is no lining to the wells which often causes the wells to collapse. Figure 6.3 shows a cross section of a shallow well (Cs) with collapsed section. These wells are dug manually in mid-November or early December, after the water-logged alluvium becomes dry enough for well construction. During the dry season, the water table recedes and the depth of the wells are extended about two to three times. Usually, the diameter of the extended section is less than the original diameter but in some cases, the wells may be enlarged at the base, giving rise to a conical flask shape. Such enlargement may occur when a lens of high transmissivity is encountered.

6.4 Timing of shallow well use and variation of well levels

Figure 6.4 shows the timing of shallow well use in relation to other sources of water supply. Deep wells in the village provide water through out the year although many may dry up at the peak of the dry season. Shallow wells on the other hand offer a major supplement for about six to seven months each year, starting about two months after the end of the rainy season. The usable period of the wells ends with the onset of the rainy season (June); they may become flooded by runoff along the stream bed and/or infilled by debris washed off by the first heavy rainstorm, or the unconsolidated alluvial material may absorb moisture and become unstable, causing the wells to collapse.

Figure 6.5 illustrates the daily variation of well levels during the transition from the dry to the wet season of 1994. The selection of the wells was based on availability of relatively long series of daily water level measurements. Water levels at the three wells seldom changed more than several centimeters on a daily basis in the dry period. The first rainfall had little effect on the well level, but the storm of June 13, depositing over 50 mm of rain, caused sharp water level rises due to local runoff. Wells R2 and R4 were soon flooded and rendered useless, while R1 followed several days later. The abruptness of water level rises shows the rapidity at which the shallow fadama wells are ruined. Wells in topographic depressions or along the stream bed are the first to succumb. Those on higher ground often follow a few days later. In subsequent years, new wells are dug close to the old wells so that the preferred locations are dotted by relict, collapsed wells and an actively used one (Figure 6.6).

The beginning of the rainy season presents a particularly precarious situation for water supply because runoff generated by the rainstorms renders the shallow wells unusable, but the deep wells are not yet recharged and the stream beds contain little more than several stagnant ponds of muddy, polluted water. Thus, there is heavy dependence on any deep groundwater wells that may still be viable and on the erratic rainfall.

Fluctuations in water level during the day reflect the intensity of use. Figure 6.7 presents the hourly measurements of water level in three wells. Water level in the wells used solely for domestic water supply (e.g. R3 and R4) rarely varies by more than 0.2 m and the time to full recovery is about 2-3 hours. In contrast, wells that provide water for irrigation show greater fluctuation. On May 11, 1994 for example, the drawdown at well W1 was about 0.3 m around 8.00 a.m. when much water was withdrawn for irrigation. There was episodic water withdrawal during the day and it was not until late in the evening that the nocturnal water level was re-gained.

At the end of the dry season, the water level in various wells ranged from 2.85 m to 4.06 m below the fadama. In clusters that are intensively used (e.g. As on Figure 6.1), the well levels were slightly deeper. However, in a typical year, well levels do not retreat below 4 m. Beyond this depth, wells used primarily for irrigation are abandoned because the cost of well extension exceeds what most farmers are prepared to invest.

6.5 Profile of water users

The village of Katarko has an estimated population of 4000 and comprises five major ethnic groups, viz, Kanuri, Fulani, Hausa, Shuwa Arabs and Kare-Kare. Islam is the only religion practised. As in most of northern Nigeria, Hausa is the *lingua franca.* Though mixing freely in every social aspect, the groups occupy different parts or wards (*Angwar* in Hausa) within the village. Furthermore, different ethnic groups specialise in different activities. Thus, the largest group, the Kanuri's, concentrate on rain-fed agriculture and some trading, the Hausa's specialise in trading and irrigation agriculture, and the Fulanis, also a major group, are largely cattle rearers.

There are 33 hand-dug wells within the village which range in depth from 8 meters near the river to 29 meters in the northeastern part. Eleven (11) of these are public wells and the rest are privately owned. In an average year, 24 of the wells dry up at the peak of the dry season, leaving 3 communal and 6 private wells to serve the village. Most people depend on shallow wells at this time. Unlike many deep wells in the village, the fadama wells are treated as communal property. Each ward, and hence a dominant ethnic group, constructs and maintains a cluster or clusters of wells. This gives rise to some segregation of water use along ethnic lines but such segregation is not consciously enforced. Our field survey showed that each cluster of wells was visited by users from several wards (Fig. 6.8). In general, most users visit those wells that are closest to them. One exception is the well cluster labelled Ds (Fig. 6.1) which are constructed and maintained by water vendors. Water vending is an exclusively male occupation. While the vendors come from all over the village, their clientele comprises largely commercial outlets such as butchers, traders and food stands as well as people from those wards farthest from the river where the labour involved and distance to shallow wells is greatest.

To obtain a pattern of water usage of the shallow wells, a survey of well users was carried out on May 6-11, 1994; June 16-21, 1995 and March 15-16, 1996 between 6.00 am and 10.00 pm each day. The interviewers/observers consisted of four men and one woman. Information was collected simultaneously at each of the sample wells on the villagers who visited the wells including their ward of origin, person (child, female or male), frequency of visits, amount of water withdrawn, the type and size of container used and the intended use for the water. For the purpose of this study, all visitors 14 years old or younger were classified as children since, in Katarko, the marriage age for girls is 15. Information obtained during the three sample periods was remarkably similar. Table 6.1 presents average frequency and amounts of water withdrawal for human use and for livestock watering during the sample periods.

Table 6.1 suggests that children (under 13 years) are particularly involved in the search for water, accounting for between 15-40% of visits at all wells. They use a variety of containers, ranging from 4 l cans to cattle-drawn carriages carting 200 l barrels. On average, children carry about 12 l of water per visit. Apart from the well cluster marked Cs, it appears that more women fetch their water from the village wells, carrying about 14 l per visit. Earthen pots and open metal cans are the most commonly used containers. On the other hand, more men visit the shallow wells than women. Using cattle-drawn carriages and large containers, they withdraw between 80-100 l per visit.

Spatially, there are large differences in the number of men and women who visit particular wells. For example, during all 3 sample periods, very few or no female visitors were recorded at well cluster As in the fadama (Table 6.1) and wells 26 and 29 within the village (result not shown). These wells are maintained and used largely by the residents of Dan Gujba and Mallam Kolori wards where the *Purdah* system is strictly observed. Purdah is a custom which keeps women hidden from men and strangers. At these wards, the burden of sourcing for water outside the compound lies almost entirely on men and children. There are also no women at Ds which is maintained by water vendors, traditionally a male occupation.

6.6 Frequency and amount of water withdrawal

Water is hauled from the wells using a skin bag or other form of container (e.g. plastic bucket) tied to the end of a hand-line. Average capacity of the container is approximately 4 l. Multiplying this value by the number of times the containers are hauled allows an estimate of the water withdrawal rate. From a previous survey, the containers commonly used to fetch water were noted and categorized. The volumes of containers in each category were then established by comparison with the known volumes of standard containers. Combining these two methods allows reasonable estimates of volumes of water withdrawal. Water consumption rate for livestock is determined by multiplying the number of animals herded to the wells by their average water requirement. A full grown cow or horse consumes 30 l/d, a donkey requires 20 l/d while a goat or sheep needs 10 l/d (Dabi, pers. Comm.).

Figure 6.9 shows average frequencies of water withdrawal at five shallow well clusters and two village wells (June 16-21, 1995) . There were two periods of intensive activity during the day, one in the morning and the other in the evening. The intensity of withdrawal is higher in the evening when many households return from work and fetch water to store for the night and for the next day. Peak withdrawal is generally around 5 p.m. In the early afternoon, particularly between noon and 2 p.m., few villagers withdraw water from the wells. However, the Fulani's routinely use all the wells to water their livestock at this time. In this way, the competition for water between livestock and people is minimised.

The frequency of visit to shallow wells depends on the yield rate of the well, the proximity to other viable wells and the population of the wards that depend on the wells. Well clusters with high hydraulic conductivities and quick recovery times such as As and Cs are used more intensively. In contrast, water depth is an important factor influencing the use of village wells. For example, well 29 (depth = 29 m) is viable but it is used far less frequently than well 21 (9 m deep) and well 14 (13 m deep). However, the frequency of visits to a well does not necessarily determine the total amount of water withdrawn. In fact, the converse is true in many cases, namely, the further the wells are from the village, the less is the frequency of use although more water is withdrawn because larger containers are used. Hence, well 14, a village well, had the highest observed average visits (85) during the sample period but total withdrawal is estimated at only 1000 l/d. On the other hand, only 32 people on average, visited well cluster Es 1.0 km from the edge of the village, but total withdrawal was about 2900 l/d. Similarly, 75 people visited Cs (500 m from the village) withdrawing about 900 l/d and 82 visitors to As (1.5 km away) withdrew an estimated 6600 l/d.

Estimated amounts of water withdrawn for animal consumption at the shallow wells are also included in Table 6.1. Because of their nomadic nature, the number of livestock within the floodplain is quite variable on any given day; passing herds of livestock may swell the number by up to five times.

6.7 Discussion and conclusion

Fadama wells represent an important source of water supply to rural northern Nigeria because, (1) in contrast to deep ground water wells, they are inexpensive to construct and maintain, (2) they represent the last measure of defense against droughts and their supply is often reliable during most part of the dry season, (3) their water table is close to the surface, thus reducing the tedium involved in hauling water, and (4) they are treated as communal properties, allowing easy access from different ethnic groups or individuals. Through generations of experimentation and adjustment, traditional systems have evolved mechanisms for accommodating the diverse and competing interests which depend on the fadama aquifers. The timing of water abstraction during the day represents one such arrangement. Irrigation farmers and other villagers fetch water during the morning and in the evenings while the herdsmen use the wells in the afternoon. The times are so spaced as to allow the wells sufficient time to recharge and neither group imposes on the other. The spacing of the wells in the floodplain is also designed to minimize conflict and avoid local overdraft of water levels.

The introduction of petrol-driven irrigation pumps has offset this balance in a few locations. Because the pumps have allowed a four-fold increase in the size of irrigation plots, farmers pump out much more water during the mornings so that the wells are not sufficiently recharged when the herdsmen need to water their livestock. There have been claims also (though these could not be verified during the period of this study) of lowering water levels in hand-dug wells located in the vicinity of pumped wells. Furthermore, the perceived profitability of irrigation agriculture has meant that more fadama land is being claimed for irrigation at the expense of livestock grazing. This has led to confrontations between pastoralists and farmers in Katarko. Elsewhere in the Hadejia-Nguru valley, Kimmage (1991) reported that at least three fatalities occurred in separate confrontations between grazers and farmers.

An important finding of the study is that in this village at least, children, women and men are involved almost to the same degree in the search for water. While no generalizations can be drawn on the basis of such a small sample, the popular notion that only women and children bear the burden of fetching water in rural parts of Africa may need to be tested in particular settings. Religious and other cultural factors may play important roles in determining who fetches water.

The beginning and end of the rainy season present peculiar problems for both the quantity and quality of water supply. In the former case, shallow wells are rendered useless by runoff, deep wells are not yet recharged and available water ponds are muddy and polluted. At the end of the rainy season, the flood plain is too muddy for well construction and water level in the deep wells drop rapidly. These periods require special consideration in any rural water supply scheme.

Population growth, rising per capita water demand and changes in agricultural technology and practices are all expected to increase pressure on scarce water resources in semi-arid environments. As is often the case, crises in rural areas are precipitated by developments in urban areas. For example, much of the need for expansion in irrigation agriculture in Katarko has been prompted by the emergence of Damaturu as the capital city of the new Yobe State. Already, there are plans (albeit preliminary) to dam the Anumma river as a source of water supply for the capital city. Such proposals portend serious implications for the fadama aquifers which deserve comprehensive analysis.

In this study, it is shown that fadama aquifers are the most dependable sources of water where they occur. The fact that they are recharged seasonally when the fadamas are flooded implies that they are sustainable as long as there are no disturbances to the valley morphology or structure and there is no serious pollution of the aquifers. While the developments of such aquifers may become inevitable, any water resources project must take into account the existing traditional mechanisms of accommodation, conflict avoidance and resolution.

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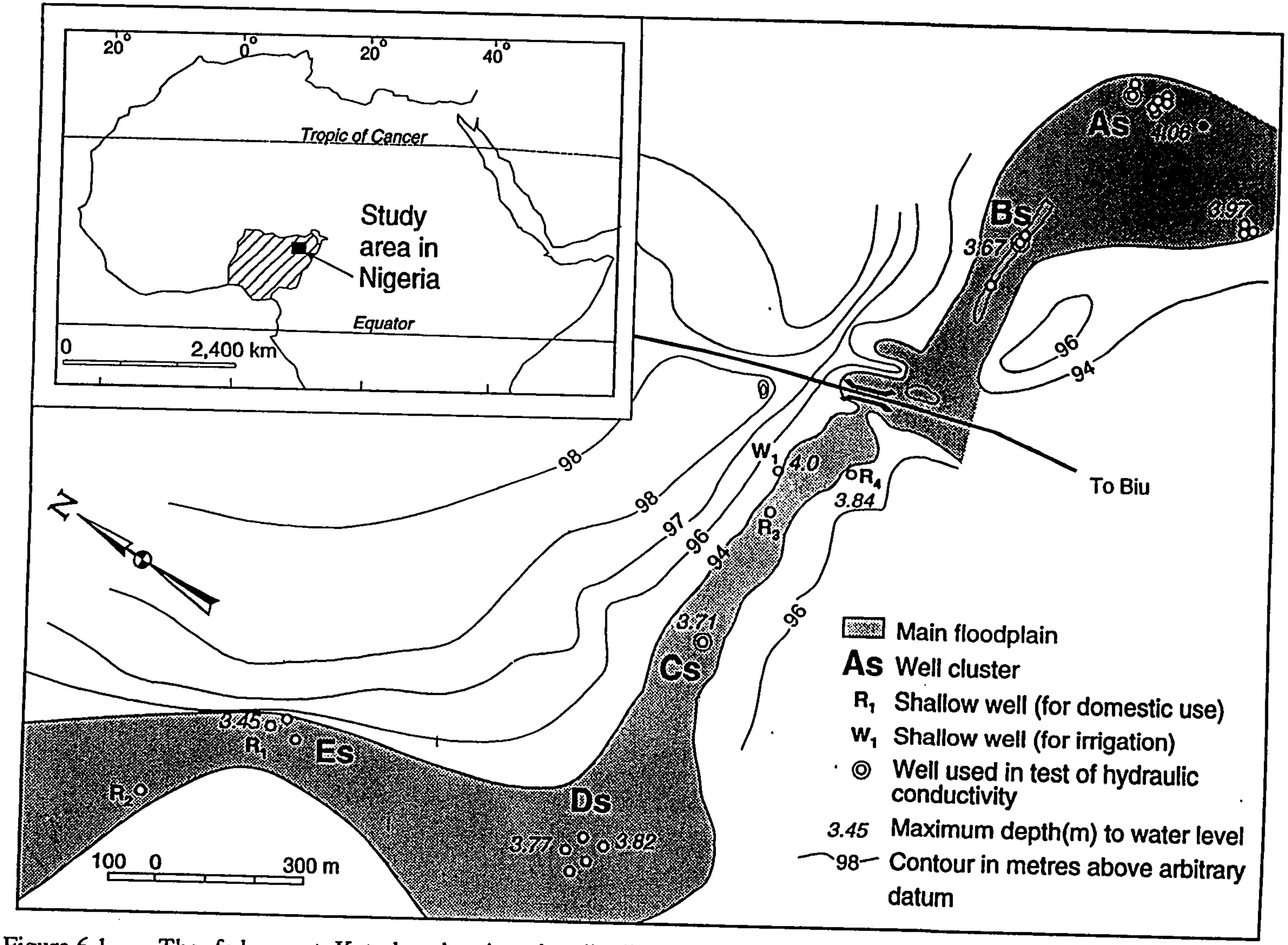


Figure 6.1 The fadama at Katarko showing the distribution of shallow wells and maximum well depths.

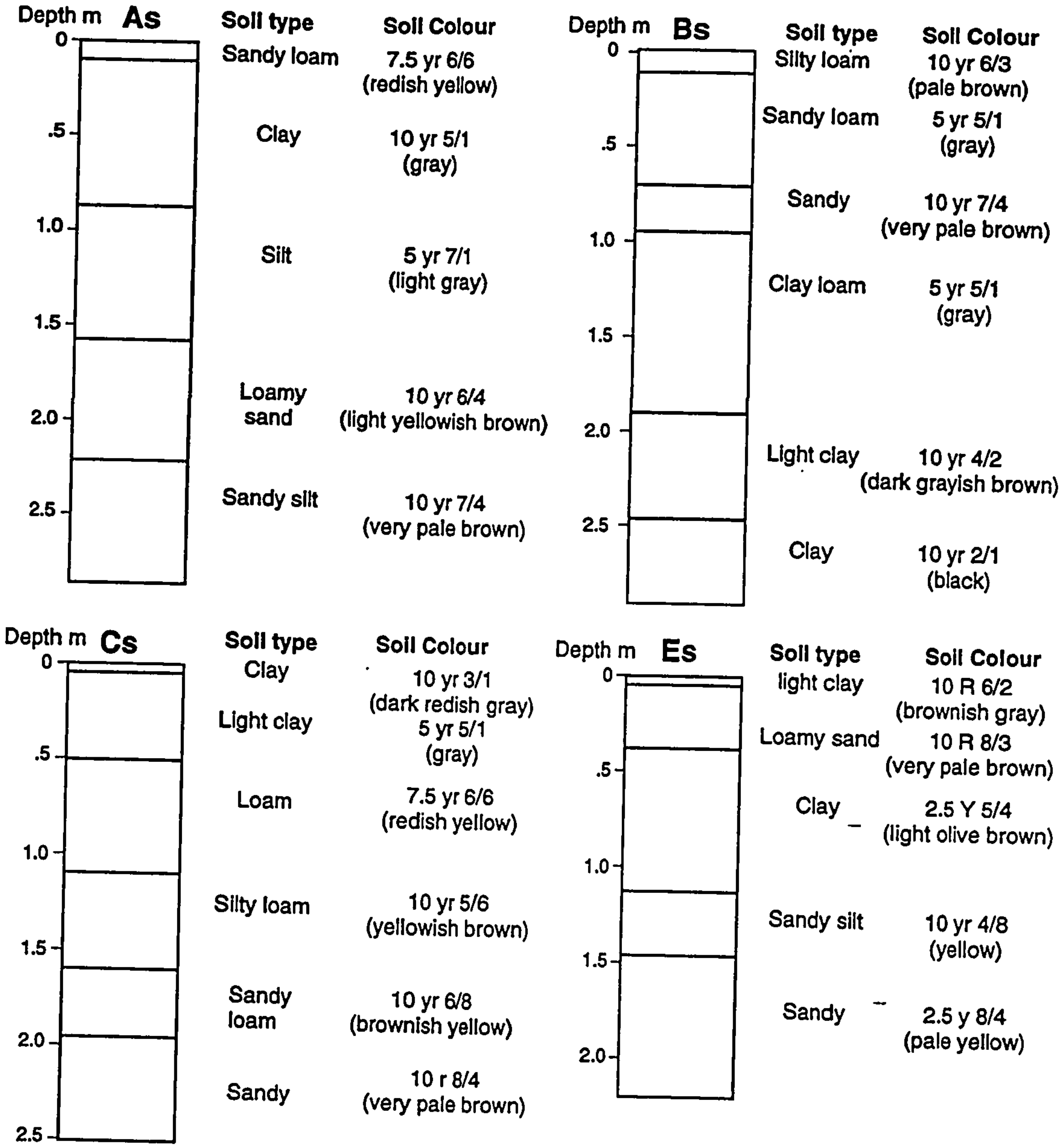


Figure 6.2 Soil stratigraphies in the fadama as revealed at four shallow wells.

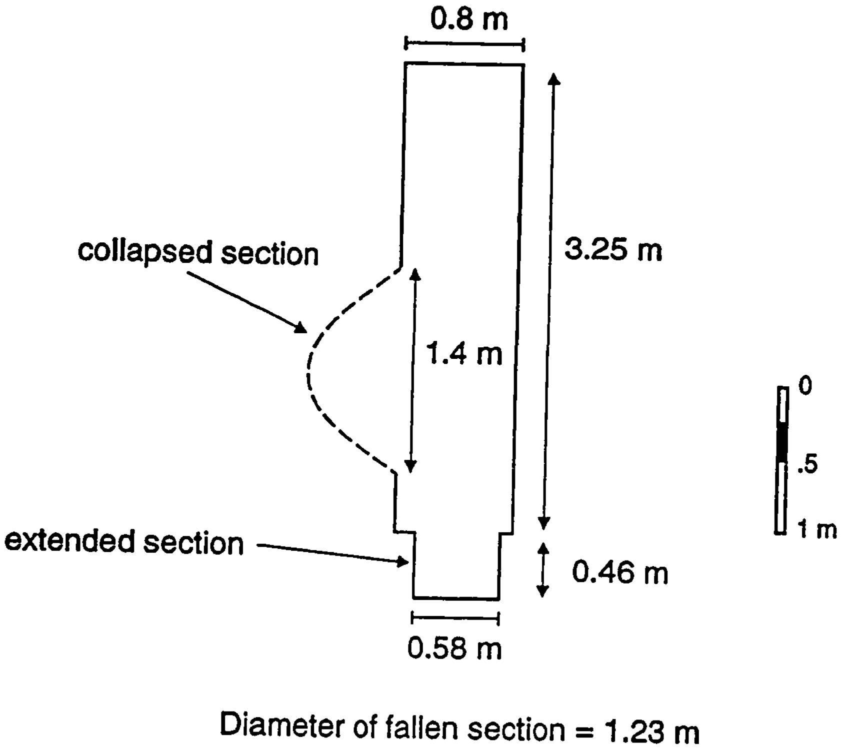


Figure 6.3 Cross-section of a collapsed shallow well (Cs).

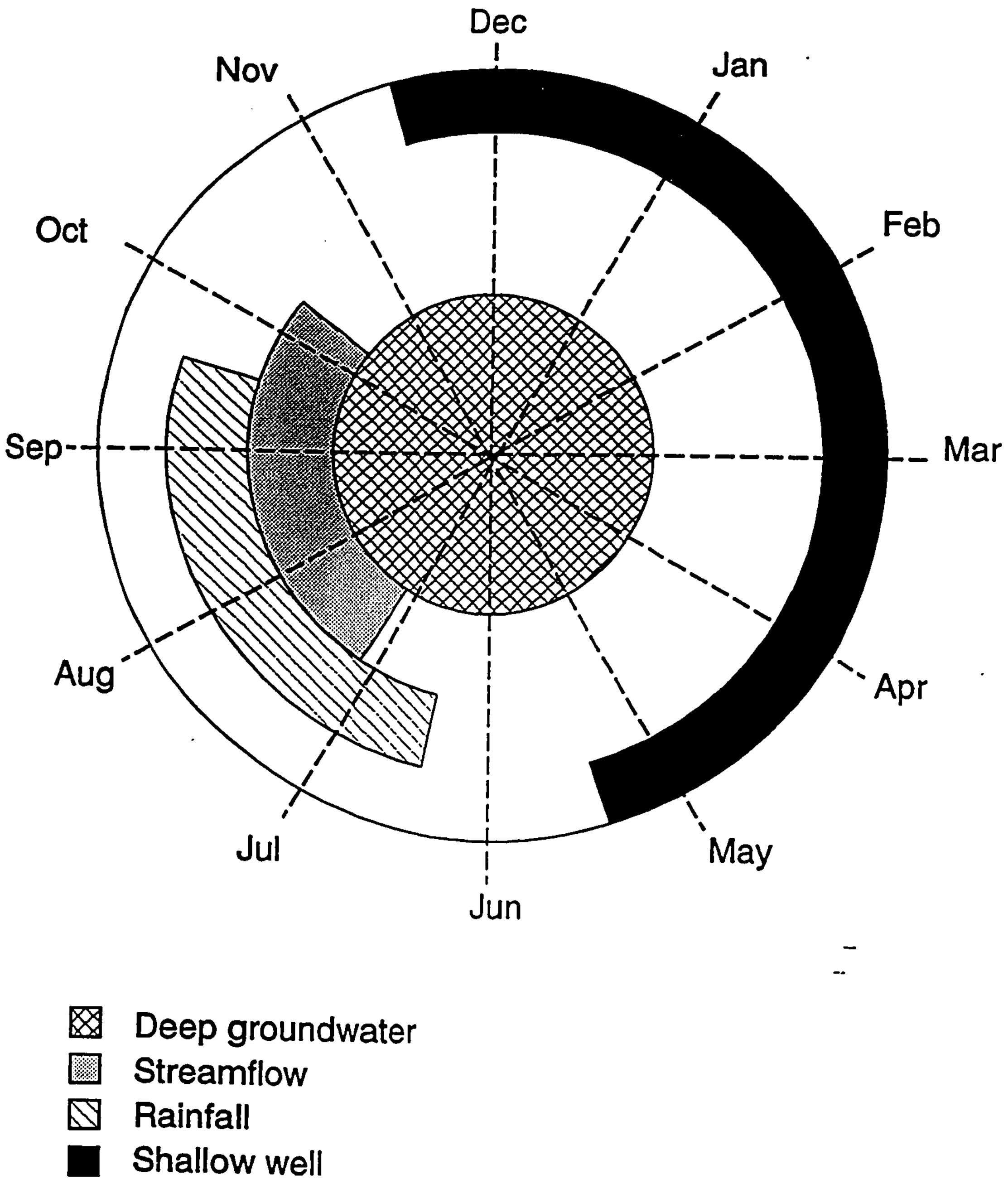


Figure 6.4 Timing of shallow well use in relation to other sources of water.

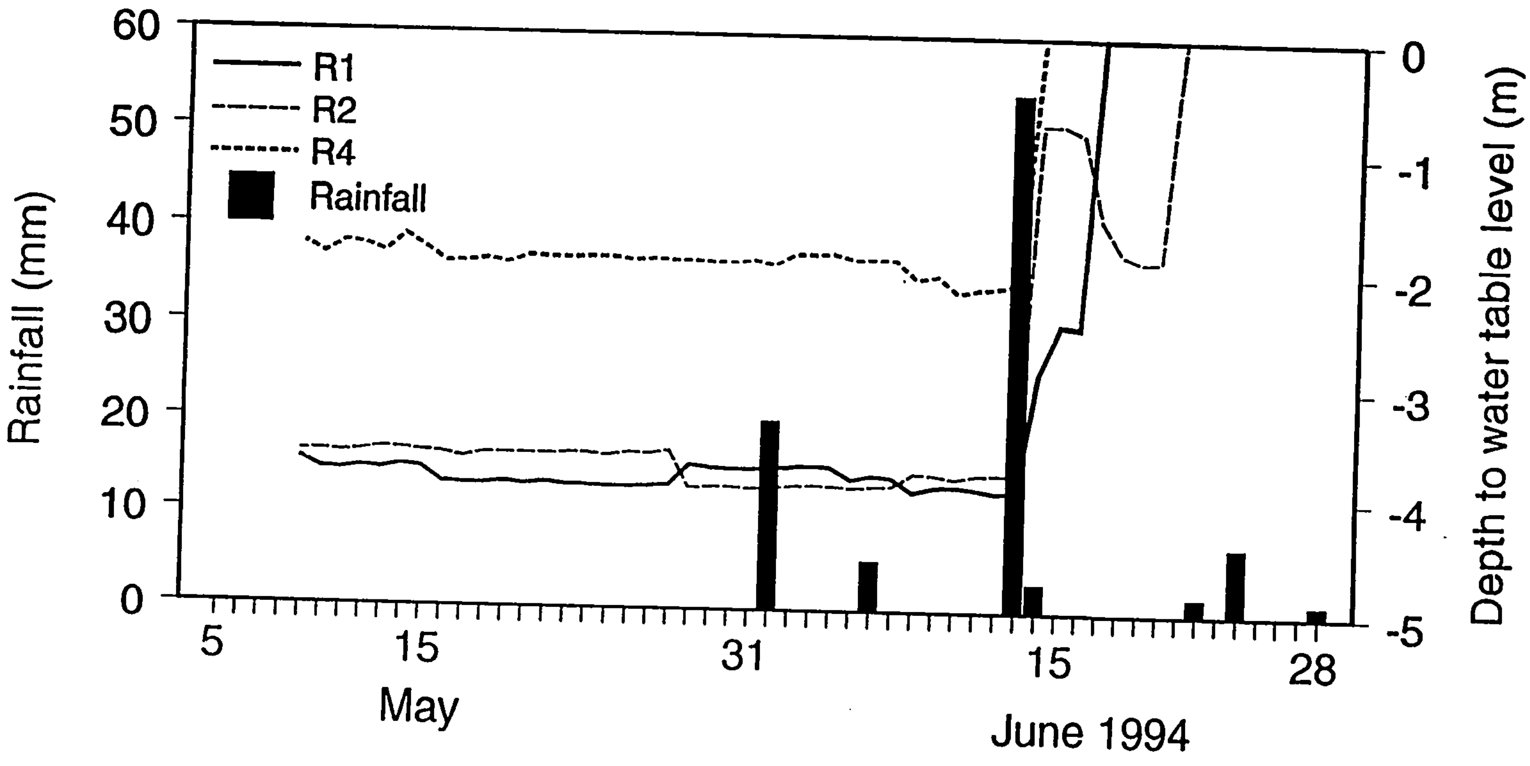


Figure 6.5 Daily variation of well levels during the transition from dry season to wet season.

Figure 6.6 A preferred well site. Pits mark the position of shallow wells in previous seasons.

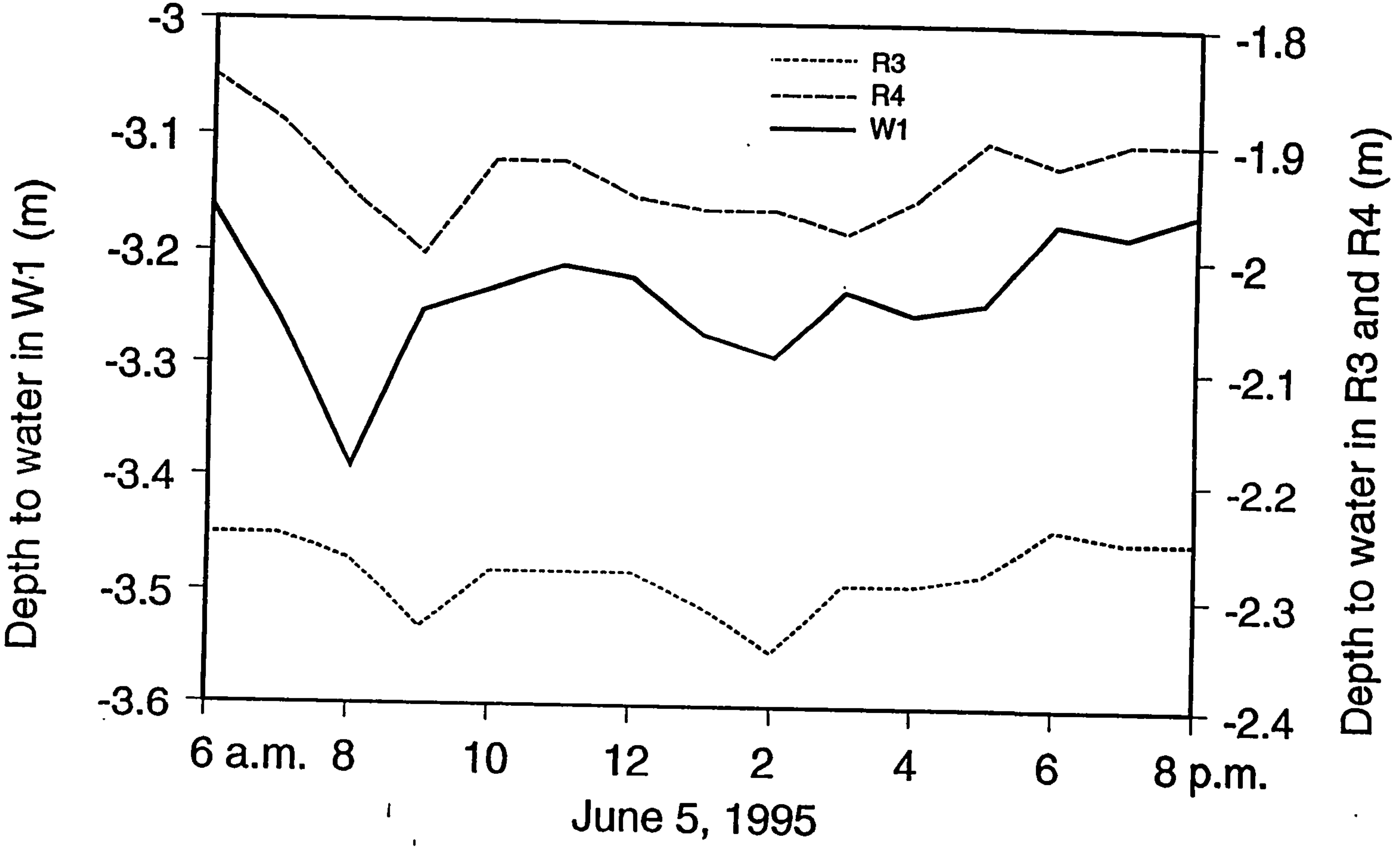


Figure 6.7 Comparison of hourly fluctuations in water level in wells used for domestic water supply (R1, R2) and irrigation (W1).

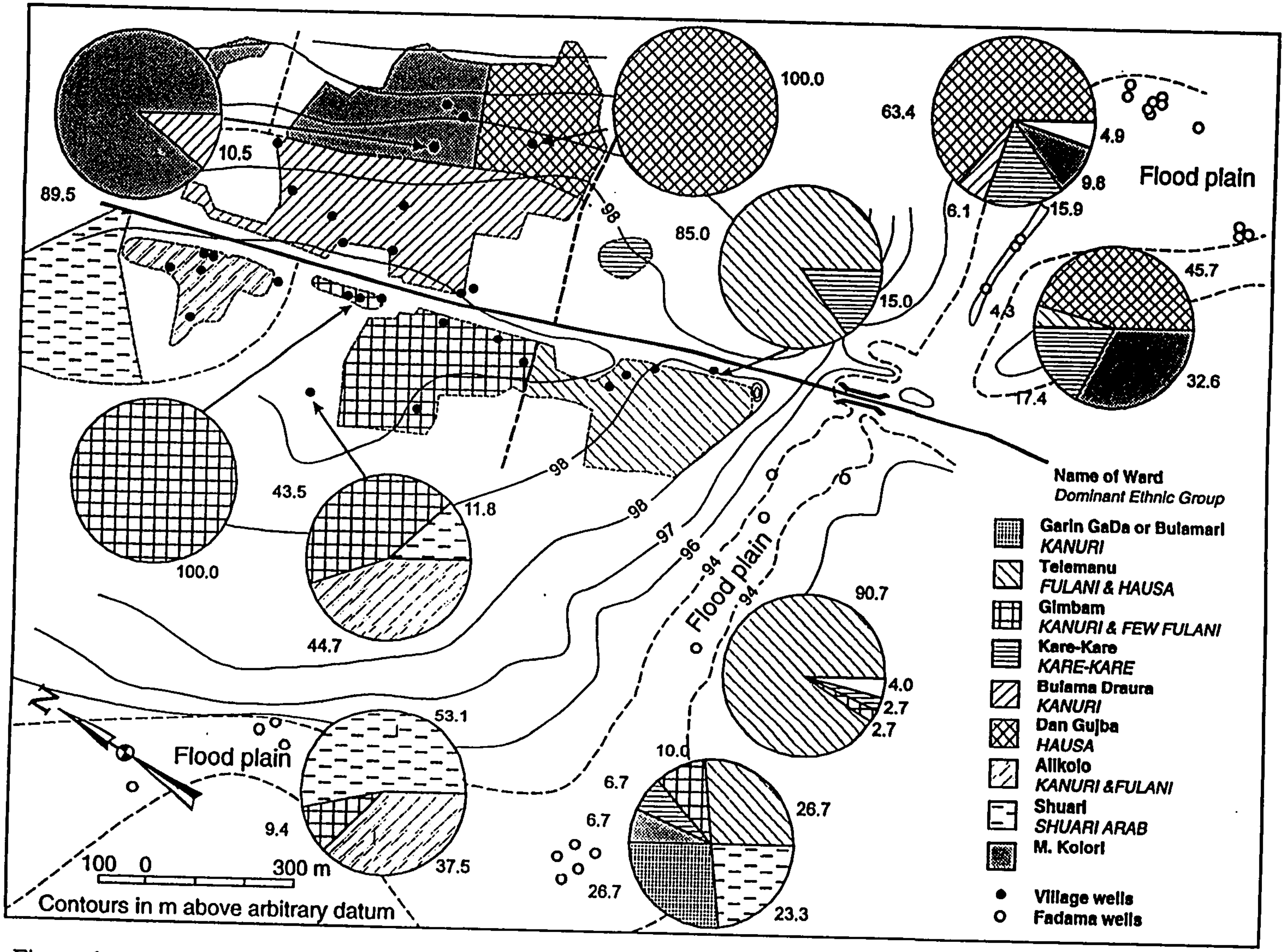


Figure 6.8 Ward origin of water users at well sites.

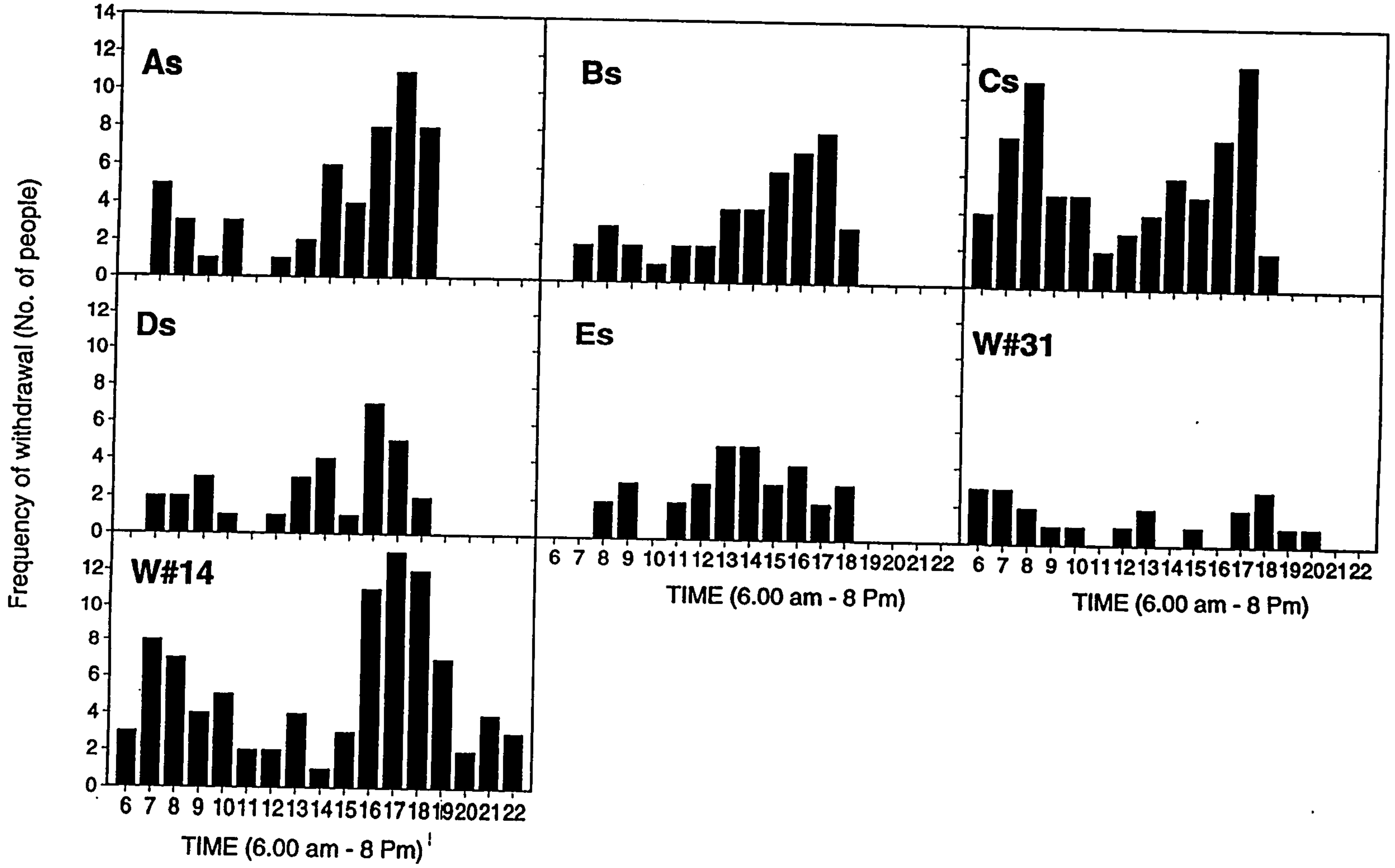


Figure 6.9 Average frequency of water withdrawal at five shallow well clusters. Average frequency at two village wells during dry season (W#31 and W#14) are included for comparison.

Table 6.1 Average frequency of visits and amount of water withdrawal from fadama and village wells during the dry season

Fadama Wells			Number of visitors				Water withdrawal for human consumption (l)		Number of animals					Livestock Water Consumptio (l)
Well Cluster	Visits per/d	Ward origin of visitors	Total	Children	Female	Male	Total	Average per person	Cows	Goats	Sheep	Donkeys	Horses	
As	82	Dan Gujba	52	14	0	38	6642	81	32	62	36	3	1	1990
		B. Daura	5	2	0	3								
		A. Kare-Kare	13	3	2	9								
		M. Kolori	8	2	0	8								
		Outskirts	4	1	0	3								
Bs	46	Dan Gujba	21	17	0	4	690	15	13	9				480
		Telemanu	2	2	0	0								
		A. Kare-Kare	8	3	4	1								
		M. Kolori	15	8	3	4								
Cs	75	Telemanu	68	13	47	8	900	12	35	122	63			2900
		Gimban	2	0	0	2								
		A. Kare-Kare	2	0	0	2								
		Outskirts	3	0	0	3								
Ds	30	Telemanu	8	5	0	3	2310	77	80	115	11	7		3800
		Gimban	3	1	0	2								
		A. Kare-Kare	2	0	0	2								
		M. Kolori	2	0	0	2								
		Bulamari	8	2	0	6								
		Shuari	7	2	0	5								
Es	32	Shuari	17	5	5	7	2880	90	44	119	67	4	2	3320
		Gimban	3	0	2	1								
		Alikolo	12	2	5	5								

Table 6.1 Continued

Village Wells

	Number of visitors						Water withdrawal (l)	
Well	Visits per/d	Ward origin of visitors	Total	Children	Female	Male	Total	Average per person
WO14	85	Shuari	10	0	7	3	1020	12
		Gimban	37	18	11	8		
		Alikolo	38	19	14	6		
W026	13	Gimban	13	7	1	5	234	18
W029	19	M. Kolori	17	2	2	13	306	18
		B. Daura	2	1	1	0		
W021	80	Telemanu	68	18	31	19	960	12
		A. Kare-Kare	12	3	4	5		
W010	18	Gimban	18	6	8	4	288	16

CHAPTER SEVEN

CONCLUSIONS

7.1.0 Major findings

Droughts and recurrent episodes of water scarcity have been a constant feature of the climate of semi-arid West Africa and will, in all likelihood, continue to plague the region in the future. To understand and predict future occurrences or develop strategies to minimize and manage their effects, comprehensive information is required on all aspects of the problem. This research investigated the phenomena at different spatial and temporal scales: from the historical to the contemporary and from the central Sahel to a sample community in northeastern Nigeria. It examined some basic and widely held assumptions prevalent in drought studies and provided information at the rural level which is necessary for the assessment of various water scarcity scenarios. The following conclusions emerged from the study:

1. Historical information on famines are suitable proxy for drought events. This revelation is of significance because unlike in other parts of the world where historical information is available in various forms, famine chronologies represent one of the few documented sources of historical climatic events in Sahelian Africa. The study utilized the existence of parallel information on climatic data and historical/folklore famine events to establish the threshold of rainfall deficit at which a famine/historical drought occurs. By relating famines and droughts in quantitative terms, the results offer a possible approach to climatic reconstruction in the Sahel. For example, through cautious interpretation and suitable assumptions, it is possible to infer the magnitude of rainfall deficit during periods of famine which predate the beginning of scientific measurements.

2. Since historical times, anomalous climatic periods of various durations have occurred over the West African Sahel region. Droughts lasting one to three years tend to be less severe, more localized, more spatially variable, and more frequent than longer duration droughts. Conversely, the latter tend to be more regional, more severe and separated by long intervals between occurrences. Since, 1600 AD, drought events approaching the duration of the recent so called, 17-year drought have occurred in the central Sahel.
3. The magnitude and duration of droughts as well as rainfall trends are sensitive to the interval over which they are evaluated. For example, depending on the interval used, the period 1970-1987 may appear as one continuous drought or three separate events of about 3-4 years in duration. Similarly, the interval may appear to be dominated by very pronounced trends (up to 8 mm y^{-1}) or by relatively stationary climate or even an upward trend. The study demonstrated that the widely used climatic normal periods are unsuitable as base periods for trend estimation and drought analysis. On the other hand, statistical change point methods offer objective criteria for the determination of base intervals for analysis and for demarcating the drought prone region into sub-zones based on the magnitude of changes in the rainfall characteristics.
4. The study showed that the recent observed changes in the total annual rainfall over northern Nigeria were driven by a reduction in the number of rain events, particularly rainfall of high daily intensity ($\geq$ 25 mm d^{-1}). Low intensity rainfall ($<$ 25 mm d^{-1}) as well as the dates of onset, termination and duration of the rainy season remained relatively unchanged.
5. Despite the occurrence of a significant discontinuity in the series of rainfall variables, the variability around the general trend lines was relatively unaffected. Furthermore, the variability can be described by the well known normal distribution and used to assess the probability of risk for various levels of water requirements.

6. Rainfall is the major source of water supply to the rural areas. Other sources such as stream discharge and groundwater may supplement the supply at various times of the year but the storage from these sources is generally small, so that their reliability is dependent on the rainfall. This fact underlines the vulnerability of the region to drought.
7. The research provides information on the interaction among various sources of water for rural communities which is useful for formulating rural planning policies for drought mitigation.
8. For communities residing on or near flood plains, shallow groundwater may be the most important source of water, supplying water for eight months of the year. This finding suggests that the alluvial aquifers should be incorporated as major components in water resources monitoring networks. The fact that the alluvial aquifers are recharged by the seasonal flooding of the streams and the interaction between alluvial aquifers and the deep aquifers suggested by the research calls for caution in river regulation and control in the semi-arid region of Nigeria.

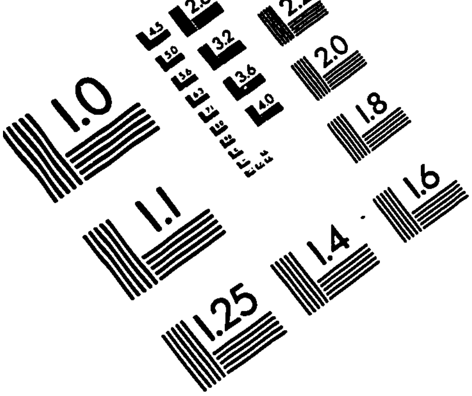
7.2.0 Future research

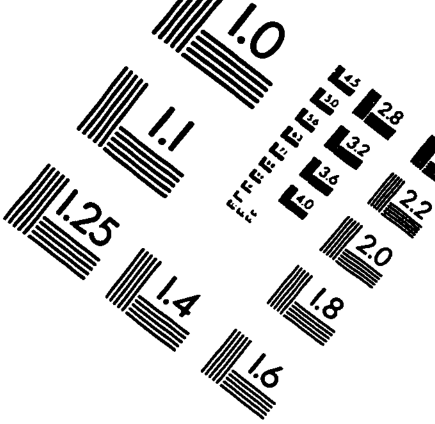
The findings enumerated above contribute significantly to the understanding of various aspects of drought in northern Nigeria and also highlight potential areas for future research. For example, concerning the historical study, a more rigorous and statistically verifiable procedure for converting records of famine into historical droughts is needed. This can be achieved by incorporating a ranking scheme in the calibration procedure. Then, after due verification of all available information, the historical famine events can be converted into ranks and the numerical ranks used in further analysis.

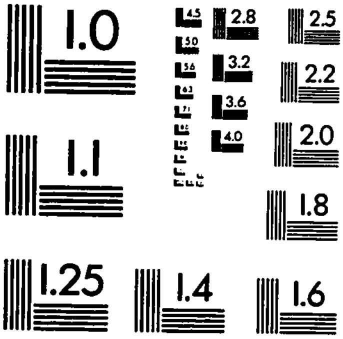
Furthermore, empirical analysis such as those presented in the research have an built-in constraint, namely; the predictive capacity is poor. A useful approach for drought analysis is one which offers the potential victims enough warning time to take evasive or preventative action. Such an approach requires better understanding of the causative processes and the lag times between the triggering mechanisms and the manifestation of drought. Preliminary studies suggest that for the West African Sahel, sea surface temperatures hold the best explanatory potential. However, such explanations often refer to regional scales and overlook important smaller scale variabilities. More research is needed to establish the predictive potential of SST's as well as improve the resolution of the scale of prediction.

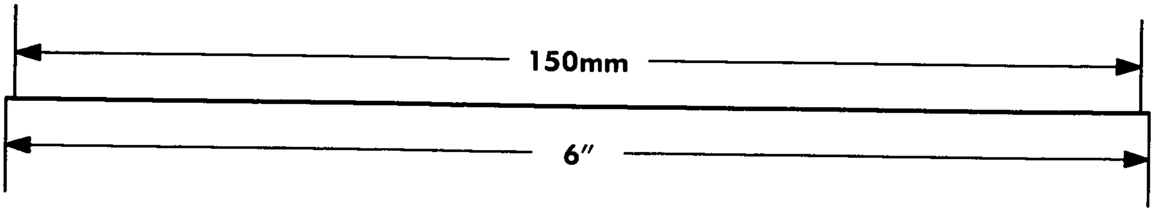
At the local level, the interaction suggested between alluvial and the deep aquifers deserve further investigation because of the implications of river regulation on domestic water supplies and downstream recharge. Furthermore, the potential of the alluvial aquifers needs to be determined. An important question is whether they are hydraulically connected to the so called deep aquifers or whether they are perched. Similarly, the capacities of water yielding sub-units within the flood plain should also be of interest to rural and water resources developers.

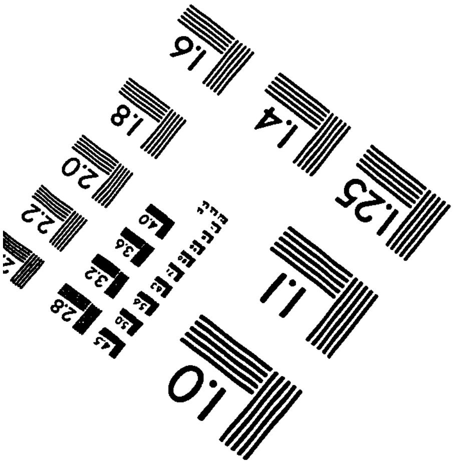
Finally, the applied value of the research would be vastly improved if it can articulate scenarios of water scarcity associated with different levels of rainfall fluctuations.

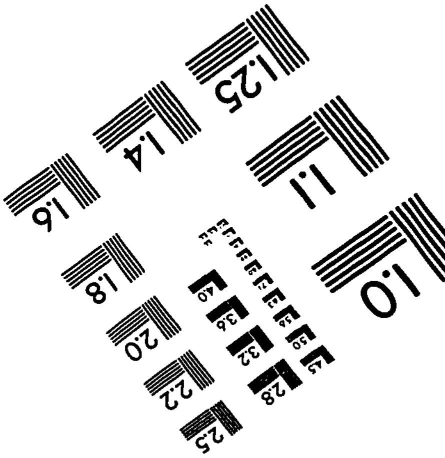












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