ANALYSIS AND QUANTIFICATION OF DROUGHT USING METEOROLOGICAL INDICES IN THE SUDANO-SAHEL REGION OF NIGERIA

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**A Dissertation Submitted to the Postgraduate School,
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**Department of Water Resources and Environmental Engineering
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AUGUST 2005.

DECLARATION

I, **Engr. OTUN, Johnson Adebola** hereby declare that this dissertation has been written by me and that the information contained herein is a record of my own research work. It has not been presented in any form for the award of any degree at the Ahmadu Bello University or any other University.

All sources of information obtained from other literary publications have been duly acknowledged by means of references.

Engr. J. A. OTUN	**Date**

CERTIFICATION

This dissertation entitled **ANALYSIS AND QUANTIFICATION OF DROUGHT USING METEOROLOGICAL INDICES IN THE SUDANO-SAHEL REGION OF NIGERIA** by **Engr. OTUN, Johnson Adebola** meets the regulations governing the award of the degree of Doctor of Philosophy (Water Resources and Environmental Engineering) of Ahmadu Bello University, and is duly approved for its contribution to knowledge and literary presentation.

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Chairman, Supervisory Committee

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Prof. C. A. Okuofu **Date**
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Head of Department **Date**
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Dean, Postgraduate School **Date**

DEDICATION

This research work is solely dedicated to GOD who makes all provisions to solve all spiritual drought problems by making whosoever believes in HIS only begotten SON to never thirst anymore and also escape the eternal drought in hell after this world.

ACKNOWLEDGMENT

First and foremost, I give my thanks to my Almighty Father whose mercy on me endures forever. I acknowledge that He is at work in me both to will and do of HIS good pleasure. One of such is this achievement of becoming a Doctor of Philosophy in the face of every difficulty. I give him all the praise and adoration in Jesus Name.

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ABSTRACT

Unlike the common use of only 'rainfall amounts' in indexing the drought in a place, this study have identified, verified and validated the potentials of nine (9) other precipitation effectiveness variables (PEV) that can equally reflect the drought conditions in any place. The 10 PEVs have been effectively combined to derive a 'at-site' operational drought index called the Conjunctive Precipitation Effectiveness Index (CPEI). A historical daily rainfall record from 1916-2003 for seven (7) stations in the SSRN was used to estimate CPEI for these stations. The CPEI obtained, using the 1023 possible arrangements for the various combinations of the 10 PEVs, were respectively statistically compared with the values for the Standard Precipitation Index (SPI), Rainfall Anomaly Index (RAI), Bhalmey-Mooley Drought Index (BMDI) and Palmer Drought Severity Index (PDSI). Results obtained showed that a maximum combination of six (6) PEVs gave an average correlation (r) value above 0.8. Those arrangements with $r > 0.8$ were further ranked and through a descriptive analysis, it was shown that the ultimate number of PEVs that can be effectively combined to get the optimum CPEI values for indexing the drought is three (3) PEVs for Gusau and Kano, five (5) PEVs for Sokoto and Maiduguri and four (4) for the rest stations under study. The drought conditions for over 50 years, in the SSRN, were therefore examined using the derived optimum CPEI index and other four indices. The results obtained for each of the indices compared very well with notable historical drought years. These preliminary applications show that most of the indices used can be considered as operational tools for a national drought watch system in the SSRN to quantify and characterize the drought conditions

objectively. As the significant level of occurrence observed with one of these PEVs, i.e. dry spell occurrence within the wet season and year, for each of the station under study, initiated some concerns and interests. The study therefore also attempted to further analyze the incidence and distribution of the dry spell occurrences in the SSRN as a way of making suggestion on how the incessant spell in the SSRN can be well accommodated. The analysis involves an empirical analysis of the dry spell (EADS) in the SSRN. The results from the EADS provided an ample of information that can be used as guides for various agricultural applications.

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LIST OF SYSMBOLS

α Coefficient of evapotranspiration
β Coefficient of recharge
γ Coefficient of recharge
σ Coefficient of moisture loss from the soil to evapotranspiration
Cv Coefficient of variation

I_k Drought intensity of the k^{th} month

K_i Climatic weighting factor for the i^{th} month

$L_{surface}$ Loss of moisture at the surface level of the soil

L_{lower} Loss of moisture at the lower level of the soil
mm Millimeter

MI Moisture Index
MI_t Accumulated moisture index over a duration of t months

R_a Actual monthly rainfall

$\bar{R_a}$ Long-term mean monthly rainfall

R_o Truncation level of a time series of a drought variable R

R_m Mean of the time series of a drought variable R

R_N Normal precipitation

$\bar{R_m}$ Mean of the ten highest values of R_a

$R_{surface}$ Recharge of the surface level of the soil

R_{lower} Recharge of the lower level of the soil

$\bar{R_x}$ Mean of the ten lowest values of p on record.
SD Standard deviation

Ss **Soil Moisture Content of the topsoil layer**

Su **Soil Moisture Content of the underlying soil layer**

W_i PDSI value for the i^{th} month

Z Moisture anomaly index

LIST OF ACRONYMS

m	meter
km	kilometres
AWC	Available Water Holding Capacity
BMDI	Bhalme and Mooley Drought Severity Index
CAFEC	Climatically Appropriate for Existing Conditions
CMI	Crop Moisture Index
CPEI	Conjunctive Precipitation Effectiveness Index
CRS	Cessation of Rainy Season
CSRE	Centre of Studies in Resources Engineering, Indian Institute of Technology, Bombay
DAS	Days after Sowing
DI	*Decile Index*
DIBM	Drought-Index Based Methods
EADS	Empirical Analysis of Dry Spell for Agricultural Applications
ET	Evapotranspiration
FORTRAN	Formula Translation
HDSI	Herbst Drought Severity Index
K	Climatic Characteristics
L	Drought Length
LDS	Length of the Dry Season
LRS	Length of the Hydrologic Rainy Season
Ls	Loss of moisture from the soil to evapotranspiration.
MAR	Mean Annual / Seasonal Rainfall Depth
MDL	Maximum Dry Spell occurring within a Wet Season.
MMD	Monthly Mean Deficit
NCDC	National Climatic Data Centre
NDMC	National Drought Mitigation Centre
NIMET	Nigerian Meteorological Agency
NR1, NR5	Non-Zero 1 or 5-Days Cumulative Rainfall Series
NRI	Normalized Rainfall Index
ORS	Onset of Rainy Season
PDSI	Palmer Drought Severity Index
PE	Precipitation Effectiveness
PET	Potential Evapotranspiration
PEV	Precipitation Effectiveness Variables
PL	Potential Loss
PNI	Percent of Normal Index
PR	Potential Recharge
PRO	Potential Runoff
PR	Potential Recharge
RE	Recharge

RAI	Rainfall Anomaly Index
RO	Runoff
SD	Standard Deviation
SMD	Soil moisture Deficit
SPI	Standardized Precipitation Index
SRI	Standardized Rainfall Index
SSRN	Sudano-Sahelian Region of Nigeria
SUSA	Sudano-Sahelian Area
TDS	Total number of Dry Spell within a Wet Season
TDW	Total number of Dry Days within a Wet Season
TDY	Total number of Dry Days within a Year
TWD	Total number of Wet Days within a rainy season
WBM	Water Balance Method
WR1, WR5	Whole Seasonal Rainfall Series with all Series (i.e with Zero rainfall depth inclusive)

GLOSSARY OF TERMS

(i) **Atmosphere**: The atmosphere of the earth refers to the envelope of air surrounding the earth and bound to it more or less permanently by virtue of the earth's gravitational attraction. It is the most energetically active component of climate.

(ii) **Weather**: It is the current state of the atmosphere mainly with respect to its effect upon life and human activities. It refers only to short term variations of the atmosphere of the order of minutes to months.

(iii) **Climate**: Climate refers to the long-term manifestations of weather conditions during a specified interval of time usually involving several decades. It is a complex system controlled by some permanent features of the earth i.e. atmosphere, oceans, cryosphere and land surface.

(iv) **Decade**: It refers to 10 days averaging periods of each month.

(v) **Dry Day**: It refers to any day with no measurable rainfall.

(vi) **Dry Spell:** It refers to consecutive days without rainfall.

(vii) **Pentad**: It refers to 5 days averaging periods of each month.

(viii) **Season:** It refers to an interval of n-days. In this study, seasons are defined for 5, 7, 10, 30 or 365 days intervals.

(ix) **Synoptic / Rainfall Stations:**
These are rainfall-gauging stations where the Nigerian Meteorological Agency records daily rainfall and other meteorological or climatic variables.

(x) **Wet Day**: It refers to any day with a rainfall greater than 0.1mm.

(xi) **Wet Spell:** It refers to consecutive days with rainfall greater than 0.1 mm.

(xii) **Whole Seasonal Rainfall**: This refers to the continuous series of rainfall data as it was observed for a season. i.e with zero rainfall depth inclusive. For instance, the WR5 seasonal rainfall depth refers to the cumulative sum of daily rainfall depths of five consecutive days, even if they sum up to zero. Similarly, WR7, WR10 and WR15 are respectively for the 7, 10 and 15 days rainfall total. The WR30 and WR365 are also respectively representing a monthly and annual rainfall sum

CHAPTER ONE

1.0 Introduction

Drought is a recurrent climatic feature that occurs in virtually every climatic zone around the world. Using a set of characteristics such as severity, duration, spatial extent, loss of life, economic loss, social effect and long term impact, Bryant (1991) ranked drought as the first among all natural hazards. It adversely affect systems that places various demands on the available water within our society e.g. agriculture, hydropower generation, rural and urban water supply schemes and various industries (Panu and Sharma, 2002).

Unlike other natural hazards like floods, hurricanes and tsunamis that develop quickly and last for a short time, drought has a creeping or insidious nature. It evolves and builds up across a vast area over a period of time and its effect lingers for years even after the end of drought (Narasimhan (2004).

This complex nature of drought and the varying scales drought operates has perhaps also made it the most mysterious of all climatic phenomena and the least understood of all natural hazards. It has scores of definitions used to describe its diverse geographical and temporal occurrence (Hounam et al., 1975, NCDC, 2002). However, drought derives its meaning from the Anglo-Saxon word *'drugoth'*, meaning 'dry ground' and is broadly accepted to refer to a deficit or shortage of available water over an extended period of time in water sciences (Sen 1980 , NCDC 2002). Hence in this study, drought is considered as a meteorological anomaly characterized by a prolonged and abnormal moisture (rainfall) deficiency.

As a consequence of the catastrophic drought that has been ravaging the West African Sahel region since the late sixties, there was a great upsurge in drought research activities. Most of these drought studies have, in the past, concentrated on investigations of temporal and spatial fluctuations in monthly, seasonal and annual rainfall series, to quantify or assess the drought conditions of the Sahelian areas of West Africa. Such studies include those by Ayoade(1971, 1973 and 1977), Lamb (1980 and 1982), Gregory (1983), Nicholson (1983), Denneth et al. (1985), Hutchingson (1985), Nicholson (1985), Adefolalu and Oguntoyinbo (1985), Adefolalu (1986), Druyan and Koster(1989), Adejuwon et al. (1990), Demaree and Nicolis (1990), Olaniran and Summer (1990), Anyadike (1992 and 1993), Iwegbu (1993), Nicholson and Palao (1993), Hess et. al (1995), Jimoh and Webster (1996), Nicholson (1998), Tarhule and Woo (1998), Adeoye (2001), Sawa(2002) and L'hote et al. (2002) to mention a few.

A review shows that most of these studies used some descriptive and statistical methods to describe, infer, discuss and make useful conclusions on the incessant drought occurrences in the Sahelian region. The very few studies involved with drought quantification concentrated on the use of only 'rainfall amount' and neglected some other rainfall variables that can equally measure the effectiveness of rainfall and describe the drought conditions over an area.

Such "neglected" rainfall variables (referred to in this study as Precipitation effectiveness variables (PEV)) include rainfall features such as its timing (i.e. onset and cessation of rainfall, length of rainy season), its effectiveness (i.e. Number of rainfall events and non rainfall events, i.e. no of wet days, number of dry days etc.), its frequency and distribution over a place. These PEVs are presumed to give first indication of drought over a place. This study therefore intends to verify the potentials of some of these defined PEVs in describing the drought conditions of the Sahelian region of Nigeria, and use them, if found capable, to derive an operational drought index for quantifying drought conditions. It is hoped that the derived drought index will be able to reveal some drought information which hitherto has remained hidden or unaccounted-for.

There is the need to study the drought features or patterns in the Sahel region. A comprehensive approach for studying the drought features of a region according to Rossi et al. (1992), includes:- (a) identification of causes and drought prediction, (b) evaluation of drought characteristics (drought analysis or monitoring); (c) analysis of economic, environmental and social effects of drought (assessment of drought impacts) and (d) definition of appropriate measures for controlling drought effects or responses to drought. In this study, emphasis is placed on the second and the last aspects.

Firstly, since drought occurrences can rarely be prevented, evaluating its characteristics (i.e its magnitude, frequency or severity) will provide some information that is extremely beneficial in the development of response and mitigation strategies and preparedness plans (Otun, 1996). It is with the aforesaid view in mind that this research work was initiated to analyse and characterize the occurrence of drought in the Sudano-Sahel region of Nigeria. It is hoped that the results from this quantitative assessment of drought in the SSRN will add to the drought database of the country and also assist the Federal Government of Nigeria (FGN) in the formulation of its drought management policy which if well implemented will help to adequately combat the recurrent drought menace in the SSRN.

1.1. Research Objectives and Benefits

The general objective of the study is to use a combination of PEVs to develop an operational drought index for quantifying drought conditions in the SSRN, with a view to contribute meaningfully to the on-going drought research efforts in the Sahelian region of Nigeria. The specific objective therefore of this study include:

(a) To verify the potentials of some defined precipitation effectiveness variables (PEV) in describing or inferring the drought conditions in the SSRN.

(b) To conjunctively use a combination of these PEVs to develop an operational drought index for quantifying the drought conditions in the SSRN.

(c) Evaluate the performance of the derived drought index along with four (4) other notable drought indices.

(d) To make applicable suggestions towards effective management of the persistent dry spell occurrences within the SSRN.

The benefits to be realised from the study will include: -

(a) Improvement in hydrological analysis of drought in the Sudano-Sahel regions of Nigeria. This will eventually lead to effective planning and management of the scarce natural resource.

(b) Increase in the assembled drought database for the country. The information contained in this database can be utilised in the design, operation and management of some water resources and environmental projects such as desertification, famine and crop breeding improvement and control programmes in Nigeria.

1.2 Statement of the Problem

Drought is an affliction that may occur in practically any part of the world. It causes the single most important weather-related natural disaster. Unlike other natural disasters, drought does not have a clearly defined beginning and end. As a result, our traditional reaction to drought has not been timely (UN, 2000).

The severe drought of recent years in the Sahel zone of western Africa has become a major concern in both political and academic circles (Druyan and Koster, 1989, Oladipo, 1993). This large scale intensive droughts has been observed to lead to massive economic losses, destruction of ecological resources, food shortages and starvation of millions of people (Oyebande, 1990, Wilhite, 2000a, Hayes, 2002).

Since the 1970-1972-drought episode in Nigeria, the government seems to have gone to sleep in effecting a continuous drought mitigating plan or strategy. Yet it is understood that drought could be destructive to all forms of development processes and so, preparation for it must be in the nature of contingency planning. Understandably, a preliminary aspect of such required drought preparedness and mitigation plan, usually evolve from a reliable drought quantification or assessment, from which a reliable drought data are obtained, verified and used for simple or complex drought predictions, monitoring and early warnings.

Up to date, rainfall-deficiency concepts and techniques formed a larger proportion of all the existing drought evaluation or quantification techniques in the literature. Furthermore, these quantifications have been based mainly on 'amount of rainfall'. They neglect the use of some other derived characteristics of rainfall that equally measures the effectiveness of rainfall occurrence over an area and importantly describes the drought conditions over such area. This study therefore aims to verify the potentials of these Precipitation Effectiveness Variables (PEVs) to efficiently describe the drought conditions in the SSRN and conjunctively uses some of these PEVs to develop an operational drought index to characterize the severity of the drought in the SSRN.

Actually, the existing ubiquity and difficulty in the physical quantification of drought has led to the proliferation and increase in the number of techniques or indices used in quantifying, monitoring or predicting drought occurrences. This development has been well accepted in recent drought research studies because of the obvious reason that the salient aspect of drought characterization that would have been lumped if not entirely omitted or hidden by one drought index or technique may be better revealed or earmarked by another (Smakhtin and Hughes, 2004).

Furthermore, the use of multi-drought indices in drought evaluations or analysis is in line with the current scientific thought in drought researches that no single drought index is adequate to measure or quantify the complex inter-relationships between the various components of the hydrological cycle and their impacts (Wilhite et al., 2003). It is with these afore-mentioned thoughts that this study intends to characterize the drought conditions in the SSRN using multi drought indices on different time scale. The performance of these multiple drought index will also be evaluated so as to know the order of their significance in relation to their capability of revealing and quantifying the historical drought in the SSRN.

It is believed that the development and utilization of a workable drought concept or technique for defining and analysing drought occurrences, durations, magnitudes and severity would go a long way in providing information needed by government and non-government agencies in developing and implementing a sound drought preparedness and mitigation plans that incorporates sound drought-combating programmes for the drought endemic areas of the country (FGN 1998a and FGN 1998b).

1.3 Brief on Drought Occurrences in Nigeria

1.3.1 Drought Characteristics and changing impacts

Oladipo (1992) reported that many historical droughts have occurred in the Northern region of Nigeria. Using the translations from Arabic chronicles, there are indications that the Sahelian zone of Nigeria was affected by droughts and famine at about 1681-1687 and 1738-1756. Similarly, over a 12-year period, between 1828 and 1839, severe droughts were also experienced around Kano and Maiduguri cities. The droughts of the 1840s were called Darara (Hausa), while those that occurred in the 1850s were referred to as Bamga-Bamga.

The moderate to severe drought of 1902-1904, referred to as Izenere (sale of children), appeared to have covered the whole northern region (Oguntoyinbo and Richards, 1977; Apeldoorn, 1981). Other drought incidences documented in the 1990s in locations north of latitude 11^{o} N in Nigeria include that of 1913-16, 1942-45, 1971-73, and 1983-84 (Oladipo, 1993; FGN 1998b). These drought episodes caused massive famines. According to Akeh et al (2001), each time drought occurs in Nigeria, the area that usually receives very severe impacts includes all areas north of 11^{o} N parallel (mainly around Sokoto, Zamfara, Katsina, Kano, Jigawa, Yobe, and Borno, states).

The effects of the 1971-73 severe drought and the 1983-84 localized droughts on agricultural production prompted the Federal Government of Nigeria (FGN) through its various relevant agencies, to put in place some institutional arrangements and schemes to minimize drought impacts (Apeldoorn, 1981, Oladipo 1994)

1.3.2 Responses to Drought

Oladipo (1994) reported that the rural people in the extreme northern parts of Nigeria have responded in a variety of ways to the hazards of drought in their localities. Over the years, most of the inhabitants with good knowledge of the local environment have developed and integrated a plethora of coping strategies within the socio-economic fabric of their society. The details of such survival tactics by farmers in the region are well reported in Watts (1983), Mortimore (1989) and Gashua (1991).

Some of the notable indigenous coping strategies include the following management practices;

(a) Minimum tillage of the light sandy soils;

(b) Cross ridging to conserve water;

(c) Dry planting, in which seeds are planted while waiting for the rains in order to make maximum use of moisture from the very unpredictable, but usually heavy, first rains;

(d) Planting of drought resistant local crop varieties;

(e) Delayed farm clearance until the middle of the rainy season in order to reduce soil erosion of exposed soils by the often-heavy showers of the first rains.

(f) Intercropping; and

(g) Exploiting a variety of micro-environments, combining upland and lowland ecological areas.

Oladipo (1994) further listed their socio-economic survival tactics to include among others;

(a) Seeking and gaining alternative employment;

(b) Liquidating accumulated assets such as livestock;

(c) Mobilizing socio networks by which wealth is distributed from relatively rich (*Hausa = masu dan hali*) to the common people (*talakawa*);

(d) Collective sustenance;

(e) Hunting and utilization of the edible leaves, roots and fruits of a great variety of plants; and

(f) Migration into cities, wetter areas farther south and into neighboring countries.

A general comment on these laudable and commendable efforts and innovations of Nigerian local farmers is that most of these responses are temporary stop-gap measures until normal rains return, which in some cases, as witnessed in the region in 1973, have proven to be inadequate, when the severity and persistence of a drought stretches these traditional responses beyond their absorptive capacities.

With respect to government responses to drought occurrences in Nigeria, it is worrisome to note that in the past, especially during the 1972-73 episodes, government responses were only on an ad hoc basis. They immediately provided relief packages that consisted of the provision of subsidized food, making water available in water tanks and through sinking of boreholes and wells and the provision of Medicare among many other things.

The Federal government of Nigeria also developed and executed many large-scale dam construction and irrigation projects within the region in the 70s as a mitigation strategy to combat drought within the region. Detailed reviews of other government interventions to drought-affected areas are documented in Oladipo (1994) and FGN (1998a).

It is only recently after more than twenty years, that a drought policy is being prepared with a Department of Drought and Desertification created in the Federal Ministry of Environment. The approach of the government to drought planning and mitigation can be best described as being inconsistent, uncoordinated, and piecemeal and basically consists of ad hoc measures. It is hoped that these recently established institutional arrangements would come in time to reduce the increasing vulnerability of the people within this region.

It is strongly believed that the outcome of the analysis presented in this study can help in providing meaningful information for the development of a workable methodological framework needed for effectively planning and implementing long-term solutions to the drought hazards.

1.4 Study Area

The Sudano-Sahelian region of Nigeria (SSRN), lies roughly between latitudes 10^{o} N – 14^{o}N and longitudes 3^{o} and 14^{o} E. As shown in Figure 1.0, SSRN

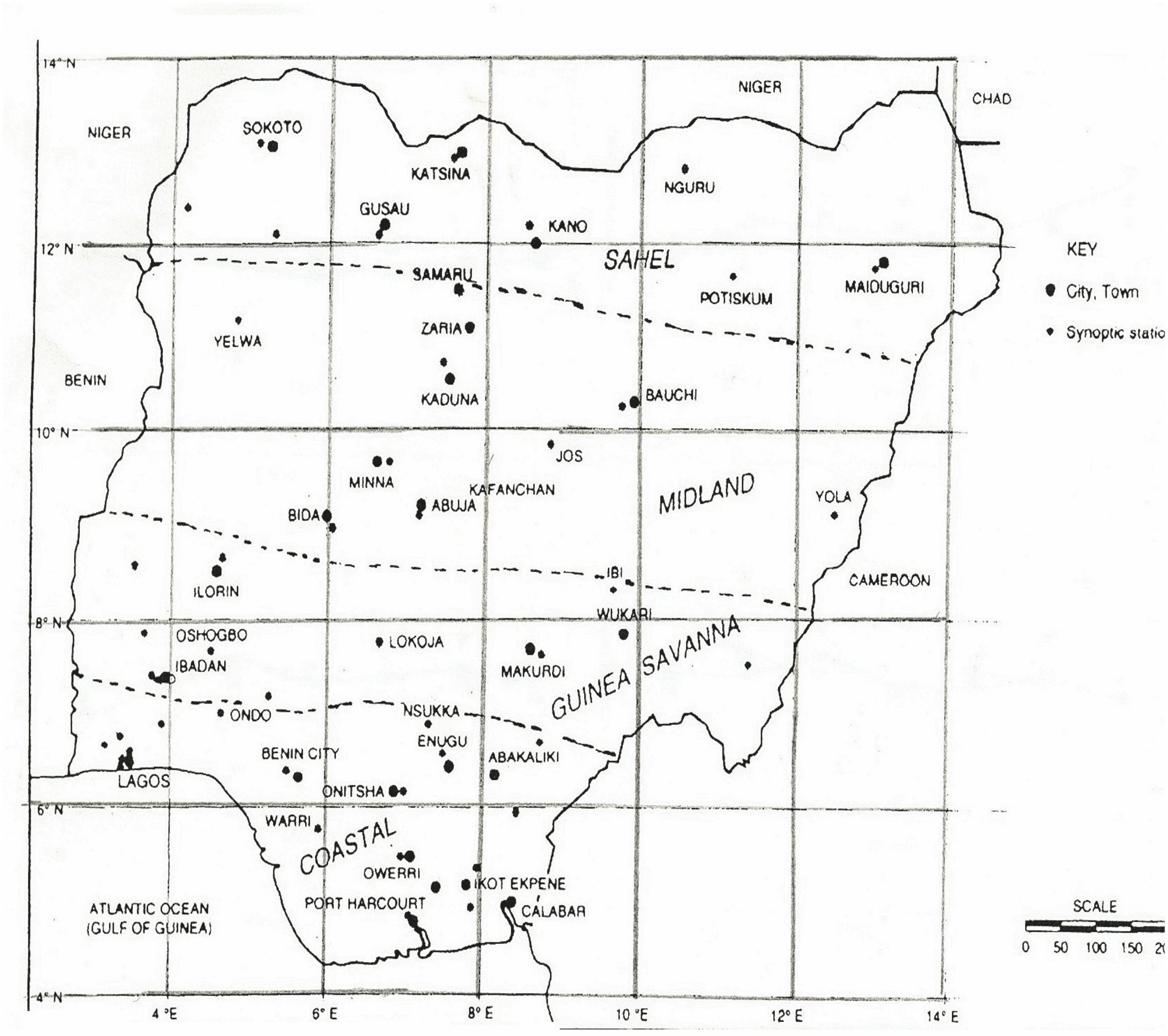


Figure 1.1: Map of Nigeria Showing the Sahelian Region and the Synoptic Stations Used in the Study.

encompasses some states in the extreme northern part of Nigeria. It includes most part of Kebbi and Zamfara, and virtually the whole of Sokoto, Katsina, Kano, Jigawa, Yobe and Bornu states.

The climate of this region results from the influence of two main wind systems: the moist, relatively cool, monsoon wind which blows from the Atlantic Ocean towards the country and brings rainfall; and the hot, dry, dust-laden Harmattan wind which blows from the north-east across the Sahara desert.

The mean temperature is generally between 25 and 35 °C In the dry season the temperatures are more extreme, ranging between 20 and 30 °C (Encarta, 2004).

The rainfall in the SSRN is largely seasonal and highly variable from year to year (Okorie (2003). It has two distinct seasons. The dry season, covers a period of about 7-8 months, from October to April/may, and the wet season with about 4-5 months, from May to September. Generally, its rainfall during the wet season is uni-modal.

The mean annual precipitation in the region is generally less that 1000 mm. The Sahel at the northern tip of Yobe and Borno states, receives less than 500mm of rain annually in about 3-4 months of rainfall. These areas often experience chronic water shortages during the dry season when rain-fed springs and streams dry up. (Apeldoon, 1981, Oladipo and Kwaghsa, 1994).

The main drainage system in the area is the Lake Chad inland drainage system comprising the Kano, Hadejia, Jama'are Misau, and Komadougou-Yobe, rivers. The other drainage system in the North West of the region is that of the Sokoto-Rima basin that drains into the Niger. Groundwater resources are limited by the geological structure of the area. There is an underlay in some areas by the Pre-Cambrian Basement Complex, and some sedimentary formations such as the Tertiary deposits of the Chad-Sokoto basins, which yield groundwater in varying quantities (Encarta, 2004).

The geomorphology and other features that affect the soil characteristics and agricultural practices in the SUSA areas were presented in the review by Kowal and Knabe (1972) and Owonubi et al. (1991). They classified the soils of the Sudano-Sahelian zone of Nigeria as belonging to the Entisols, Alfisols, Ultisols and Vertisols soil classification orders. Other details of the relief, vegetation cover and climatological characteristics of the area have been discussed by Kowal and Kassam (1973), Ojo (1977), Owonubi et al. (1991) and Sawa (2002).

The 1991 census shows that an estimated 31,740,012 people (about 30% of the population of Nigeria) inhabit the study area. As an agrarian society, the region is rich in agricultural production but the larger inter and intra annual variability of its rainfall subjects it to frequent dry spells which sometimes results in severe and widespread drought thus imposing some serious socio-economic constraints on the region (Okorie, 2003). Their main crops are grains that are predominantly guinea corn and millet and grain legumes (cowpea and groundnuts).

1.5 Study Limitations

Within the study area, the required rainguage density and networks for drought assessment and monitoring are not available to adequately characterize the spatial and temporal variability of rainfall. Consequently, this step has placed some constraints and limitations in making any spatial interpolation from the few available point observations. Hence this study is limited to at- site temporal quantification of the drought occurrences in the SSRN only.

1.6 Data Used in the Study

The meteorological data used in this study include daily rainfall, daily temperature data and monthly records of relative humidity data for seven (7) randomly distributed synoptic stations within the study area. The stations are as shown in Figure 1.1 above.

The data were retrieved from the achieves of the Nigerian Meteorological Agency (NIMET), Oshodi. NIMET is the main government agency with the responsibility for collecting; archiving and disseminating meteorological data in the country.

Although there are other meteorological stations within the study area, close reviews of the information on these other stations, shows that most of them have records for just less than ten years and wide ranges of gaps in their records that cannot be relied upon for any meaningful analysis. As shown on Table 1.1, the seven (7) stations selected for the study have approximately over 50 years' continuous long-term records.

Table 1.1 Information on the Meteorological Stations Used in the Study

S/No	Station	Period of Record Used		Latitude	Longitude	Altitude (m)	Years with Missing Records (Exempted in the Analysis)
1	Gusau	1942	2002	12° 10′ N	06° 42′ E	461	1995,1996,1997,1998,2000
2	Kano	1916	2003	12° 03′ N	08° 32′ E	469	Nil
3	Katsina	1922	2003	13° 10′ N	07° 41′ E	514	1925,32,43,44,45,46,47,48, 1966,67,68,95,97
4	Maiduguri	1945	2003	11° 51′ N	13° 05′ E	351	1949,1972,1981,1997
5	Nguru	1942	2001	12° 53′ N	10° 28′ E	341	1961,1965,1986,1994, 1996
6	Potiskum	1936	2003	11° 22′ N	11° 02′ E	412	1940,66,67,68,70,87,91,93
7	Sokoto	1952	2003	13° 10′ N	05° 11′ E	348	1995

1.7 Introducing Key Concepts in Drought Studies

The quantitative analysis or study of drought requires a basic understanding of some of the key concepts usually involved. Some of the non-controversial concepts are discussed below, while others are deliberately detailed in the literature review section.

(a) Weather is not the only cause of drought.

Drought results from both natural events, such as a long dry spell, and from human activities that increase demand for water. Expanding population, irrigation, and environmental awareness all put pressure on water supplies and increase vulnerability to drought.

(b) Drought differs from aridity.

Drought is a temporary deviation from normal. Aridity is a permanent feature of climates that receive little rain.

(c) Drought is not the same as desertification,

Although some researchers speculate that the two are linked, desertification is a long-term ecosystem change. The Food and Agriculture Organization of the United Nations describes desertification as "the sum of the geological, climatic, biological and human factors which lead to the degradation of the physical, chemical and biological potential of lands in arid and semi-arid zones, and endanger biodiversity and the survival of human communities.

(d) Each locality needs its own working definition of drought.

650 mm of rain in a year would be slightly wetter than normal in Nguru, in a semi-arid region of Nigeria, but would be a severe drought in Lagos, in the coastal region of Nigeria.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

Thorough analysis of drought has often been hindered by lack of a quantitative system for defining the degree of dryness and the extent of a drought area. As drought definitions and concepts vary so the types of drought analysis employed have widely different connotations for different geographical locations and purposes (Otun, 1996).

In the field of water and hydrological sciences, drought is usually viewed as a hydrologic system consisting of three major components namely, input (the water source i.e. precipitation), output (outcome or the water usage i.e. crop, livestock etc.) and the environment (i.e. the watershed system). Two major approaches, which have been applied, to drought analysis are:

(i) Analysis of individual component of the hydrologic system. This includes for instance, an analysis of the stochastic or deterministic structure of observed or measured precipitation, run-off, groundwater and soil moisture within the system, and

(ii) Composite analysis of the three components as one hydrologic system.

Many scientists have taken primary interest in the first approach using time series of precipitation, stream flow, reservoir-water storage and soil moisture deficits for drought analysis. While Gupta and Duckstein (1975), Mustapha (1984), Sharma(1997) Freitas and Billib (1997) and Ozer et. al (2003) concentrated on the use of rainfall series as a single hydrological input in their drought studies, Thomas and Olson (1992), Woo and Tarhule (1994), Kjeldsen et al. (2000) and Tate and Freeman (2000) rather used the streamflow.

Some of the several studies that used the second approach include the use of rainfall-runoff model (Crawford 1960), use of precipitation drought frequency and a lumped geomorphic index to estimate runoff drought frequency (Huff and Changnos, 1964), the use of multiple regression technique to estimate low stream flows from climatic, geologic and geographic indices (Chin, 1973, Thomas and Olson, 1992) and drought occurrences and risks of dependent hydrologic processes (Chung and Salas, 2000).

Firstly, it is necessary for one to understand the nature of each component before it can be combined in a complete system analysis. Secondly, the analysis of the combined systems often becomes very complex and difficult to solve thus making it mandatory for useful assumptions to be made. Most of such assumptions rarely fit into practical situations. This explain why the first approach has prevailed more in practice and why it will be adopted and further discussed in this study.

In particular, the single hydrological system input to be considered in this drought study is precipitation. Although a deficiency in precipitation is not the sole cause of drought, most researchers undergoing drought studies, acceptably uses its data because rainfall acts as the major production function of drought in any area.

2.2 Understanding and Defining Drought

Drought is a complex phenomenon of widespread significance (Oladipo, 1985). This complex nature of drought and the varying scale of its occurrence has perhaps made it the most enigmatic of all climatic phenomena and the least understood of all natural hazards (Oladipo, 1989).

Drought has no quantitative definition that is universally accepted. (Loukas and Vasilliades (2004). It has scores of definitions used to describe its diverse geographical and temporal occurrence (Hounam et al., 1975). Some of the most common drought definitions are summarized in Hisdal and Tallaksen (2000), Tate and Gustard (2000), Wilhite and Glantz (1985), Dracup et. al. (1980) and WMO (1975).

2.2.1 Drought Classification

Using a broad classification, Wilhite and Glantz (1985) categorized drought definitions into conceptual and operation definitions. The former refers to those basic definitions formulated in general terms, which are not applicable to current (i.e. real time) drought assessments. The latter category includes definitions attempting to identify the onset, severity and termination of drought episodes (Hisdal and Tallaksen, 2000). According to CSRE (2003), information on various drought characteristics and its recurrence probability that are usually provided by such definitions, are found extremely beneficial in the development of response and mitigation strategies and preparedness plans.

Another classification, based on disciplinary perspectives, was initially proposed by Dracup et. al (1980) and later modified and integrated by Wilhite and Glantz (1985). It is the most well-known and widely used classification of droughts. It was recently adopted by the American Meteorological Society (2004). It covers the four wide varieties of disciplines affected by drought, i.e. Meteorological, Agricultural, hydrological and socio-economical disciplines. The definitions for these four discipline-perspectives of drought as reviewed by NDMC(2000), NCDC(2002), CSRE (2002), Okorie (2003) and Loukas and Vasilliades (2004), are presented as follows:

(a) Meteorological Drought: It is an expression of precipitation's departure from 'normal' over some period of time. It also connotes the degree of dryness (in comparison to some 'normal' or average amount) and the duration of the dry period. This definition is usually specific to a region since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. Hence, it always reflects one of the primary causes of a drought.

(b) Agricultural Drought: It is usually expressed in terms of needed soil moisture of a particular crop at a particular time (Hisdal and Tallaksen, 2000). An agricultural drought is considered to have set in, when the soil moisture deficits has dropped to such a level that it adversely affects the crop yield and hence agricultural production (Panu and Sharma, 2002). In short, the definitions of agricultural drought hover around soil moisture deficiency in relation to meteorological droughts and climatic factors and their impacts on agricultural production. Such agricultural impacts are caused by short-term precipitation shortages, temperature anomaly that caused increased evapotranspiration and soil water deficits that could adversely affect crop production (Narasimhan, 2004).

(c) Hydrological Drought: Hydrological drought is an expression of deficiencies in surface or subsurface water supply (i.e., stream flow, artificial and natural reservoirs, ground water).

(d) Socioeconomic Drought: The socio-economic effect of meteorological, hydrological, and agricultural drought associated with the supply and demand of the society. The supply of many economic goods, such as water, forage, food grains, fish, and hydroelectric power, depends on weather. In most instances, the demand for economic goods increases as a result of increasing population and per capita consumption. The supply may also increase because of improved production efficiency, technology, or the construction of reservoirs that increase surface water storage capacity. If the demand increases more rapidly than supply, then vulnerability and the incidence of drought may increase in the future since supply and demand trends converge.

The relationship between these four drought categories is illustrated in Figure 2.1. A meteorological drought in terms of lack of precipitation is the primary cause of drought (Hidal and Tallaksen(2000). It usually first leads to an agricultural drought due to lack or reduce soil moisture deficit. If precipitation deficiencies continue a hydrological drought in terms of surface water deficits develops. The groundwater is usually the last to be affected, but also the last to return to normal water levels.

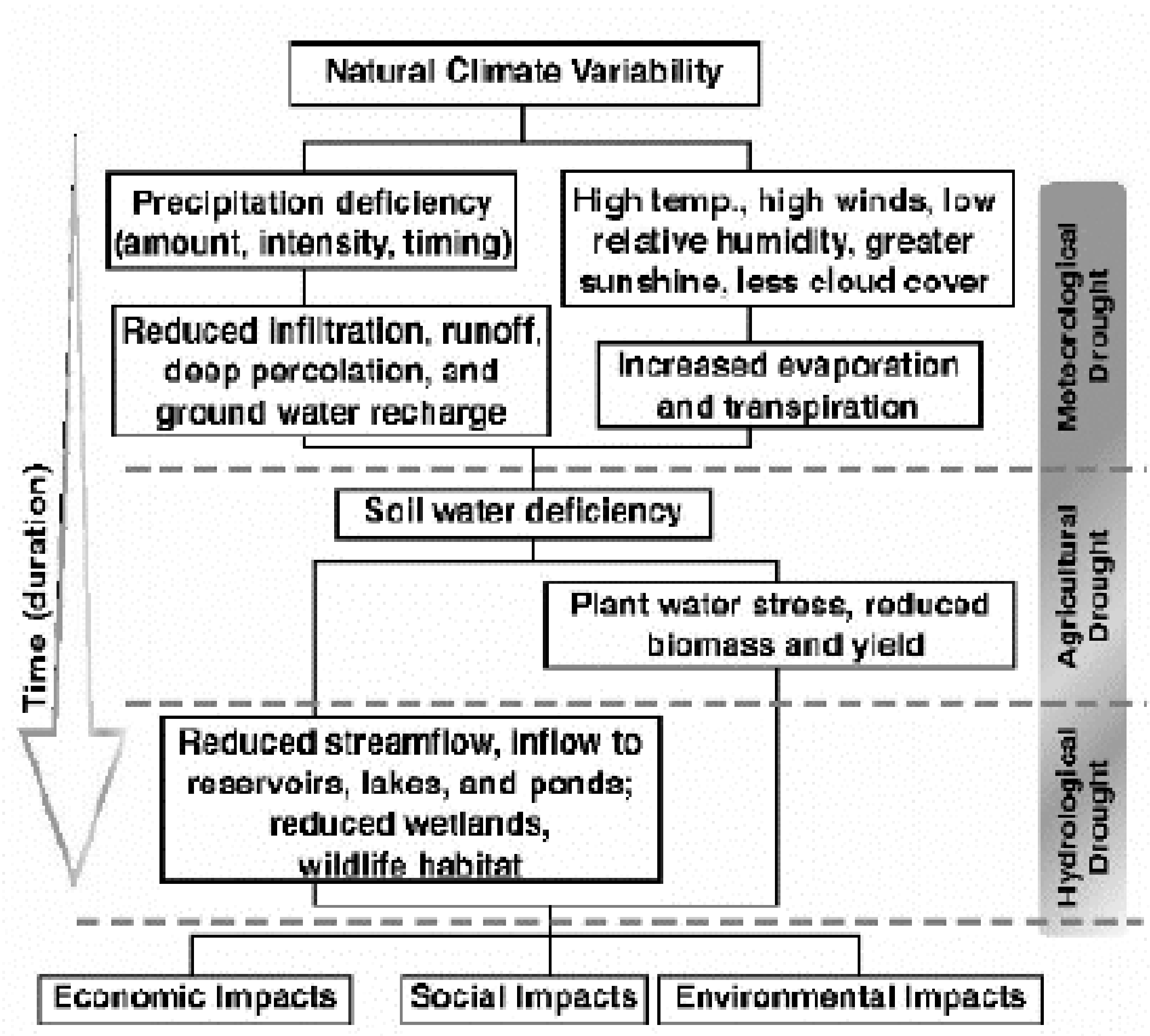


Figure2.1 The sequence of drought impacts associated with meteorological, agricultural and hydrological drought (Source: NDMC(2000),)

If the departure sustains over a period of several months to a year, then the flow in the rivers and streams will reduce as will the storage in the reservoir. This affects the water supply to cities, hydro-electricity plants and navigation, and thus, it creates 'hydrologic drought', If the drought sustains for more than a year and affects the society and the regional economy, then it creates 'socioeconomic drought' (Wilhite and Glantz, 1985, Narasimhan, 2004)

As different definitions leads to different conclusions regarding the drought phenomenon, the choice of a definition is carefully based on the particular problem under study, the available data and the climatic and regional characteristics of the area under consideration.

2.2.2 Drought Quantification and Characterization

Drought quantification or characterization is an important subject in the planning and management of water resources systems in any region. The principal properties of drought that is usually used to quantify or characterize the drought conditions or occurrence at a place are described as follows:

(a) Drought Variables

According to Panu and Sharma (2002), a drought variable is considered as a prime variable responsible for assessing drought occurrence. It is also a key element in defining drought and deciding on the technique for its analysis. The determinant variable for meteorological drought is precipitation, whereas for hydrological drought it is either river runoff/streamflow or reservoir levels and or groundwater levels. For agricultural drought, the governing variables are soil moisture and /or consumptive use. Therefore, the time series of any of the above variables provides the framework for evaluating the drought parameters of interest.

(b) Drought Parameters

The important parameters quantifying a drought condition or occurrence are duration or drought length (L), severity (S), ratio of severity to duration (called magnitude or intensity (I) by Dracup et al., 1980) and the area of coverage. The definitions for some of the parameters above are detailed in Panu and Sharma(2002).

Figure 2.2 shows that uninterrupted sequence of deficits can be regarded as a drought length (i.e. its duration). It is equal to the number of deficits in the sequence, designated by L (L=1, 2, 3, …). The drought duration is associated with a deficit sum D, i.e. the sum of the individual deficits in the successive epochs of the spell.

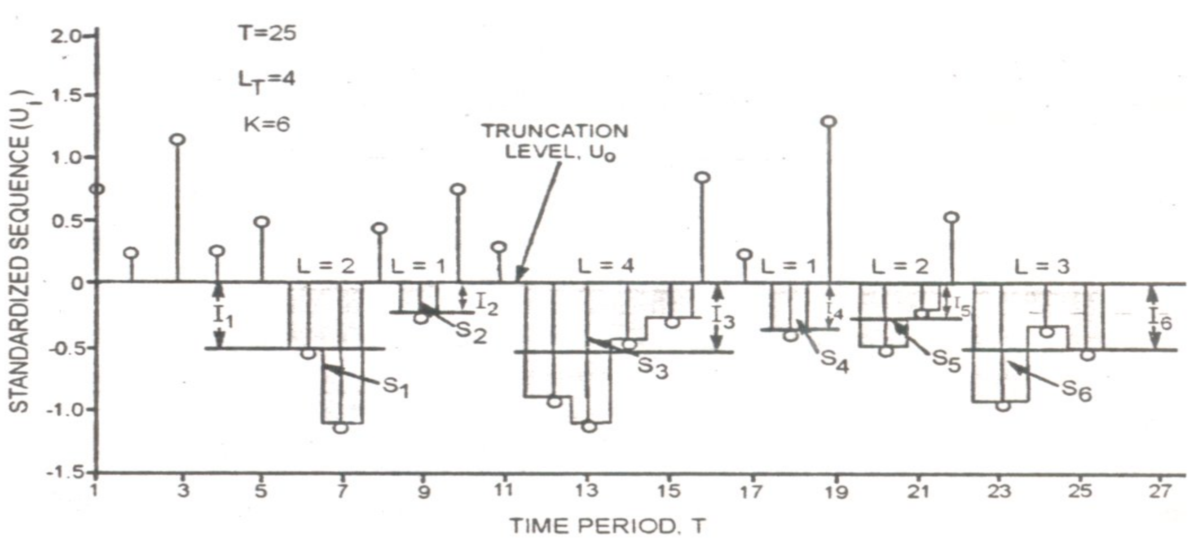


Figure 2.2: Definition sketch of drought parameters

The most basic element for deriving the above parameters is the truncation or the threshold level, which may be a constant or a function of time. The truncation level specifies some statistics of the drought variable and serves to divide the time series of the variable in question into "deficit" and "surplus" sections. The parameters of a drought such as duration, severity and intensity are based on properties of the deficit section. Dracup et al. (1980) defined the truncation level by the expression in equation 2.1.

$$R_0 = R_m - e.\ SD = R_m\ (1 - e.\ c_v) \qquad (2.1)$$

where R_0 is the truncation level, R_m, SD, and c_v are the mean, standard deviation and the coefficient of variation of time series of the drought variable R i.e. rainfall time series, and e is the effective scaling factor. An evaluation of the truncation level with respect to its being constant or a function of time has been made in studies by Tallaksen et al. (1997) and Demuth and Stahl (2001). They have also made some recommendations as to which procedure is suitable for a given purpose.

2.2.2.1 Drought Severity as a measure of drought

Unlike other drought parameters, considerable disagreement exists among various drought scholars as to the precise definitions for the term 'severity'. Presently, some researchers express drought severity by means of some indices. Operational definitions of droughts are now formulated in terms of indices; they include the drought severity index introduced by Foley (1957) through the analyses of dry spells using the residual mass curve technique for monthly rainfall records.

Other developed indices include the decile range (Gibbs and Maher, 1967), the standardized rainfall index (Gibbs, 1975), the Palmer drought severity index (PDSI) (Palmer, 1965, Guttman, 1991) and the standardized precipitation index (SPI) (Guttman, 1998).

Herbst et al (1966), Yevjevich (1967) and Dracup et al. (1980) also defined severity as the cumulative shortage or deficit sum with reference to a desired truncation level. After a threshold is selected, a drought severity analysis can be conducted based on the drought duration as a function of the selected threshold level. The severity of drought is a function of the drought duration and probability distribution of the drought variable (Panu and Sharma, 2002).

2.2.3 Adopted drought concept and definition

In order to avoid the usual confusion that arises when an attempt is made to apply a single definition to various types of drought, this study attempts, to focus on meteorological drought definition. The sequent concept adopted is basically meteorological but has implications for agricultural applications. This is based on the following points of reasoning:

(a) Precipitation is the primary factor controlling the formation of drought conditions. The first view of drought over an area is given by its characteristics. Previous drought analysis has been confined to meteorological drought because long-term rainfall records are often available. Rainfall data alone may not reflect the spectrum of drought related conditions, but they can serve as a pragmatic solution in data-poor regions. (Smakhtin and Hughes(2004).

(b) At present, the status of hydrological data acquisition in Nigeria is very poor; hence it will be difficult to gather reliable long-term streamflow and reservoir-level records.

(c) In the case of agricultural drought, the measurement of its determinant factor (soil moisture) for a large area is relatively difficult (NCDC, 2002, Owonubi et al. 1991), and hence, the related data sets for any historic periods are not usually available on a widespread, national scale (Kenyantash and Dracup(2004). The reason put forward by Narasimhan (2004) is that the soil moisture variability, both spatially and temporally, is due to the heterogeneity in soil properties, land cover, topography, and non-uniform distribution of precipitation and evapotranspiration (ET). Therefore, there has been a very limited effort towards evaluating agricultural droughts using measured soil moisture data.

(d) Furthermore, it is unlikely that soil moisture data generated from Soil moisture deficit (SMD) models could be used in this study for two important reasons. Firstly, the network of soil moisture records required in simulation analysis (i.e. for obtaining optimum model parameters) for the reason given in (c) above, is less extensive both in time and space, than the available rainfall networks. Secondly, the cost involved in designing, setting up and obtaining soil moisture data from various fields within the whole SSRN would be prohibitive. Thus, the initial attempt to carry out simulation analysis using some SMD models for further drought analysis was severely limited.

(e) Similarly, it is true that agricultural drought is explicitly related to significant reduction in crop yield. Furthermore, the crop yield is a function of numerous factors such as water availability, time of sowing, crop variety, soil fertility status, fertilizer input, pest control measures etc. Hence, this intricate relationship between yield and soil moisture deficit has further complicated the direct assessment of agricultural drought. However, if the effect of other yield affecting factors mentioned above are relatively stable, then as suggested by Kumar and Panu (1997), for an arid environment such as the study area, it is reasonable to assume that crop yield significantly depends on rainfall input (i.e. rainfall amount, variability, the time of rainfall ONSET and Cessation). Under this assumption, the characteristics of rainfall can be used to infer the occurrence of drought that has direct application for agriculture planning. Hence, it can easily be seen that agricultural drought links various characteristics of meteorological drought to agricultural impacts, focusing on the ability of precipitation shortages to meet the crop water needs. For instance, as rainfall fail to meet plant water needs, it leads to deficient topsoil moisture at planting, which may hinder germination and lead to low plant populations per hectare and a reduction of final yield (CSRE, 2002).

The sequence of drought occurrence earlier discussed in section 2.2.1 also shows that 'meteorological drought', which often set in before others, has some level of relationship with other types of drought. This study therefore attempts to characterize the meteorological drought in the SSRN using some precipitation effectiveness variables as drought indicators. The approach will have direct application to agriculture planning and thus be relevant in an agrarian community as that of the Sudano-Sahelian region of Nigeria.

2.3 Review of Theories and Techniques used for Drought Analysis

The identification and prediction of droughts are achieved through analyses of time series of a drought variable such as rainfall, groundwater levels, and soil moisture data, on a variety of time scale. The most commonly used time scale in drought analysis is the year followed by the month (Bonacci, 1993; Sharma, 1997). In situations related to agriculture, water supply and groundwater abstractions, the use of the monthly time scale has been widely accepted. However, in order not to neglect some important short-term drought events within a year or season, the weekly and daily time scales has also been used (Sharma 1996, Tallaksen et al., 1997).

The data series often used for drought analysis are either derived (measured / observed) or synthesized (generated) data. The data series are at times stochastically generated or generated through physically based concepts such as water balance or soil accounting procedures. For instance, the PDSI data can be generated using a soil moisture accounting algorithm (Palmer, 1965). According to Chin, (1973) and Panu & Sharma (2002), proxy data such as 'dendrochronology' (measuring / counting tree rings), ice coring, 'palynology' (pollen analysis), 'palaeontology', indices of geological movements, sea-level fluctuations, and palaeomagnetic data could also be invoked in the analysis and synthesis of long-term droughts.

In this study, the quantification of the droughts in SSRN will principally be achieved by analyzing the time series of rainfall, (variable for meteorological drought), on a variety of time scales. The details of the commonly used methods for characterizing, quantifying or predicting meteorological droughts are discussed as follows:

2.3.1 Index-Based Methods:

Index based methods integrates various hydrological and meteorological parameters like rainfall, evapotranspiration (ET), runoff and other water supply or deficiency indicators into a single number to provide an overview of drought in a region. The index usually used for decision making defines the magnitude, duration or severity of droughts (Narasimhan, 2004, Hayes, 2002**)**.

The most commonly used meteorological drought indices include the Palmer Drought Severity Index (PDSI) (Palmer 1965), Bhalme and Mooley Drought Severity Index(BMDI) (Bhalme and Mooley, 1980), Rainfall Anomaly Index (RAI) (Rooy, 1965), Reclamation Drought Index (RDI), Surface Water Supply Index (SWSI) (Shafer and Dezman 1982), and Standardized Precipitation Index (SPI) (McKee et al 1993). A few of these indices, which are to be used in this study, has been further reviewed and presented below.

2.3.1.1 Percent of Normal index

The Percent of Normal index (PNI) is as expressed in equation 2.2. R_a is the actual precipitation and R_N is the normal precipitation, typically considered to be 30-year mean according to World Meteorological Organization rules. This indicator can be calculated for different time scales (i), ranging from a single month, to a particular season, or to a couple of years.

$$PNI_i = \frac{R_{a,i}}{R_N} * (100) \tag{2.2}$$

The normal condition of precipitation for a specific area is considered to be 100%, while values lower than 100% indicate drought conditions. One of the major disadvantages arising from the use of this index is that the precipitation distribution for a given time scale is not always normally distributed. This means, among other things, that the average precipitation is often not the same as the median precipitation (Bordi and Sutera, 2000). This makes it difficult to compare values of this index for different locations or time scales.

2.3.1.2 Deciles index (DI)

Gibbs and Maher (1967) proposed to arrange monthly precipitation data into deciles to avoid some of the limitations of the percent of normal index approach. Monthly rainfall totals from a long-term record are first ranked from highest to lowest to construct a cumulative frequency distribution. The distribution is then split into ten parts (deciles). By definition the first decile is the precipitation not exceeded by the lowest 10% of all precipitation values in a record, the second is between the lowest 10 and 20%, etc. Any precipitation value (e.g. from the current or previous month) can be compared with, and interpreted in terms of these deciles. Decile Indices (DI) are grouped into five classifications as shown in table 2.1. The DI is relatively simple to calculate, requires only precipitation data. This index can be calculated for several time scales and a long precipitation record (30-50 years) is needed to calculate the deciles accurately. This is however not a shortcoming of this approach, but rather a requirement of the statistical analysis (Smakhtin and Hughes, 2004).

Table 2.1 Deciles classification

Decile	Percentage	Class
Deciles 1-2	Lowest 20%	Much below normal
Deciles 3-4	Next lowest 20%	Below normal
Deciles 5-6	Middle 20%	Near normal
Deciles 7-8	Next highest 20%	Above normal
Deciles 9-10	Highest 20%	Much above normal

Source: NCDC(2002)

2.3.1.3 Palmer Drought Severity Index (PDSI)

Palmer (1965) provided an objective index, PDSI that measures the severity of drought as a single numerical value. The PDSI is standardized for different regions and time periods. The procedure considers precipitation, evapotranspiration and soil moisture conditions and run-off, which are determinants of hydrological drought and, indirectly, of agricultural drought (Palmer 1965, Alley, 1984, Karl and Knight, 1985). Hence, the PDSI, though a measure of meteorological drought, is used extensively as a measure of drought for both agricultural and water resource management.

While the details of Palmer's methodology are given in Palmer (1965), Alley(1984) and Kim et al. (2002), a brief recapitulation of the approach is given below:-

(I) ***Hydrological accounting concept***

The computation of the PDSI begins with a climatic water balance using long series of monthly precipitation and temperature records as inputs. Its approach is similar to that used by Odigie (1984) which assumes a 2-soil layer water balance model to account for soil moisture storage. The upper layer of the soil is assumed to contain a 25mm of available moisture at field capacity.

According to UNL(2002), PDSI computation is based on a supply and demand model of the moisture of its 2-layered soil. The supply is the amount of moisture in the soil plus the amount that is absorbed into the soil from rainfall. The demand, owing to the amount of water lost from the soil, depends on several factors, such as temperature and the amount of moisture in the soil.

The preliminary calculation in the soil modeling is that of the potential evapotranspiration (PET). Basically, we understand that evapotranspiration (ET) is the combination of evaporation and transpiration, and in this context, refers to the amount of water lost from the environment through vegetation and evaporation. PET is calculated using Thornthwaite's method. Details of the Thornthwaite's method is given by Linsley et al.(1982). The calculation of monthly PET depends on a month's average temperature, average temperature of that month over all historical record, and the latitude of the weather station.

The Available Water Holding Capacity (AWC) is the amount of water the soil is capable of holding. The underlying soil moisture content is the amount of moisture that is being held beneath the topsoil. The top soil moisture content is the amount of moisture in the topsoil.

The potential recharge (PR), is the amount of water that could be absorbed by the soil, or the difference between the AWC and current soil moisture, hence, PR = AWC - (Su + Ss). Su and Ss are the soil moisture of the underlying and top soil layer respectively. The potential runoff, PRO is calculated by assuming that any precipitation that falls is absorbed until the ground is saturated, and then the rest runs off. Thus, PRO is the difference between the potential precipitation and the amount of moisture the soil can absorb. Palmer(1965) decided to set the potential precipitation to AWC, and the amount of moisture the soil can absorb is simply PR, so PRO = AWC - PR = AWC - (AWC - (Su + Ss)) = Su + Ss

Potential loss, PL is the amount of moisture that could be lost from the soil to evapotranspiration provided precipitation during the period was zero. Computing PL usually involves the value of PET. The PDSI uses a two-leveled approach to soil moisture holding. The upper level, the topsoil, can lose all of its moisture. Only once the topsoil has lost all its moisture does the underlying soil lose its moisture, and then only a fraction is taken out at one time (UNL, 2002).

(a) If **Ss >= PET** *The moisture in the top soil is enough to meet the demand, so most of the moisture that can be lost is from that in the top soil, then*

PL = PE

(b) If **Ss < PET** *The moisture in the top soil is not enough, so some of the moisture in the lower soil may be lost. However, only a fraction of the moisture in the lower level is actually at risk of being lost.*

PL = ((PET - Ss) * Su) / AWC + Ss

(i) If PL > PRO

The potential moisture loss cannot be more than the amount of moisture in the soil. The amount of moisture in the soil is :

(Ss + Su) = PRO, hence **PL = PRO**

The loss from the underlying soil layer depends on the initial moisture content as well as on the computed potential evapotranspiration (PET) and the available water capacity (AWC) of the soil system. Based on the soil types for the study area, a range of 150-170 mm is estimated for AWC from Table 2.2. Runoff is also assumed to occur, if and only if, both layers reach their combined moisture capacity, AWC.

Table 2.2 Soil storage for available water moisture held in cm per cm depth of soil of Northern Nigeria.

Textural Class	Field Capacity		Wilting Point		Available Water	
	Range	Mean	Range	Mean	Range	Mean
Coarse sand less 10% clay and silt	0.75 – 1.33	1.04	0.33 – 0.50	0.42	0.42 – 0.83	0.63
Fine sand less 10% clay and silt	1.17 – 1.67	1.42	0.42 – 0.67	0.58	0.75 – 1.00	0.83
Fine loamy sand 10-29% clay and silt	1.67 – 2.50	2.08	0.50 – 1.00	0.75	1.17 – 1.50	1.33
Sand clay 30-50% clay and silt	2.33 – 2.67	2.50	0.83 – 1.17	1.00	1.50	1.50
Clay loam 45-60% clay and silt	3.00 – 3.33	3.17	1.17 – 1.33	1.25	1.83 – 2.00	1.91
Sandy clay 60 – 70 % clay and silt	3.50 – 4.08	3.75	2.17 – 2.33	2.25	1.33 – 1.75	1.50
Vertisol 50 % clay	5.00 – 7.50	6.25	3.33 – 5.00	4.17	1.67 – 2.50	2.08

(Source Kowal and Knabe , 1972)

(II) The Water Balance Equation

Along with the four potential values (PET, PR, PRO, and PL), their actual values (ET, RE, RO, and L) are also calculated. The rules for determining the values of these actual values are very complicated, depending on the relationship of precipitation (P), PET, and the soil moisture model. This is where the two-leveled model of the soil is most important. The topsoil is assumed to be able to hold 25 mm of moisture. This moisture is the first to be used up when demand is higher than supply, and the first to be recharged when there is a surplus. The lower level of the soil can then hold up to **(AWC – 25.4)** mm of moisture. When the top soil is depleted, only a fraction of the moisture in the lower level can be removed at one time. The several cases, sub cases, and sub-sub cases to consider in determining how much moisture is gained or lost for each level of soil are discussed below.

(A) *If P >= PET, there is enough precipitation to meet the demand from PET, so ET occurs at the potential rate, there is no loss, and there is the possibility for recharge and runoff. Hence,* ET = PET and L = 0

(a) *if (P - PET) > (25.4 - Ss), there is enough extra moisture from precipitation to recharge both layers of soil;* **R_surface = (25.4 - Ss)**

(i) If **(P - PET - R_surface) < ((AWC – 25.4) - Su),** *The amount of moisture remaining after PET and recharge of the top soil can be entirely absorbed by the lower level of the soil. Thus, the recharge of the lower level is the remaining moisture and* *there is no runoff;* **R_lower = (P - PET - R_surface) and RO = 0**

(ii) If **(P - PET - R_surface) >= ((AWC - 1.0) - Su),** *There is more than enough moisture to satisfy PET and recharge both levels of the soil.* **R_lower = ((AWC - 1.0) - Su) and** RO = (P - PET - (R_surface + R_lower)).

However, the total recharge is the recharge of the two layers combined.

RE = R_surface + R_lower

(b) If (P - PET) <= (1.0 - Ss), then there is only enough moisture to recharge the top layer. Hence RE = (P - PET) and RO = 0

(B) If P < PET, then there is not enough precipitation to satisfy the PET, so some soil moisture must be lost. Clearly, there cannot be any recharge or runoff. Hence, RE = 0 and RO = 0.

(a) If Ss > (PE - P), then the top soil moisture content is enough to meet the demand remaining after the precipitation is used up. Therefore, moisture is only lost from the topsoil. Hence, L_surface = (PE - P) and L_lower = 0.

(b) If Ss <= (PE - P), then the top soil does not have enough moisture to meet the demand. The top soil will be completely drained and a fraction of the lower level soil moisture will also be lost. **L_surface = Ss, and L_lower = (PE - P - L_surface) * Su / AWC**

The total lost is the combined amount of moisture lost from the two soil layers and the ET is equal to the total amount of water used, which is the precipitation and the moisture lost from the soil. **L = L_surface + L_lower and ET = P + L**

(III) ***Climatic Coefficient:***

The climate coefficients ($\alpha, \beta, \gamma, \sigma$) are computed as a proportion between averages of actual versus potential values for each of 12 months at each location i.e. the coefficients of evapotranspiration as ($\alpha = \frac{\overline{ET}}{\overline{PE}}$), recharge as ($\beta = \frac{\overline{R}}{\overline{PR}}$), runoff as ($\gamma = \frac{\overline{Ro}}{\overline{PRo}}$) and loss to evapotranspiration from the soil (L) as ($\sigma = \frac{\overline{L}}{\overline{PL}}$). The bars above the terms represent the averages for evapotranspiration (ET), potential evapotranspiration (PE), recharge (RE), potential recharge (PR), runoff (Ro), potential runoff (PRo), potential loss(PL) and Loss (L) the actual amount of moisture lost from the soil to evapotranspiration.

(IV) Moisture Departure and Moisture Anomaly

The climate coefficients are used to compute the amount of precipitation $(\hat{P})$ that takes account of the antecedent moisture conditions stated in water balance above and would be considered normal and climatically appropriate for existing conditions (CAFEC),

$$\hat{P} = \alpha\, PE + \beta\, PR + \gamma\, PRo - \sigma\, PL \qquad (2.3)$$

In each month, the difference, d, between the actual (P) and CAFEC precipitations $(\hat{P})$ is an indication of water deficiency or surplus for that month at the studied area. The value of d is regarded as a moisture departure from normal because the CAFEC precipitation is an adjusted normal precipitation. The departures are converted into indices of moisture anomaly, Z, defined as

$$Z = K_i \, d \tag{2.4}$$

where K_i is a climatic weighing factor for the month i which takes into account also the spatial variability of the departures (d). After considerable experiments, Palmer (1966) suggested empirical relationships for K such that $K_i = \left[\frac{17.6}{\sum_{i=1}^{12} \bar{D}_i \, K_i'} \right] K_i'$ where $\bar{D}_i$ is the average of the absolute values of d, and K_i' is dependent on the average water supply and demand given by

$$K_i' = 1.5 \log_{10} \left(\left[\frac{\bar{PE} + \bar{R} + \bar{RO}}{\bar{P} + \bar{L}} + 2.8 \right] \bar{D}^{-1} \right) + 0.5 \tag{2.5}$$

(V) The Palmer Drought Severity Index (PDSI)

In the last step, the Z-index time series are analysed to develop criteria for the beginning and ending of drought periods. Equation 2.5 is used for determining PDSI for each month.

$$W_i = p \, . W_i + q \, . Z_i \tag{2.6}$$

Where Z_i represents values of the moisture anomaly index for the dry intervals and W_i is the value of PDSI for the i th month. For the original monthly PDSI, p=0.897 and q = 1/3, and for a self-calibrating, PDSI, p and q are adjusted according to the time scale as well as the characteristics of the climate at the location.

Palmer (1965) gave the classification of PDSI values obtained as a stepwise gradation from PDSI < -4 (extreme drought condition) to PDSI > +4 (extreme wet conditions) as listed in table 2.3.

Table 2.3 PDSI values classification.

Class No	**PDSI value**	**Class**
1	> 4	Extremely wet
2	3.0 to 3.99	Very wet
3	2.0 to 2.99	Moderately wet
4	1.0 to 1.99	Slightly wet
5	0.5 to 0.99	Incipient wet spell
6	0.49 to 3.99	Near normal
7	-0.5 to -0.99	Incipient dry spell
8	-1 to -1.99	Mild drought
9	-2 to -2.99	Moderate drought
10	-3 to -3.99	Severe drought
11	< -4	Extreme drought

Source: NCDC(2002)

Applications of PDSI to monitor drought events on different locations may have had some limitations in the past (Alley 1984, Karl and Knight 1985, Iwegbu 1993 and Narasimhan (2004). Several of the limitations observed by them are outlined below.

- In PDSI, potential evapotranspiration (ET) is calculated using Thornthwaite's method. Thornthwaite's equation for estimating ET is only an approximation; there are presently better methods of estimation.
- In the water balance model, Palmer (1965) assumed that runoff occurs when the top two soil layers become completely saturated. In reality, runoff depends on soil type, land use, and management practices. However, Palmer (1965) does not account for these factors while estimating runoff.
- Similarly, the assumption that actual evapotranspiration (ET) for a period is equal to the potential evapotranspiration (PET) whenever rainfall, P is greater than PET is not always correct.
- The assumption and designation of 25mm as the moisture capacity of the upper soil layer from which evapotranspiration takes place at the potential rate is rather too arbitrary.
- The use of constants (called duration factors) to evaluate the weighting factor that are arbitrarily based on Palmer's study of central Iowa and western Kansas in USA.

These limitations are however being addressed in some respect. For instance, a self-calibrating PDSI has recently been developed to address some of these previous shortcomings (UDL, 2002). The self-calibrating PDSI analyzes the climate of each location and adjusts the Duration Factors accordingly. Hence the PDSI can now be correctly applied to regions characterized by different climatic conditions from those ones studied by Palmer.

2.3.1.4 Bhalme and Mooley Drought Severity Index (BMDI)

Bhalme and Mooley (1980) modified PDSI because it failed to give a realistic picture of drought conditions in arid, semi-arid and dry sub-humid region of India. They developed BMDI based on the assumption that plant life and established human activities in a region are adjusted to average rainfall conditions.

The basic method devised by Bhalme and Mooley (1980) uses the percentage departure of monthly rainfall from the long-term mean to compute a moisture index MI given by equation 2.7 below.

$$MI = 100\,\frac{(R_a - \bar{R}_a)}{SD} \qquad (2.7)$$

where R_a is the monthly precipitation, $\bar{R}_a$ is the long-term mean monthly precipitation and SD is the corresponding standard deviation.

Averages of the highest accumulated values of the negative moisture index during the various intervals of time (i.e. months) are then obtained for all the stations under study. This provides a relative measure of regional moisture anomalies because it permits numerical designation of extreme drought in various parts of the study region (Oladipo, 1985).

The extreme drought condition from the monthly highest accumulated negative MI is given by a least squares equation below: -

$$\sum_{t=1}^{k} MI_t = a + b\,k \qquad (2.8)$$

where MI_t is the accumulated moisture index over a duration of t months, k is the number of months and a, b are constants. The values of a and b for Northern Nigeria, is cited in Oladipo (1993), as -66.74 and -88.59 respectively.

Using a plot of the accumulated monthly index against the length of driest month, Bhalme and Mooley (1980) developed a technique for identifying the various drought conditions. As shown in Figure 2.3, the ordinate distance between the solid line (representing extreme drought condition) and the top of the graph is divided into four equal lengths and the body of the graph correspondingly divided by three more lines, to define the extreme, severe, moderate and mild drought statistics.

The equation of the family of lines corresponding to the four drought categories may be given as:

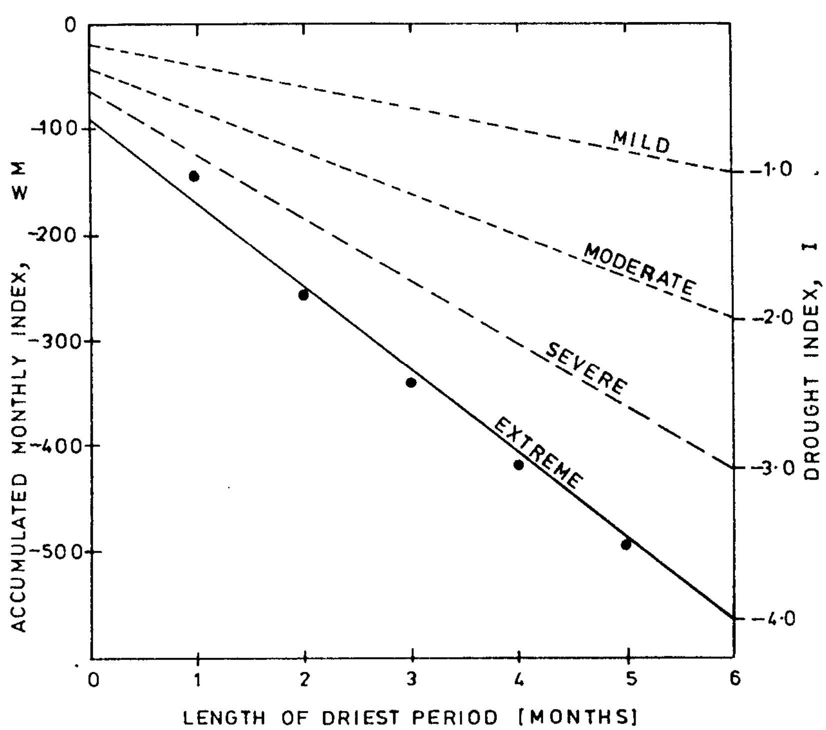


Figure 2.3: Plot of accumulated moisture index during the growing season
(Source: Oladipo 1993 and Iwegbu, 1993)

$$I_k = \sum_{t=1}^{k} \frac{MI_t}{\left[0.25(a + b\,k)\right]} \tag{2.9}$$

Where I_k is the drought intensity of the kth month. The contribution of M to drought for each month is then obtained by setting k=1 in equation 2.10, that is

$$I_1 = \frac{MI_1}{\left[0.25(a + b\,k)\right]} \tag{2.10}$$

For an initial month under consideration, $I_0 - 0$, hence

$$I_1 - I_0 = \Delta I_1 = I_1 \tag{2.11}$$

In successive months, a negative value of MI is then required to make I_k more negative and maintain the existing dryness. The rate at which M must increase to sustain a constant I depends on the value of I that is to be maintained. Thus for all months that follows an initial dry months, an additional term is introduced to account for any carry over effect of the antecedent condition. This concept makes equation (2.11) become

$$\Delta I_k = \left(\frac{MI_k}{d}\right) + c\,I_{k-1} \tag{2.12}$$

where d = 0.25 (a + b), $\Delta I_k = I_k - I_{k-1}$, and c is a constant. It means equations (2.10) and (2.12) respectively become:

$$I_1 = (MI_1 / d) \tag{2.13}$$

$$I_k = \left(\frac{MI_k}{d}\right) + (1 + c)\,I_{k-1} \tag{2.14}$$

The values of c and d in Equation (2.13) for northern Nigeria are -0.57 and 38.84 respectively (Oladipo, 1993). These values are used in Equations (2.13) and (2.14) to generate monthly values of BMDI. The negative or positive value of BHMI obtained gives a relative measure of dryness or wetness respectively. Similar to that of PDSI, BMDI are also classified as in table 2.4 below.

Table 2.4 BMDI values classification.

Class No	BMDI value	Class
1	> 3.00	Extremely wet
2	1.0 to 3.00	Moderately wet
3	-1.0 to 1.00	Normal
4	-1 to -3.00	Moderate drought
5	< -3.00	Severe drought

Source: Oladipo (1993)

2.3.1.5 Rainfall Anomaly Index (RAI)

Rooy (1965) derived a rainfall anomaly index (RAI) in the form given by equations (2.15) for the positive anomalies and equation (2.16) for the negative anomalies.

$$RAI = 3\left[\frac{(R_a - \bar{R}_a)}{(\bar{R}_m - \bar{R}_a)}\right] \quad (2.15)$$

$$RAI = -3\left[\frac{(R_a - \bar{R}_a)}{(\bar{R}_x - \bar{R}_a)}\right] \quad (2.16)$$

where R_a is the actual monthly rainfall, $\bar{R}_a$ is the long-term mean monthly rainfall, $\bar{R}_m$ is the mean of the ten highest values of p on record and $\bar{R}_x$ is the mean of the ten lowest values of p on record. The arbitrary threshold values of +3 and -3 have, respectively, been assigned to the mean of the ten most extreme positive and negative anomalies. The RAI values obtained also gives a scale of numerical values of the relative rainfall anomaly. They are accordingly also classified into nine abnormality classes, ranging from extremely wet to extremely dry conditions.

2.3.1.6 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) developed by McKee et al. (1993), is relatively a new drought index based only on precipitation. It requires less input data and calculation effort than PDSI and can be computed on different time steps (e.g. 3 months, 6 months …., 48 months). The use of different time scale under the umbrella of the same index allows the effects of a precipitation deficit on different water resources components (groundwater, reservoir storage, soil moisture, streamflow) to be assessed (Smakhtin and Hughes, 2004).

This temporal flexibility also allows the SPI to be useful in both short-term agricultural and long-term hydrological applications. Moreover, because the SPI is normalized, wetter and drier climates can be monitored in the same way and a comparison between different locations can be made (Bordi and Sutera 2000).

The SPI calculation is based on the long-term precipitation record for the desired time scale. The computation of the SPI involves fitting the long term precipitation record from a desired climate station into a gamma probability density distribution.

$$g(x) = \frac{1}{(\mu^{\phi}\Gamma(\phi))}\chi^{\phi-1}e^{-x/\mu} \quad (2.17)$$

where ϕ > 0, ϕ is a shape parameter, β > 0, β is a scale parameter, x > 0, x is the precipitation amount and $\Gamma(\phi) = \int_0^{\infty} y^{\phi-1}e^{-y}\,dy$, $\Gamma(\phi)$ is the gamma function.

The ϕ and μ parameters of the gamma probability density function are estimated for each station, for each time scale of interest (1, 4, 13 weeks, etc.) and for each month of the year.

The optimal estimate of ϕ and μ by maximum likelihood solutions are given in equations (2.18) and (2.19) respectively.

$$\phi = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad (2.18)$$

$$\mu = \frac{\overline{x}}{\phi} \quad (2.19)$$

where $A = \ln(\overline{x}) - \frac{\sum_{i=1}^{n}\ln(x_i)}{n}$ and n = number of precipitation observations. The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given month or desired time scale for the station in question. The cumulative probability is given by equation (2.20).

$$G(x) = \int g(x)dy = \frac{1}{(\mu\,\phi\,\Gamma(\phi))}\int_0^x \chi^{\phi-1}e^{-x/\mu}dx \quad (2.20)$$

if v = x / β, equation (2.19) becomes the incomplete gamma function given as:

$$G(x) = \frac{1}{\Gamma(\phi)} \int_0^x v^{\phi - 1} e^{-v} dv \qquad (2.21)$$

since the gamma function is undefined for x=0 and a precipitation distribution may contain zeros, the cumulative probability becomes

$$H(x) = q + (1 - q)\, G(x) \qquad (2.21)$$

where q is the probability of a zero. If m is the number of zeros in a precipitation time series, q can be estimated by m/n. The cumulative probability, H(x) is then transformed to the standard normal random variable Z with mean zero and variance of one, which is the value of the SPI.

$$Z = SPI = -\left(v - \frac{c_0 + c_1 v + c_2 v^2}{1 + d_1 v + d_2 v^2 + d_3 v^3} \right) \quad for \quad 0 < H(x) \le 0.5 \qquad (2.22)$$

$$Z = SPI = +\left(v - \frac{c_0 + c_1 v + c_2 v^2}{1 + d_1 v + d_2 v^2 + d_3 v^3} \right) \quad for \quad 0.5 < H(x) \le 1.0 \qquad (2.23)$$

where $v = \sqrt{\ln\left(\frac{1}{(H(x))^2} \right)} \quad for \quad 0 < H(x) \le 0.5$ (2.24)

$$v = \sqrt{\ln\left(\frac{1}{(1 - H(x))^2} \right)} \quad for \quad 0.5 < H(x) \le 1.0 \qquad (2.25)$$

c_0 = 2.515517, c_1 =0.802853, c_3= 0.010328, d_1= 1.432788, d_2 =0.189269 and d_3= 0.001308.

Thus, the SPI represents a Z-score, or the number of standard deviations that a particular event deviates above or below from the normal conditions. The classification of drought and wet intensities resulting from the SPI calculation is shown in table 2.5 .

Table 2.5 SPI values classification.

Class No	**SPI value**	**Class**
1	2 +	Extremely wet
2	1.5 - 1.99	Very wet
3	1.0 -1.49	Moderately wet
4	-0.99 – 0.99	Near Normal
5	-1 to -1.49	Moderately dry
6	-1.5 to -1.99	Severely dry
7	-2 and less	Extremely dry

Source: NCDC(2002)

As part of the advantages of SPI, it is able to produce a meaningful estimate of drought for different locations and time scales. It has been widely and largely used operationally to quantify and monitor the wet and dry conditions across different locations, in the United States, Italy, Greece, Mexico and Spain to mention a few (Dalezios et al. (2000), Bordi and Sutera (2000), and Wihilte (2003).

2.3.1.7 Herbst Drought Index

These are the severity and intensity index developed by Herbst et al., (1966), used and verified by Shaw (1989) as being a reliable estimate for drought over an area. It used the concept of cumulative residuals or departures from averages to confine the definition of droughts more specifically to periods in which rainfall deficits were in excess of average deficits. The sequences of months with extremely dry conditions are identified beyond the shortfalls in monthly rainfall amounts that are normally experienced in some months of each year. The average monthly drought intensity over the period of drought can be calculated from the expressions given in equations 2.26 to 2.29 below.

$$Y = \frac{\sum_{t=1}^{D}[(E_t - M_t) - (MMD)_t]}{\sum_{t=1}^{D}((MMD)_t)} \quad (2.26)$$

$$E_t = [(R_{t-1} - M_{t-1})\ W_t + R_t] \quad (2.27)$$

$$(MMD)_t = \sum_{t=1}^{n} \frac{(M_t - R_t)}{n} \quad (2.28)$$

$$W_t = 0.1\left(1 + \frac{M_t}{\frac{1}{N_S} . MAP}\right) \quad (2.29)$$

where E_t = effective rainfall, M_t = monthly mean rainfall, W_t = carry-over factor, (t = 1,2,3,....12), R_t = monthly rainfalls, MMD_t = monthly mean deficit (t=1,2,..., 12), D = drought duration in months (this can be altered for other time scale i.e 5-days, 7-days, 10-days, 30-days), N_s = 12 (but differs if other time scale is used), n = number of months with rainfall drought deficit and MAP is the mean annual rainfall.

In order to compare drought of varying duration and intensity in regions of high or low rainfall irrespective of the seasonal variation, Herbst et. al. (1966) introduced an index of drought severity. This index is determined by calculating the average monthly mean deficits for the period of drought (D) divided by the sum of the mean monthly deficits for the same period, the product Y and D being the weighted index of drought severity.

2.3.1.8 Surface Water Supply Index (SWSI)

The Surface Water Supply Index, SWSI was developed by Shafer and Dezman (1982) to complement the Palmer index. It integrates reservoir storage, streamflow and two precipitation type (snow and rain) at high elevations into a single index number. SWSI is expressed in equation 2.30 as:

$$SWSI = \frac{aP_{snow} + bP_{rain} + cP_{stream} + dP_{reserv} - 50}{12} \tag{2.30}$$

where a,b,c and d are weights for snow, rain, streamflow and reservoir storage respectively, (a+b+c+d = 1) and P_i is the probability (%) of non-exceedance for each of these four water-balance components. Calculations are performed on a monthly time step. For each month, the values of each component measured at all stations across the stations (or reservoirs) across the region / basin are summed. Each sum is normalized and its non-exceedance probability is determined. Weights are assigned to each water balance components depending on its typical contribution to surface water within a basin. Subtracting 50 and dividing by 12 constitute the normalization procedure designed to make SWSI values have a similar range as PDSI (Smakhtin and Hughes, 2004).

Since the SWSI calculation is unique to each basin or region, it may be difficult to make a comparison between different regions since the weights may differ substantially from one part of the region to another (Doesken et al. 1991). If the measurements at any stations are discontinued, observations on one or more of the components are interrupted and new frequency distributions need to be calculated. Similarly, new dams or diversions in the basin / region will require modification of weights for each water-balance components.

A modification of SWSI is known as the **Reclamation Drought index (RDI)**. Its calculation is similar to that of SWSI, but it also includes an evaporation component. According to Smakhtin and Hughes (2004), the similarity between RDI and SWSI implies that RDI also has similar limitations, although RDI may be adapted to any region as it takes into account both climatic and water-supply factors. These limitations might have been the serious limitation for the use of both SWSI and RDI for drought analysis in Nigeria.

2.3.2 Frequency- or probability-based methods

In these methods, low flows or low-flow volumes during a specified period are analysed in a manner similar to that of flood peak analysis (Joseph, 1970; Yevjevich *et* a!., 1978; Clausen and Pearson, 1995; Dalezios et al., 2000). At times, drought durations based on threshold levels have also been modeled through probability functions (Joseph (1970), Gupta and Duckstein, 1975; Lee et al., 1986; Zelenhasic and Salvai, 1987; Woo and Tarhule, 1994; Demuth and Külls, 1997, Tate and Freeman, 2000; Kjeldsen et al., 2000; Dalezios *et al.,* 2000).

The drought frequency analysis is used to estimate the re-occurrence interval of a drought magnitude or duration. The frequency analysis of drought-indicative variable(s) is helpful in choosing design criteria for many water resources projects (i.e. hydrological drought), and the selection of a cropping breeding system or pattern (i.e. agricultural drought (Sen, 1980; Sharma, 2000).

2.3.3 Regression-based methods

Regression analyses have been conducted to relate drought parameters with geomorphic and/or climatic factors, crop yield factors, and other relevant factors for prediction of duration and severity of droughts (Paulson *et al.,* 1985; Mimikou *et al.,* 1993; Kumar and Panu, 1997).

2.3.4 Runs-based methods

The concept of runs (Yevjevich, 1972) allows one to analyse the probabilistic structure of drought durations (run length) and severities (run sum). In these methods, the drought parameters such as the longest duration and the largest severity are analysed. The analysis is carried out on the time series of random or Markovian drought variables (Sen. 1980; Sharma, 2000). Another approach within this category of Run models is the use of discrete autoregressive and moving average (DARMA) processes to model the variability of wet and dry years (Chung and Salas, 2000), Iwegbu, 1993).

The expected arid nature of the study area brings about high temporal variability in its rainfall and the existence of many zero values in the rainfall time series of the study area. Using Run Theory (RT) for such data leads to exaggeration of the wet spells and downplays the importance of dry periods (Bahram S. et al. 2003).

2.3.5 Group-based methods

The characteristics of droughts in terms of their durations or lengths can be expressed as groups and clusters of groups. In turn, such data sets can be analysed to develop drought prediction and forecasting techniques utilizing the concepts of pattern recognition (Kumar and Panu, 1994) and neural networks (Shin and Salas, 2000). However, group-based methods are still in the initial stages of development.

2.3.6 Drought Inference Technique (DIT)

Different drought indicators or indicative variables (DIV) are traditionally used to identify and infer the occurrence of drought in a place. In its simplest form, they include indicative weather or climatic variables or conditions such as, precipitation timing (i.e. principal season of occurrence, delays in the start of the rainy season, occurrence of rains in relation to principal crop growth stages) and its usefulness (i.e. Rainfall intensity, number of rainfall events and non events (dry spells) etc.). These variables are described in the literature as "precipitation effectiveness variables" (PEV).

In Nigeria, DIT has been applied to descriptively describe the occurrence of drought in the country. Though not quantitatively, various studies have been able to infer the occurrence of drought using some aspects of the PEVs as drought indicators:- rainfall anomaly i.e. periods with low rainfall (Ilesanmi 1972, Olaniran 2002, Nicholson, 1985), sparse rainfall distribution (high variance or coefficient of variation) (Ayoade 1973 & 1977), high uncertainty in rainfall occurrence (timeliness) (Nicholson, 1985), short duration or intervals of rainy seasons (Benoit (1977), frequent false or delayed onset of rain (Olaniran and Summer 1989a) and abrupt end (cessation) of rainy season (Stern et al. (1981) .

DIT therefore presumes that the first view of drought in any area is given by these precipitation effectiveness variables. A number of these PEVs have been identified and discussed below.

(i) Onset of rainy season (ORS)

Although there is a great difficulty in defining the onset of rain, it simply refers to the first occurrence of rain within a specified time period. Some other definitions have been suggested by Stern et al. (1980) and Sivakumar (1988).

A delay in the arrival of rains is generally associated with drought.

(ii) Cessation of rainy season (CRS)

Similarly, like ORS, CRS also simply refers to the date of the last occurrence of rain within a year. An early termination of rain is an indication of shortage of rainfall which is naturally linked to drought occurrence.

(iii) Length of the rainy season (LRS)

LRS is the difference between ORS and CRS. It indicates longevity and relevance of the wet season on agricultural planning and drought management.

(iv) The total no of wet days (TWD)

This refers to the number of rainfall event per rainy season. It is a measure of the degree of wetness and conversely drought.

(v) Total no of dry spell (TDS)

TDS is the total number of dry spell within wet season i.e. frequency of dry spell in a wet a season. It is also a measure of the degree of dryness.

(vi) Total no of dry days within a wet season (TDW)

TDW is the corresponding number of dry days within a wet season.

(vii) Total no of dry days within a year (TDY)

TDW is the number of dry days within a year. It is an individual measure of the degree of dryness.

(viii) Length of the dry season (LDS),

LDS also stand as the intra-annual dry spell, i.e. interval between the previous year CESSATION of rains and current year ONSET of rains.

(ix) Maximum dry spell length within a wet season (MDL),

MDL is a measure of the breaks in the course of a normal rainy season (Drought Spells).

(x) Mean Annual / Seasonal Rainfall Depth (MAR),

It is a measure of the amount of the rainfall received within a season or a year. It is also the commonest PEV that is widely and traditionally used in indexing drought.

Mustapha (1984) used four (4) of these PEVs namely, ORS, CRS, MAR and LDW to develop a drought scoring technique for indexing the drought in Nigeria. In his approach, the values obtained for each variable are ranked; the maximum and minimum values have a score of 5 and 1 respectively. For each annual record for a station, the observed values for ORS, CRS, LDW and MAR are accordingly scored in proportion to the maximum and minimum scores of 5 and 1 respectively. The final drought score for each year is the conjunctive addition of the score obtained for the ORS, CRS, LDW and MAR.

The scoring technique presented by Mustapha (1984) is station specific since there is no uniform range for classifying the score. Secondly, the classification is arbitrarily done. The maximum and minimum values will differ for the different variables and different stations. It is a bit of simplistic measure of precipitation variability. This study therefore aims to improve on this pioneering effort of indexing drought by standardizing the values obtained for each PEVs so as to make the technique adaptable to any region.

The inclusion of these PEVs for the quantification of drought in the Sudano-Sahelian region of Nigeria is very significant. In SSRN, it is not so much the amount of rainfall that matters considering the arid nature of the area, what matter most is how effective it is. For instance, the ONSET (i.e. the beginning) of rains may results in poor seasonal distribution, even when the total rainfall received in the season is normal or above average. Similarly, pre-mature cessation (i.e rains stops before the normal period) constitutes a major problem. The worst condition is to be expected when both onset is delayed and cessation is premature or advanced resulting in shortened rainy season length.

Ayoade (1970), Ojo (1977), Olaniran (1983 and 1987) and Adefolalu (1991), also observed that the strong relationship between water availability and some of the precipitation effectiveness variables have important connotations and impacts to agricultural productions.

CHAPTER THREE

3.0 METHODOLOGICAL FRAMEWORK FOR THE DROUGHT ANALYSIS

3.1 General

The main conceptual approach used in this study follows the philosophical thought that, apart from the usual use of only 'rainfall amount' in indexing the drought conditions of a place, there exist some other measures of rainfall or precipitation effectiveness variables that can be conjunctively and effectively used to achieve the same feat. The adopted concept for this study therefore considers various precipitation effectiveness variables to infer, characterize and quantify the drought in the Sudano-Sahelian Region of Nigeria (SSRN).

The methodological framework for the study is partly shown in Figure 3.1. An outline of the major drought techniques conceptualised in the framework is as presented below.

(A) **Drought Quantification Analysis**

The logical steps involve in identifying, quantifying and characterizing the drought in the SSRN are outlined below:

(a) **Drought Indexing (Drought Inference Method)**

The steps involved include:

(i) Define some Precipitation effectiveness variables (PEV) i.e Rainfall amount, Rainy days, Onset and Cessation of wet season etc. as given in section 2.3.6

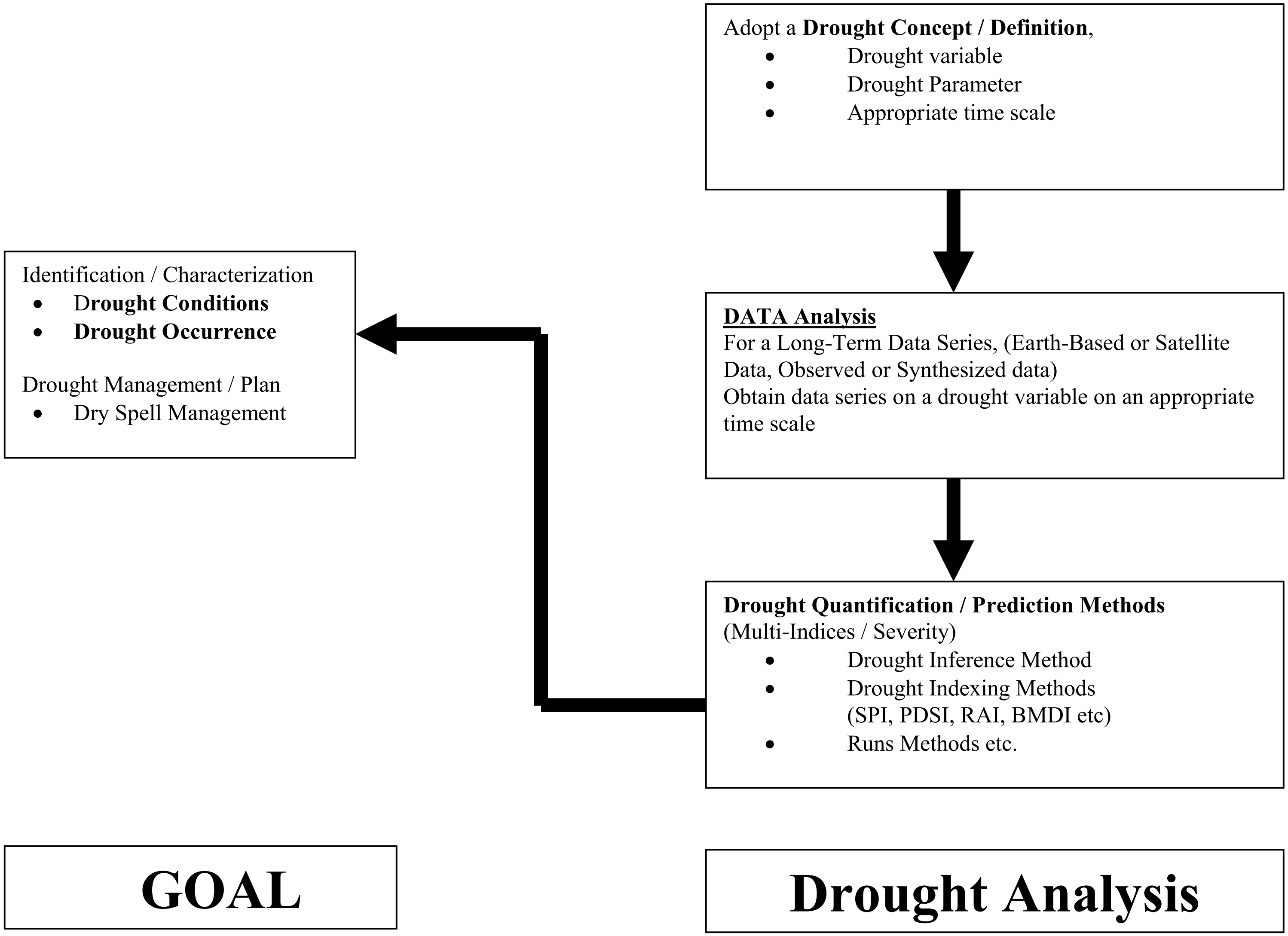


Figure 3.1: Methodological Framework for Drought Quantification

(ii) Verify the potentials of some PEVs in describing or identifying historical droughts. Firstly, it involves a thorough variability analysis. This approach will descriptively give relevany information from which drought occurrences can be inferred. Secondly, using some of the PEVs, seasonal rainfall index (SRI) and Normalised Rainfall index (NRI) will be used to infer the occurrences of drought in the SSRN.

(iii) Define and review the relationships between each PEVs (Correlation Analysis)

(iv) Conjunctively, use the various combinations of the PEVs to define an operational drought index referred to in this study as Conjunctive Precipitation Effectiveness Index (CPEI). The CPEI is to be computed for various combinations of the defined PEVs.

(b) **Drought Indexing (Drought Index-Based Method)**

This include the use of Palmer drought severity index (PDSI), Bhalme and Mooley drought index (BMDI), Standardized Precipitation Index (SPI), and Rainfall anomaly index (RAI), as drought severity measure to describe drought.

(c) **Comparative Analysis**

Verify the performance of the CPEI with other four drought indices of DIBM i.e. PDSI, BMDI, SPI and RAI.

(i) For all the possible 1023 combinations of 10 PEVs, Obtain the corresponding CPEIs.

(ii) Obtain the Correlation matrix for the five (5) indices, i.e the CPEI, PDSI, BMDI, SPI and RAI. The coefficient of correlation (r) obtained for each combinations gives clue to obtaining the optimum combination of PEVs with optimum CPEI value.

(B) **Dry Spell Analysis (Aspect of Drought Management)**

This mainly involves an empirical analysis of dry spell (EADS) to further reveal the characteristics of one these PEVs, i.e Dry Spell, to give additional spotlight on the nature of the drought in the SSRN and provide some numerical data as guides for the management of these droughts conditions.

3.2 Rainfall Variability analysis

Variability is defined as the variation of the hydrological time series over the mean. A dimensionless measure of variability that is widely used in hydrology is the coefficient of variation (CV). Thus, for each stations under study, the CV and some other basic precipitation statistics are to be computed for some PEVs on various time scale (i.e. 1, 5, 7, 10, 30, 365 days). The CV for a particular set of data is obtained by squaring the values for the standard deviation (SD) for the same set of data.

As shown in equation 3.1 and 3.2 below, a measure of variability is effectively combined in an index known as the standardized rainfall index (SRI) and Normalized rainday index (NRI). It is a measure of the rainfall shortfall in terms of the number of standard deviations above or below the average.

$$SRI_i = \frac{R_i - \bar{R}}{SD_R} \tag{3.1}$$

$$NRI_i = \frac{ND_i - \bar{ND}}{SD_{ND}} \tag{3.2}$$

Where R_i is rainfall amount for period/season I, ND_i is the number of raindays for period/season i the standard deviation of the for the rainfall amount and rainy days series are respectively defined as SD_R and SD_{ND}. Generally standard deviation (SD_R or SD_{ND}), is given by $SD_R = \left[\frac{1}{n-1} \sum_{i=1}^{n} \left(R_a i - \bar{R} \right)^2 \right]^{\frac{1}{2}}$, $SD_{ND} = \left[\frac{1}{n-1} \sum_{i=1}^{n} \left(R_a i - \bar{R} \right)^2 \right]^{\frac{1}{2}}$ and n is total no of data in rainfall amount or rainy days series.

SRI and NRI, used as a drought index, can adequately describe the relative severity of deficits between the widely scattered rainfall data. It can therefore show the potentials of some of the PEVs in describing or identifying historical droughts. It also helps to suppress local factors which cause strong variation of rainfall pattern over time and space. It expresses the seasonal means as a proportion of the long-term averages.

3.3 Development of Conjunctive Precipitation Index (CPEI) (Drought Indexing using CPEI)

Various combinations of the ten (10) precipitation effectiveness variables (PEVs) defined in section 2.3.6 are to be conjunctively used to derive an operational drought index. The main reason for their use is that, in the Sudano-Sahelian region of Nigeria, it is not so much the amount of rainfall that matters considering the arid nature of the area, what matter most is how effective it is.

10 PEVs, namely ORS, CRS, LRS, TWD, TDS,TDW, TDY, LDS, MDL and MAR have been identified for indexing drought in the SSRN. The combinations of 1, 2, 3, …10 variables, in any order and without any repetition give a possible total of 1023 arrangements. For illustration, let The PEVs be redefined as V1=ORS, V2=CRS, V3=LRS, V4=TWD, V5=TDS, V6=TDW, V7=TDY, V8=LDS, MDL=V9 and MAR=V10. i.e. for a possible combination of four (4) variables, possible arrangements include, (V1, V2, V3, V4), (V9, V7, V5, V1), (V7, V4, V3, V2), (V10, V6, V4, V3), etc.

The standardized values of V1, V2, V3,……V10, is given as ${}_kSV_{l,j}$ in equation 3.3.

$$ {}_kSV_{l,j} = \frac{{}_kV_{l,j} - {}_k\bar{V}_{l,j}}{\sigma_{{}_kV_j}} \qquad (3.3) $$

where k stands for the PEV variable under consideration (i.e. for ORS, k=1, LRS, k=2, LRS, k=3 …., MDL, k=9 and MAR, k=10). l is the year under consideration, j is the season under consideration i.e. for pentad series for a year, j varies from 1 to 73 seasons while for the monthly step data, j varies from 1 to 12 seasons, $_k\overline{V}_{l,j}$ and $\sigma_{_kV_j}$ are respectively the mean and standard deviation for the jth season and for variable k. By using Equation 3.3 the seasonality inherent in the PEVs was removed. Hence the deficit values for each PEVs can be compared across seasons.

For each of the 1023 arrangements, the respective computation of each conjunctive precipitation effectiveness index (CPEI), developed in this study is as defined in equation 3.4 for any particular year (i) and season (j) under consideration.

$$CPEI_{i,j} = \tfrac{1}{3}\left(\left[\tfrac{1}{nv} \sum_{m=1}^{nv} \left({}_kSV_{i,j} \right) \right] + \left[\tfrac{1}{nv} \sum_{m=1}^{nv} \left({}_kSV_{i,j} \right)^2 * \left({}_kSGN \right) \right] + \left[\tfrac{1}{nv} \sum_{m=1}^{nv} \left({}_kSV_{i,j} \right)^3 \right] \right) \quad (3.4)$$

For each arrangement, nv is the no of variables in the arrangement, $_kSV_{l,j}$ is the standardized value and $_kSGN$ is the sign of the deficit for the variable k.

The standardized deficit, $_kSV_{l,j}$ was raised to the power of two and three in the CPEI equation so as to magnify the effect of the deficit on the computation of the index. The sign, $_kSGN$ was also included in the CPEI equation, so as not loose the effect of a negative deficit when it is squared. The application of the CPEI equation is illustrated with the example below.

For example, assume, V1, V6,, V8 and V9 are the variables in one arrangement. It means nv=4 and the CPEI can be computed as follows:

(i) Use equation 3.3 above to derive $_1SV_{l,j}$, $_6SV_{l,j}$, $_8SV_{l,j}$, $_9SV_{l,j}$, for each season (j) and year (i).

(ii) For each time scale, the standardized values obtained in step (i) above will be conjunctively combined in equation (3.5)to obtain the derived drought index.

$$CPEI_{i,j} = \tfrac{1}{3}\left(\begin{array}{l} \left[\tfrac{1}{4}\left({}_{1}SV_{i,j} + {}_{6}SV_{i,j} + {}_{8}SV_{i,j} + {}_{10}SV_{i,j} \right) \right] \\ + \left[\tfrac{1}{4}\left(\begin{array}{l} \left\langle \left({}_{1}SV_{i,j} \right)^2 * ({}_{1}SGN) \right\rangle + \left\langle \left({}_{6}SV_{i,j} \right)^2 * ({}_{6}SGN) \right\rangle \\ + \left\langle \left({}_{8}SV_{i,j} \right)^2 * ({}_{8}SGN) \right\rangle + \left\langle \left({}_{10}SV_{i,j} \right)^2 * ({}_{10}SGN) \right\rangle \end{array} \right) \right] \\ + \left[\tfrac{1}{4}\left(\left\langle \left({}_{1}SV_{i,j} \right)^3 \right\rangle + \left\langle \left({}_{6}SV_{i,j} \right)^3 \right\rangle + \left\langle \left({}_{8}SV_{i,j} \right)^3 \right\rangle + \left\langle \left({}_{10}SV_{i,j} \right)^3 \right\rangle \right) \right] \end{array} \right) \tag{3.5}$$

3.4 Comparative Analysis (CPEI Versus PDSI, BMDI, RAI and SPI)

The derived drought index, the CPEI will be compared with four other drought indices defined by the Palmer drought severity index (PDSI), Bhalme and Mooley drought index (BMDI), Standardized Precipitation Index (SPI) and the Rainfall anomaly index (RAI). Details of the procedures for the computation of these four indices have been fully described in section 2.3.

Basically the statistical tool to be used for comparing the performance of these indices with each other is the Pearson correlation coefficient (r) defined in equation 3.6.

$$r = \frac{n\left(\sum_{i=1}^{n} X_i Y_i\right) - \left(\sum_{i=1}^{n} X_i\right)\left(\sum_{i=1}^{n} Y_i\right)}{\sqrt{\left(n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2\right)\left(n\sum_{i=1}^{n} Y_i^2 - \left(\sum_{i=1}^{n} Y_i\right)^2\right)}} \tag{3.6}$$

The Pearson correlation coefficient r, is a dimensionless number that ranges from -1.0 to 1.0 inclusive and reflect the extent of a linear relationship between two data sets.

Within the available records i.e. 1918 – 2002, and on a particular time scale, i.e monthly, the CPEI values obtained for each of the 1023 arrangements will be compared with the various values for PDSI, BMDI, RAI and SPI .

The arrangements which an average correlation coefficient higher than 0.8 ($r > 0.8$) for each respective comparison with BMDI, RAI and SPI will be further ranked and evaluated using some descriptive tests with historical drought records to obtain the optimum CPEI.

3.5 **Drought Indexing using Multiple Indices**

As earlier presented in section 2.3.1, the severity of drought in a place can be summarized with a single number defined as drought index. The optimum drought index obtained for the newly developed CPEI and other four indices, namely the PDSI, BMDI, RAI and SPI Indices, will be used describe the occurrence of drought in the Sudano-Sahelian Region of Nigeria.

These four indices have been included in this study because of their wide applications and adaptations. Several researchers have used data from similar climatic regions as the SSRN to evaluate the performance of these indices. For instance, Oladipo (1993) analyzed rainfall records of 34 to 80 years, to obtain BMDI to identify drought periods corresponding with the history of drought-related famines in the entire northern region of Nigeria. Iwegbu (1993) also used RAI and BMDI to describe the temporal characteristics of the drought in some parts of Nigeria. On a global scene, Kim et al. (2002) carried out a frequency and spatial characteristics of drought in the Concho River Basin of Mexico using PDSI as an indicator of drought severity. Oladipo (1985) compared the performance of RAI, BMDI and PDSI using meteorological data from Nebraska, USA, Vicente-Serrano et. al. (2004) and Dalenzios et al. (2000) respectively used the most recent SPI Spain and Greece.

The use of these multi-drought indices is in line with widely accepted thought in drought researches that no single drought index is adequate to measure or quantify the complex inter-relationships between the various components of hydrological cycle and their impacts (Wihite et al. 2003). Understandably, each additional drought index used help to further reveal some other and extra information that could have remain hidden or lumped together if only one single drought index and time-scale is used.

Consequently, in order to avoid missing some important drought events in an agrarian environ like the Sudano-Sahelian region of Nigeria, the study intend to quantify the drought in the SSRN on a multi-index scale.

Information obtained from these analyses if well interpreted can also serve as useful information for drought monitoring, and can also be used to trigger actions associated with the development and operation of effective drought contingency and management plans.

3.6 Dry spell analysis (Aspect of Drought Management)

The empirical analysis of dry spell, EADS approach, aims at studying the characteristics and the distribution of the dry spells especially within the growing season in order to provide a guide for the management of drought i.e. provide guides for an appropriate time of sowing, type of crop to grow, cropping pattern to be adapted in the midst of the prevailing drought conditions of the Sudano-Sahelian region of Nigeria.,

As part of the major variable determining the effectiveness of rains, a clear understanding of the characteristics of dry spell occurrence over a place is imperative to the successful execution of any meaningful water resource project and the sequel agricultural production in the country.

The study area has a distinct and well-defined long dry season of continuous dry spells, starting from the month of October to March of the next consecutive year. Over the years, the occurrence of this kind of dry spell within the dry season is gradually being adapted to. What has become worrying is the occurrence of dry spell within the wet season of this semi-arid region. It is therefore necessary to study the distribution and the probability of occurrence of these dry spells within the months of the growing season.

Furthermore, an empirical analysis of the dry spell for agricultural applications (EADS) will also be carried out. It aims at obtaining the following:

(i) Distribution of dry days within the month

Obtain the number of dry days in each month of each year so as to obtain for each station, the average no of dry days for each month.

(ii) The likelihood decadal date in each month when the maximum dry spell will start and end. (This step requires a frequency analysis of the various starting and ending dates of occurrence of the maximum spell).

(iii) Distribution of the dry spell length into < 2, 3-4, 5-6, 7-8, 8-10 and > 10 days spell lengths.

(iv) Analysis of the maximum dry spells within 30 day periods starting from the first day of each decade of each growing month.

(a) Calculate the Probabilities of dry spells computed on calendar day basis. i.e. Obtain the probabilities of dry spells exceeding 7, 10 and 15 days within the 30 days after the first day of each decade of the year at each station.

(b) Length and frequencies of dry spells computed on sowing-day basis. It involves using seven (7) different rainfall threshold values (i.e 1, 5, 7, 10, 15, 20, 25mm) to define dry spell or moisture inadequacy, Obtain the length of dry spell (in days) at three probability levels for different days after sowing (DAS).

Two basic definition of sowing dates defined by Stern et al. (1980) and Sivakumar (1992) will be adopted in the study because of their use of a simple and practical definition of soil moisture adequacies as a condition for starting or planting date.

(c) Calculating the percentage frequency of dry spells for different rainfall threshold at each station.

It is strongly believed that the approach used for the dry spell analysis in this study will along with identifying drought occurrences; also provide adequate information needed for practical understanding and handling of the dry spell anomaly. It is an attempt by this study to provide useful information for agricultural applications. This information can be employed after meaningful interpretations as guides in breeding varieties of crops with various maturity durations that can adequately cope with the various dry spell conditions. The study is also a contribution to developing long-term cropping strategies within the Sudano-Sahelian region of Nigeria.

CHAPTER FOUR

4.0 ANALYSIS AND DISCUSSION OF RESULTS

The methodological framework presented in the previous chapter was applied to identify and quantify the drought conditions in the Sudano-Sahelian region of Nigeria. The analyses carried out in this study include, preliminary data analysis, rainfall variability analysis, drought indexing analysis, comparative analysis of derived drought index and dry spell analysis. The results from each of these analyses that was carried out in this study are also presented and discussed in this chapter.

4.1 Data analysis

Prior to any analysis and as required in any hydrological analysis, the quality of the rainfall data collected for the seven (7) stations under study was tested in terms of their consistency. The consistency of these data sets was verified using the double mass curve analysis. As shown in Figures 4.1 (a-g) below, the daily rainfall series have been found to be consistent. The deviations observed in the plots in Figures 4.1a and 4.1e are however relatively small and symmetrically balanced over the period.

4.2 Rainfall Variability in the Sudano-Sahelian Region of Nigeria

For each station under study, the day-to-day and the season-to-season structured data synthesized from the raw daily data were used for the rainfall variability analyses on different time scales. The analysis and results are presented as follows:

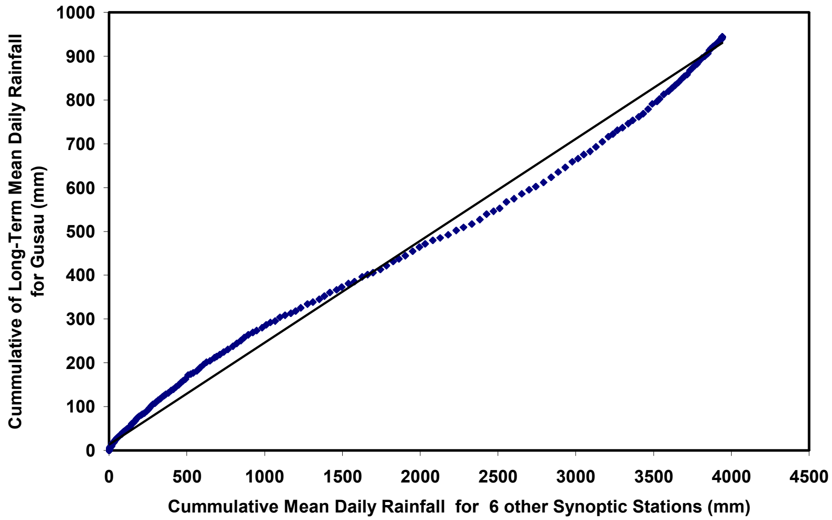


Figure 4.1a: Double Mass Curve Diagram for Gusau (1942-2002)

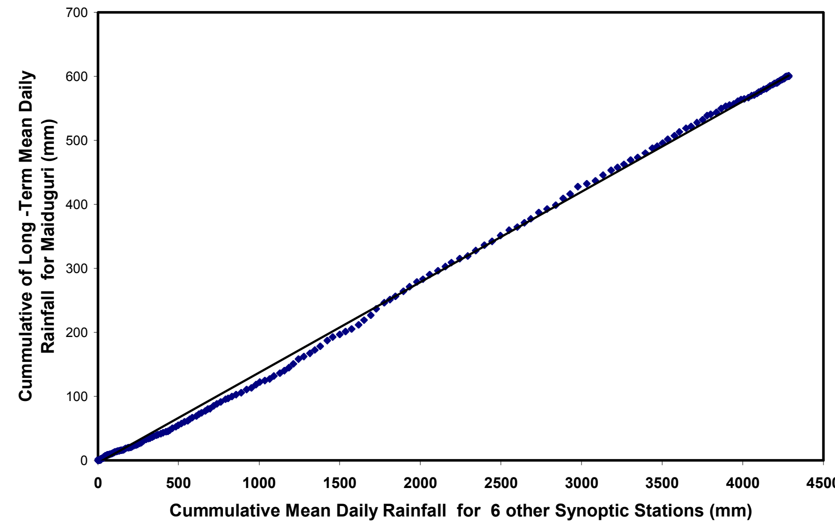


Figure 4.1d: Double Mass Curve analysis for Maiduguri (1945-2003)

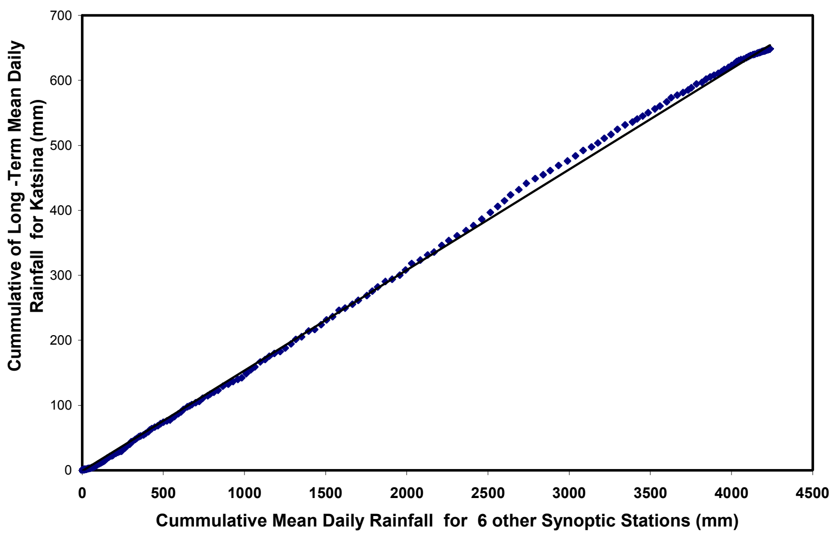


Figure 4.1c: Double Mass Curve analysis for Katsina (1922-2003)

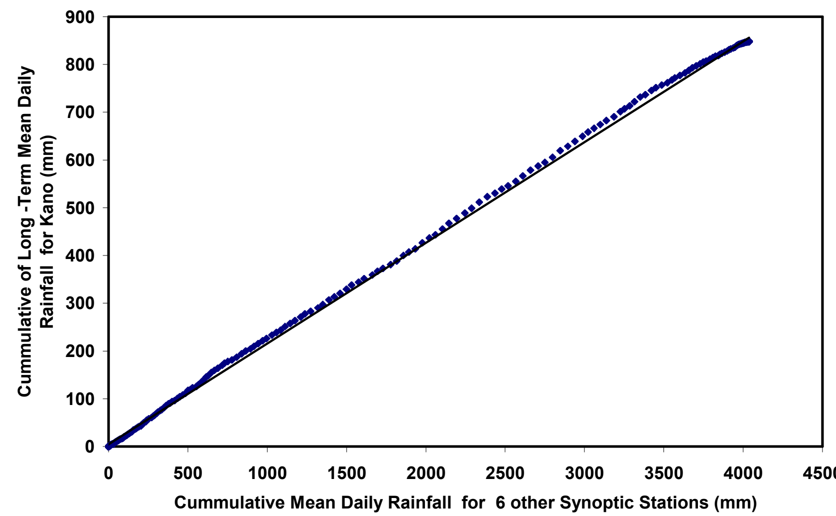


Figure 4.1b: Double Mass Curve Diagram for Kano (1916-2003)

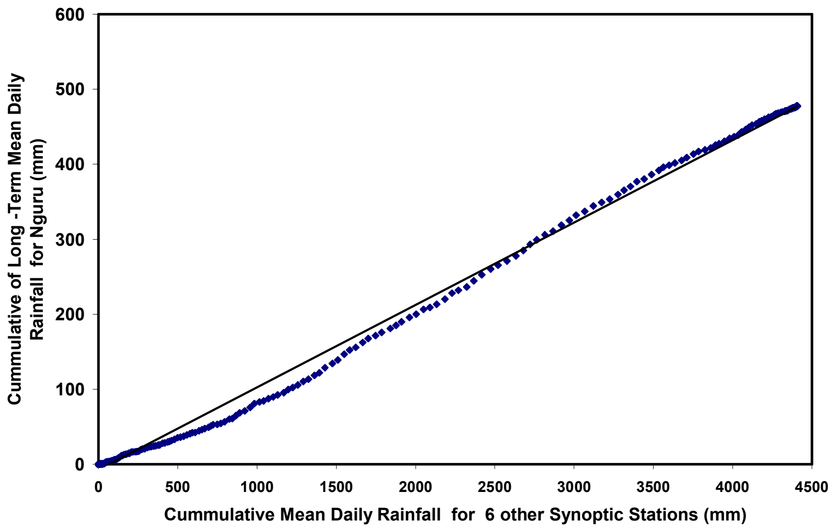


Figure 4.1e: Double Mass Curve Diagram for Nguru (1942-2001)

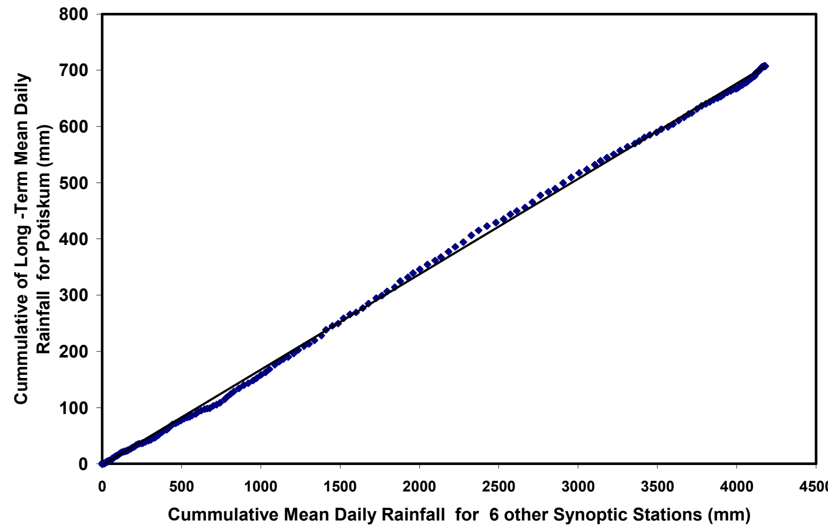


Figure 4.1f: Double Mass Curve Diagram for Potiskum (1936-2003)

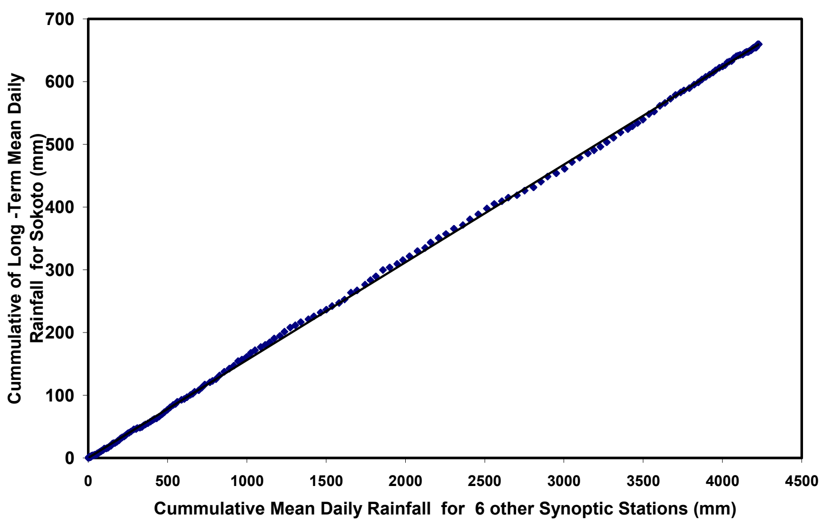


Figure 4.1g: Double Mass Curve analysis for Sokoto (1952-2003)

4.2.1 **Seasonal Distribution of rainfall amount**

For each station under study, the descriptive statistics of the time series of 1-day (WR1), 5-days (WR5), 7-days (WR7), 10-days (WR10), 15-days (WR15),30-days (WR30) and 365-days (WR365) rainfall totals (i.e. 'whole seasonal rainfall' series) are given in tables 4.1a– 4.1g.

Table 4.1a Descriptive Statistics for Whole Seasonal Rainfall Series at Gusau

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
WR1	20087	2.58	0.00	0.00	279.40	0.00	0.00	8.47	3.28	6.06
WR5	4015	12.91	0.00	0.00	283.90	0.00	18.80	23.47	1.82	2.74
WR7	2860	18.13	0.00	0.00	296.90	0.00	29.20	29.78	1.64	2.19
WR10	1980	26.19	0.80	0.00	315.60	0.00	42.90	40.19	1.53	1.99
WR15	1320	39.28	3.05	0.00	350.60	0.00	67.98	56.41	1.44	1.63
WR30	660	78.56	12.35	0.00	589.30	0.00	148.30	106.15	1.35	1.46
WR365	55	942.69	896.50	637.30	1662.10	809.90	1045.50	202.47	0.21	1.32

Table 4.1b Descriptive Statistics for Whole Seasonal Rainfall Series at Kano

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
WR1	32142	2.38	0.00	0.00	253.10	0.00	0.00	8.80	3.70	6.17
WR5	6424	11.90	0.00	0.00	301.80	0.00	13.00	24.33	2.04	3.05
WR7	4576	16.70	0.00	0.00	313.50	0.00	21.50	31.70	1.90	2.84
WR10	3168	24.13	0.00	0.00	395.50	0.00	34.48	42.64	1.77	2.50
WR15	2112	36.19	0.00	0.00	495.70	0.00	56.90	59.45	1.64	2.11
WR30	1056	72.38	2.50	0.00	571.80	0.00	118.28	110.43	1.53	1.72
WR365	88	868.52	841.50	346.10	1869.30	714.63	989.73	242.72	0.28	1.08

Table 4.1c Descriptive Statistics for Whole Seasonal Rainfall Series at Katsina

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
WR1	25201	1.77	0.00	0.00	110.20	0.00	0.00	6.80	3.85	5.60
WR5	5037	8.83	0.00	0.00	140.00	0.00	8.30	18.51	2.10	2.82
WR7	3588	12.40	0.00	0.00	188.50	0.00	14.70	24.21	1.95	2.61
WR10	2484	17.91	0.00	0.00	218.90	0.00	25.10	32.43	1.81	2.38
WR15	1656	26.86	0.00	0.00	275.60	0.00	41.63	45.75	1.70	2.12
WR30	828	53.73	0.70	0.00	425.30	0.00	84.28	84.60	1.57	1.81
WR365	69	644.75	652.30	262.00	993.60	518.35	758.25	165.90	0.26	-0.05

Table 4.1d Descriptive Statistics for Whole Seasonal Rainfall Series at Maiduguri

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
WR1	20088	1.65	0.00	0.00	126.50	0.00	0.00	6.88	4.18	6.62
WR5	4015	8.23	0.00	0.00	161.20	0.00	6.60	18.28	2.22	3.29
WR7	2860	11.56	0.00	0.00	188.30	0.00	12.50	23.24	2.01	2.73
WR10	1980	16.70	0.00	0.00	216.60	0.00	21.50	31.20	1.87	2.49
WR15	1320	25.04	0.00	0.00	360.80	0.00	34.90	43.37	1.73	2.25
WR30	660	50.09	1.70	0.00	467.70	0.00	76.75	79.61	1.59	1.88
WR365	55	601.03	631.20	234.50	888.50	491.00	705.90	151.96	0.25	-0.53

Table 4.1e Descriptive Statistics for Whole Seasonal Rainfall Series at Nguru

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
WR1	20089	1.30	0.00	0.00	112.50	0.00	0.00	5.97	4.61	7.01
WR5	4015	6.48	0.00	0.00	178.80	0.00	3.00	15.93	2.46	3.72
WR7	2860	9.10	0.00	0.00	207.90	0.00	7.08	20.52	2.26	3.34
WR10	1980	13.14	0.00	0.00	244.50	0.00	13.78	26.39	2.01	2.78
WR15	1320	19.71	0.00	0.00	227.00	0.00	24.98	36.10	1.83	2.26
WR30	660	39.42	0.00	0.00	361.10	0.00	56.33	67.57	1.71	2.02
WR365	55	473.07	461.40	238.70	866.40	382.90	558.40	131.30	0.28	0.38

Table 4.1f Descriptive Statistics for Whole Seasonal Rainfall Series at Potiskum

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
WR1	21915	1.93	0.00	0.00	139.70	0.00	0.00	7.58	3.92	6.34
WR5	4380	9.68	0.00	0.00	165.70	0.00	9.20	20.53	2.12	3.10
WR7	3120	13.59	0.00	0.00	204.70	0.00	16.00	26.51	1.95	2.73
WR10	2160	19.62	0.00	0.00	228.30	0.00	27.90	34.72	1.77	2.31
WR15	1440	29.44	0.00	0.00	290.50	0.00	43.18	48.53	1.65	2.06
WR30	720	58.87	5.40	0.00	535.00	0.00	94.20	89.00	1.51	1.73
WR365	60	706.47	701.65	366.80	1012.20	594.68	831.08	156.50	0.22	-0.08

Table 4.1g Descriptive Statistics for Whole Seasonal Rainfall Series at Sokoto

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
WR1	18628	1.83	0.00	0.00	139.40	0.00	0.00	7.17	3.92	5.92
WR5	3723	9.15	0.00	0.00	245.00	0.00	8.90	19.35	2.11	3.28
WR7	2652	12.85	0.00	0.00	299.30	0.00	15.65	24.89	1.94	2.86
WR10	1836	18.56	0.00	0.00	248.30	0.00	27.45	32.64	1.76	2.34
WR15	1224	27.84	0.00	0.00	318.30	0.00	43.50	45.18	1.62	2.01
WR30	612	55.67	3.80	0.00	509.50	0.00	100.25	84.43	1.52	1.73
WR365	51	668.04	697.30	324.50	928.90	557.50	768.70	147.35	0.22	-0.16

From tables 4.1a - 4.1g, the whole rainfall time series within the study area exhibit considerable variability over a hierarchy of timescales. In particular and in all the stations under study, the daily series, i.e. WR1, shows the highest variations among the whole seasonal rainfall series. As expected for a semi-arid region of this kind, the CVs values are above 300% in all the stations under study, reflecting the haphazard nature of its occurrences. The decreasing trend in the values of CVs (and also skewness) from the WR1 series to the WR365 series, is also a clear indication of the its variability in all the stations. The annual series, WR365, though more stable, can only be relied upon in water resources management for successful reservoir-storage analysis and not for short season-agricultural planning.

In order to get the true picture of the exact or actual rainfall occurrence, the zero wet day or dry day occurrence were extracted from each whole seasonal rainfall series (WRs) to get the non-zero seasonal rainfall series (also designated in a similar way as the WR series as NR1, NR5, NR7, NR10, NR15 etc. series). The essential information from the set of the non-zero rainfall series (NRs) have been extracted through a descriptive statistical analysis. Its results are presented on Tables 4.2a – 4.2g.

Table 4.2a Descriptive Statistics for Non-Zero Seasonal Rainfall Series at Gusau

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
NR1	3828	13.5	8.6	0.1	279.4	2.8	19.8	15.09	1.11	3.08
NR5	1723	30.1	23.1	0.1	283.9	9.1	42.9	27.68	0.92	1.93
NR7	1344	38.6	31.1	0.1	296.9	12.7	56.2	33.13	0.86	1.47
NR10	1004	51.6	42.4	0.2	315.6	17.8	77.0	43.27	0.84	1.39
NR15	707	73.3	61.2	0.2	350.6	26.1	111.9	58.68	0.80	1.02
NR30	393	131.9	116.3	0.2	589.3	34.6	201.7	109.01	0.83	0.93
NR365	55	942.7	896.5	637.3	1662.1	809.9	1045.5	202.47	0.21	1.32

Table 4.2b Descriptive Statistics for Non-Zero Seasonal Rainfall Series at Kano

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
NR1	5129	14.9	9.1	0.1	253.1	2.7	20.7	17.27	1.16	2.56
NR5	2438	31.3	22.6	0.2	301.8	8.9	45.0	30.82	0.98	1.91
NR7	1881	40.6	30.5	0.2	313.5	12.2	59.2	38.38	0.94	1.90
NR10	1422	53.7	40.2	0.3	395.5	17.0	78.7	49.58	0.92	1.68
NR15	1017	75.2	59.8	0.2	495.7	22.8	109.1	66.43	0.88	1.36
NR30	573	133.4	105.9	0.3	571.8	31.7	206.7	119.74	0.90	1.02
NR365	88	868.5	841.5	346.1	1869.3	715.2	989.4	242.72	0.28	1.08

Table 4.2c Descriptive Statistics for Non-Zero Seasonal Rainfall Series at Katsina

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
NR1	3559	12.5	7.4	0.1	110.2	2.2	18.5	13.90	1.11	1.88
NR5	1822	24.4	17.9	0.1	140.0	6.0	35.8	23.80	0.97	1.51
NR7	1414	31.5	23.4	0.1	188.5	8.3	45.0	29.79	0.95	1.48
NR10	1076	41.3	31.8	0.1	218.9	12.2	59.6	38.20	0.92	1.42
NR15	769	57.9	46.2	0.1	275.6	15.3	83.7	52.11	0.90	1.26
NR30	425	104.7	81.4	0.1	425.3	26.4	154.8	92.82	0.89	1.04
NR365	69	644.7	652.3	262.0	993.6	526.0	756.4	165.90	0.26	-0.05

Table 4.2d Descriptive Statistics for Non-Zero Seasonal Rainfall Series at Maiduguri

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
NR1	2789	11.9	6.1	0.1	126.5	2.0	16.5	14.83	1.25	2.38
NR5	1432	23.1	15.7	0.1	161.2	5.1	33.7	24.39	1.06	1.91
NR7	1132	29.2	20.6	0.1	188.3	6.6	41.2	29.15	1.00	1.55
NR10	858	38.5	28.1	0.1	216.6	9.4	56.1	37.50	0.97	1.49
NR15	633	52.2	37.0	0.2	360.8	12.4	77.3	50.04	0.96	1.40
NR30	351	94.2	70.9	0.3	467.7	19.6	148.6	88.14	0.94	1.14
NR365	55	601.0	631.2	234.5	888.5	491.0	705.9	151.96	0.25	-0.53

Table 4.2e Descriptive Statistics for Non-Zero Seasonal Rainfall Series at Nguru

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
NR1	2179	11.9	6.6	0.1	112.5	2.0	16.3	14.19	1.19	2.14
NR5	1221	21.3	14.0	0.1	178.8	4.8	30.6	22.78	1.07	2.02
NR7	975	26.7	17.0	0.1	207.9	6.5	37.9	27.68	1.04	1.90
NR10	758	34.3	24.2	0.1	244.5	8.9	50.5	33.04	0.96	1.61
NR15	552	47.1	37.3	0.1	227.0	13.1	70.3	42.71	0.91	1.22
NR30	314	82.9	60.7	0.1	361.1	17.9	125.4	77.47	0.93	1.10
NR365	55	473.1	461.4	238.7	866.4	382.9	558.4	131.30	0.28	0.38

Table 4.2f Descriptive Statistics for Non-Zero Seasonal Rainfall Series at Potiskum

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
NR1	3173	13.4	7.8	0.1	139.7	2.6	18.8	15.63	1.17	2.42
NR5	1628	26.0	18.6	0.1	165.7	6.1	36.5	26.62	1.02	1.84
NR7	1284	33.0	24.1	0.1	204.7	8.7	46.3	32.66	0.99	1.66
NR10	984	43.1	32.0	0.2	228.3	11.2	61.6	40.46	0.94	1.41
NR15	710	59.7	45.5	0.2	290.5	15.7	86.0	54.51	0.91	1.28
NR30	390	108.7	82.9	0.3	535.0	28.7	170.5	95.98	0.88	1.05
NR365	60	706.5	701.7	366.8	1012.2	594.8	827.7	156.50	0.22	-0.08

Table 4.2g Descriptive Statistics for Non-Zero Seasonal Rainfall Series at Sokoto

Variable	Valid N	Mean	Median	Min.	Max.	Lower Quart.	Upper Quart.	Std. Dev.	C.V	Skew
NR1	2529	13.5	8.4	0.1	139.4	2.6	19.7	14.90	1.11	2.06
NR5	1311	26.0	19.3	0.2	245.0	7.3	38.0	25.01	0.96	2.08
NR7	1044	32.6	24.6	0.2	299.3	10.0	47.3	30.48	0.93	1.86
NR10	806	42.3	34.6	0.3	248.3	13.0	59.0	37.75	0.89	1.46
NR15	584	58.3	46.7	0.3	318.3	17.3	86.2	49.99	0.86	1.24
NR30	324	105.2	88.7	0.2	509.5	27.3	161.4	90.92	0.86	1.03
NR365	51	668.0	697.3	324.5	928.9	557.5	768.7	147.35	0.22	-0.16

The statistics for the WR365 and NR365 series are the same in all the stations. The main difference between the statistics derived for other WRs and NRs series is that lower values are obtained for the mean, median, minimum, 25th and 75th percentiles of the WRs series because of the inclusion of zero rainfall depth values in the WRs series. This should caution most water resources planners and engineers who use these statistical parameters to clearly differentiate the statistical values for each series before applying them. While an analyst involved in a reservoir- storage analysis is much concerned with the NRs series, the agriculturalist on the other hand, is interested in the WR series.

It is also clear that the over 300% variability noticed in the whole seasonal rainfall (WRs) series drastically dropped to 125% for the non-zero rainfall (NRs) series. This mild variation in the 'actual' rains is a clear indication that the rains in the Sudano-Sahelian region can to some extent be relied upon quantity-wise. There is therefore the challenge of knowing better the nature of the incessant dry spell occurrence that strongly combine and affect the less variable rains observed during the wet season. Perhaps, a further analysis of the entire WRs series on different perspectives and time scales might just reveal them.

The frequency distribution of depth of each of the whole seasonal rainfall series i.e. rainfall depths for the 1, 5, 7, 10, 15, 30 and 365 days rainfall totals, was carried out as a way of showing from historical data, the temporal variability of the seasonal rainfall depths for all the stations under study. Figures 4.2 and 4.3 show the cumulative frequency diagrams for the n-day rainfall depths in these stations.

A close look at these plots in Figures 4.2 and 4.3 indicates clearly that:

(i) Over 80% of the daily rainfall observations are concentrated around the zero rainfall depth. This also accounts for the wide variability between the WRs and the NRs series.

(ii) The special form of the Gamma distributions suggestively describes these observations. The distribution can be used to synthesize future observations of rainfall depths in probability terms for each station. This result agrees with the findings of Stern et al. (1984) and Jimoh and Webster (1996) that rainfall depths on wet days can be modeled by gamma distributions.

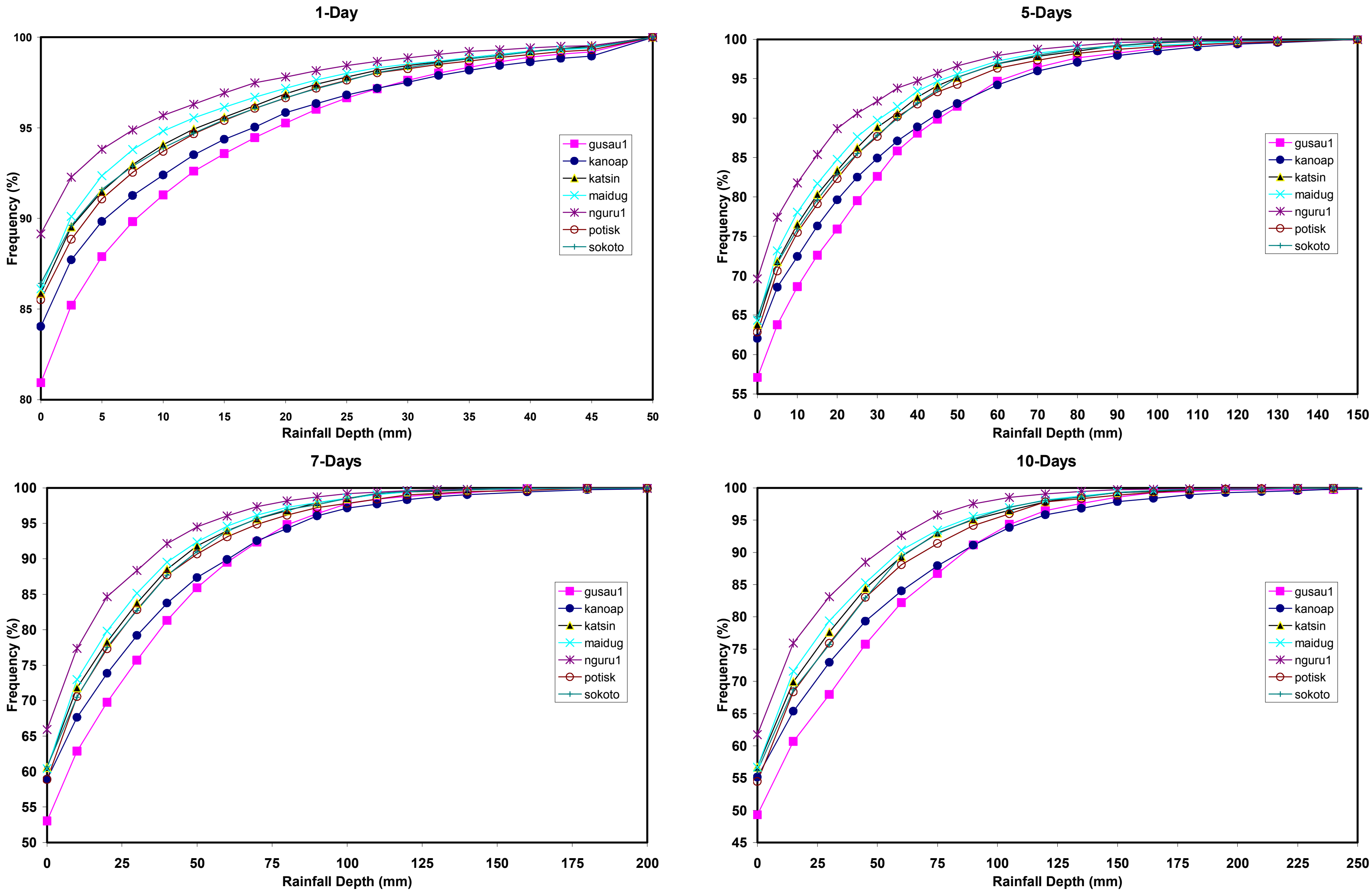


Figure 4.2: Cumulative Frequency Distribution of 1, 5, 7, and 10-Day Rainfall Depths in Stations under study

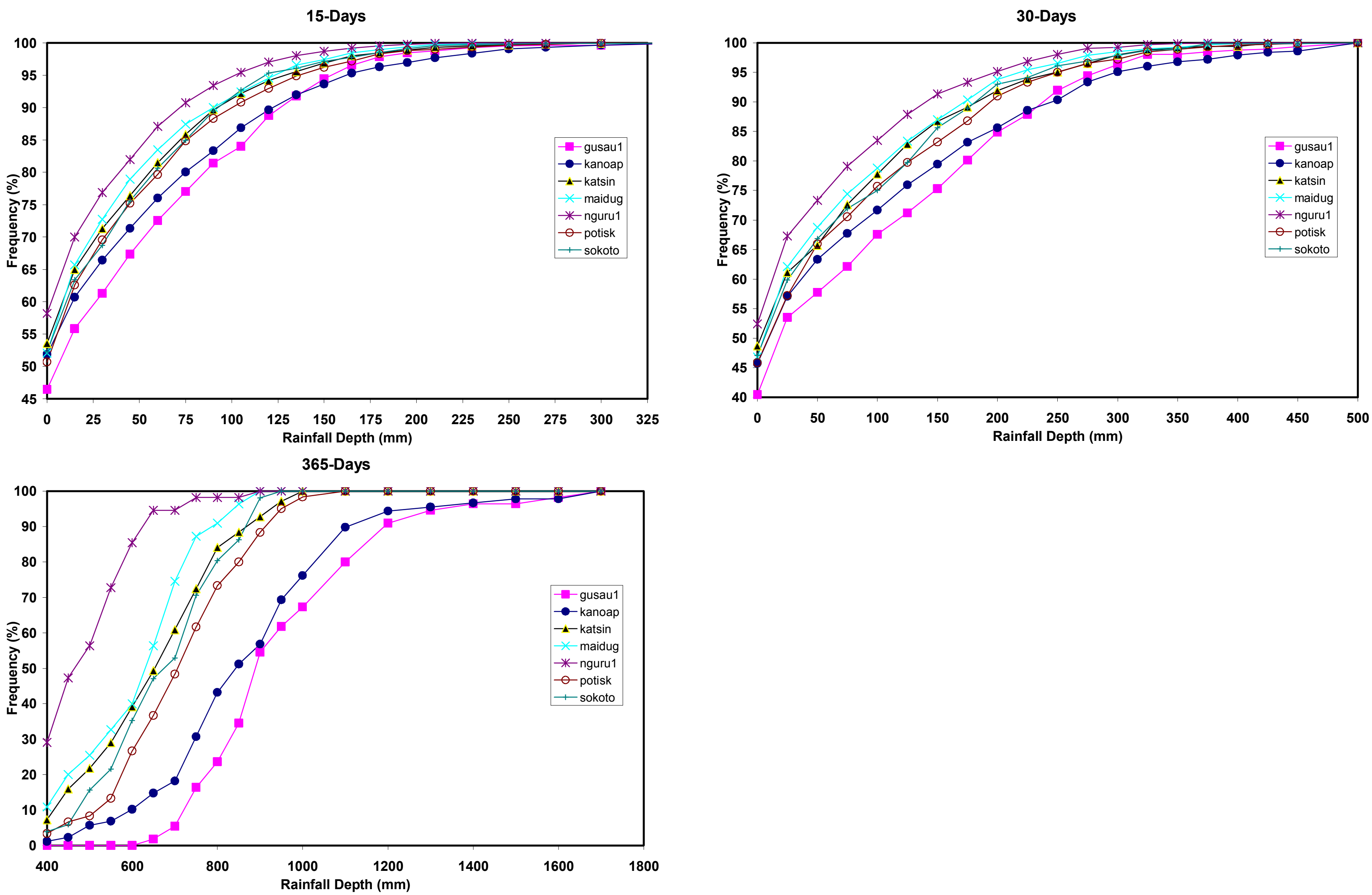


Figure 4.3: Cumulative Frequency Distribution of 15, 30, and 365-Days Rainfall Depths in Stations under study

The zero values integrated in the WRs make up the percentage shown in table 4.3 below for the dry days or season. The low percentage of wet seasons observed corresponds to the period when rainfall was actually observed in each of the stations.

Table 4.3 Percentage Occurrence of Dry and Wet Seasons for each Seasonal Rainfall Totals

Station	Percentage Occurrence of Dry and Wet Seasons for each Seasonal Rainfall Totals (%)											
	1-Day		5-Days		7-Days		10-Days		15-Days		30-Days	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Gusau	80.9	19.1	57.1	42.9	53.0	47.0	49.3	50.7	46.4	53.6	40.5	59.6
Kano	84.0	16.0	62.1	38.0	58.9	41.1	55.1	44.9	51.9	48.2	45.7	54.3
Katsina	85.9	14.1	63.8	36.2	60.6	39.4	56.7	43.3	53.6	46.4	48.7	51.3
Maiduguri	86.1	13.9	64.3	35.7	60.4	39.6	56.7	43.3	52.1	48.0	46.8	53.2
Nguru	89.2	10.9	69.6	30.4	65.9	34.1	61.7	38.3	58.2	41.8	52.4	47.6
Potiskum	85.5	14.5	62.8	37.2	58.9	41.2	54.4	45.6	50.7	49.3	45.8	54.2
Sokoto	86.4	13.6	64.8	35.2	60.6	39.4	56.1	43.9	52.3	47.7	47.1	52.9

In all the stations, the percentage of the dry days or seasons decreases from over 80% for the 1-Day series to a little above 40% for the 30-Days series. This variability trend might also be linked to the reliability level of these seasonal rainfall series, as the percentage of the problematic dryness reduces.

Plots of the histogram of the non-zero seasonal rainfall totals in Figures 4.4 and 4.5 below are also used to express the variability in the actual rainfall series over entire the study area. These histogram diagrams reveal the following distinctive characteristics:

(a) All the frequency plots have their maximum frequencies at the lowest daily rainfall depth. This is an indication that very low rainfall occur rather frequently all over the Sudano-Sahel region. This is also reflected in the lower median values obtained in the earlier Tables 4.1 and 4.2 above.

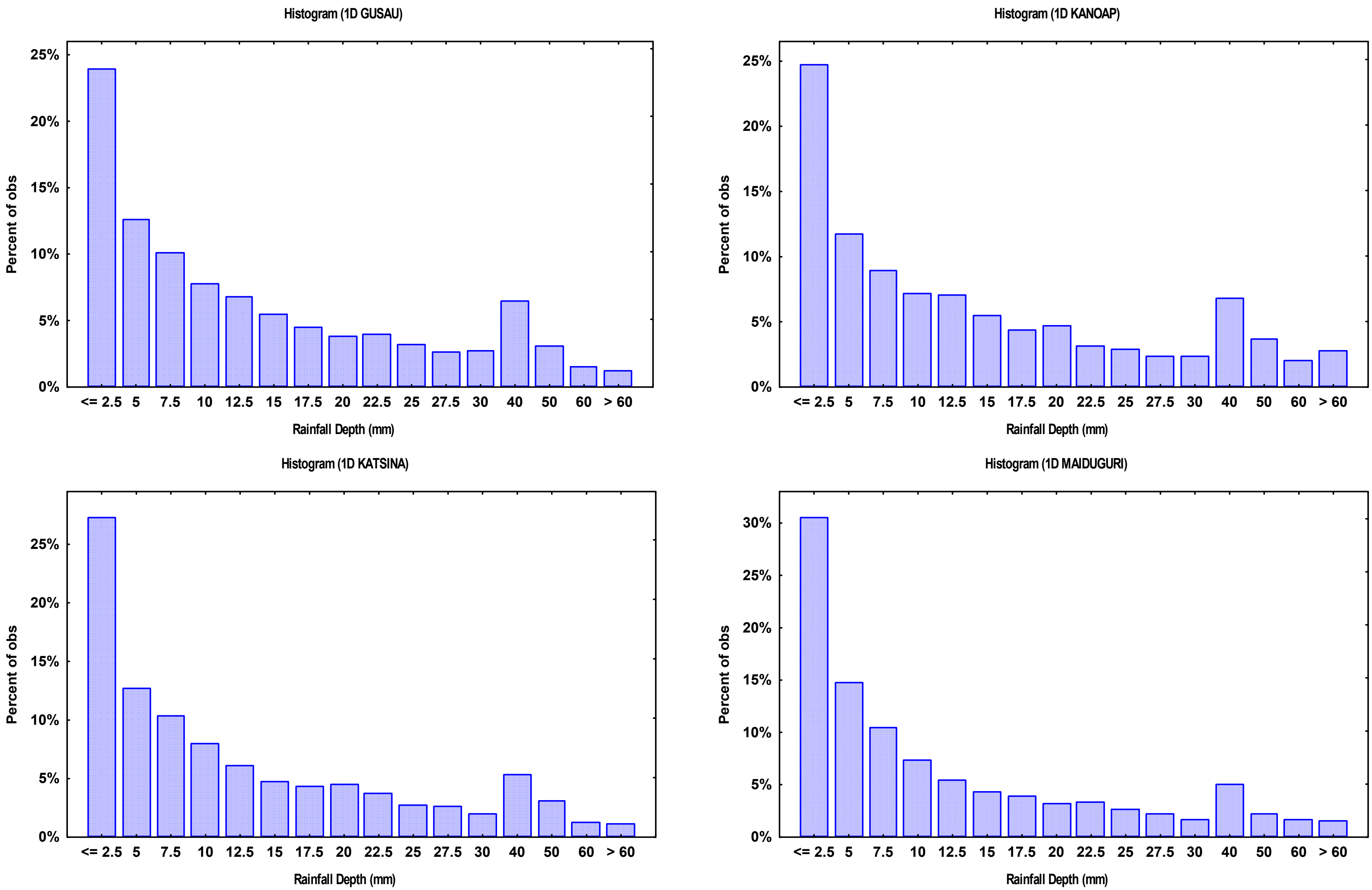


Figure 4.4: Histogram of 1-Day Rainfall Depths (NR Series) in Gusau, Kano, Katsina and Maiduguri Stations

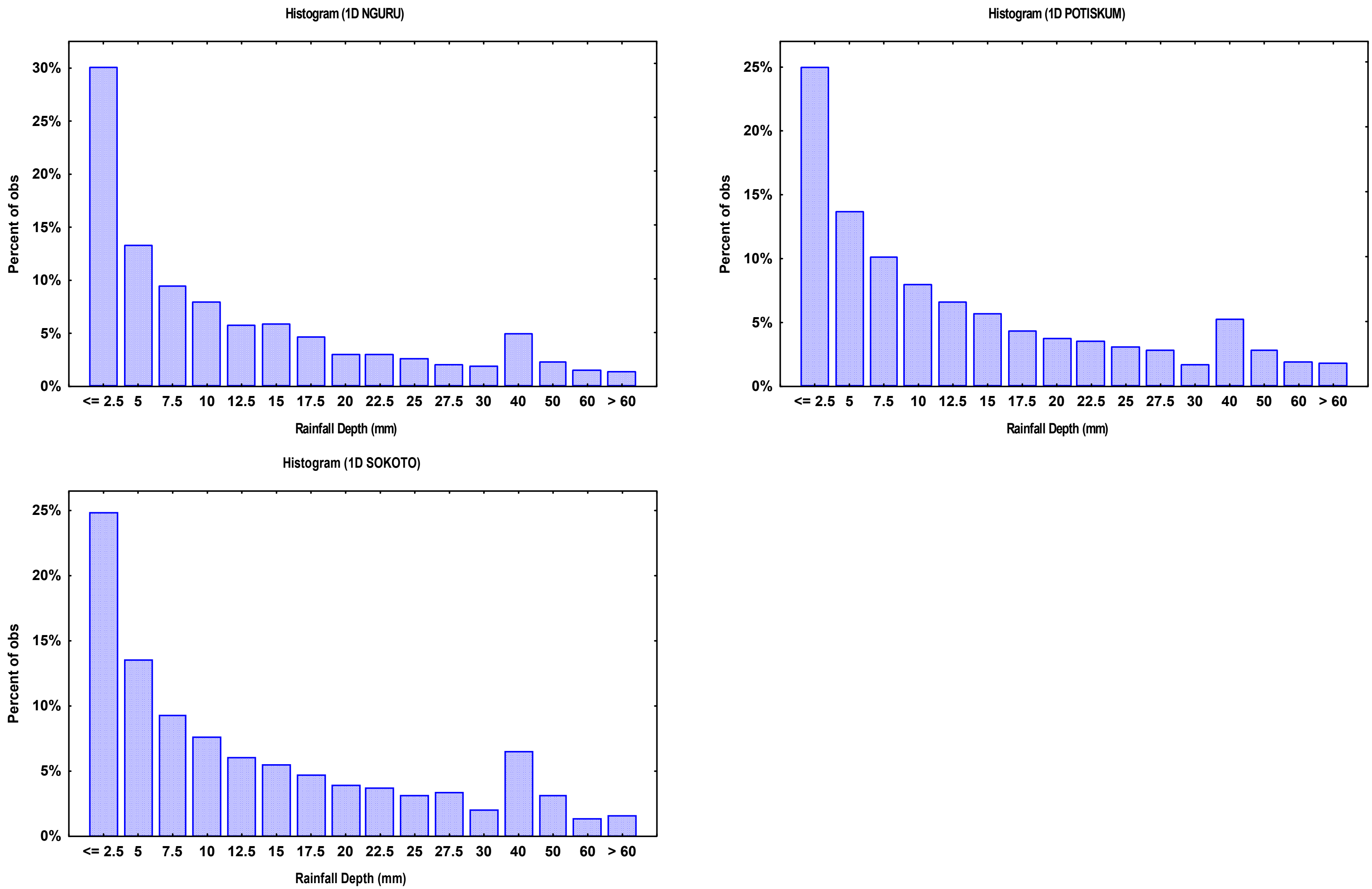


Figure 4.5: Histogram of 1-Day Rainfall Depths (NR Series) in Nguru, Potiskum and Sokoto Stations

(b) The distribution of the frequencies within each class interval of the data has different variability ranges.

(c) The rainfall pattern for the region is uni-modal.

In Figure 4.6, a plot of cumulative mean daily rainfall (depth) over a year for each station is presented. There is a sharp change of slope from about the 160th day (beginning of 2nd decade in June) until about the 260th day (the last decade in September), indicating the most prominent wet season for these area. The aftermath horizontal slope is an indication of the end of the wet season when no significant changes or zero fall is observed in the daily rainfall. This also brings about the onset of the long-inter-annual dry spells, which end around the 120th day of the next year.

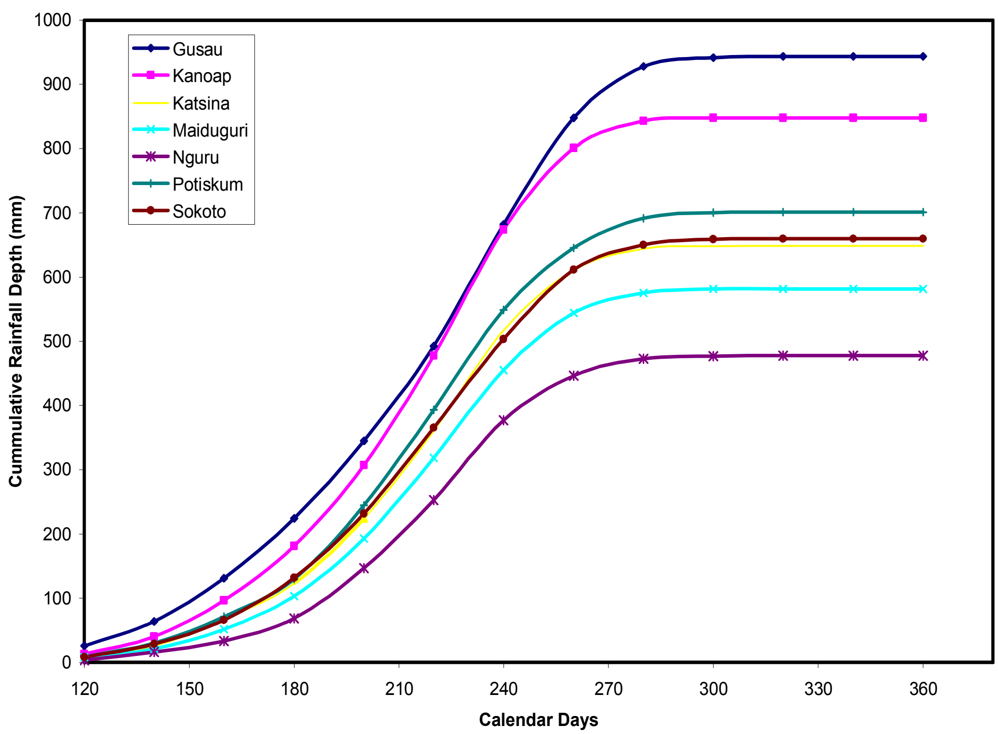


Figure 4.6: Distribution of the Long-Term Mean Daily Rainfall Depths for Stations under study

The distribution of the annual rainfall depths for all the stations is shown in Figure 4.7 while that of the long term mean for the monthly totals is shown in Figure 4.8. There is a noticeable downward trend shown on Figure 4.7 indicating that the annual rainfalls of most of these stations are on the decrease from the early 50s.

Although a sharp increase was noticed from the late 1990, this trend cannot be concluded now, as it might be a sign that the area is recovering from the long spell of drought that the entire Sudano-Sahel region has so far experienced in the recent past years. Figure 4.9 also clearly illustrates another obvious change in the slope of the seasonal rainfall curve, from about the 160th day (beginning of 2nd decade in June), as also indicated in Figure 4.6 above. This is an unambiguous sign that the onset of the rains within this zone starts around this 160th day of the year.

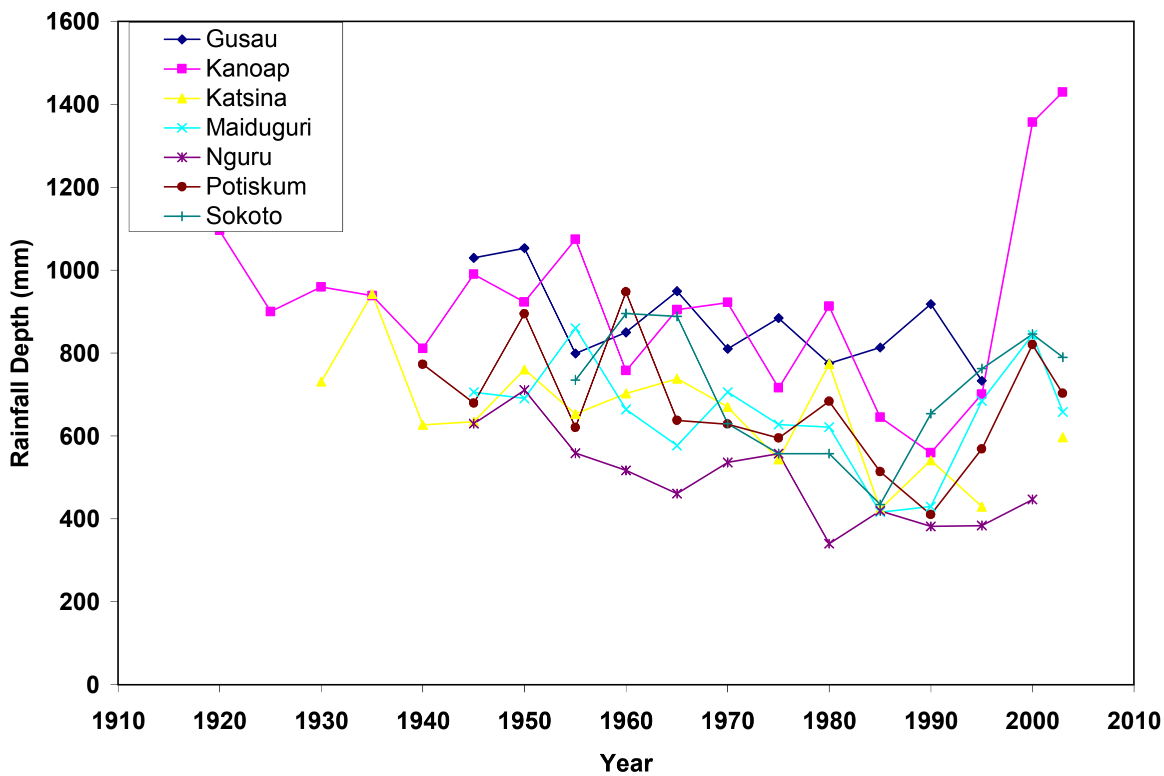


Figure 4.7: Distribution of Annual Rainfall Depths for Stations under study.

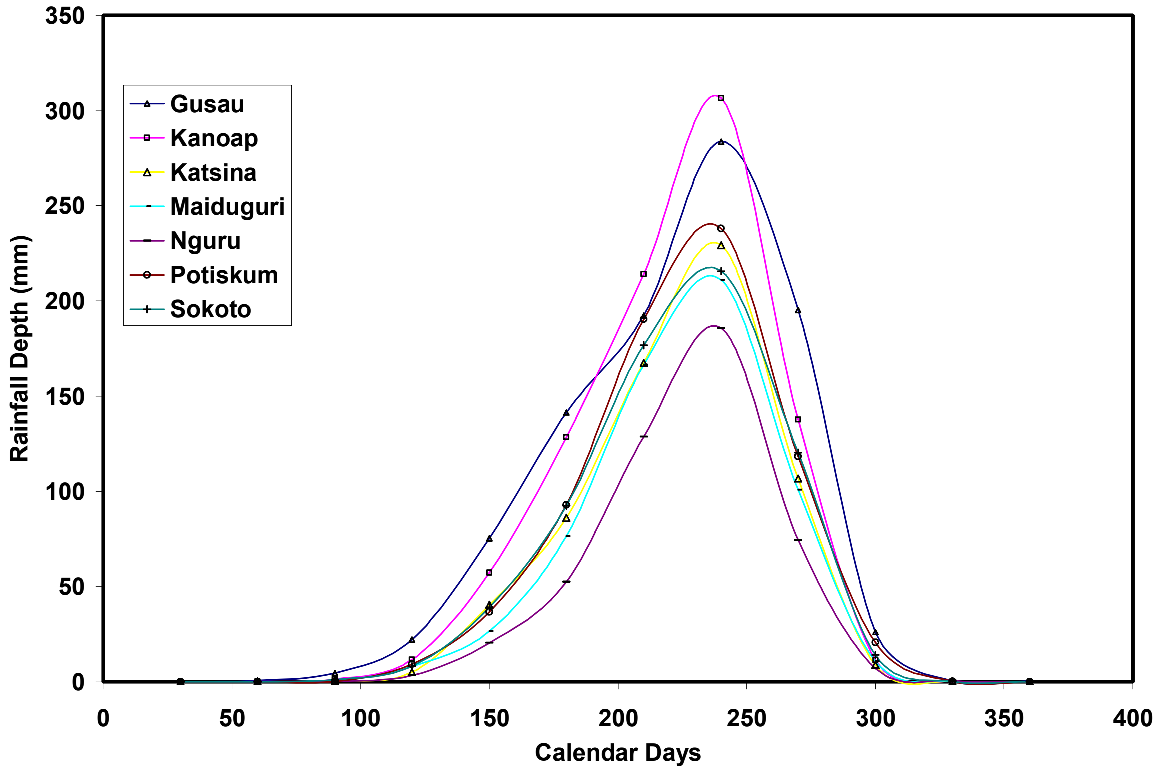


Figure 4.8: Distribution of Long-Term Mean Monthly Rainfall Depths for Stations under study.

Another form of the variation in the monthly rainfall depths is shown in Figures 4.9 and 4.10. The stacked columns shown in these Figures compare the contributions of various rainfall depths for various growing months.

By comparing Figures 4.4 and 4.5 with Figures 4.9 and 4.10, it can be seen that the heavy rainfall above 20mm, though few in some months, occurs through out the entire growing months in most of the stations. It consequently account for the total amounts of rains observed for the different months. The impact of these heavy rainfalls in the earlier growing months helps to lower the negative soil moisture from the extended dry spells of the well spanned dry season.

During the mid growing season i.e. months of July and August, the accumulated soil moisture deficit is expected to have been completely satisfied and the excess rainfalls from these heavy rainfalls are loss to runoff and soil drainage. While these heavy rainfalls lasts, the impact of the intervening dry spells during this mid growing season poses no threat or danger to crops. But and regretfully, the predominant occurrence of these heavy rainstorms at these periods cannot be retained for use in the future months. Hence, the intervening dry spells, which later occur, overpower the subsequent light rainstorms that prevail towards the end of the year.

Also noticeable in Figures 4.9 and 4.10 is the predominant occurrence of the less that 10 mm rainfall depths across the entire growing months. As the daily water demand of most of the crops grown in the SSRN rarely goes above the 7.5 mm/day, the cumulative sum of these rainstorms with lower depths help in varying degrees to meet the basic or minimum water requirements of the region while the rain lasts.

A drought condition only sets in whenever the degree of satisfaction is below a particular threshold and also when the inter-event time between their occurrences stays long and eventually results in a long dry spells.

The variation or distribution of this daily or monthly rainfall depth also determines the functionality and performance from every water use or demand activity such as rain-fed farming within the entire SSRN.

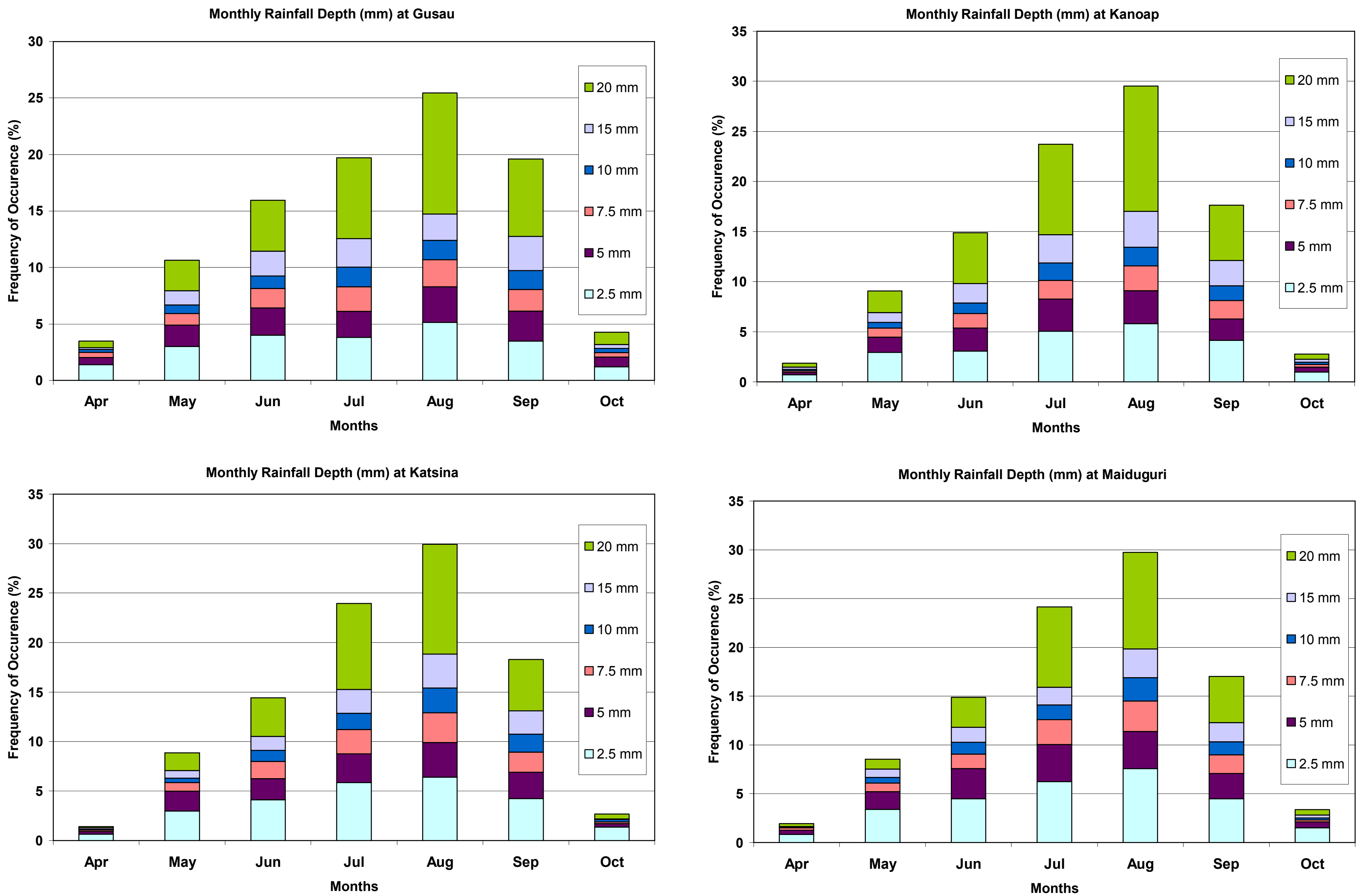


Figure 4.9: Distribution of Mean Monthly Rainfall Depths in Gusau, Kano, Katsina and Maiduguri Stations

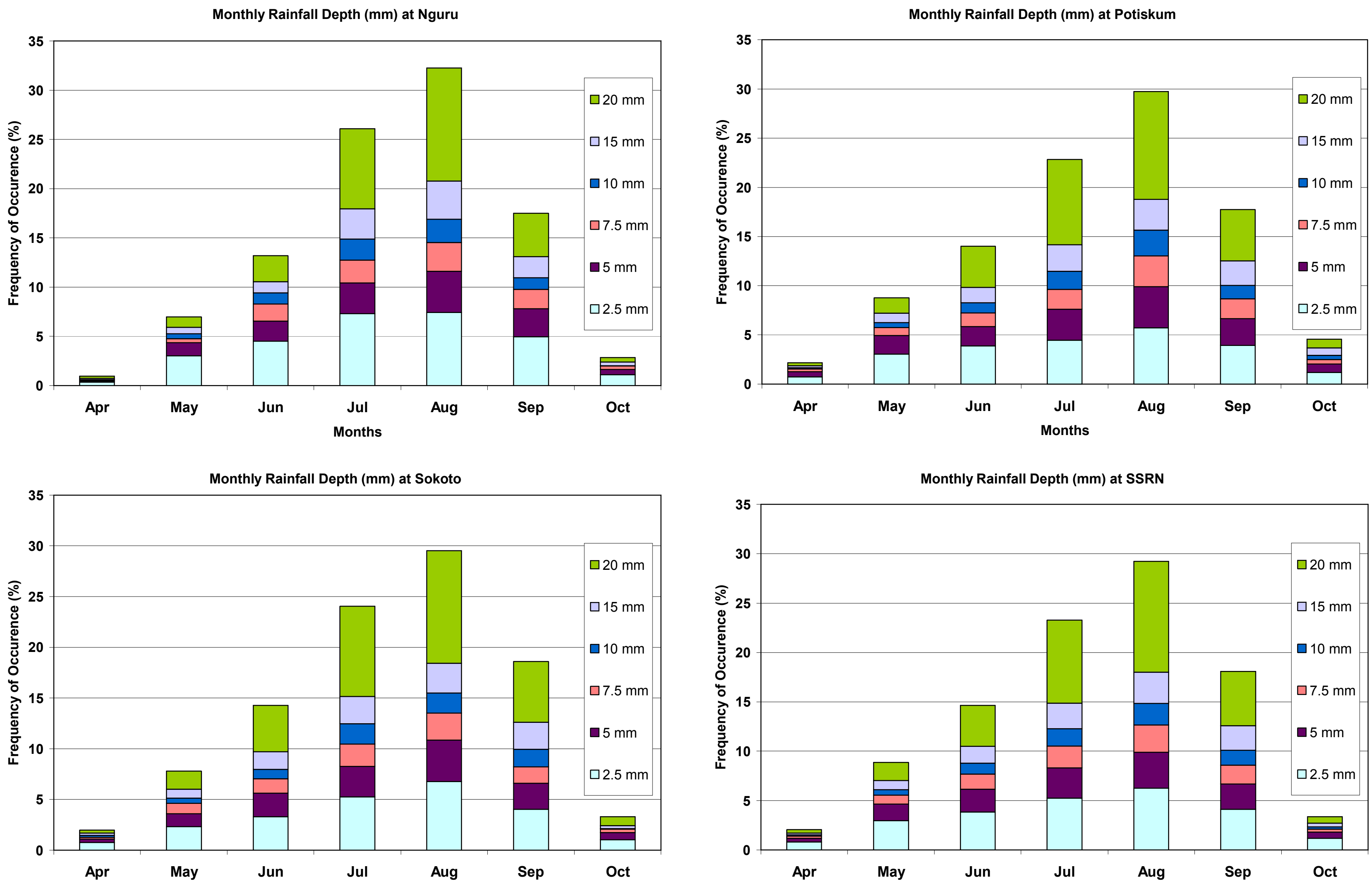


Figure 4.10: Distribution of Mean Monthly Rainfall Depths in Nguru, Potiskum, Sokoto Stations and in the SSRN

Within each calendar day of a year, the intra-variations among all the seasonal rainfall series are depicted in the plots on Figures 4.11 and 4.12. The trend shown by each of these seasonal rainfall series is similar in all the stations. The average regional rainfall depth for the SSRN is less than 250 mm for the 30-day series, 120mm for the 15-day series, 100mm for the 10day series, 75mm for the 7-day series and the 50mm for the 5-day series. The implication is that persistent demand for rainfall above these values cannot be satisfied. Similarly, the wide difference between the peaks of each seasonal rainfall series is a clear pointer to the poor distribution of the rainfall depths at shorter interval of days.

Following the results so far obtained, it is reasonable to agree with the thought highlighted by Vincente-Serrano et al. (2004) and Oladipo (1995), that there is a high dependence of drought characteristics on the spatial and temporal variability in precipitation.

4.2.2 **Seasonal Distribution of rain days**

While a lot of previous studies have concentrated on only rainfall amounts to describe the variability of rainfall occurrence over a place, this study has gone a step further to use the distribution of rain days and some other PEVs to further magnify such rainfall variability.

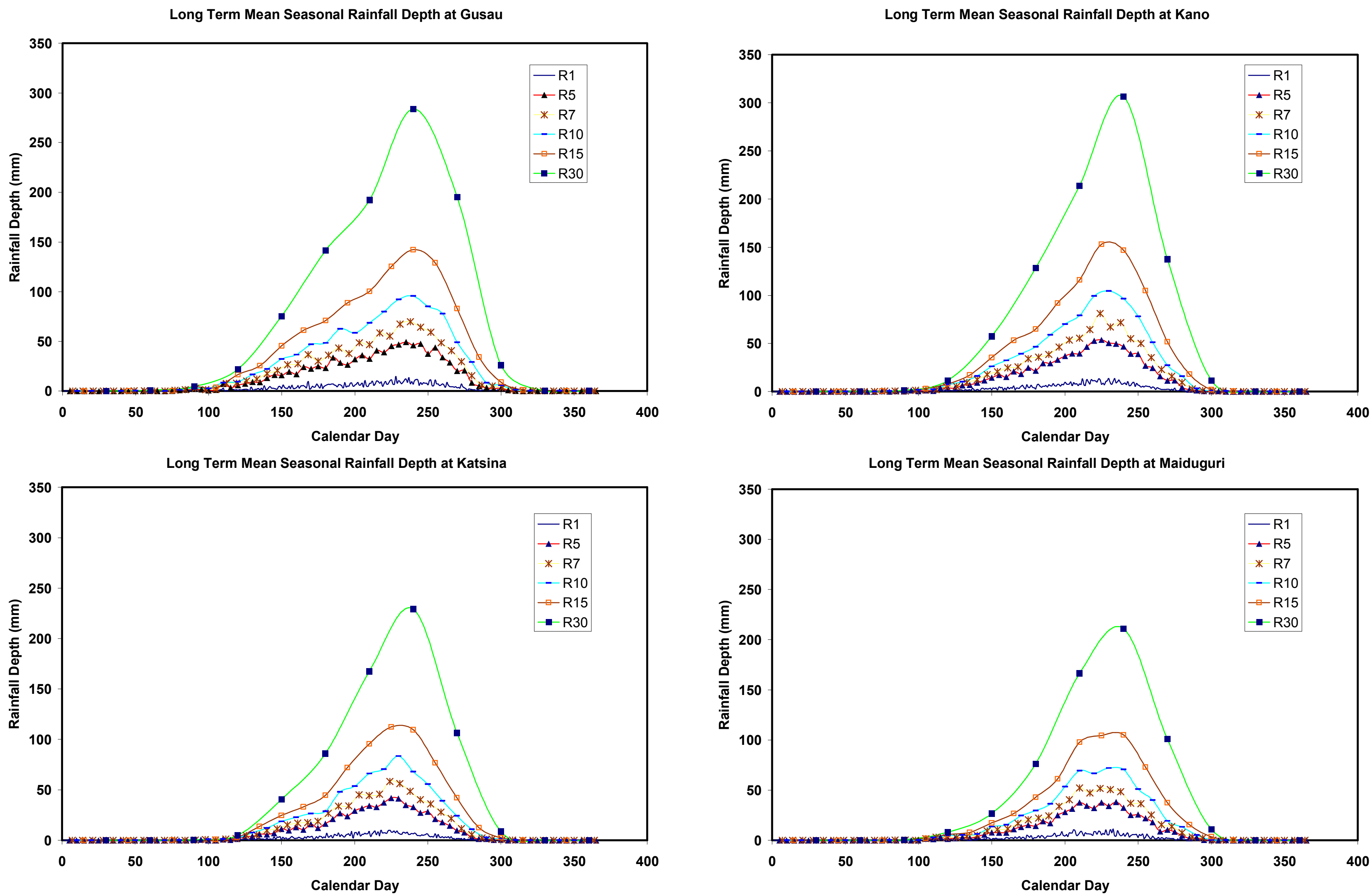
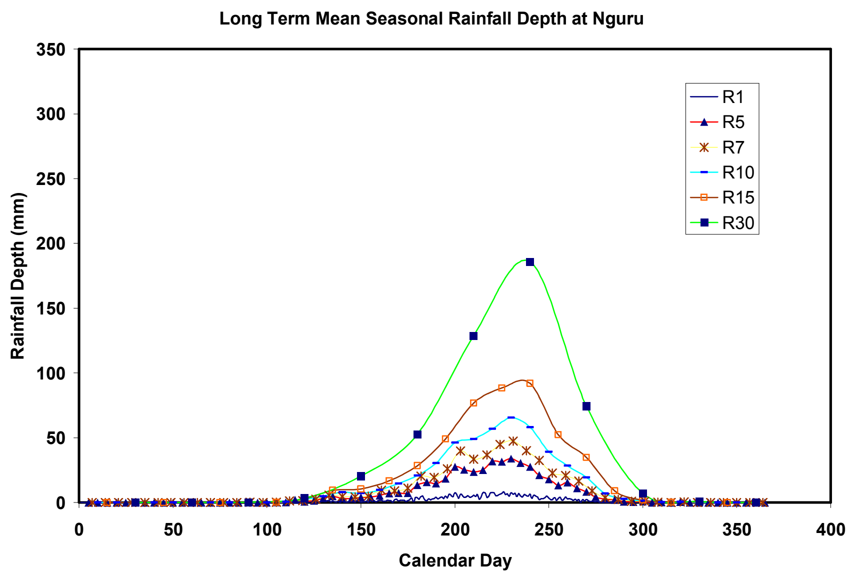
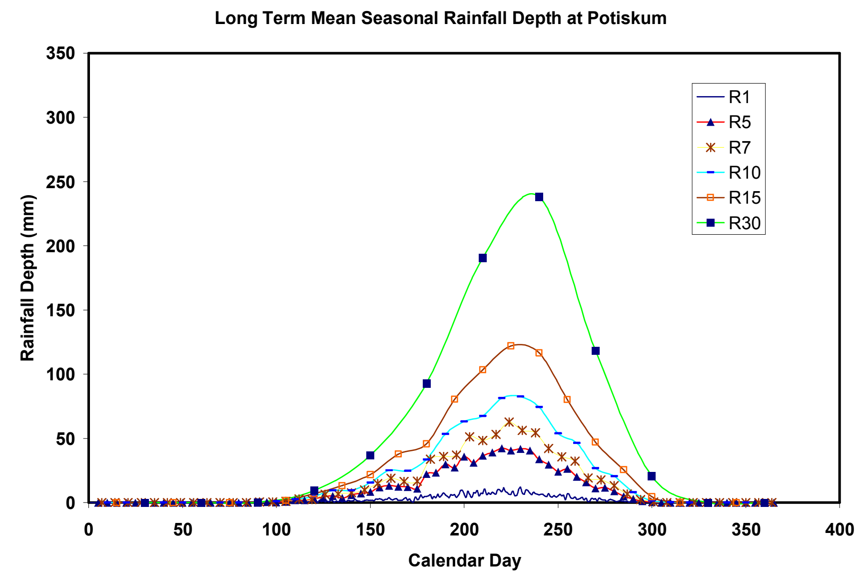
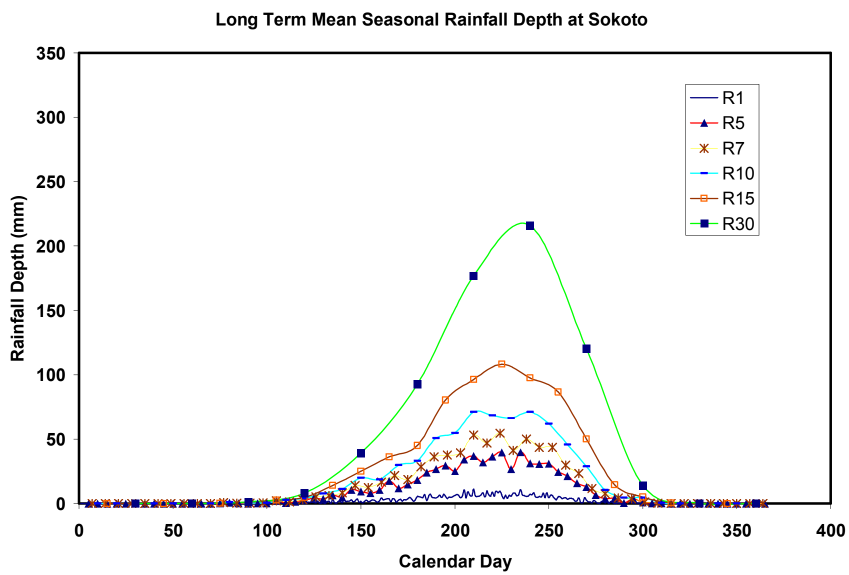
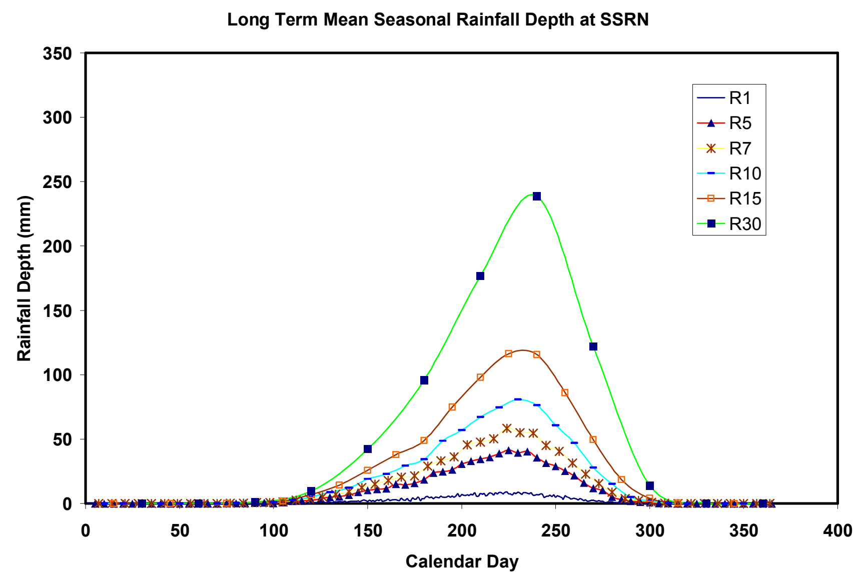


Figure 4.11: Distribution of Long Term Mean Seasonal Rainfall Depth at Gusau, Kano, Katsina and Maiduguri Stations


Long Term Mean Seasonal Rainfall Depth at Nguru
Rainfall Depth (mm)
Calendar Day
R1
R5
R7
R10
R15
R30
0
50
100
150
200
250
300
350
400


Long Term Mean Seasonal Rainfall Depth at Potiskum
Rainfall Depth (mm)
Calendar Day
R1
R5
R7
R10
R15
R30
0
50
100
150
200
250
300
350
400


Long Term Mean Seasonal Rainfall Depth at Sokoto
Rainfall Depth (mm)
Calendar Day
R1
R5
R7
R10
R15
R30
0
50
100
150
200
250
300
350
400


Long Term Mean Seasonal Rainfall Depth at SSRN
Rainfall Depth (mm)
Calendar Day
R1
R5
R7
R10
R15
R30
0
50
100
150
200
250
300
350
400

On a monthly basis, Figure 4.13 shows the mean monthly distribution of the rainy days for all the stations. As expected the dry months starting from November to about April of next years are still notably reflected. The Figure also divides the rainy months into two distinct sub-periods, namely the core rainy months consisting of July and August, and the marginals, which have the months of May-June and September-October.

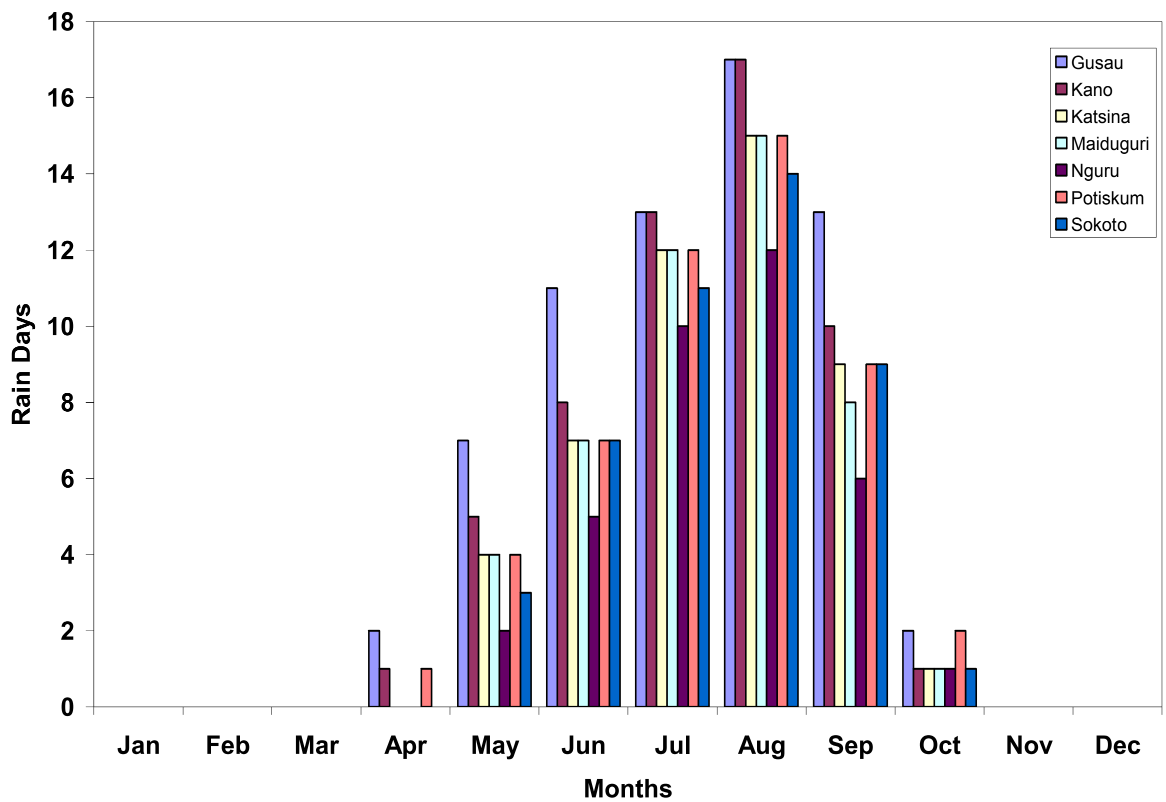


Figure 4.13: Temporal Variation of Average Number of Rain days for Stations under study

The core season is characterized by greater numbers of rainy days than for the marginal periods. By comparing Figures 4.11, 4.12 and 4.13, it can be deduced that the intra-seasonal variability at the 10-days and monthly scales is greater during the marginal periods than during the core period. Similarly, it can also be clearly seen that over 70% of the total annual rains fall in the core season. This revelation poses the challenge that the variation in the number of rain days recorded in any place has a potential of revealing the drought conditions over a place. This was evaluated in this study with the computation of the normalized rain-day index (NRI) earlier defined in equation 3.2.

4.3 Drought Inference from Rainfall Variability Analysis

Further to the rainfall variability analysis earlier discussed in sections 4.2.1 and 4.2.2 above, There is the need to further infer the occurrences of drought from such variableness that have been earlier identified to have prevailed over the SSRN.

The normalized rain-day index (NRI) plotted for all the stations in Figures 4.14 and 4.15 were also used to show the inter-seasonal rainfall variability within the SSRN. Generally, in these Figures, the downward trend observed in the values of NRI, since the late 60s are sharply defined. There is also some degree of spatial variations observed in the NRI values obtained for each of the stations under study. While Kano and Gusau, located within the central region of the SSRN, can be said to have mild drought incidence due to the lower negative values of NRI, Nguru and Maiduguri, coincidentally at the eastern part of SSRN, are worse off for the larger negative values of this index.

The historical drought years experienced in the SSRN between the 1970-1972 and 1983-1987 are also well reflected in all the NRI plots for each of the stations under study

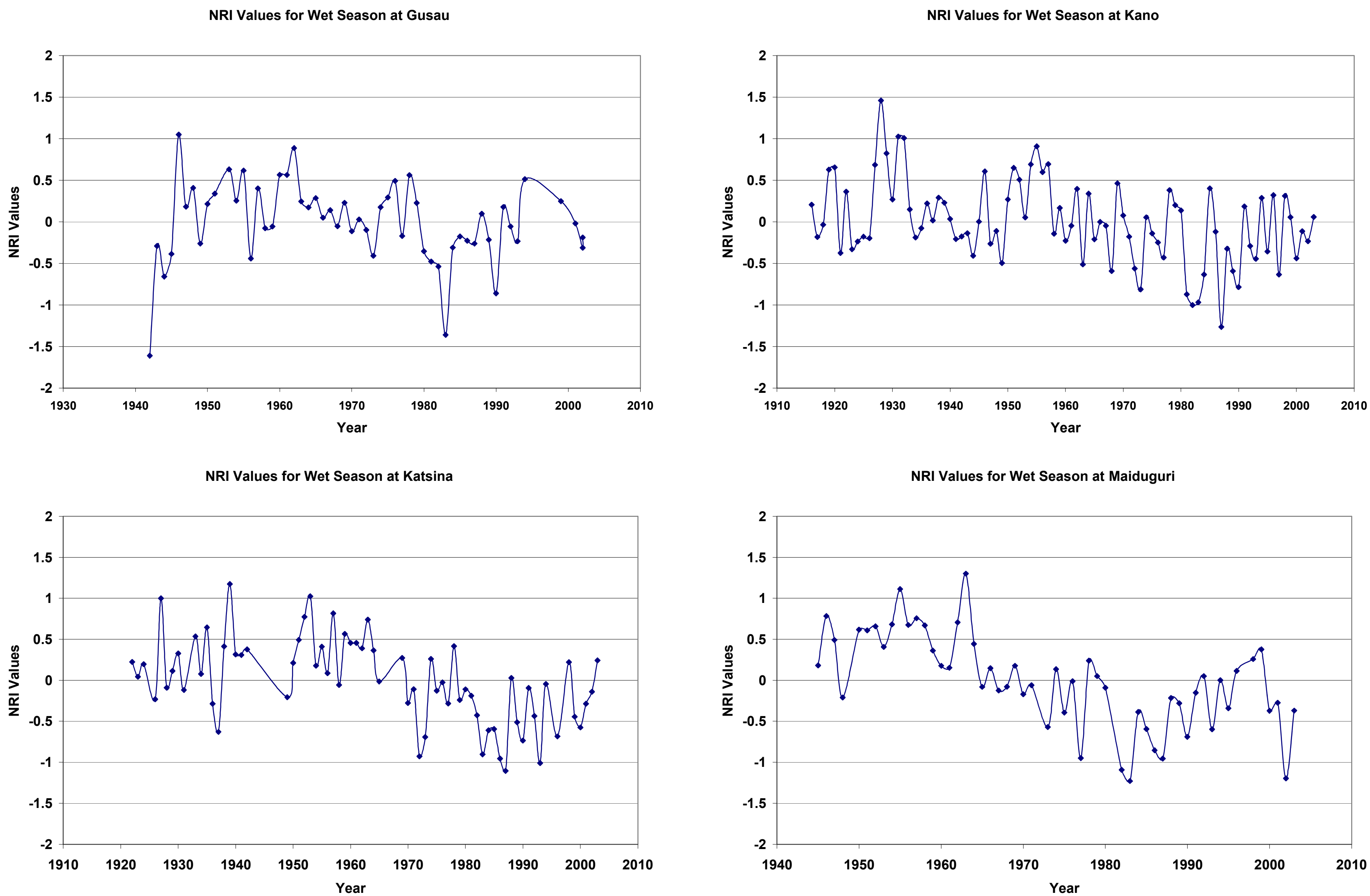


Figure 4.14: Distribution of Normalized Rain days Index (NRI) at Gusau, Kano, Katsina and Maiduguri Stations

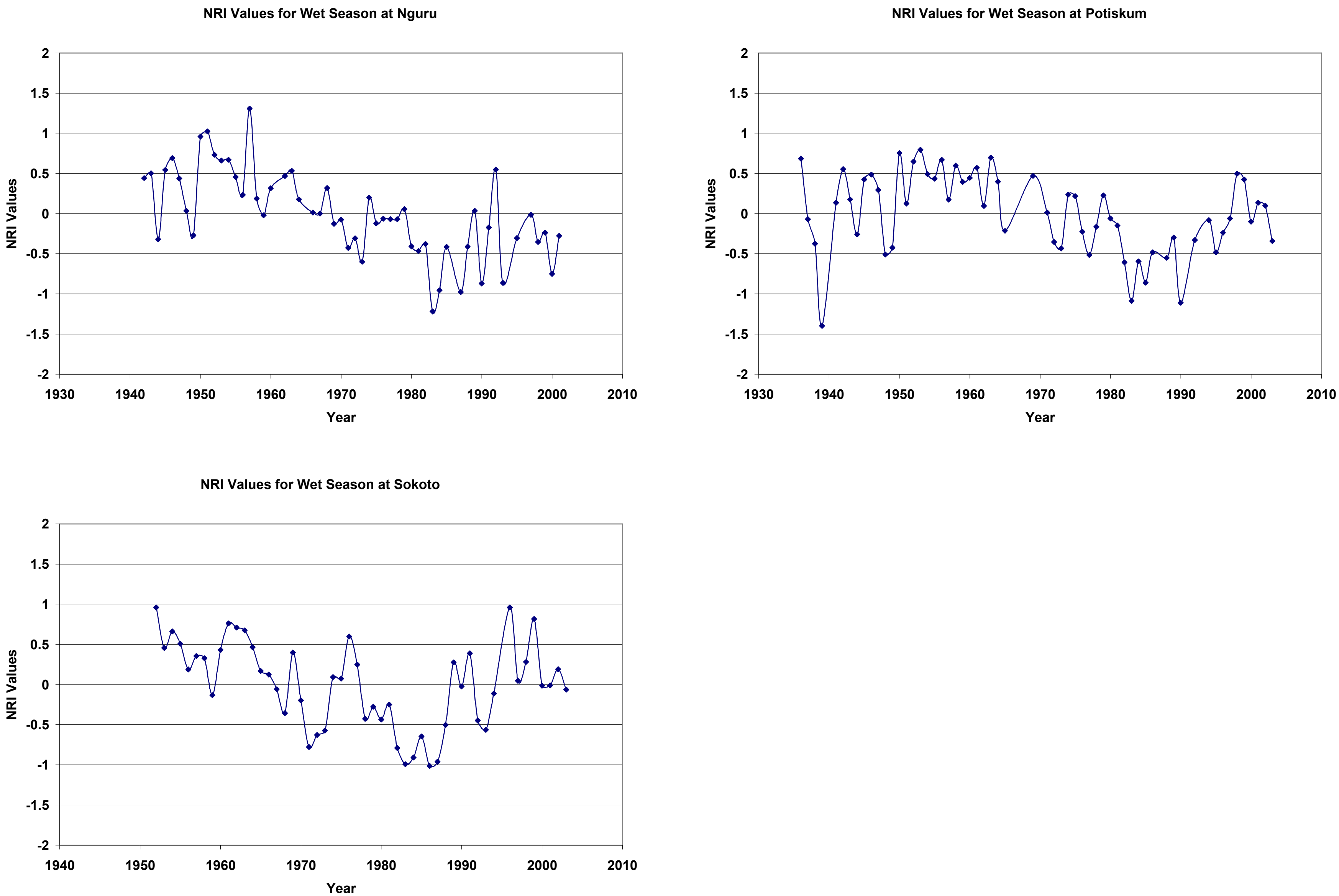


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Figure 4.15: Distribution of Normalized Rain days Index (NRI) at Nguru, Potiskum and Sokoto Stations

A predominant consequence of rainfall variability in SSRN is the occurrence of extended periods with much less than “normal” precipitation (in variance with the seasonal rainfall means), which is usually defined as drought occurrence. The severity of such occurrences can be further expressed by the standardized rainfall index (SRI), a measure of drought severity earlier discussed and defined previously in equation 3.1.

For each of the stations under study, the SRI analysis was mainly carried out, on an annual and a monthly time scales, to describe relative severity of rainfall depth variations over time. The SRI values computed for each WET month was averaged to obtain the seasonal SRI values plotted in Figures 4.16 and 4.17.

Figures 4.16 and 4.17 prominently demonstrate the inter-annual variability of the SSRN rainfall depth. The continuous negative trend in the SRI values for most of these stations shows the pseudo-periodic fluctuations of dry years with the drought spells of 1972-1974 and 1983-1984 being clearly indicated by the peaks.

There is however marginal difference in both the NRI and SRI values obtained for each of the stations under study. Comparing these SRI and NRI values, stations like Katsina, Maiduguri, Nguru and Potiskum have continued to have values below zero since the 1972. This is possibly an indication of drought signaled by the low values of rainfall received since 1972.

The seasonal SRI values obtained from the rainfall depths of the core and marginal wet months respectively, were further examined to show the significance or contribution of the rainfall amounts recorded within these months to drought

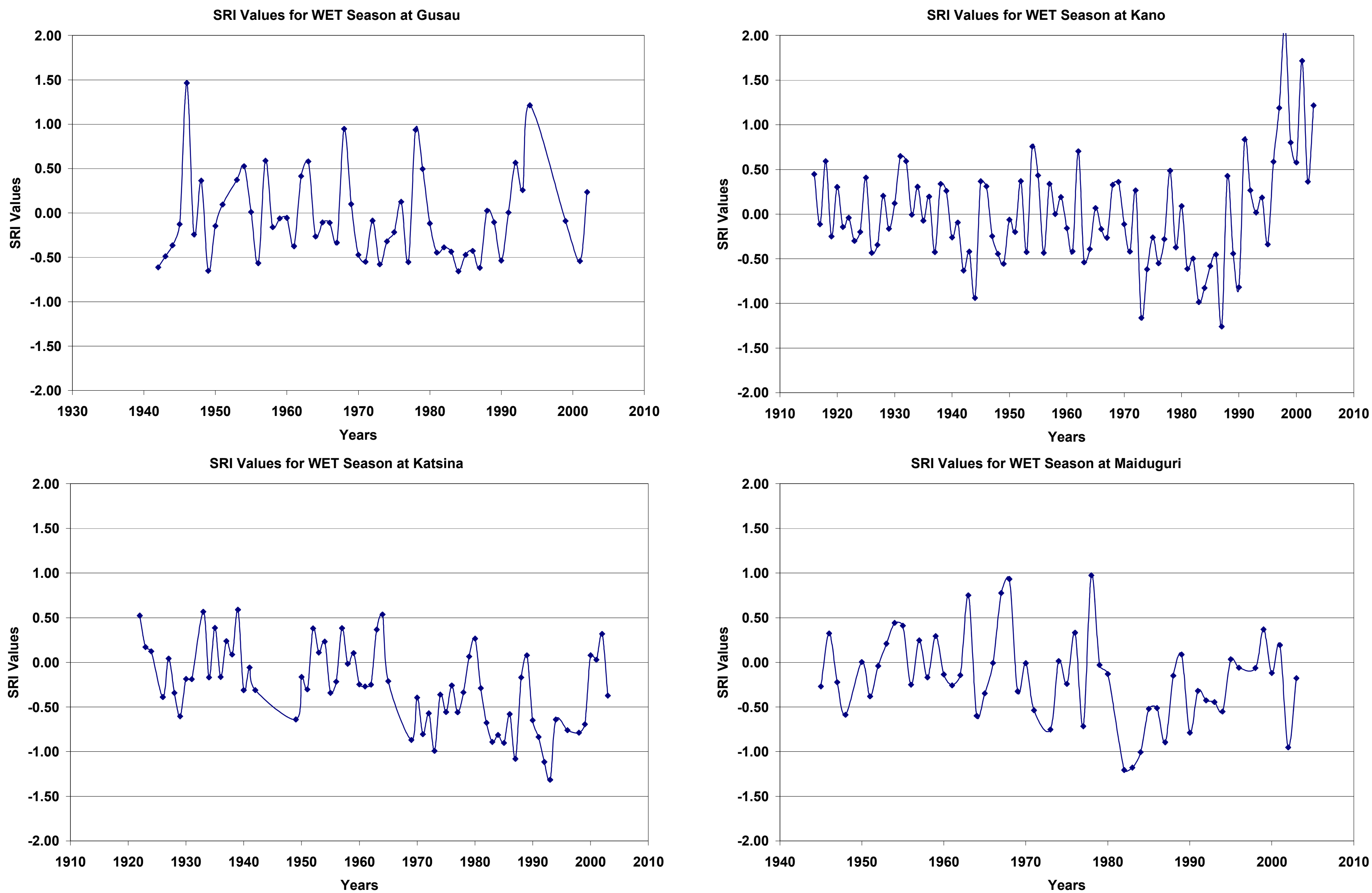
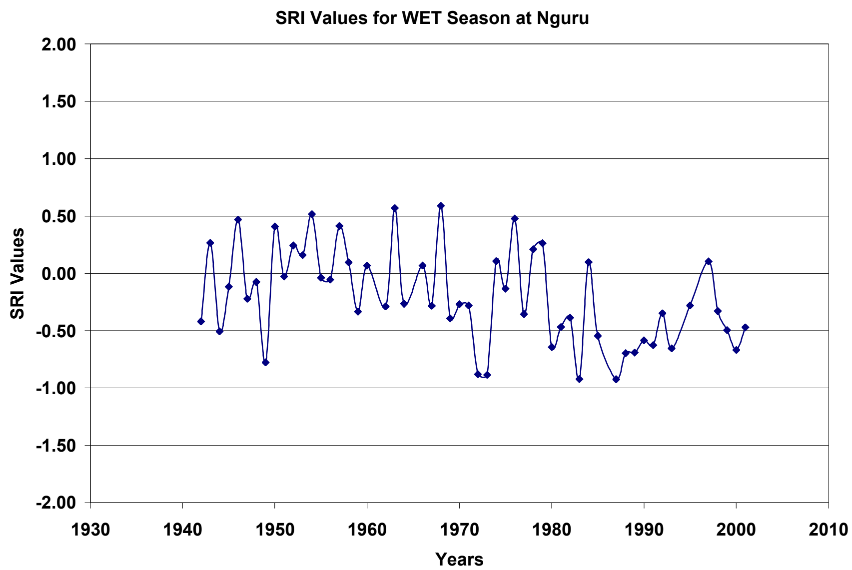
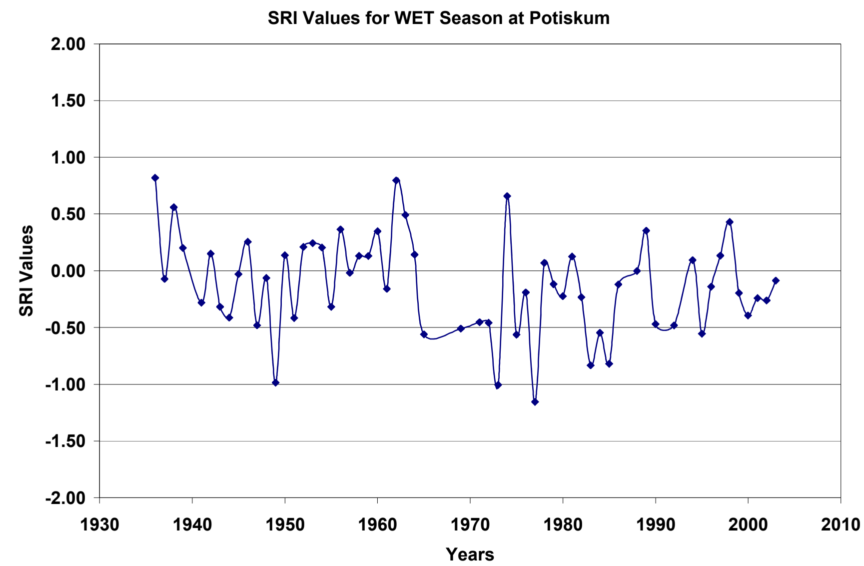


Figure 4.16: Distribution of Seasonal (Annual) SRI Values for Gusau, Kano, Katsina and Maiduguri Stations





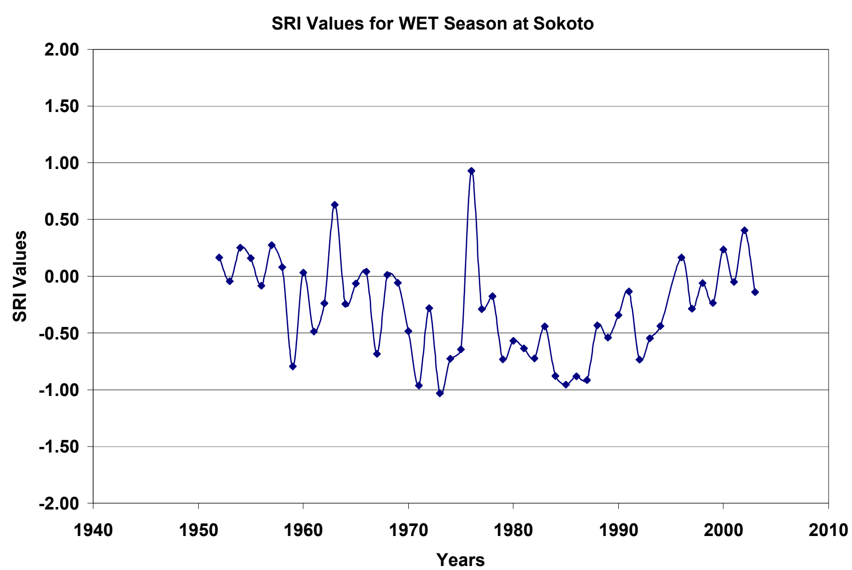


Figure 4.17: Distribution of Seasonal (Annual) SRI Values for Nguru, Potiskum and Sokoto Stations and SSRN

occurrence. The plots of the SRI values for the core wet months are presented in Figure 4.18 and 4.19 (as 6th, 7th, and 8th month in its legend) and that of the marginal wet months (i.e 4th, 5th, 9th and 10th month) on Figures 4.20 and 4.21.

The predominant negative SRI values obtained from the early 70s for the core wet months in most of the stations under study are "extended" periods with much less than "normal" rainfall. As with the NRI plots in Figures 4.14 and 4.15, stations at the extreme right of the SSRN (i.e. Nguru, Maiduguri and Potiskum) are having higher SRI values than those at the central region (i.e. Kano and Gusau).

A close look at the plots of SRI for the core wet months (Figures 4.18 and 4.19) and that of the marginal wet months (Figures 4.20 and 4.21) shows that both Figures indicate similar features and patterns. This means that the variability of rainfall observed in these respective months significantly reflect and determine the magnitude or occurrence of drought within the SSRN.

Similarly, the normalized raindays index (NRI) earlier shown in Figures 4.14 and 4.15 have also implicitly inferred drought occurrences from the distribution of the number raindays observed within the stations under study.

Hence, both the SRI and the NRI have been indirectly used to magnify the variability in the rainfall depths and the number of raindays. The trends observed in each of the plots that summarize the values of SRI and NRI values tally with that from historical drought records of the SSRN over the years.

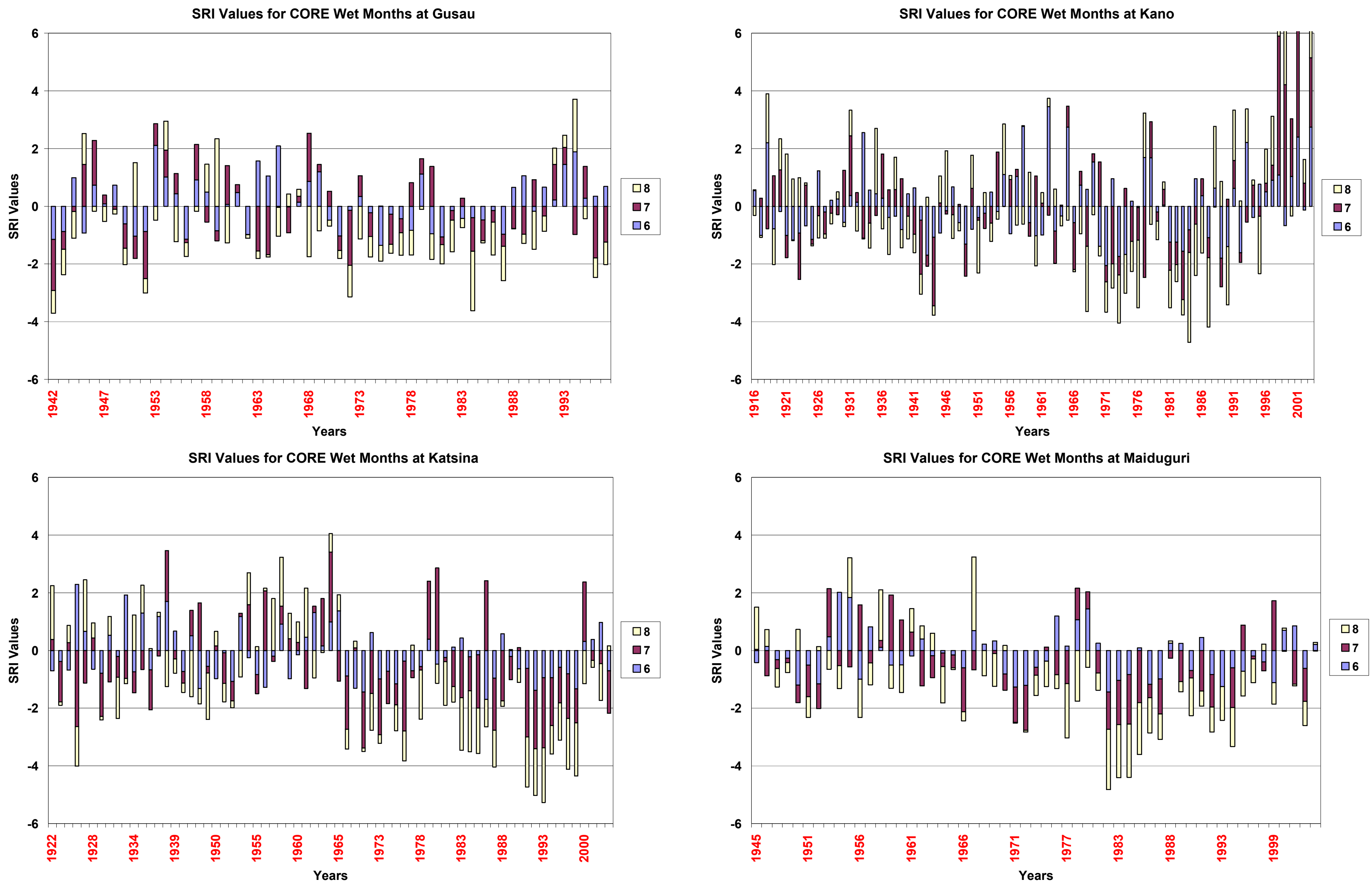


Figure 4.18: Distribution of SRI Values for Core WET Months at Gusau, Kano, Katsina and Maiduguri Stations

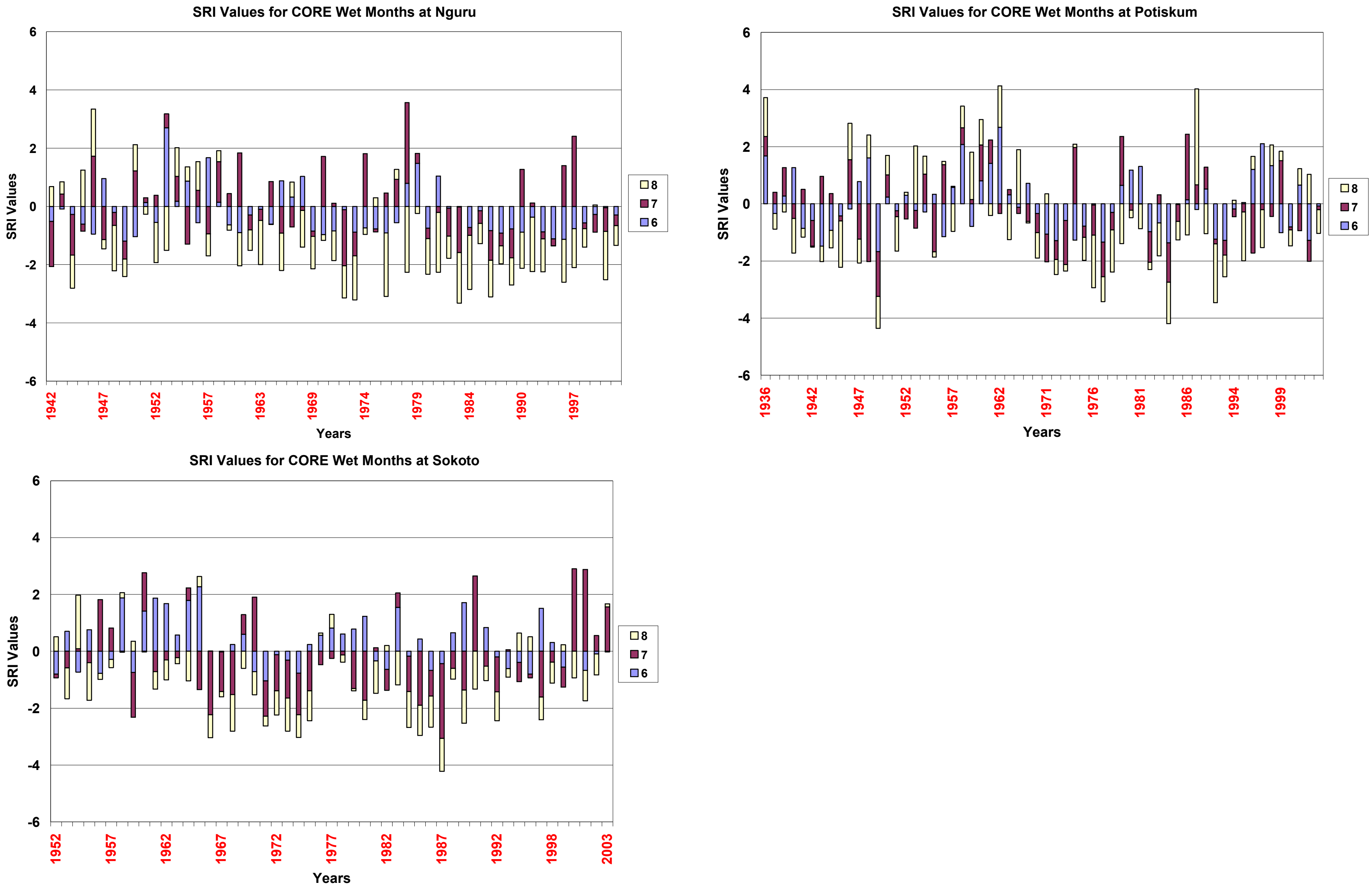


Figure 4.19: Distribution of SRI Values for Core WET Months at Nguru, Potiskum and Sokoto Stations

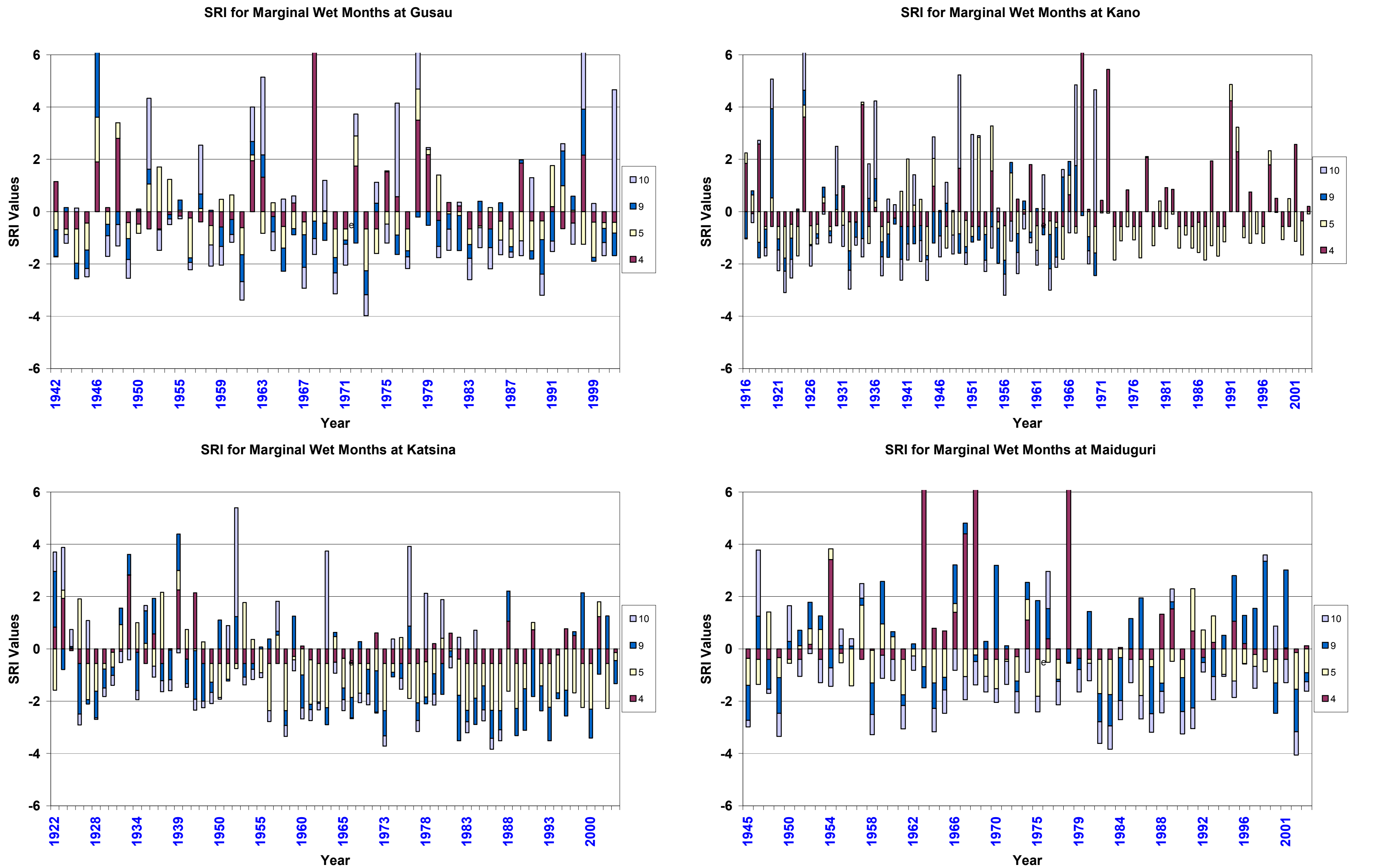


Figure 4.20: Distribution of SRI Values for Marginal WET Months at Gusau, Kano, Katsina and Maiduguri Stations

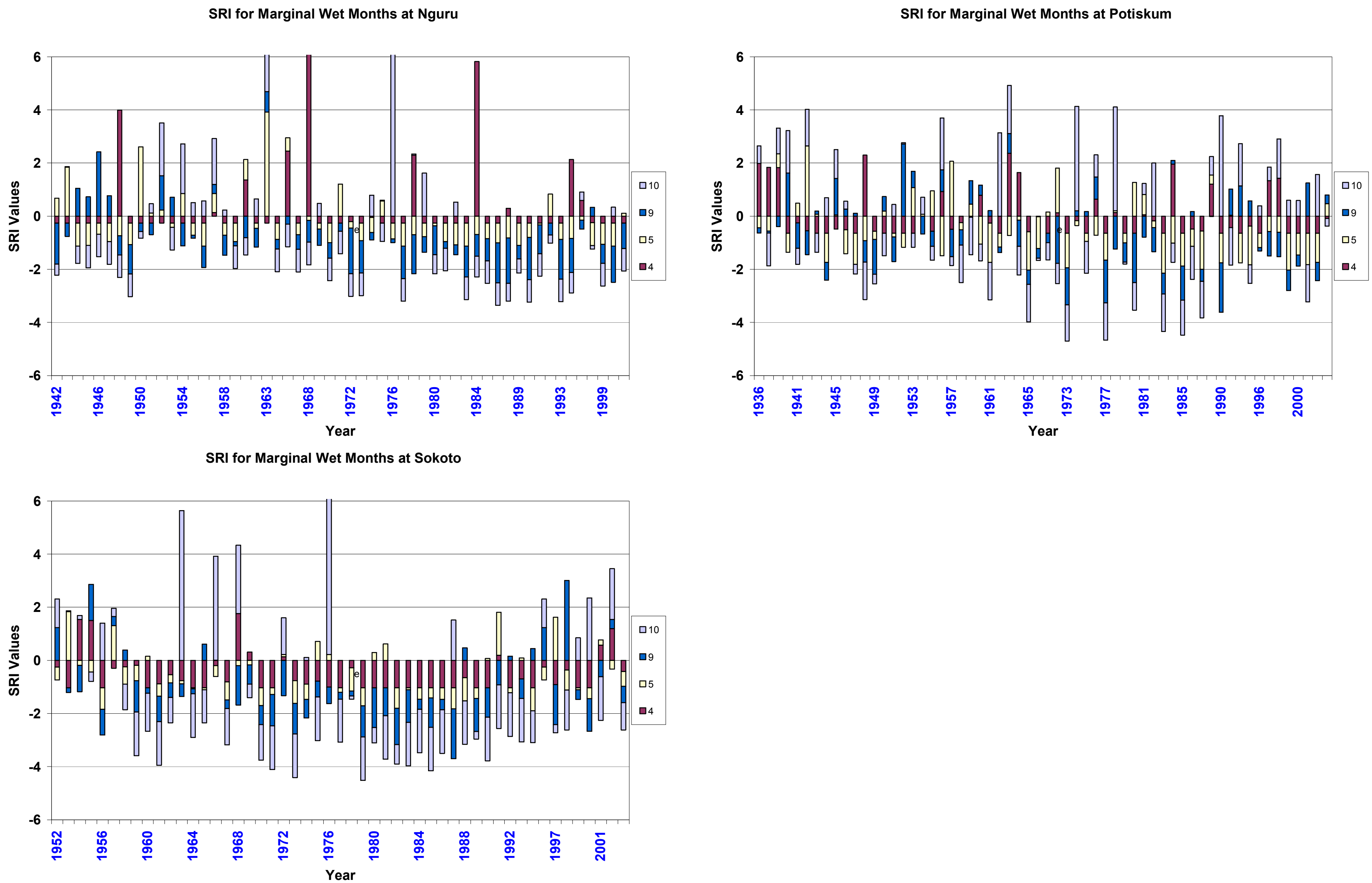


Figure 4.21: Distribution of SRI Values for Marginal WET Months at Nguru, Potiskum and Sokoto Stations

It is worthwhile to mention here that the rainfall variability observed within the SSRN is largely a consequence of the south-north and the north-south movement of the Inter-Tropical Convergence Zone (ITCZ). The rainy season and its consequent variations is related to the south-north movement and the dry season to the north-south movement. Hence, the ITCZ is highly related to the onset and cessation of rainy season in the SSRN.

4.4 Drought Indexing Analysis

4.4.1 Development of Conjunctive Precipitation Effectiveness Index

Ten (10) precipitation effectiveness variables (PEV) namely, Onset of rainy season (ORS), Cessation of rainy season (CRS), Length of the rainy season (LRS), Total no of wet days (TWD), Total no of dry spell (TDS), Total no of dry days within a wet season (TDW), Total no of dry days within a year (TDY), Length of the dry season (LDS), Maximum dry spell length within a wet season (MDL), and Mean Annual / Seasonal Rainfall Depth (MAR) have been identified and described in section 2.3.6 as having the potential of indicating the occurrence of drought.

Prior to using these PEVs for drought indexing, a correlation analysis was carried out to measure the relationship between them. The results are shown in the correlation matrices on Tables 4.4 (a-f) for each of the stations under study. The coefficient of correlation(R) in each table shows the proportion of common variation between any two of the ten PEV variables.

Table 4.4a: Correlation Coefficient (R) between PE Variables for Gusau

	ORS	CRS	LRS	TWD	TDS	TDW	TDY	LDS	MDL	MAR
ORS	1.00	-0.27	-0.93	-0.29	-0.21	-0.89	0.30	0.90	-0.81	-0.19
CRS	-0.27	1.00	0.61	0.22	0.39	0.57	-0.22	-0.26	0.33	0.14
LRS	-0.93	0.61	1.00	0.33	0.32	0.95	-0.33	-0.84	0.80	0.21
TWD	-0.29	0.22	0.33	1.00	0.56	0.03	-1.00	-0.26	-0.03	0.67
TDS	-0.21	0.39	0.32	0.56	1.00	0.16	-0.56	-0.17	-0.08	0.22
TDW	-0.89	0.57	0.95	0.03	0.16	1.00	-0.03	-0.81	0.85	0.01
TDY	0.30	-0.22	-0.33	-1.00	-0.56	-0.03	1.00	0.26	0.02	-0.67
LDS	0.90	-0.26	-0.84	-0.26	-0.17	-0.81	0.26	1.00	-0.80	-0.24
MDL	-0.81	0.33	0.80	-0.03	-0.08	0.85	0.02	-0.80	1.00	-0.05
MAR	-0.19	0.14	0.21	0.67	0.22	0.01	-0.67	-0.24	-0.05	1.00

Table 4.4b: Correlation Coefficient (R) between PE Variables for Kano

	ORS	CRS	LRS	TWD	TDS	TDW	TDY	LDS	MDL	MAR
ORS	1.00	0.11	-0.92	-0.45	-0.34	-0.89	0.45	0.92	-0.83	-0.17
CRS	0.11	1.00	0.29	0.19	0.38	0.26	-0.19	0.15	0.07	0.22
LRS	-0.92	0.29	1.00	0.51	0.48	0.96	-0.50	-0.83	0.83	0.25
TWD	-0.45	0.19	0.51	1.00	0.48	0.24	-1.00	-0.42	0.31	0.46
TDS	-0.34	0.38	0.48	0.48	1.00	0.38	-0.48	-0.34	0.11	0.26
TDW	-0.89	0.26	0.96	0.24	0.38	1.00	-0.23	-0.80	0.83	0.13
TDY	0.45	-0.19	-0.50	-1.00	-0.48	-0.23	1.00	0.41	-0.30	-0.46
LDS	0.92	0.15	-0.83	-0.42	-0.34	-0.80	0.41	1.00	-0.78	-0.18
MDL	-0.83	0.07	0.83	0.31	0.11	0.83	-0.30	-0.78	1.00	0.11
MAR	-0.17	0.22	0.25	0.46	0.26	0.13	-0.46	-0.18	0.11	1.00

Table 4.4c: Correlation Coefficient (R) between PE Variables for Katsina

	ORS	CRS	LRS	TWD	TDS	TDW	TDY	LDS	MDL	MAR
ORS	1.00	-0.04	-0.89	-0.32	-0.24	-0.88	0.31	0.87	-0.82	-0.16
CRS	-0.04	1.00	0.50	0.33	0.43	0.45	-0.32	-0.02	0.15	0.15
LRS	-0.89	0.50	1.00	0.43	0.41	0.97	-0.42	-0.77	0.78	0.21
TWD	-0.32	0.33	0.43	1.00	0.67	0.18	-1.00	-0.31	0.18	0.63
TDS	-0.24	0.43	0.41	0.67	1.00	0.25	-0.67	-0.22	0.07	0.40
TDW	-0.88	0.45	0.97	0.18	0.25	1.00	-0.18	-0.75	0.80	0.05
TDY	0.31	-0.32	-0.42	-1.00	-0.67	-0.18	1.00	0.31	-0.18	-0.63
LDS	0.87	-0.02	-0.77	-0.31	-0.22	-0.75	0.31	1.00	-0.73	-0.21
MDL	-0.82	0.15	0.78	0.18	0.07	0.80	-0.18	-0.73	1.00	0.12
MAR	-0.16	0.15	0.21	0.63	0.40	0.05	-0.63	-0.21	0.12	1.00

Table 4.4d: Correlation Coefficient (R) between PE Variables for Maiduguri

	ORS	CRS	LRS	TWD	TDS	TDW	TDY	LDS	MDL	MAR
ORS	1.00	0.02	-0.81	-0.25	-0.30	-0.75	0.24	0.83	-0.65	-0.13
CRS	0.02	1.00	0.57	0.20	0.31	0.52	-0.21	0.07	0.22	0.05
LRS	-0.81	0.57	1.00	0.32	0.43	0.92	-0.32	-0.64	0.66	0.14
TWD	-0.25	0.20	0.32	1.00	0.78	-0.07	-1.00	-0.31	-0.12	0.67
TDS	-0.30	0.31	0.43	0.78	1.00	0.14	-0.78	-0.29	-0.16	0.49
TDW	-0.75	0.52	0.92	-0.07	0.14	1.00	0.07	-0.55	0.74	-0.13
TDY	0.24	-0.21	-0.32	-1.00	-0.78	0.07	1.00	0.30	0.12	-0.67
LDS	0.83	0.07	-0.64	-0.31	-0.29	-0.55	0.30	1.00	-0.47	-0.19
MDL	-0.65	0.22	0.66	-0.12	-0.16	0.74	0.12	-0.47	1.00	-0.05
MAR	-0.13	0.05	0.14	0.67	0.49	-0.13	-0.67	-0.19	-0.05	1.00

Table 4.4e: Correlation Coefficient (R) between PE Variables for Nguru

	ORS	CRS	LRS	TWD	TDS	TDW	TDY	LDS	MDL	MAR
ORS	1.00	-0.04	-0.78	-0.08	-0.21	-0.77	0.08	0.72	-0.63	0.13
CRS	-0.04	1.00	0.66	0.33	0.40	0.55	-0.33	-0.13	0.03	0.28
LRS	-0.78	0.66	1.00	0.27	0.41	0.93	-0.27	-0.62	0.49	0.08
TWD	-0.08	0.33	0.27	1.00	0.84	-0.11	-1.00	-0.18	-0.32	0.78
TDS	-0.21	0.40	0.41	0.84	1.00	0.09	-0.84	-0.33	-0.25	0.58
TDW	-0.77	0.55	0.93	-0.11	0.09	1.00	0.11	-0.57	0.63	-0.22
TDY	0.08	-0.33	-0.27	-1.00	-0.84	0.11	1.00	0.19	0.31	-0.79
LDS	0.72	-0.13	-0.62	-0.18	-0.33	-0.57	0.19	1.00	-0.44	-0.12
MDL	-0.63	0.03	0.49	-0.32	-0.25	0.63	0.31	-0.44	1.00	-0.36
MAR	0.13	0.28	0.08	0.78	0.58	-0.22	-0.79	-0.12	-0.36	1.00

Table 4.4f: Correlation Coefficient (R) between PE Variables for Potiskum

	ORS	CRS	LRS	TWD	TDS	TDW	TDY	LDS	MDL	MAR
ORS	1.00	0.06	-0.87	-0.32	-0.25	-0.77	0.31	0.89	-0.72	-0.17
CRS	0.06	1.00	0.45	0.16	0.42	0.40	-0.16	0.08	-0.09	0.09
LRS	-0.87	0.45	1.00	0.36	0.44	0.89	-0.36	-0.76	0.60	0.20
TWD	-0.32	0.16	0.36	1.00	0.63	-0.10	-1.00	-0.33	0.02	0.59
TDS	-0.25	0.42	0.44	0.63	1.00	0.16	-0.63	-0.30	-0.18	0.37
TDW	-0.77	0.40	0.89	-0.10	0.16	1.00	0.10	-0.65	0.63	-0.08
TDY	0.31	-0.16	-0.36	-1.00	-0.63	0.10	1.00	0.33	-0.02	-0.59
LDS	0.89	0.08	-0.76	-0.33	-0.30	-0.65	0.33	1.00	-0.64	-0.14
MDL	-0.72	-0.09	0.60	0.02	-0.18	0.63	-0.02	-0.64	1.00	0.06
MAR	-0.17	0.09	0.20	0.59	0.37	-0.08	-0.59	-0.14	0.06	1.00

Table 4.4g: Correlation Coefficient (R) between PE Variables for Sokoto

	ORS	CRS	LRS	TWD	TDS	TDW	TDY	LDS	MDL	MAR
ORS	1.00	0.05	-0.88	-0.22	-0.37	-0.84	0.22	0.89	-0.66	-0.14
CRS	0.05	1.00	0.44	0.24	0.57	0.37	-0.24	0.01	-0.05	0.32
LRS	-0.88	0.44	1.00	0.32	0.61	0.94	-0.32	-0.80	0.57	0.28
TWD	-0.22	0.24	0.32	1.00	0.63	-0.04	-1.00	-0.29	-0.14	0.70
TDS	-0.37	0.57	0.61	0.63	1.00	0.41	-0.63	-0.40	-0.07	0.53
TDW	-0.84	0.37	0.94	-0.04	0.41	1.00	0.04	-0.73	0.66	0.03
TDY	0.22	-0.24	-0.32	-1.00	-0.63	0.04	1.00	0.29	0.14	-0.69
LDS	0.89	0.01	-0.80	-0.29	-0.40	-0.73	0.29	1.00	-0.61	-0.25
MDL	-0.66	-0.05	0.57	-0.14	-0.07	0.66	0.14	-0.61	1.00	0.00
MAR	-0.14	0.32	0.28	0.70	0.53	0.03	-0.69	-0.25	0.00	1.00

Clearly, for all the stations under study, there is no significant relationship between the annual / seasonal rainfall depth (MAR) and the rest of the nine PEVs. This observation tallies with the primary notion of this study that using rainfall depth only for drought indexing ignores some specific information about the drought that might have been caused by other precipitation effectiveness variables.

Furthermore, Table 4.4(a –g) shows that there is strong correlation (with $R > 0.80$) between the arrival of rain (ORS) and the occurrences of dry spells (i.e LDS, TDW and MDL) for most of the stations studied within the SSRN. This preliminary analysis shows that any delay in the arrival of rains considerable influence the amount of rains received within the year. Hence, the agricultural prosperity or doom of the SSRN to a large extent depends on the timely arrival and subsequent distribution of its rains.

Consequent to this revelation, information about rainfall depth, no of raindays and other PEVs was used to develop a 'at-site' operational drought index called conjunctive precipitation index (CPEI).

Combining these 10 PEVs in different order without any repetition gives a total possible 1023 arrangements. These 1023 arrangements have a total 1, 2, 3, 4, 5, 6, 7…. 10 PEVs combined. For each available record, i.e 1918-2003 for Kano, and using a particular time scale i.e year, equation 3.4 was used to obtain 1023 set of CPEI values.

4.4.2 Evaluating Ultimate PEV Combination for Optimum CPEI

In order to evaluate the ultimate combination of PEV that will produce the optimum CPEI values, the study employed the regression technique to compare the CPEI values with values from four other renowned drought indices. The four drought indices used are PDSI, SPI, BMDI and RAI. The conceptual theories and techniques for evaluating these indices have been presented in section 2.3 and 3.22.

The set of CPEI values for each of the 1023 arrangements was correlated with the set of values for PDSI, BMDI, RAI and SPI indices. The arrangements with a correlation coefficient (R > 0.8) for each compared values of BMDI, RAI and SPI were selected. For each station under study, the total number of arrangements out of the possible 1023 arrangements with an average score of R>0.8 is shown in the first column of Table 4.5.

Table 4.5: Percentage Distribution of Total PEVs Used to Obtain CPEI with an Average Score (R> 0.8) in each Station under Study

		Frequency of Occurrence of total variables Used to Score R > 0.8 (%)						
	NOC	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Gusau	37	0.0	0.0	13.3	40.0	33.3	6.7	6.7
Kanoap	43	0.0	16.3	30.2	25.6	18.6	7.0	2.3
Katsina	54	1.9	13.0	27.8	22.2	25.9	7.4	1.9

		Frequency of Occurrence of total variables Used to Score R > 0.8 (%)						
	NOC	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Maiduguri	28	0.0	3.6	14.3	35.7	32.1	10.7	3.6
Nguru	65	4.6	16.9	**29.2**	24.6	15.4	6.2	3.1
Potiskum	60	3.4	22.0	23.7	25.4	20.3	3.4	1.7
Sokoto	64	4.7	17.2	31.3	25.0	17.2	3.1	1.6

NOC – Total number of occurrence i.e no of arrangements out of 1023 with average score r> 0.8

It is clear from table 4.5 that a combination of more than seven (7) of the PEVs was ineffective in indexing the drought in the SSRN. Using the maximum percentage of occurrence, the optimum no of variables in Gusau, Maiduguri and Potiskum is four (4), while the rest stations under study had five (5) variables as their optimum. The frequency of occurrence observed with the use of three (3) variables was also significant in most of the stations.

Table 4.5 above also gives a clue to how many PEVs should be used in indexing drought in each of the stations under study. Although not conclusive, Table 4.5 signifies that the use or a combination of three (3), four (4) or five (5) PEVs have a fair potential for indexing the drought in most of the stations under study.

Out of the number of arrangements with an average score R> 0.8, the frequency of occurrence of each variable in each arrangement used for obtaining an optimal drought index (i.e. with CPEI value having an average R > 0.8 when compared with SPI, RAI and BMDI indices) was evaluated. Table 4.6 gives the frequency of occurrence of each PEV in the lots of arrangements with average score R>0.8. At 50% level of occurrence, variables no 10 and 4 (i.e MAR and TWD) predominates in all the stations and at 40% level of occurrence, variables 10, 4, 8 and 1 (i.e. MAR, TWD, LDS and ORS) becomes the most predominant variables.

Table 4.6: Performance Level of Each PEVs (%)

Station	MAR	MDL	LDS	TDY	TDW	TDS	TWD	LRS	CRS	ORS
	10	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Gusau	100.0	13.3	46.7	20.0	20.0	0.0	73.3	40.0	0.0	33.3
Kanoap	100.0	14.0	48.8	20.9	27.9	37.2	79.1	44.2	4.7	46.5
Katsina	100.0	40.7	38.9	25.9	20.4	25.9	75.9	29.6	7.4	48.1
Maiduguri	100.0	21.4	28.6	28.6	3.6	46.4	71.4	14.3	0.0	42.9
Nguru	98.5	9.2	40.0	13.8	18.5	56.9	80.0	27.7	36.9	58.5
Potiskum	100.0	41.7	48.3	18.3	15.0	56.7	81.7	38.3	5.0	46.7
Sokoto	100.0	28.1	50.0	17.2	20.3	54.7	78.1	31.3	12.5	59.4

Using the average of R values obtained from the correlation of CPEI versus SPI, RAI and BMDI respectively, the arrangements were ranked to get the PEV combination that gives the optimum CPEI value. Tables 4.7 (a-g) shows the rankings and the best combinations, if one, two, three, four, five or six PEVs, are used to obtain the optimum CPEI (R > 0.8). Using the average values of R, Table 4.7 (a-g) also gives the respective comparison between the optimum CPEI obtained using a combination of 1, 2, 3, 4, 5, or 6 PEVs and the correlation coefficient, R values obtained for CPEI index versus the SPI, BMDI and RAI indices.

Table 4.7a: Optimum CPEI Derived using the Best 1, 2, 3, 4, 5 and 6 PEVs for Gusau

Ranking	A/No (Out of 1023)	NOV	Combined Variables	Pearson Correlation Coefficient (R)			
				SPI	RAI	BMDI	Average
1	10	1	10	0.999	0.976	0.995	0.990
2	152	3	10,7,4	0.960	0.940	0.950	0.950
3	40	2	10,4	0.899	0.901	0.894	0.898
6	239	4	10,9,4,1	0.862	0.879	0.853	0.865
7	599	5	10,8,7,4,3	0.847	0.889	0.853	0.863
36	722	6	10,8,6,4,3,1	0.772	0.81	0.772	0.785
37	1023	10	10,9,8,7, 6,5,4,3,2,1	0.422	0.436	0.415	0.424

Key : Variables (i.e. no 10=MAR, no 9=MDL, no 8= LDS, etc.) are as defined in table 4.6 above

Table 4.7b: Optimum CPEI Derived using the Best 1, 2, 3, 4, 5 and 6 PEVs for Kano

Ranking	A/No (Out of 1023)	NOV	Combined Variables	Pearson Correlation Coefficient (R)			
				SPI	RAI	BMDI	Average
1	10	1	10	0.973	0.983	0.954	0.970
2	152	3	10,7,4	0.956	0.971	0.935	0.954
4	233	4	10,6,4,1	0.927	0.983	0.912	0.941
5	453	5	10,7,4,3,1	0.914	0.963	0.905	0.927
9	40	2	10,4	0.901	0.939	0.883	0.908
12	722	6	10,8,6,4,3,1	0.860	0.935	0.853	0.882
44	1023	10	10,9,8,7, 6,5,4,3,2,1	0.606	0.662	0.590	0.619

Key : Variables (i.e. no 10=MAR, no 9=MDL, no 8= LDS, etc.) are as defined in table 4.6 above

Table 4.7c: Optimum CPEI Derived using the Best 1, 2, 3, 4, 5 and 6 PEVs for Katsina

Ranking	A/No (Out of 1023)	NOV	Combined Variables	Pearson Correlation Coefficient (R)			
				SPI	RAI	BMDI	Average
1	10	1	10	0.999	1.000	1.000	1.000
2	152	3	10,7,4	1.000	1.000	1.000	1.000
3	453	5	10,7,4,3,1	0.935	0.943	0.944	0.941
5	40	2	10,4	0.929	0.939	0.941	0.937
6	239	4	10,9,4,1	0.922	0.928	0.931	0.927
19	751	6	10,9,7,5,4,1	0.866	0.864	0.865	0.865
55	1023	10	10,9,8,7, 6,5,4,3,2,1	0.550	0.542	0.542	0.545

Key : Variables (i.e. no 10=MAR, no 9=MDL, no 8= LDS, etc.) are as defined in table 4.6 above

Table 4.7d: Optimum CPEI Derived using the Best 1, 2, 3, 4, 5 and 6 PEVs for Maiduguri

Ranking	A/No (Out of 1023)	NOV	Combined Variables	Pearson Correlation Coefficient (R)			
				SPI	RAI	BMDI	Average
1	10	1	10	0.995	1.000	1.000	0.998
2	152	3	10,7,4	0.993	0.999	1.000	0.997
3	40	2	10,4	0.936	0.915	0.944	0.932
6	239	4	10,9,4,1	0.881	0.866	0.889	0.879
14	483	5	10,7,5,4,1	0.837	0.836	0.858	0.844
18	751	6	10,9,7,5,4,1	0.841	0.829	0.848	0.839
29	1023	10	10,9,8,7, 6,5,4,3,2,1	0.359	0.352	0.341	0.351

Key : Variables (i.e. no 10=MAR, no 9=MDL, no 8= LDS, etc.) are as defined in table 4.6 above

Table 4.7e: Optimum CPEI Derived using the Best 1, 2, 3, 4, 5 and 6 PEVs for Nguru

Ranking	A/No (Out of 1023)	NOV	Combined Variables	Pearson Correlation Coefficient (R)			
				SPI	RAI	BMDI	Average
1	10	1	10	1.000	1.000	1.000	1.000
2	152	3	10,7,4	1.000	0.988	0.996	0.995
3	40	2	10,4	0.973	0.968	0.977	0.973
4	209	4	10,4,3,1	0.936	0.929	0.934	0.933
12	455	5	10,8,4,3,1	0.878	0.875	0.877	0.877
29	716	6	10,8,5,4,3,1	0.853	0.847	0.848	0.849
66	1023	10	10,9,8,7, 6,5,4,3,2,1	0.361	0.380	0.379	0.374

Key : Variables (i.e. no 10=MAR, no 9=MDL, no 8= LDS, etc.) are as defined in table 4.6 above

Table 4.7f: Optimum CPEI Derived using the Best 1, 2, 3, 4, 5 and 6 PEVs for Potiskum

Ranking	A/No (Out of 1023)	NOV	Combined Variables	Pearson Correlation Coefficient (R)			
				SPI	RAI	BMDI	Average
1	10	1	10	0.994	1.000	1.000	0.998
2	152	3	10,7,4	0.994	1.000	1.000	0.998
3	40	2	10,4	0.938	0.949	0.948	0.945
4	233	4	10,6,4,1	0.915	0.924	0.923	0.921
8	453	5	10,7,4,3,1	0.897	0.900	0.900	0.899
16	845	6	10,9,8,7,5,4	0.879	0.886	0.885	0.884
61	1023	10	10,9,8,7, 6,5,4,3,2,1	0.533	0.530	0.530	0.531

Key : Variables (i.e. no 10=MAR, no 9=MDL, no 8= LDS, etc.) are as defined in table 4.6 above

Table 4.7g: Optimum CPEI Derived using the Best 1, 2, 3, 4, 5 and 6 PEVs for Sokoto

Ranking	A/No (Out of 1023)	NOV	Combined Variables	Pearson Correlation Coefficient (R)			
				SPI	RAI	BMDI	Average
1	10	1	10	1.000	1.000	1.000	1.000
2	152	3	10,7,4	1.000	1.000	1.000	1.000
3	453	5	10,7,4,3,1	0.944	0.965	0.971	0.960
5	40	2	10,4	0.944	0.957	0.961	0.954
6	233	4	10,6,4,1	0.938	0.950	0.954	0.947
12	752	6	10,9,8,5,4,1	0.900	0.909	0.914	0.908
65	1023	10	10,9,8,7, 6,5,4,3,2,1	0.575	0.604	0.606	0.595

Key : Variables (i.e. no 10=MAR, no 9=MDL, no 8= LDS, etc.) are as defined in table 4.6 above

It is also clear from Tables 4.7 (a-g) that the use of the entire 10 PEVs resulted in a very poor level of performance (in terms of R values) in all the stations under study. On the contrary, the use of PEV variable no 10, i.e. MAR proved to give the best performance in all the stations under study. This is well expected since SPI, RAI and BMDI indices used for the comparisons also used only 'rainfall depth' like MAR for drought indexing. It may therefore be misleading to base the decision of how many PEVs to use on this result alone.

By comparing Table 4.5 and Tables 4.7 (a-g), it may be seen that the CPEI values obtained by using a combination of three (3), four (4), or five (5) PEVs respectively, has good rankings and highest frequency of occurrence in all the stations under study. The use of these variables has also resulted in high level of performance (average R > 0.9) in most stations under study. It may therefore be suggestive that the performance level is relatively fair when 3, 4 or 5 variables are used.

A further descriptive test was conducted so as to know the optimum number of PEVs that gives the optimum CPEI for each of the station under study. The values of CPEI obtained using 3, 4, or 5 variables were compared with the historical accounts of drought and famines in the area that were discussed in Apeldoorn (1981) and Oladipo (1994). It can be deduced from Tables 4.8 (a-g) that the CPEI derived from three (3) PEVs gives a better picture of severity of drought in each of the historical drought years in most of the stations under study.

Table 4.8a: Comparison of Optimum CPEI Values derived using 3, 4, and 5 PEVs with Historical Accounts of Drought in Gusau

Historical Drought Year		CPEI-1	CPEI-3	CPEI-4	CPEI-5	SPI	RAI	BMDI	PDSI
1926	1926								
1942	1944	-1.92	-1.01	-1.03	-0.59	-0.80	-1.93	-1.88	
1971	1973	-2.39	-2.89	-1.00	-0.62	-1.03	-2.40	-2.34	-0.74
1983	1987	-2.11	-2.17	-1.09	-0.54	-0.90	-2.11	-2.05	-2.68

Table 4.8b: Comparison of Optimum CPEI Values derived using 3, 4, and 5 PEVs with Historical Accounts of Drought in Kanoap

Historical Drought Year		CPEI-1	CPEI-3	CPEI-4	CPEI-5	SPI	RAI	BMDI	PDSI
1926	1926	-0.65	-0.30	0.75	0.08	-0.28	-0.70	-0.88	
1942	1944	-1.79	-2.20	-0.99	-1.25	-1.05	-1.95	-2.49	
1971	1973	-2.07	-2.24	-1.56	-1.73	-1.25	-2.26	-2.88	-0.48
1983	1987	-2.56	-2.68	-1.73	-0.06	-1.62	-2.79	-3.57	-2.60

Table 4.8c: Comparison of Optimum CPEI Values derived using 3, 4, and 5 PEVs with Historical Accounts of Drought in Katsina

Historical Drought Year		CPEI-1	CPEI-3	CPEI-4	CPEI-5	SPI	RAI	BMDI	PDSI
1926	1926								
1942	1944								
1971	1973	-1.83	-1.75	-2.11	-1.80	-1.04	-2.05	-2.74	-0.61
1983	1987	-2.17	-2.06	-2.36	-2.16	-1.31	-2.42	-3.25	-0.77

Table 4.8d: Comparison of Optimum CPEI Values derived using 3, 4, and 5 PEVs with Historical Accounts of Drought in Maiduguri

Historical Drought Year		CPEI-1	CPEI-3	CPEI-4	CPEI-5	SPI	RAI	BMDI	PDSI
1926	1926								
1942	1944								
1971	1973	-1.03	-1.03	-0.49	-0.15	-0.50	-1.18	-1.62	-0.15
1983	1987	-2.60	-2.59	-2.43	-2.16	-1.66	-2.97	-4.06	-2.53

Table 4.8e: Comparison of Optimum CPEI Values derived using 3, 4, and 5 PEVs with Historical Accounts of Drought in Nguru

Historical Drought Year		CPEI-1	CPEI-3	CPEI-4	CPEI-5	SPI	RAI	BMDI	PDSI
1926	1926								
1942	1944	-1.01	-0.38	1.03	1.22	-0.38	-1.00	-1.17	
1971	1973	-2.58	-2.44	-2.02	-1.33	-1.28	-2.53	-2.96	-1.23
1983	1987	-2.44	-1.38	-1.06	-2.70	-1.18	-2.39	-2.81	-1.59

Table 4.8f: Comparison of Optimum CPEI Values derived using 3, 4, and 5 PEVs with Historical Accounts of Drought in Potiskum

Historical Drought Year		CPEI-1	CPEI-3	CPEI-4	CPEI-5	SPI	RAI	BMDI	PDSI
1926	1926								
1942	1944	-0.45	-0.38	0.22	0.23	-0.14	-0.51	-0.64	
1971	1973	-1.97	-1.90	-1.62	-1.54	-1.08	-2.18	-2.76	-0.91
1983	1987	-1.53	-1.42	-2.28	-1.49	-0.86	-1.73	-2.19	-2.58

Table 4.8g: Comparison of Optimum CPEI Values derived using 3, 4, and 5 PEVs with Historical Accounts of Drought in Sokoto

Historical Drought Year		CPEI-1	CPEI-3	CPEI-4	CPEI-5	SPI	RAI	BMDI	PDSI
1926	1926								
1942	1944								
1971	1973	-2.32	-2.30	-2.99	-2.14	-1.42	-2.88	-3.51	-0.80
1983	1987	-2.36	-1.95	-3.33	-1.70	-2.93	-3.57	-3.57	-1.53

In a similar descriptive comparison shown in Figures 4.22 and 4.23, the approximate number of PEVs to use for indexing the drought in any station is significantly shown by the most conspicuous plot. For Gusau and Kano, the plot of 56CPEI obtained using a combination of 3-PEVs predominates, while a combination of 4-PEVs predominates in Maiduguri, Potiskum and Sokoto, the rest stations under study had a combination of 5-PEVs plots predominating.

Combining the predictive ability test results obtained from the use of the Pearson Correlation coefficient (R) and that of descriptive ability test where CPEI values and plots were compared with historical drought, the following conclusion is suggestive. Firstly, it is suggestive that a combination of three (3) optimum PEVs (i.e. MAR, TDY and TWD) can be used for indexing the drought in Gusau and Kano, combination of five (5) optimum PEVs for Katsina and Sokoto and a combination of four (4) PEVs for the rest stations under study. Secondly, the usual use of only rainfall depth i.e. one (1) PEV in indexing the drought in the study area might be elusive since some other distinctive drought features revealed with the use of three (3), four (4) and five (5) PEVs in Figures 4.22 and 4.23 might have remained hidden.

Based on the afore analysis and results, the optimum combinations of PEVs suggested for each stations is shown in Table 4.9 below.

Table 4.9: Suggested PEV Combinations for Indexing Drought in each Station under Study

Station	Optimum No of PEV	Suggested PEV Combination (Codes)	Suggested PEV Combination
Gusau	3	10,7,4	MAR, TDY, TWD
Kanoap	3	10,7,4	MAR, TDY, TWD
Katsina	5	10,7,4,3,1	MAR, TDY, TWD, LRS, ORS
Maiduguri	4	10,9,4,1	MAR, MDL, TWD,ORS
Nguru	4	10,4,3,1	MAR, TWD,LRS,ORS
Potiskum	4	10,6,4,1	MAR, TDW, TWD,ORS
Sokoto	5	10,7,4,3,1	MAR, TDY, TWD, LRS, ORS

It is clear that along with seasonal rainfall depth (MAR), drought in the SSRN can be indexed by other PEVs such as length of the rainy season (LRS), total no of wet days (TWD), total no of dry days within a year (TDY), maximum dry spell length within a wet season (MDL), and onset of rainy season (ORS),

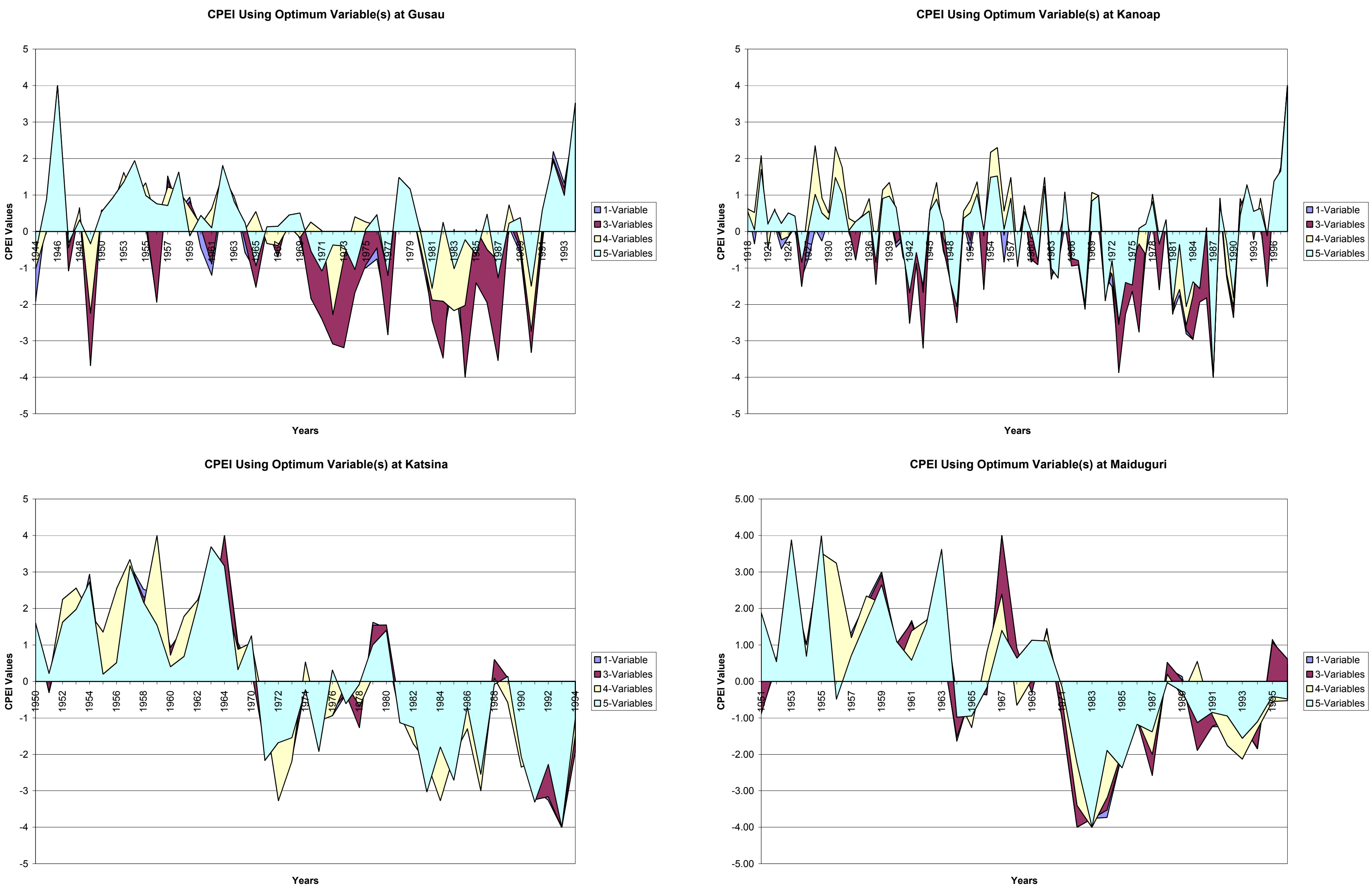


Figure 4.22: Comparison of Optimum CPEI obtained using 1, 3, 4, and 5 PEVSs at Gusau, Kano, Katsina and Maiduguri Stations

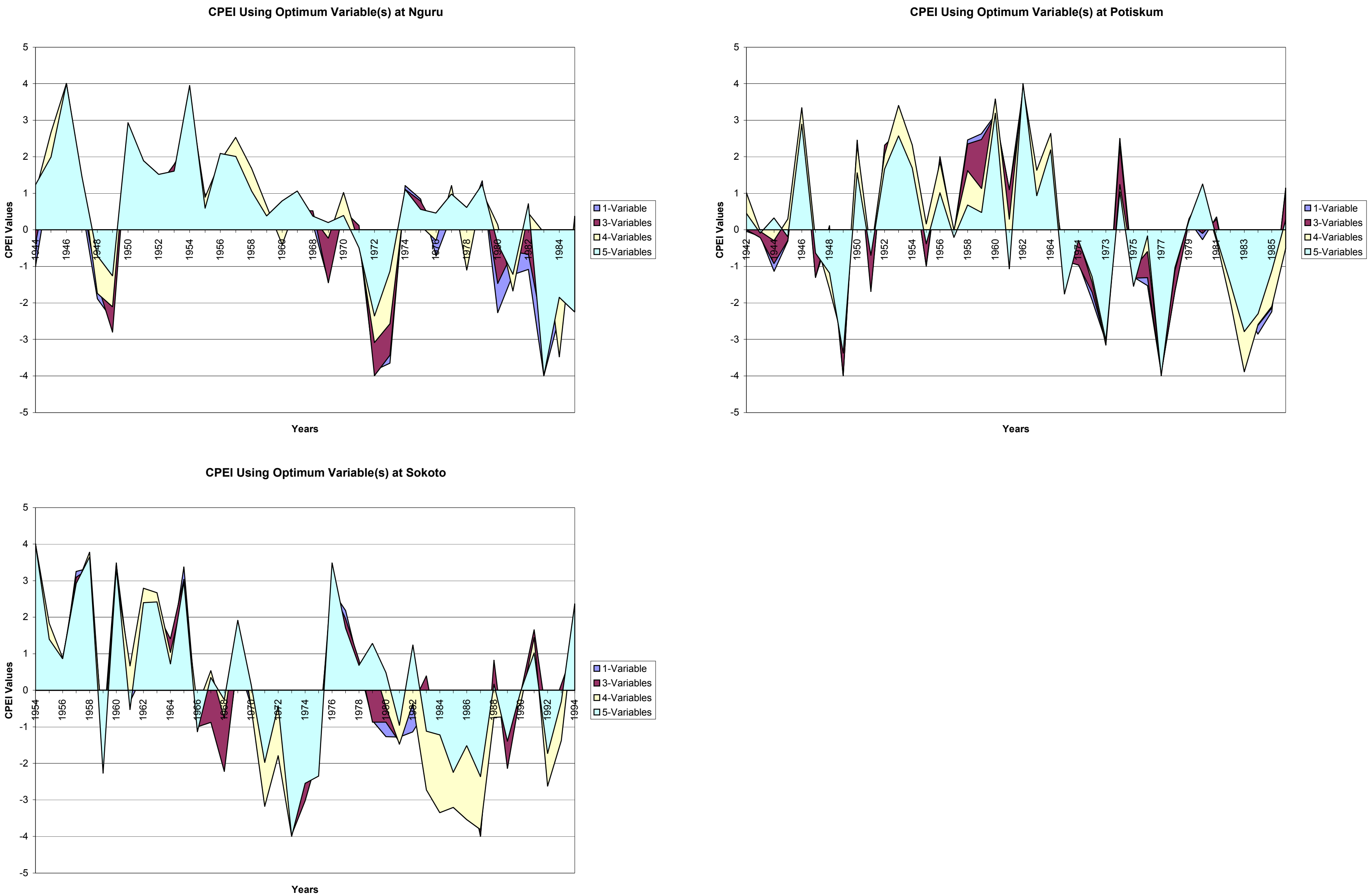


Figure 4.23: Comparison of Optimum CPEI obtained using 1, 3, 4, and 5 PEVSs at Nguru, Potiskum and Sokoto Stations

4.4.3 Drought Indexing using Multiple Indices (CPEI, PDSI, BMDI, RAI and SPI Indices)

Using the ultimate PEVs combination suggested in Table 4.9 for each station under study, the optimum CPEI was computed and used along the values computed for PDSI, BMDI, RAI and SPI indices to quantify the drought in the SSRN. The results obtained for each of these indices are presented as follows;

(a) **Drought Evaluation using the Derived CPEI**

The distributions of the annual series of the optimum CPEI values for each of the stations under study are shown in Figures 4.24 and 4.25. The historical drought spells of 1969-1973 as well as those that occurred in the early 80s are clearly and noticeably pin pointed on these Figures. Within its limits, it is a clear evidence that the CPEI values obtained for each of the stations within the SSRN unambiguously depict the historical drought conditions of the SSRN as presented in Appeldoorn (1981) and Oladipo (1993).

(b) **Drought Evaluation using the SPI**

Drought conditions within the SSRN were also analyzed using the SPI (Mckee et al. 1993). SPI, although relatively recent, has been considered the most reliable index for measuring the intensity, duration and spatial extent of drought (Guttman 1998, Kenyantash & Dracup, 2002). Using a time series of monthly precipitation data, the SPI values for 3, 6, 12 and 24 months time scales were computed for each of the stations under study.

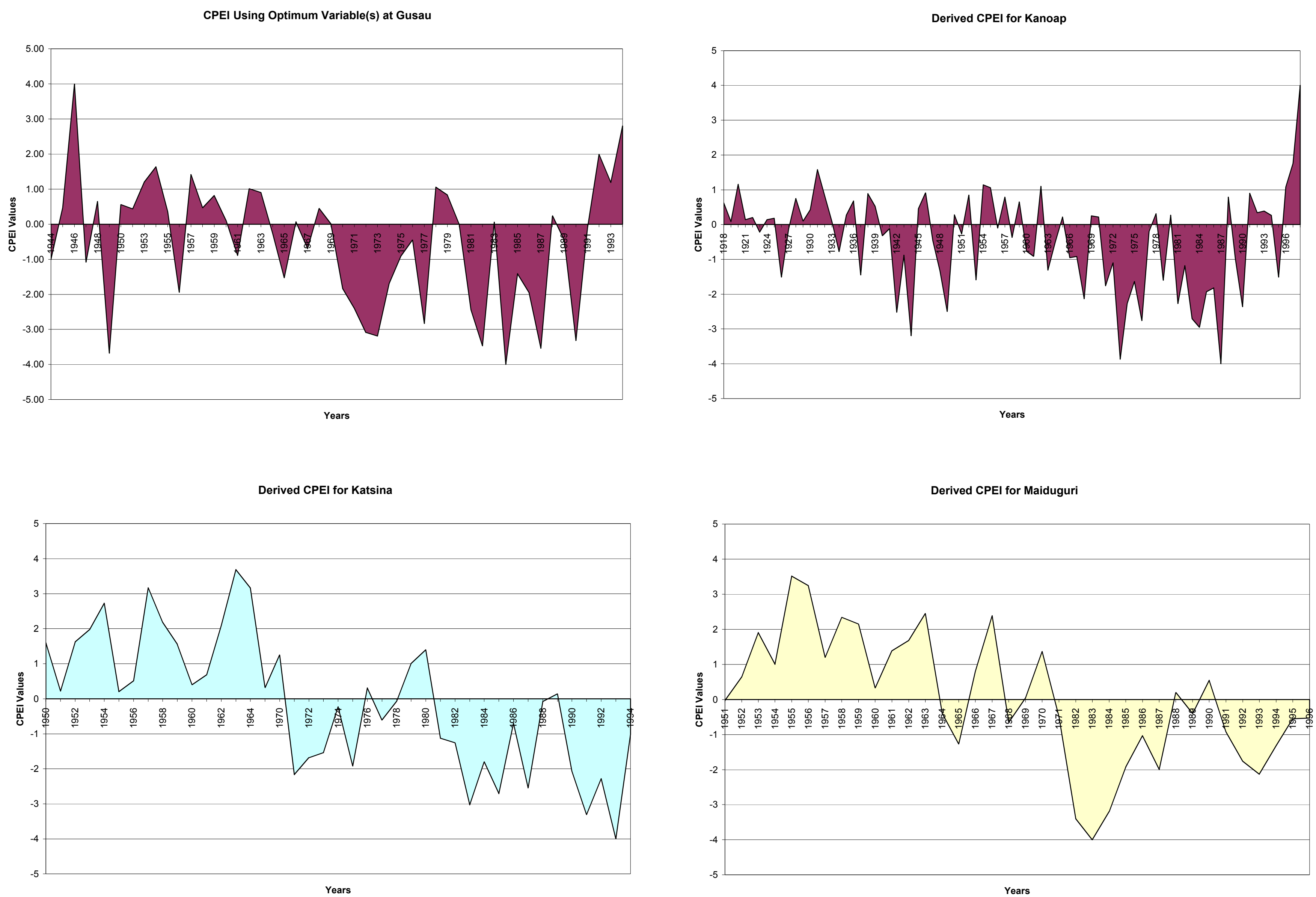


Figure 4.24: Distribution of Annual CPEI at Gusau, Kano, Katsina and Maiduguri Stations

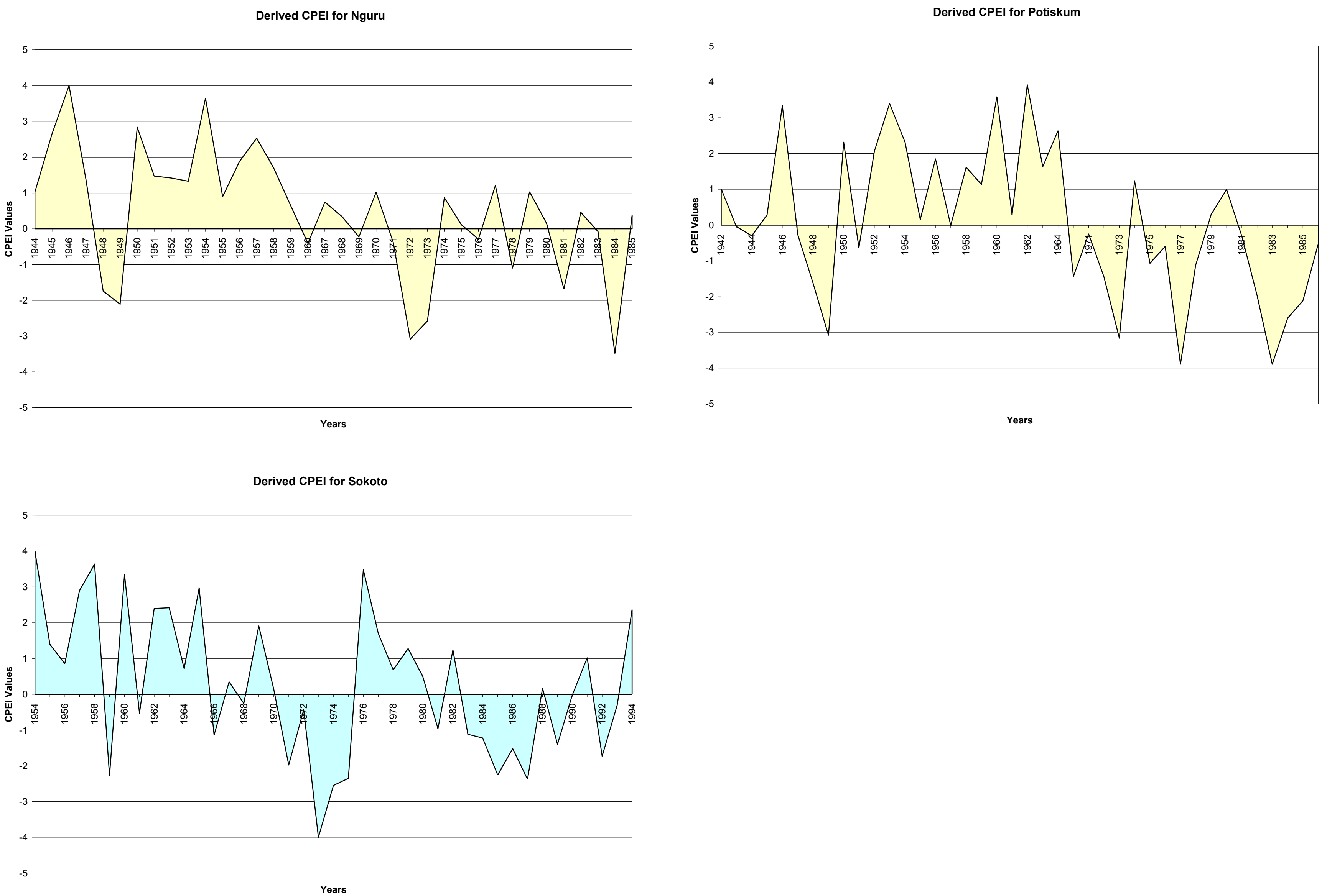


Figure 4.25: Distribution of Annual CPEI at Nguru, Potiskum and Sokoto Stations

For this study, a 3-month SPI is used for a short-term or seasonal drought index, 6 months for the WET season analysis, 12-months for the annual or intermediate-term drought index and a 24-months SPI for a long-term drought index. The SPI for a month / year in the period of record is therefore dependent upon the time scale. For instance, the 3-months SPI calculated for January 1973 utilized the precipitation total of November 1972, through January 1973 in order to calculate the SPI index. Likewise, the 12-months SPI for January 1973 utilized the precipitation total for February 1972 through January, 1973, while the 24 months SPI for January 1973 utilized the precipitation total for February 1971 through January 1973.

Figures 2.26 and 2.27 show the example of the 12-month SPI used to depict the drought conditions of each of the stations under study. These Figures aptly give a vivid picture of the effectiveness of the rainfall occurrences for over 50 years in the SSRN. They are indicative of water deficits of varied magnitude.

(c) Drought Evaluation using the PDSI

A FORTRAN program using the PDSI technique earlier presented in section 2.3.1 was received from the National Climatic Data Center (NCDC) and used to evaluate the PDSI for each of the station under study. The program listing is presented in Appendix II. Using rainfall and temperature data obtained from each station as inputs, the program computes monthly and weekly PDSI values for each of the stations.

Figure 4.26: Distribution of Annual SPI at Gusau, Kano, Katsina and Maiduguri Stations

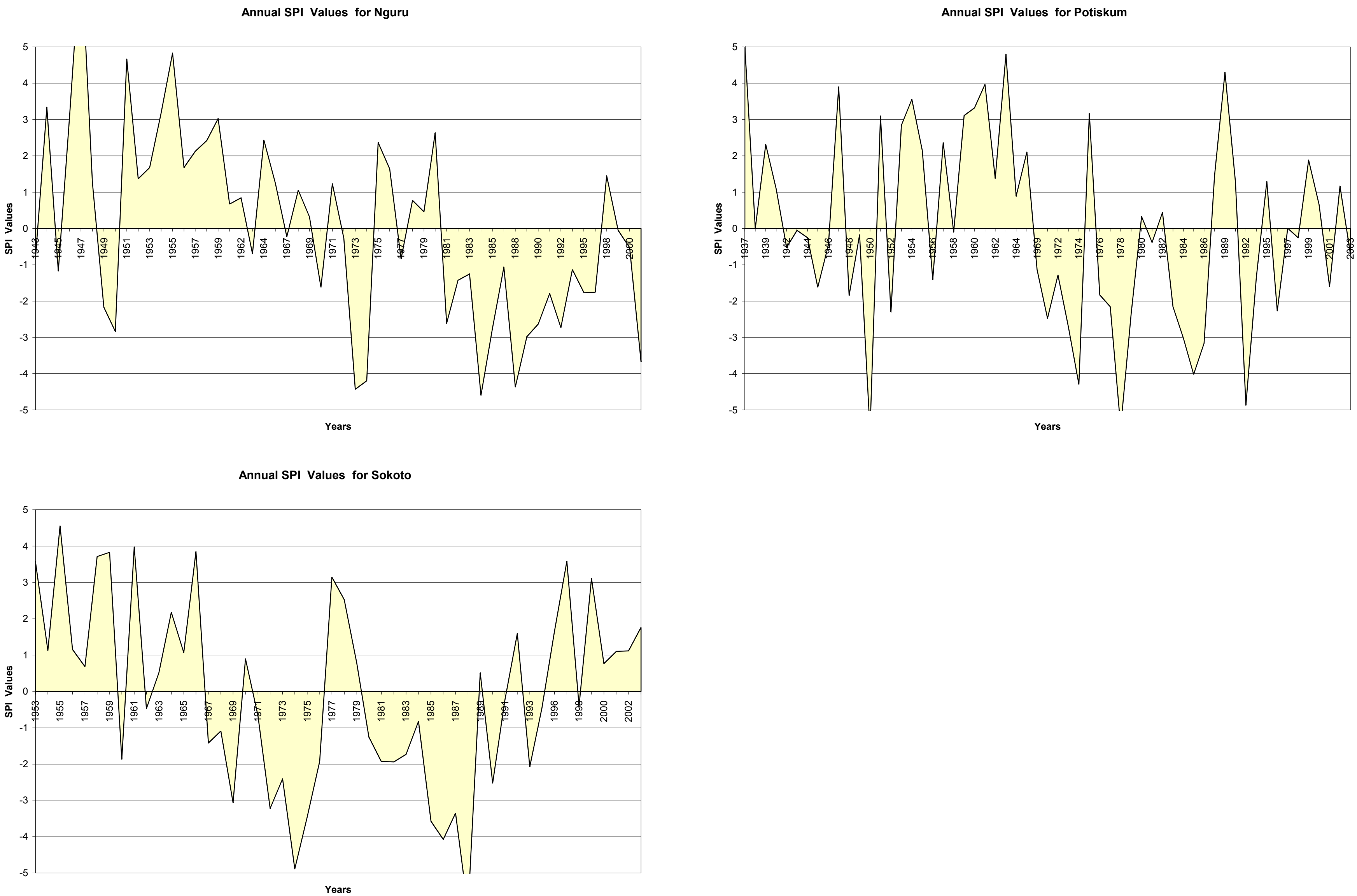


Figure 4.27: Distribution of Annual SPI at Nguru, Potiskum and Sokoto Stations

Owing to the accounting structure of PDSI, the PDSI value for the last month of each year gives the PDSI value for the year. The PDSI values computed for each of the year using both rainfall and temperature data are plotted in Figures 2.28 and 2.29.

The total length of available daily temperature records in each station limited the computation of PDSI for each station under study. This probably explains the reasons why PDSI is rarely used for drought indexing in Nigeria. Similarly, for the few available records, the plots in Figures 2.28 and 2.29 may suggest that the PDSI values obtained for the various years in each station under study has over-amplified the duration of the historical droughts recorded in the SSRN. Judging also from the PDSI values obtained for the historical drought years in Table 4.8 a-g above, PDSI seems not sensitive to the rainfall deficiency in the SSRN. It does not accentuate the dry periods of this region.

(d) Drought Evaluation using the BMDI and RAI

Similar to SPI computations, the monthly precipitation totals for each of the stations were also extracted and used for the calculations of the rainfall anomaly index (RAI) and the Bhalme and Mooley Drought Index (BMDI). Using the calculated values of –0.57 and 38.84 for Northern Nigeria (Oladipo and Shuaibu, 1989) for c and d respectively in equations (2.14), monthly values of BMDI were computed.

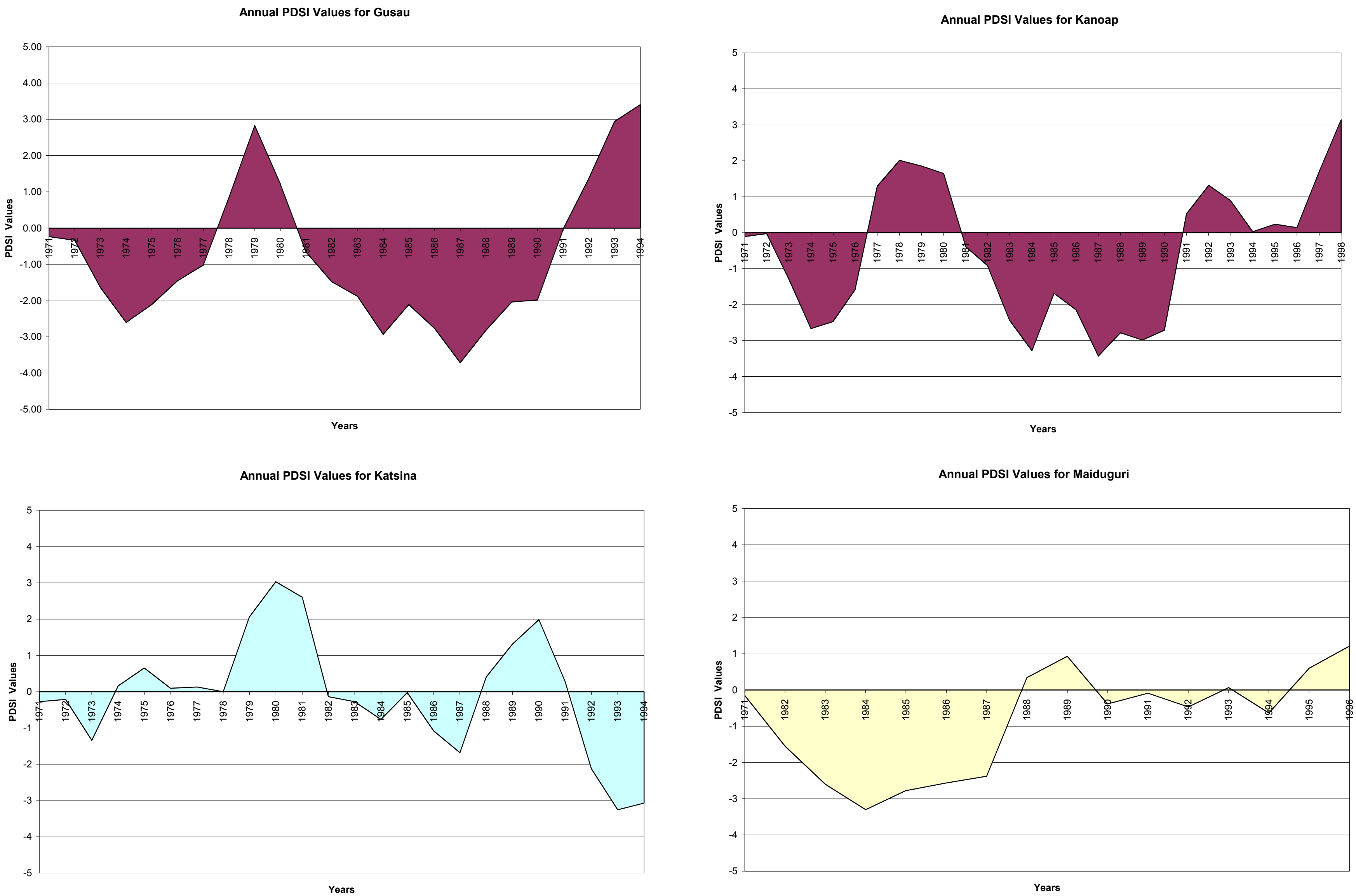
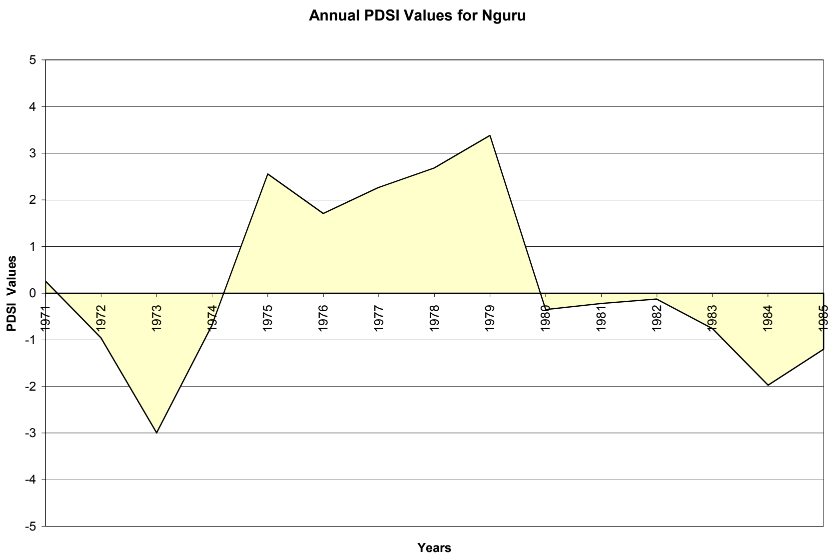
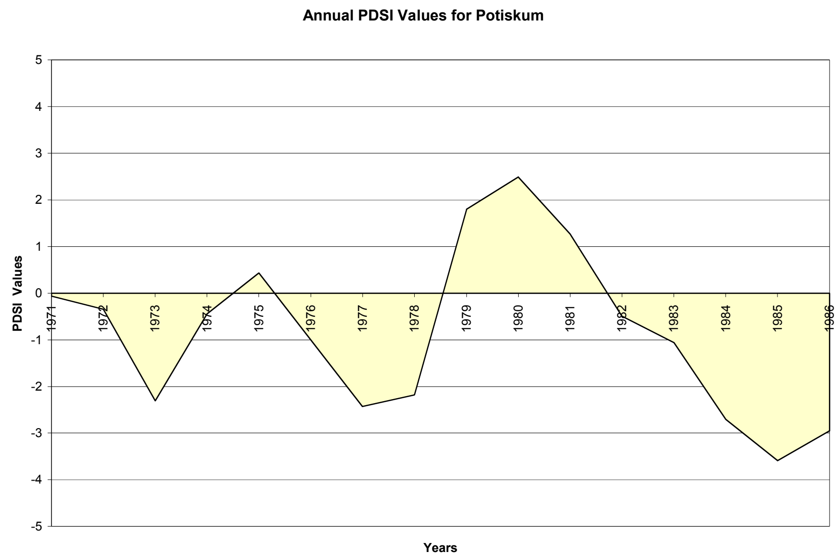


Figure 4.28: Distribution of Annual PDSI at Gusau, Kano, Katsina and Maiduguri Stations





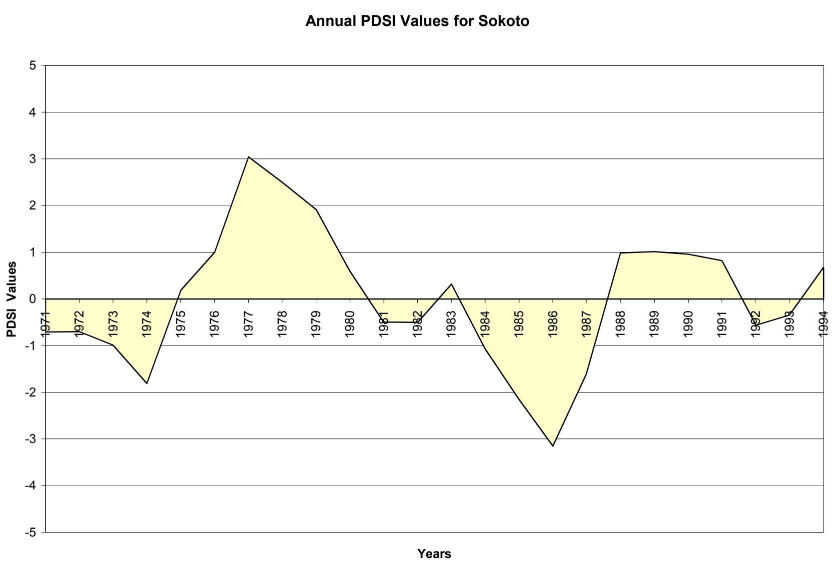


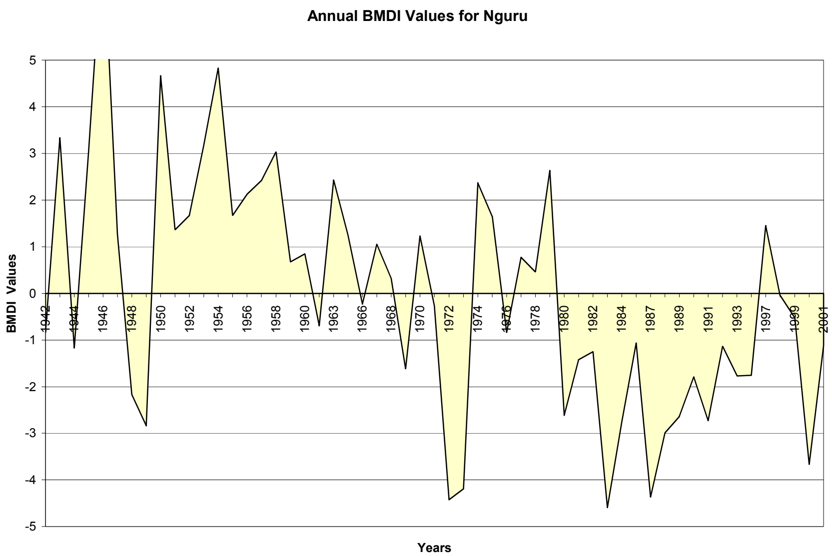
Figure 4.29: Distribution of Annual PDSI at Nguru, Potiskum and Sokoto Stations

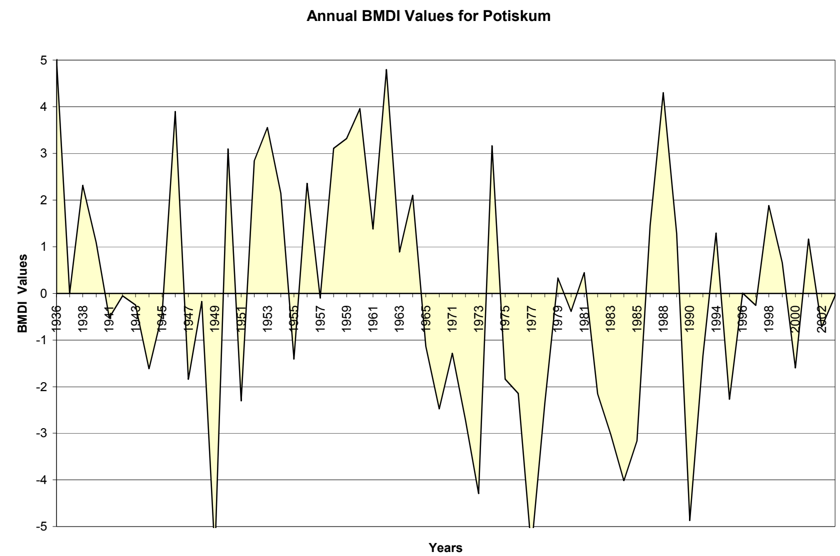
The listing of the computer program used for the computation of BMDI and RAI are presented in APPENDIX II. The plots in Figures 2.30 and 2.31 and Figures 2.32 and 2.33 respectively show the drought conditions in each of the stations under study using the RAI and BMDI respectively.

The difference between the drought severity estimates of BMDI and RAI is small in each of the stations under study. The BMDI and RAI values obtained prior to 1990 in Kano, Sokoto and Maiduguri tallies with the results obtained by Iwegbu (1993). The BDMI and RAI values in Figures 2.30 and 2.31 have also been able to identify the drought years of 1942-44, 1972-74 and 1983-84 in Kano and other stations under study.

In general, all the four (4) indices (PDSI, SPI, BMDI and RAI) appear to be effective in detecting drought periods. Without any specific reference to the absolute values of drought indices, the number of years with negative values for the three indices agrees very well. The well-known extensive drought of early 70s and 80s in the SSRN are also quantitatively well documented by each of these four drought indices.

Figure 4.30: Distribution of Annual BMDI at Gusau, Kano, Katsina and Maiduguri Stations





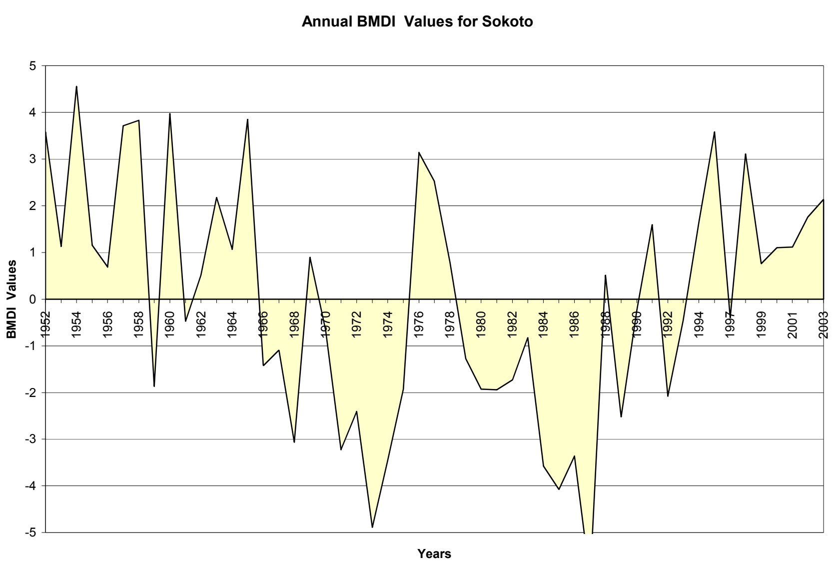


Figure 4.31: Distribution of Annual BMDI at Nguru, Potiskum and Sokoto Stations

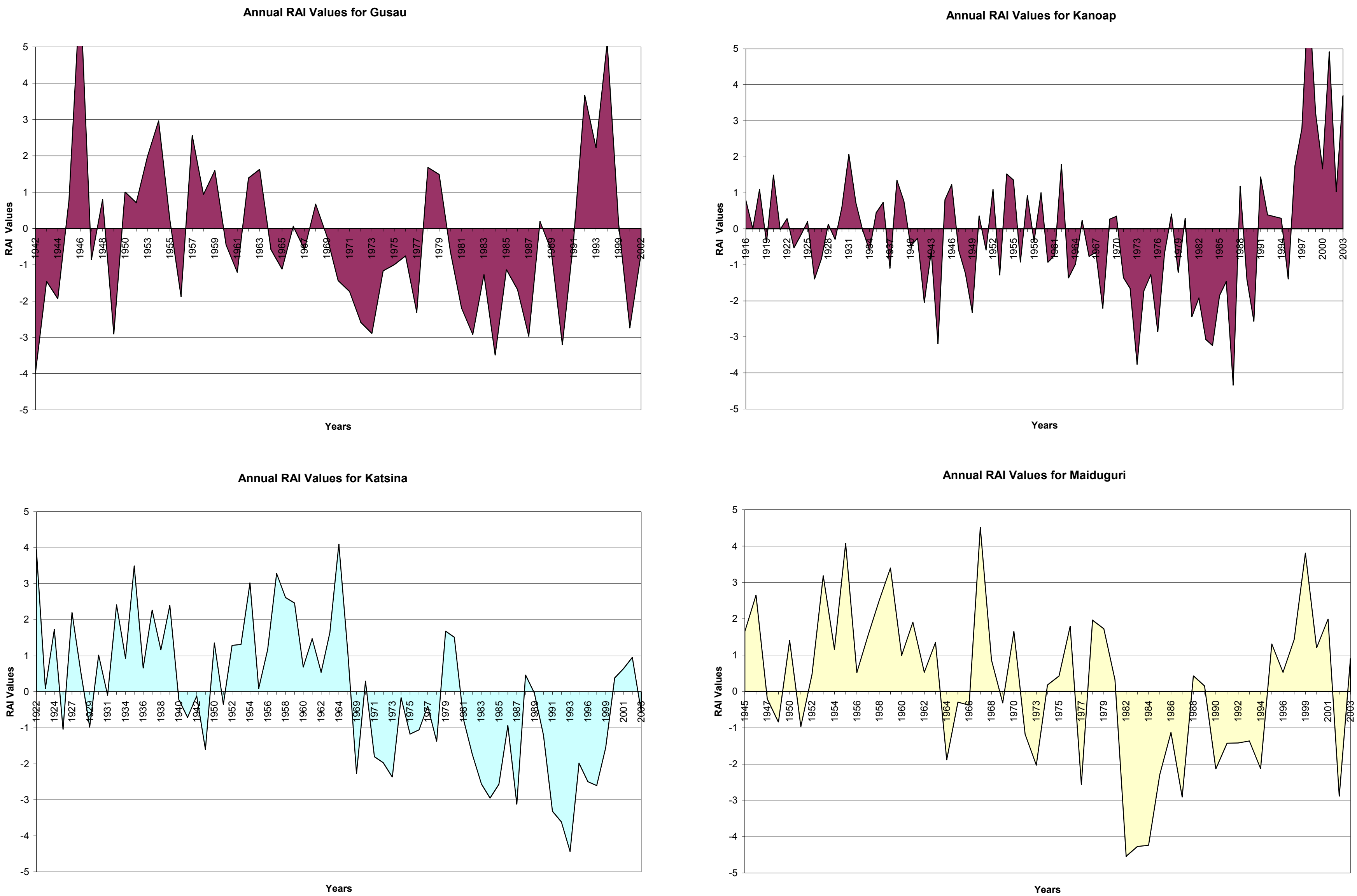
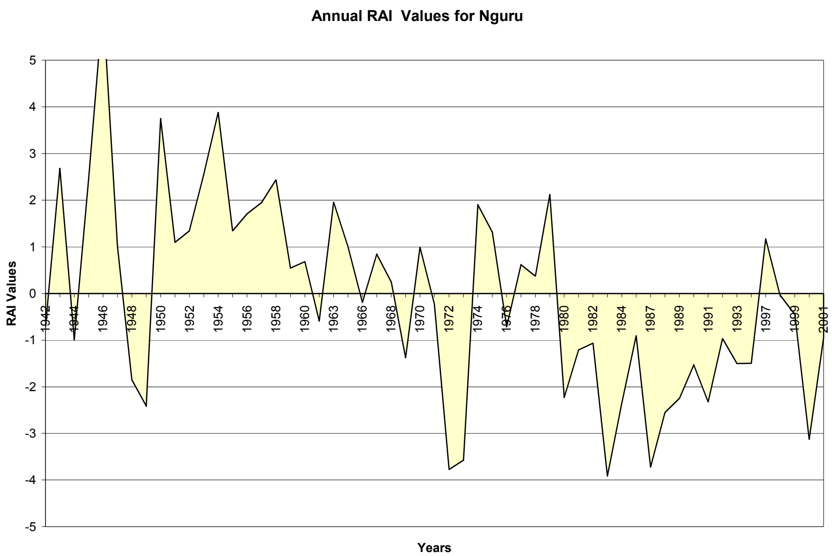
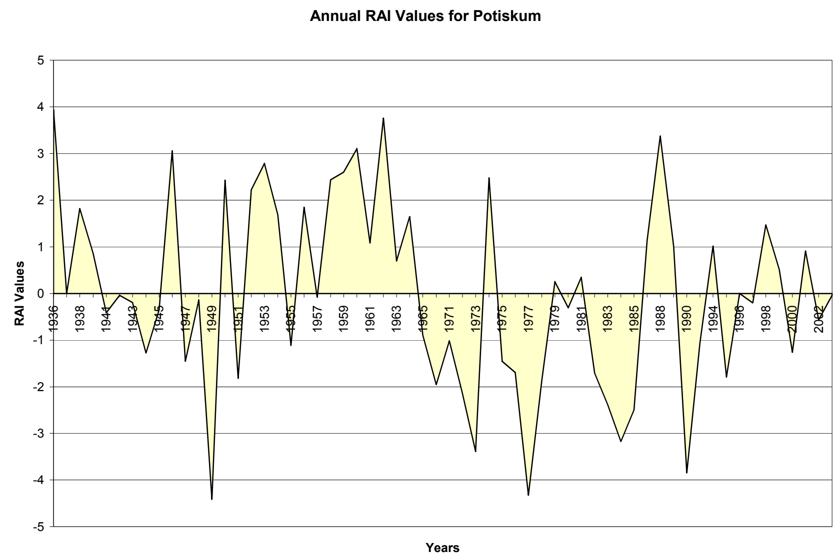


Figure 4.32: Distribution of Annual RAI at Gusau, Kano, Katsina and Maiduguri Stations





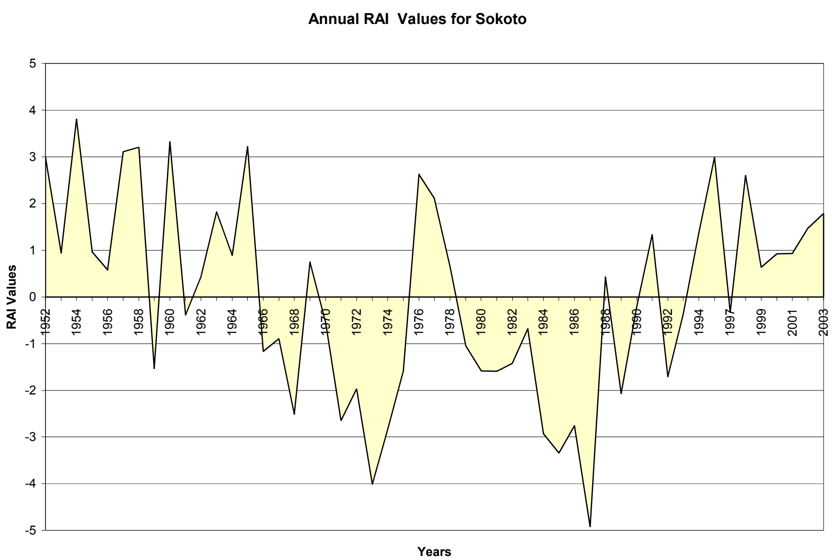


Figure 4.33: Distribution of Annual RAI at Nguru, Potiskum and Sokoto Stations

4.5 Dry Spell Analysis:

Dry spell is the most notable consequent conditions revealed by the previous analysis on the PEVs. A detailed study of its nature, depicted by the derived CPEI can further give information on how to cope with its incessant conditions in the SSRN. The sequent dry spell analysis described below was carried out as a way of contributing and increasing the knowledge of how to better understand the dry spell in the SSRN and providing scientific information that can lead to its effective management.

A dry day and its sequence called dry spell are also another useful proxy definition of drought condition or occurrence at a place. The characteristics of dry spell observed in an arid or semi-arid region, determines the extent of what becomes of the few, scanty and poorly distributed rains in such areas.

Hydrologically, the occurrence of dry spell over an area impinges and heavily affects the effect of the previous rainfall occurrences. Owing to heat interactions and exchanges within an environment, dry spells are usually associated with high rate of evaporation and transpiration, high demand for water among human beings and animals. Knowing the danger posed in any place where such occurrence is prevalent, it becomes imperatively necessary to carefully study its frequency and , distribution so as to provide useful information for its management.

Table 4.3 above shows the percentage of the average number of dry days, periods or seasons without any rain. It is clear from this table that for each of the stations under study, the dry season is up-to four times the wet season for each of the seasonal rainfall totals. This makes it crucial to look closer into the pattern of the dry days and make a clearer picture of the dry spells within the wet season and within the year for all the stations under study.

Two different broad based definitions were used to define periods where rainfall deficiency constitutes a dry spell. They are as defined as follows:

(a) Dry spell starts when there is no rainfall at all. This is referred to as Major rainfall deficiency

(b) Dry spell starts when accumulated rainfall of N-days is less than a particular threshold. This is based on the understanding that the effect of rainfall can be felt over some days. A cumulative N-day(s) rainfall depth will have a lasting effect than that of a single day. It is referred to as partial or minor rainfall deficiency.

The dry spell lengths were processed to give maximum dry spell in 30-day periods starting from the first day of each decade. Each month is divided into three decades starting from the 1st, 11th and 21st day of the month. The last decade of the month, which includes all the days to the end of the month, could either be 8, 9, 10 or 11 days, depending on the month.

Probabilities of maximum dry-spell lengths exceeding 7, 10 and 15 days over the next 30-days starting from the first day of each decade were then calculated. According to Sivakumar (1992), the choice of these spell lengths reflect the need to consider shorter spell lengths for drought-sensitive crops such as Maize, as opposed to drought-hardy crops such as millet, which can withstand longer dry spells of even 15 days. Also, for a given crop certain growth stages are more sensitive to droughts and have a higher water requirement.

In addition to the maximum dry spell, conditional dry spell were also calculated. These are the length of dry spells conditional on the day prior to the beginning of a spell being rainy. These data as believed will help its user to assess if a break in dry spells due to rain has a significant impact on the subsequent spell length.

4.5.1 Dry Spell Analysis for Agricultural Applications

The probabilities of dry spells exceeding 7, 10 and 15 days within the 30days after the first day of each decade of the year at each station under study are shown on Table 4.10a-g below. These data provides a quick overview of the drought risks during the year. Up-to mid June the probability of maximum dry-spell lengths exceeding 7 and 10 days is above 25%. The conditional dry-spell probabilities also show that even if the dry spell is broken due to rain, the risk of a long dry spell exceeds 20% upto 1st decade in June. These data show that sowing field crops with first rains before June is prone with considerable risks.

Table 4.10a: Probability (%) of Maximum and Conditional Dry Spells Exceeding Indicated lengths within 30 days after a starting date at Gusau.

Date		Maximum Dry Spell Exceeding 5, 7, 10 and 15 days.							
		Maximum Dry Spell				Conditional Dry Spell			
		>5	>7	>10	>15	>5	>7	>10	>15
1	May	87	76	47	20	70	54	27	10
11	May	78	50	18	7	65	40	12	7
21	May	61	20	3	1	54	14	0	0
1	Jun	43	16	1	1	41	14	1	1
11	Jun	27	10	1	1	23	10	1	1
21	Jun	25	9	0	0	23	7	0	0
1	Jul	27	9	0	0	25	7	0	0
11	Jul	27	5	1	0	23	5	1	0
21	Jul	21	5	1	0	21	5	1	0
1	Aug	14	1	1	0	10	0	0	0
11	Aug	7	0	0	0	7	0	0	0
21	Aug	20	9	0	0	20	9	0	0
1	Sep	41	23	9	0	41	23	9	0
11	Sep	87	61	32	12	87	61	32	12
21	Sep	98	81	65	43	96	80	63	41
1	Oct	100	94	87	65	83	78	69	47

Table 4.10b: Probability (%) of Maximum and Conditional Dry Spells Exceeding Indicated lengths within 30 days after a starting date at Kano

Date	Maximum Dry Spell Exceeding 5, 7, 10 and 15 days.							
	Maximum Dry Spell				Conditional Dry Spell			
	>5	>7	>10	>15	>5	>7	>10	>15

1	May	98	87	59	39	68	51	27	17
11	May	93	73	42	18	78	55	22	10
21	May	82	55	26	5	69	44	19	4
1	Jun	67	40	13	4	62	34	12	4
11	Jun	56	22	9	2	50	15	4	1
21	Jun	38	13	2	0	34	11	2	0
1	Jul	31	10	2	0	30	10	2	0
11	Jul	19	6	1	0	17	5	1	0
21	Jul	13	1	0	0	13	1	0	0
1	Aug	10	1	0	0	10	1	0	0
11	Aug	18	3	1	0	18	3	1	0
21	Aug	34	17	7	1	34	17	7	1
1	Sep	63	44	20	5	62	43	19	4
11	Sep	88	80	55	31	86	78	53	30
21	Sep	100	95	87	65	92	87	79	55
1	Oct	100	98	96	92	69	65	64	60

Table 4.10c: Probability (%) of Maximum and Conditional Dry Spells Exceeding Indicated lengths within 30 days after a starting date at Katsina

Date		Maximum Dry Spell Exceeding 5, 7, 10 and 15 days.							
		Maximum Dry Spell				Conditional Dry Spell			
		>5	>7	>10	>15	>5	>7	>10	>15
1	May	97	85	66	39	68	46	28	13
11	May	97	84	57	24	79	62	34	10
21	May	89	69	42	14	75	53	27	11
1	Jun	85	59	28	4	76	47	17	1
11	Jun	69	36	11	0	60	34	11	0
21	Jun	52	21	2	0	46	18	2	0
1	Jul	33	10	0	0	28	8	0	0
11	Jul	27	4	0	0	27	4	0	0
21	Jul	24	4	0	0	24	4	0	0
1	Aug	17	2	1	0	17	2	1	0
11	Aug	18	7	2	0	18	7	2	0
21	Aug	40	20	8	1	40	20	8	1
1	Sep	68	49	18	10	68	49	18	10
11	Sep	92	85	69	36	89	82	63	31
21	Sep	98	95	85	65	88	85	75	55
1	Oct	100	100	98	89	59	59	55	44

Table 4.10d: Probability (%) of Maximum and Conditional Dry Spells Exceeding Indicated lengths within 30 days after a starting date at Maiduguri

Date	Maximum Dry Spell Exceeding 5, 7, 10 and 15 days.							
	Maximum Dry Spell				Conditional Dry Spell			
	>5	>7	>10	>15	>5	>7	>10	>15

1	May	100	94	81	45	76	63	49	20
11	May	92	78	61	32	80	54	36	12
21	May	89	76	47	16	72	56	34	7
1	Jun	81	63	34	1	70	47	21	1
11	Jun	67	32	14	1	60	25	9	0
21	Jun	61	21	7	0	50	18	5	0
1	Jul	34	14	1	0	30	10	1	0
11	Jul	29	5	0	0	25	3	0	0
21	Jul	29	7	1	0	29	7	1	0
1	Aug	25	10	1	0	23	9	1	0
11	Aug	34	18	3	0	34	18	3	0
21	Aug	49	23	3	3	47	23	3	3
1	Sep	83	52	25	5	83	52	25	3
11	Sep	94	81	65	27	92	81	65	27
21	Sep	98	98	89	60	89	87	78	47
1	Oct	100	100	98	81	72	72	65	49

Table 4.10e: Probability (%) of Maximum and Conditional Dry Spells Exceeding Indicated lengths within 30 days after a starting date at Nguru

Date		Maximum Dry Spell Exceeding 5, 7, 10 and 15 days.							
		Maximum Dry Spell				Conditional Dry Spell			
		>5	>7	>10	>15	>5	>7	>10	>15
1	May	100	96	92	69	70	58	47	27
11	May	98	92	78	41	74	56	40	16
21	May	98	92	65	25	80	69	34	7
1	Jun	92	81	56	21	81	65	38	10
11	Jun	96	70	47	7	81	54	30	5
21	Jun	78	50	20	3	61	34	14	1
1	Jul	65	36	14	1	63	32	12	1
11	Jul	54	23	7	0	50	20	7	0
21	Jul	41	18	5	1	41	16	5	1
1	Aug	43	18	9	0	41	14	7	0
11	Aug	54	20	9	1	54	20	9	1
21	Aug	76	43	18	3	72	41	18	3
1	Sep	85	69	40	16	85	69	40	16
11	Sep	96	89	76	45	89	78	67	38
21	Sep	100	100	96	69	81	81	76	45
1	Oct	100	100	100	92	60	58	58	50

Table 4.10f: Probability (%) of Maximum and Conditional Dry Spells Exceeding Indicated lengths within 30 days after a starting date at Potisk

Date		Maximum Dry Spell Exceeding 5, 7, 10 and 15 days.							
		Maximum Dry Spell				Conditional Dry Spell			
		>5	>7	>10	>15	>5	>7	>10	>15

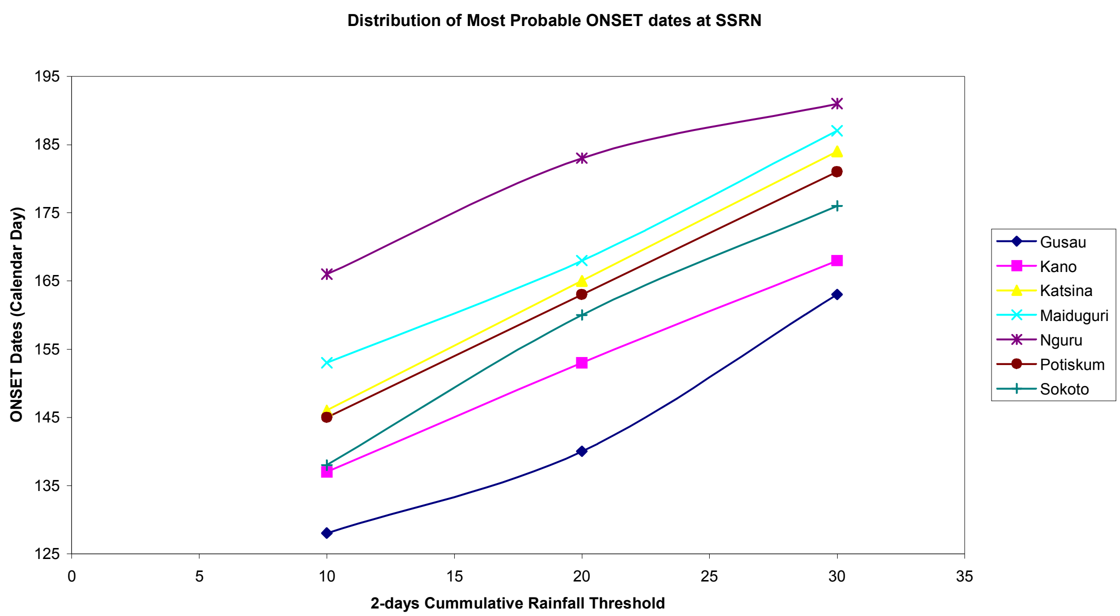
1	May	95	91	70	31	83	75	48	18
11	May	96	86	61	15	86	63	38	8
21	May	93	68	41	6	78	53	30	3
1	Jun	80	63	30	8	76	56	23	5
11	Jun	68	45	21	1	55	30	10	1
21	Jun	48	23	5	0	41	16	5	0
1	Jul	35	8	3	0	33	5	0	0
11	Jul	30	1	1	0	28	1	1	0
21	Jul	25	1	1	0	23	1	1	0
1	Aug	23	8	1	0	23	6	1	0
11	Aug	36	13	6	0	35	13	6	0
21	Aug	53	28	13	1	53	26	13	1
1	Sep	78	45	25	5	75	45	25	5
11	Sep	91	70	48	20	91	68	48	20
21	Sep	98	88	70	38	98	88	66	38
1	Oct	100	100	96	71	85	85	81	55

Table 4.10g: Probability (%) of Maximum and Conditional Dry Spells Exceeding Indicated lengths within 30 days after a starting date at Sokoto

Date		Maximum Dry Spell Exceeding 5, 7, 10 and 15 days.							
		Maximum Dry Spell				Conditional Dry Spell			
		>5	>7	>10	>15	>5	>7	>10	>15
1	May	100	92	80	35	76	58	45	11
11	May	100	74	50	29	84	54	31	15
21	May	90	64	39	23	78	52	25	17
1	Jun	70	52	25	9	62	39	13	5
11	Jun	70	43	17	1	64	35	11	1
21	Jun	50	21	3	0	47	21	1	0
1	Jul	41	17	1	0	41	17	1	0
11	Jul	31	15	3	0	31	15	3	0
21	Jul	23	9	3	0	21	9	3	0
1	Aug	29	7	3	0	27	7	3	0
11	Aug	33	11	1	0	33	11	1	0
21	Aug	41	23	3	1	41	23	3	1
1	Sep	82	58	21	3	82	58	21	3
11	Sep	92	80	60	33	92	80	60	33
21	Sep	100	94	84	64	88	82	72	52
1	Oct	98	98	96	88	66	66	62	52

In order to know the most probable day to sow crop, the ONSET of rains was simulated using two of the most practical definitions of the ONSET of rains in the literature. The definitions are those by Stern et. al. (1981) and Sivakuma (1992) which uses the cumulative of N-days rains above a threshold as the criteria to define the ONSET of rains.

Coincidentally, the ONSET of the rains is often being used as a guide for sowing dates for the year. The frequency distribution of the first dates of each year with cumulative of N-days rainfall above 10, 20 and 30mm were analyzed and used



to obtain the most probable ONSET dates. Using N=2 days (Stern et al. (1982), and with the assumption that a 80% probability of occurrence of this dates can be a guide as SOWING dates, the various dates obtained in Figure 4.34 below were used to predict the risk of planting on, before or after this most probable sowing dates (see Figures 4.35 and 4.36).

The length of dry spells for consecutive 10-day after sowing (DAS) was determined for each of the five rainfall thresholds at five probability levels (90%, 75%, 50%, 25% and 10%). The five rainfall thresholds, 5, 10, 15, 20 and 25mm depths were also chosen as representative demands of water. For instance, in

Figure 4.34: Distribution of the most probable ONSET dates at SSRN for different 10, 20 and 30mm Rainfall Thresholds.

agriculture applications, it could stand as percentages of various crop water requirements. The choice of the probability levels also reflects the degree of certainty with which the user would like to determine the dry spell length. The computed values for all the stations under study are shown on Table 4.11 a-g below. The results show the mean rainfall and the dry-spell length at different probability levels.

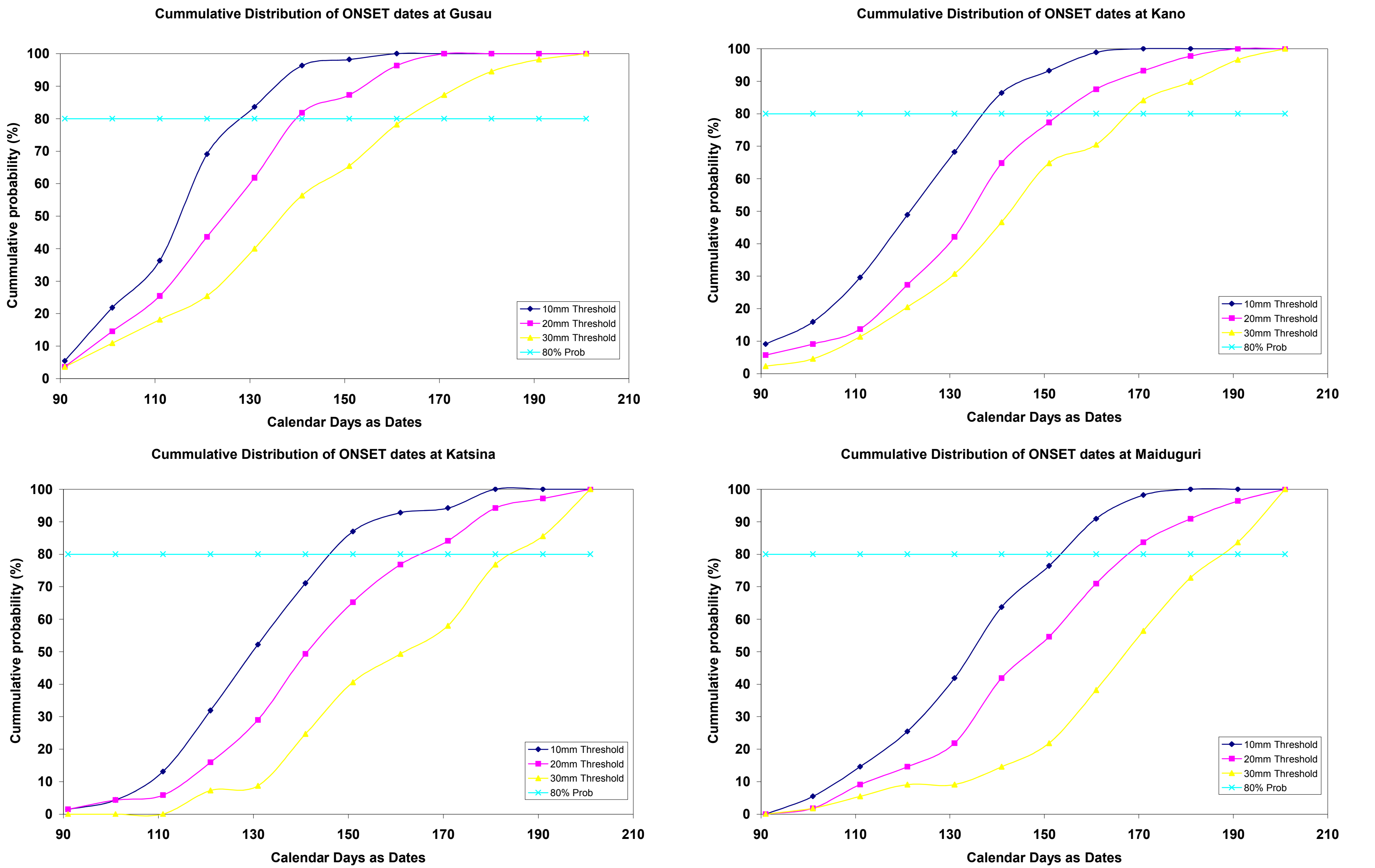


Figure 4.35: Distribution of ONSET dates at Gusau, Kano, Katsina and Maiduguri Stations for different 10, 20 and 30mm Rainfall Thresholds

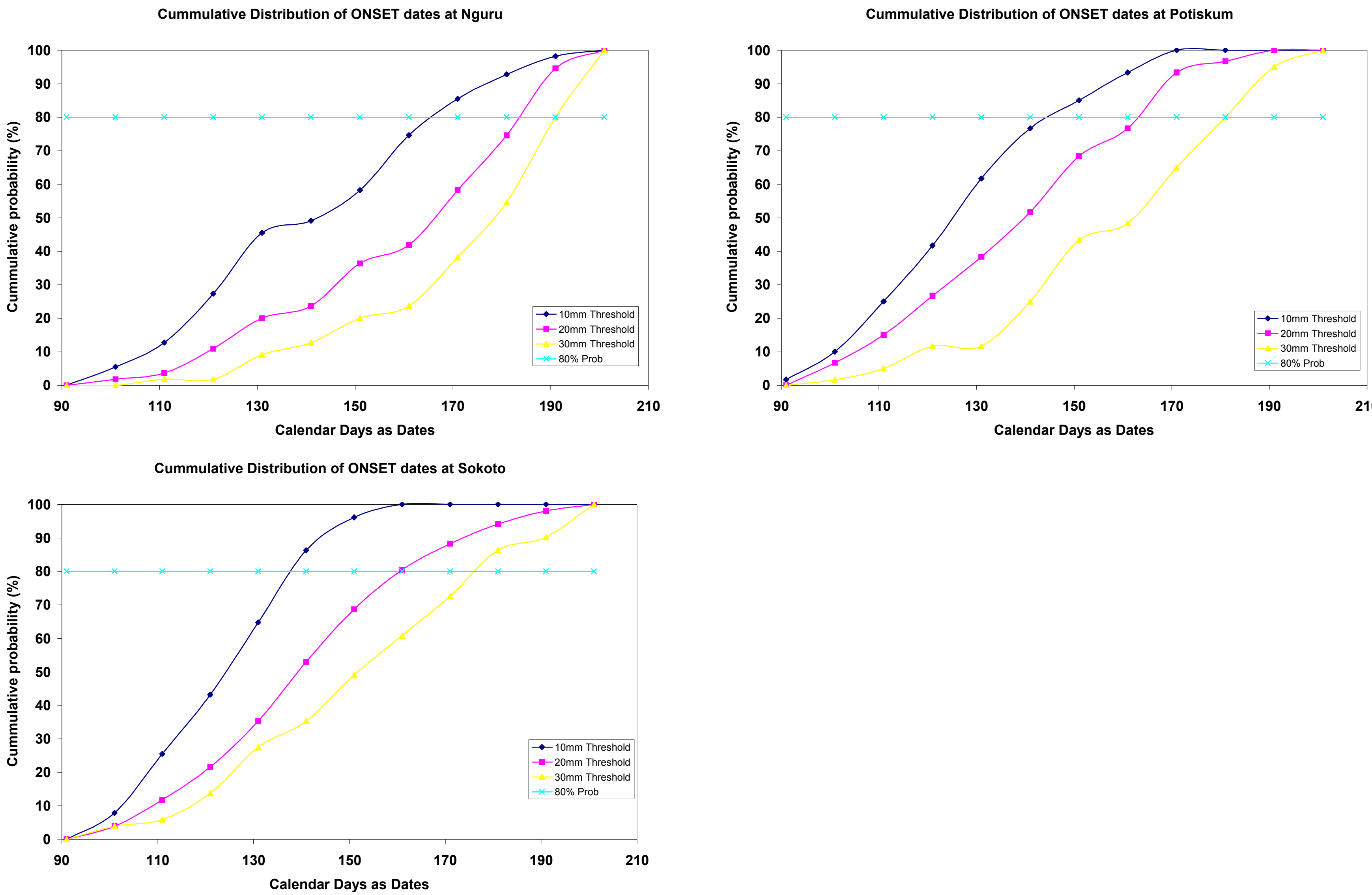


Figure 4.36: Distribution of ONSET dates at Nguru, Potiskum and Sokoto Stations for different 10, 20 and 30mm Rainfall Thresholds

Table 4.11a: Maximum length of Dry Spell (Days) at Five probability levels for different DAS at Gusau.
Data are presented under each of the four rainfall thresholds used for dry-spell computations. (Optimum Sowing Day: 163[rd] day)

DAS	Rainfall Depth (mm)	5mm					10mm					15mm					20mm					25mm				
		90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10
10	51.3	5.5	3.2	1.0	1.0	0.0	9.0	5.2	2.0	1.0	0.0	16.0	9.0	4.0	1.0	1.0	22.5	11.2	4.0	1.7	1.0	31.0	19.0	11.0	3.7	1.0
20	59.3	4.0	2.2	1.0	0.0	0.0	7.0	4.0	2.0	1.0	0.0	13.5	7.0	3.0	1.0	0.0	17.0	11.2	3.5	1.0	0.0	23.5	15.2	6.5	2.0	0.5
30	66.8	7.0	4.0	2.0	0.0	0.0	7.0	4.0	2.0	0.0	0.0	10.0	6.2	3.5	1.0	0.0	14.5	9.0	4.0	1.0	0.0	21.0	14.0	7.0	3.7	0.0
40	71.5	6.0	3.2	2.0	0.0	0.0	7.0	4.0	2.0	0.7	0.0	8.5	6.0	2.5	1.0	0.0	12.0	8.0	4.0	1.7	0.0	16.0	10.2	5.5	2.7	1.0
50	76.1	5.0	3.0	1.5	0.0	0.0	7.0	4.0	2.0	1.0	0.0	8.0	5.2	3.0	1.0	0.0	11.5	8.0	4.0	2.0	0.0	15.0	11.0	5.0	2.0	0.5
60	86.0	4.0	2.2	1.0	0.0	0.0	6.0	4.0	2.0	0.0	0.0	6.5	5.0	2.0	1.0	0.0	10.5	6.0	2.5	1.0	0.0	13.5	8.5	4.5	1.7	0.5
70	101.6	3.0	2.0	1.0	0.0	0.0	3.5	2.0	1.0	0.0	0.0	4.0	3.0	2.0	1.0	0.0	10.0	4.0	2.0	1.0	0.0	16.5	8.0	3.0	1.0	0.5
80	112.6	4.0	2.2	1.0	0.0	0.0	6.0	4.0	2.0	0.0	0.0	9.0	6.0	2.0	0.0	0.0	12.5	8.0	3.0	1.0	0.0	24.0	9.0	6.0	1.0	0.0
90	89.9	3.5	2.0	1.0	0.0	0.0	8.5	4.0	2.0	0.7	0.0	12.5	6.0	3.0	1.7	0.0	41.0	10.2	4.0	2.0	1.0	41.0	41.0	10.0	2.0	1.0
100	74.5	7.0	3.0	1.0	0.0	0.0	41.0	6.7	3.0	0.0	0.0	41.0	16.7	4.5	1.0	0.0	41.0	41.0	6.0	1.0	0.0	41.0	41.0	11.0	2.0	0.0
110	52.9	41.0	41.0	6.5	1.0	0.0	41.0	41.0	18.5	2.0	0.5	41.0	41.0	41.0	3.0	1.0	41.0	41.0	41.0	7.7	1.0	41.0	41.0	41.0	13.2	1.5
120	25.2	41.0	41.0	41.0	7.5	2.0	41.0	41.0	41.0	13.7	3.0	41.0	41.0	41.0	41.0	3.0	41.0	41.0	41.0	41.0	7.0	41.0	41.0	41.0	41.0	11.5
130	8.7	41.0	41.0	41.0	37.2	3.5	41.0	41.0	41.0	41.0	8.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
140	4.8	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
150	0.2	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0

Table 4.12a: Indications of Probable Length of Growing Season in Gusau (days)

	Dry Spell Threshold (days)	5mm					10mm					15mm					20mm					25mm				
		90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%
1	5	30	120	120	130	150	20	100	120	130	140	20	20	120	130	140	20	20	110	120	130	20	20	20	120	130
2	10	120	120	130	140	150	110	120	120	130	150	20	110	120	130	140	20	20	120	130	140	20	20	100	120	130
3	15	120	120	130	140	150	110	120	120	140	150	100	110	120	130	140	20	110	120	130	140	20	20	120	130	140
4	20	120	120	130	140	150	110	120	130	140	150	110	120	120	130	140	90	110	120	130	140	20	100	120	130	140
5	25	120	120	130	140	150	110	120	130	140	150	110	120	120	130	140	100	110	120	130	140	90	100	120	130	140

Table 4.11b: Maximum length of Dry Spell (Days) at Five probability levels for different DAS at Kano.
Data are presented under each of the four rainfall thresholds used for dry-spell computations. (Optimum Sowing Day: 168th day)

DAS	Rainfall Depth (mm)	5mm					10mm					15mm					20mm					25mm				
		90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10
10	52.4	7.0	4.0	2.0	1.0	0.0	9.0	6.0	3.0	1.0	0.0	15.0	9.0	4.0	2.0	0.0	18.0	11.0	6.0	3.0	1.0	23.6	16.0	8.0	4.0	1.0
20	56.6	7.0	4.0	2.0	1.0	0.0	9.0	5.0	2.0	1.0	0.0	12.2	7.0	4.0	1.0	0.8	18.0	9.0	4.0	2.0	1.0	23.6	13.0	7.0	3.0	1.0
30	71.1	5.0	3.0	1.0	0.0	0.0	6.0	4.0	2.0	0.0	0.0	10.2	6.0	3.0	1.0	0.0	17.0	8.0	4.0	2.0	0.0	17.0	11.0	5.0	2.0	0.0
40	89.1	4.0	3.0	2.0	0.0	0.0	7.2	4.0	2.0	1.0	0.0	10.0	6.0	3.0	1.0	0.0	14.0	8.0	4.0	1.0	0.0	15.4	10.0	5.0	2.0	0.0
50	99.2	4.0	2.0	1.0	0.0	0.0	5.0	3.0	1.0	0.0	0.0	6.2	4.0	1.0	0.0	0.0	11.0	5.0	2.0	0.0	0.0	14.0	8.0	3.0	1.0	0.0
60	114.6	5.0	2.0	1.0	0.0	0.0	5.0	3.0	2.0	0.0	0.0	6.0	4.0	2.0	1.0	0.0	10.8	5.0	2.0	1.0	0.0	21.0	7.0	4.0	1.0	0.0
70	115.4	3.0	2.0	1.0	0.0	0.0	6.2	3.0	1.0	0.0	0.0	10.2	5.0	2.0	1.0	0.0	18.0	9.0	3.0	2.0	0.0	36.2	13.0	5.0	2.0	0.0
80	87.8	7.0	3.0	1.0	0.0	0.0	8.2	4.0	2.0	1.0	0.0	21.4	9.0	3.0	1.0	0.0	41.0	23.0	6.0	2.0	1.0	41.0	41.0	9.0	3.0	1.0
90	63.4	12.0	5.0	2.0	0.0	0.0	41.0	13.0	5.0	1.0	0.0	41.0	41.0	9.0	2.0	0.0	41.0	41.0	17.0	3.0	0.0	41.0	41.0	41.0	7.0	2.0
100	36.0	41.0	41.0	6.0	1.0	0.0	41.0	41.0	13.0	2.0	1.0	41.0	41.0	41.0	5.0	1.8	41.0	41.0	41.0	7.0	2.0	41.0	41.0	41.0	41.0	4.0
110	21.4	41.0	41.0	41.0	10.0	1.0	41.0	41.0	41.0	41.0	3.0	41.0	41.0	41.0	41.0	9.8	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
120	5.8	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
130	1.3	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
140	0.9	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
150	0.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0

Table 4.12b: Indications of Probable Length of Growing Season in Kano (days)

		5mm					10mm					15mm					20mm					25mm				
	Dry Spell Threshold (days)	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%
1	5	20	110	110	120	130	20	90	110	120	130	20	20	100	120	120	20	20	80	110	120	20	20	20	100	120
2	10	100	110	120	130	130	100	100	110	120	130	20	100	110	120	130	20	80	100	120	120	20	20	100	110	120
3	15	110	110	120	130	130	100	110	120	120	130	90	100	110	120	130	20	90	100	120	120	20	80	100	110	120
4	20	110	110	120	130	130	100	110	120	120	130	90	100	110	120	130	90	90	110	120	120	20	90	100	110	120
5	25	110	110	120	130	130	100	110	120	120	130	100	100	110	120	130	90	100	110	120	120	80	90	100	110	120

Table 4.11c: Maximum length of Dry Spell (Days) at Five probability levels for different DAS at Katsina.
Data are presented under each of the four rainfall thresholds used for dry-spell computations. (Optimum Sowing Day:184th day)

DAS	Rainfall Depth (mm)	5mm					10mm					15mm					20mm					25mm				
		90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10
10	52.1	5.1	3.8	1.0	0.2	0.0	8.0	5.0	2.5	1.0	0.0	13.1	7.8	4.0	1.0	0.0	17.3	12.0	5.0	2.0	0.9	22.0	14.0	7.0	3.0	1.0
20	66.8	6.0	4.0	2.0	1.0	0.0	11.0	5.0	3.0	1.0	0.0	12.2	7.0	4.0	2.0	1.0	20.1	9.8	5.0	2.0	1.0	22.2	13.5	6.0	3.0	1.0
30	71.5	4.0	3.0	1.0	0.0	0.0	5.1	4.0	2.0	1.0	0.0	8.1	5.0	3.0	1.0	0.0	15.2	9.0	4.0	1.0	0.0	20.2	11.8	5.0	2.0	0.0
40	86.0	5.0	2.0	1.0	0.0	0.0	8.1	4.0	2.0	0.0	0.0	10.1	4.8	2.0	0.0	0.0	16.1	6.8	3.0	1.0	0.0	34.7	15.5	4.0	1.0	0.0
50	87.9	4.0	2.0	1.0	0.0	0.0	7.5	4.8	2.0	0.2	0.0	14.0	6.8	2.0	1.0	0.0	41.0	14.0	5.0	2.0	0.0	41.0	35.5	9.0	3.0	1.0
60	70.6	6.1	4.0	2.0	1.0	0.0	8.1	5.0	2.5	1.0	0.0	18.3	10.5	4.5	1.2	0.0	41.0	18.0	6.0	3.0	0.0	41.0	41.0	13.0	5.0	1.0
70	52.4	17.0	8.0	3.0	1.0	0.0	41.0	11.8	4.0	1.0	0.0	41.0	25.3	6.0	1.0	0.9	41.0	41.0	10.0	3.0	1.0	41.0	41.0	41.0	4.5	1.0
80	40.0	41.0	17.8	3.5	1.0	0.0	41.0	41.0	11.0	2.0	0.9	41.0	41.0	41.0	3.2	1.0	41.0	41.0	41.0	9.0	1.0	41.0	41.0	41.0	27.5	2.0
90	21.3	41.0	41.0	41.0	8.0	1.0	41.0	41.0	41.0	41.0	5.8	41.0	41.0	41.0	41.0	6.9	41.0	41.0	41.0	41.0	12.3	41.0	41.0	41.0	41.0	12.3
100	6.6	41.0	41.0	41.0	41.0	6.9	41.0	41.0	41.0	41.0	13.0	41.0	41.0	41.0	41.0	38.2	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
110	2.4	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
120	0.9	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
130	0.2	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
140	0.1	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
150	0.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0

Table 4.12c: Indications of Probable Length of Growing Season in Katsina (days)

	Dry Spell Threshold (days)	5mm					10mm					15mm					20mm					25mm				
		90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%
1	5	20	80	100	100	110	20	80	90	100	100	20	20	80	100	100	20	20	70	90	100	20	20	20	90	100
2	10	80	90	100	110	120	70	80	90	100	110	20	70	90	100	110	20	50	90	100	100	20	20	70	90	100
3	15	80	90	100	110	120	80	90	100	100	120	70	80	90	100	110	20	70	90	100	110	20	50	80	90	110
4	20	90	100	100	110	120	80	90	100	100	120	80	80	90	100	110	50	80	90	100	110	20	60	80	90	110
5	25	90	100	100	110	120	80	90	100	100	120	80	80	90	100	110	60	80	90	100	110	50	60	80	90	110

Table 4.11d: Maximum length of Dry Spell (Days) at Five probability levels for different DAS at Maiduguri.
Data are presented under each of the four rainfall thresholds used for dry-spell computations. (Optimum Sowing Day: 187th day)

DAS	Rainfall Depth (mm)	5mm					10mm					15mm					20mm					25mm				
		90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10
10	50.7	6.0	4.0	1.0	0.7	0.0	9.0	5.2	3.0	1.0	0.0	12.0	7.0	3.0	1.0	0.0	14.0	9.2	5.0	1.0	0.0	29.5	11.0	7.0	2.0	0.0
20	74.9	4.5	3.0	1.0	0.0	0.0	6.0	4.0	2.0	1.0	0.0	11.5	5.0	3.0	1.0	0.0	18.5	7.0	4.0	1.7	0.0	26.0	14.0	4.5	2.0	0.0
30	74.3	4.5	3.0	1.0	0.0	0.0	11.5	4.2	3.0	1.0	0.0	13.0	7.2	4.0	2.0	0.0	15.0	9.2	4.0	2.7	0.5	24.5	14.2	6.0	3.0	1.0
40	76.3	4.0	2.0	1.0	0.0	0.0	8.0	4.0	2.0	1.0	0.0	9.5	6.0	3.0	1.0	0.0	19.0	9.0	5.0	1.0	0.0	40.0	14.2	6.0	1.7	1.0
50	82.1	6.0	3.2	1.0	0.0	0.0	9.0	6.0	3.0	1.0	0.0	14.5	8.0	4.0	2.0	0.0	41.0	14.0	6.0	2.0	0.0	41.0	41.0	10.0	3.0	0.0
60	59.7	7.5	4.0	2.0	0.0	0.0	13.0	5.2	2.0	0.7	0.0	37.5	10.0	4.0	1.0	0.0	41.0	35.0	6.0	2.0	0.0	41.0	41.0	19.5	4.0	1.0
70	52.2	26.0	7.0	3.0	0.0	0.0	41.0	19.2	6.0	2.0	0.0	41.0	41.0	11.5	3.0	0.5	41.0	41.0	41.0	7.0	2.5	41.0	41.0	41.0	17.0	8.0
80	25.5	41.0	41.0	7.0	2.0	0.0	41.0	41.0	21.5	4.0	1.0	41.0	41.0	41.0	7.7	2.0	41.0	41.0	41.0	10.0	2.0	41.0	41.0	41.0	41.0	4.5
90	18.1	41.0	41.0	41.0	5.0	1.5	41.0	41.0	41.0	10.5	2.5	41.0	41.0	41.0	41.0	3.0	41.0	41.0	41.0	41.0	4.5	41.0	41.0	41.0	41.0	41.0
100	7.9	41.0	41.0	41.0	41.0	12.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
110	2.7	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
120	0.3	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
130	0.2	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
140	0.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0
150	0.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0

Table 4.12d: Indications of Probable Length of Growing Season in Maiduguri (days)

		5mm					10mm					15mm					20mm					25mm				
	Dry Spell Threshold (days)	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%
1	5	50	80	90	110	110	20	50	80	100	110	20	30	80	90	110	20	20	60	80	110	20	20	30	80	90
2	10	80	90	100	110	110	60	80	90	100	110	20	80	80	100	110	20	60	80	100	110	20	20	70	80	100
3	15	80	90	100	110	120	80	80	90	110	110	70	80	90	100	110	40	70	80	100	110	20	60	70	80	100
4	20	80	90	100	110	120	80	90	90	110	110	70	80	90	100	110	60	70	80	100	110	20	60	80	90	100
5	25	80	90	100	110	120	80	90	100	110	110	70	80	90	100	110	60	70	80	100	110	20	60	80	90	100

Table 4.11e: Maximum length of Dry Spell (Days) at Five probability levels for different DAS at Nguru.
Data are presented under each of the four rainfall thresholds used for dry-spell computations. (Optimum Sowing Day: 191st day)

DAS	Rainfall Depth (mm)	5mm					10mm					15mm					20mm					25mm				
		90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10
10	52.2	7.5	4.0	2.0	1.0	0.0	12.0	8.0	3.0	1.0	0.0	16.0	9.2	4.0	2.0	0.5	20.5	15.0	9.0	3.0	1.0	29.5	18.2	9.0	3.7	1.5
20	53.9	7.0	4.2	2.0	1.0	0.0	9.0	5.0	3.0	1.0	0.0	12.5	9.0	4.5	2.0	0.0	14.5	10.0	5.0	3.0	0.5	24.0	16.0	8.0	3.7	1.0
30	64.1	5.0	3.0	1.0	0.0	0.0	9.0	5.0	2.0	1.0	0.0	12.5	7.2	3.5	1.0	0.0	16.0	10.2	4.0	1.0	0.0	33.0	13.0	5.5	2.0	0.0
40	71.9	6.5	3.2	1.0	0.0	0.0	9.0	5.2	2.0	0.7	0.0	17.5	7.2	3.5	1.0	0.0	20.5	11.2	5.0	2.0	0.5	41.0	24.2	8.0	3.0	1.0
50	61.2	9.0	4.0	1.5	1.0	0.0	13.0	8.0	2.0	1.0	0.0	41.0	17.2	8.0	2.0	0.5	41.0	25.0	9.5	4.5	1.0	41.0	41.0	21.5	6.7	2.0
60	41.5	41.0	8.0	4.0	1.0	0.0	41.0	15.0	5.5	2.7	1.0	41.0	41.0	9.0	4.7	1.5	41.0	41.0	13.0	7.7	2.0	41.0	41.0	41.0	8.8	2.0
70	31.5	41.0	41.0	7.0	1.0	0.0	41.0	41.0	13.5	2.7	0.0	41.0	41.0	41.0	4.7	1.0	41.0	41.0	41.0	5.0	1.0	41.0	41.0	41.0	8.8	1.5
80	20.9	41.0	41.0	41.0	6.5	1.0	41.0	41.0	41.0	9.8	3.0	41.0	41.0	41.0	41.0	7.0	41.0	41.0	41.0	41.0	19.5	41.0	41.0	41.0	41.0	33.0
90	7.4	41.0	41.0	41.0	41.0	6.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
100	2.8	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
110	1.3	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
120	0.2	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
130	0.4	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
140	0.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
150	0.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0

Table 4.12e Indications of Probable Length of Growing Season in Nguru (days)

	Dry Spell Threshold (days)	5mm					10mm					15mm					20mm					25mm				
		90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%
1	5	20	70	80	90	100	20	40	70	90	100	20	20	60	90	90	20	20	50	80	90	20	20	20	60	90
2	10	70	80	90	100	110	50	70	80	100	100	20	60	80	90	100	20	30	70	90	90	20	20	60	90	90
3	15	70	80	90	100	110	70	80	90	100	100	40	60	80	90	100	30	60	80	90	90	20	20	60	90	90
4	20	70	80	90	100	110	70	80	90	100	100	60	70	80	90	100	40	60	80	90	100	20	50	60	90	90
5	25	70	80	90	100	110	70	80	90	100	100	60	70	80	90	100	60	70	80	90	100	30	60	70	90	90

Table 4.11f: Maximum length of Dry Spell (Days) at Five probability levels for different DAS at Potiskum.
Data are presented under each of the four rainfall thresholds used for dry-spell computations. (Optimum Sowing Day: 181st day)

DAS	Rainfall Depth (mm)	5mm					10mm					15mm					20mm					25mm				
		90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10
10	58.2	6.0	4.0	2.0	1.0	0.0	8.0	5.0	3.0	1.0	0.0	12.0	7.0	4.0	1.0	0.0	13.0	10.0	6.0	2.0	0.0	22.0	14.0	7.0	3.0	1.0
20	67.0	5.0	3.0	2.0	1.0	0.0	7.0	5.0	2.0	1.0	0.0	12.0	8.0	4.0	2.0	1.0	14.0	9.0	4.0	2.0	1.0	21.0	14.0	7.0	3.0	1.0
30	78.1	6.0	3.0	1.0	0.0	0.0	9.0	5.0	2.0	1.0	0.0	10.0	6.0	3.0	1.0	0.0	11.0	8.0	4.0	2.0	0.0	19.0	11.0	7.0	2.0	0.0
40	92.7	3.0	2.0	1.0	0.0	0.0	6.0	3.0	1.0	0.0	0.0	9.0	4.0	2.0	0.0	0.0	16.0	8.0	2.0	1.0	0.0	20.0	11.0	6.0	1.0	0.0
50	90.4	5.0	3.0	1.0	0.0	0.0	10.0	4.0	2.0	1.0	0.0	12.0	7.0	3.0	1.0	0.0	19.0	10.0	4.0	2.0	0.0	41.0	15.0	6.0	2.0	1.0
60	80.9	6.0	3.0	2.0	0.0	0.0	11.0	5.0	3.0	1.0	0.0	15.0	9.0	4.0	1.0	0.0	27.0	14.0	6.0	2.0	0.0	41.0	27.0	8.0	3.0	1.0
70	60.2	7.0	4.0	2.0	0.0	0.0	13.0	5.0	3.0	0.0	0.0	22.0	8.0	4.0	1.0	0.0	41.0	18.0	6.0	3.0	0.0	41.0	41.0	12.0	4.0	1.0
80	49.3	16.0	9.0	2.0	1.0	0.0	28.0	16.0	6.0	2.0	0.0	41.0	41.0	13.0	3.0	1.0	41.0	41.0	22.0	4.0	2.0	41.0	41.0	41.0	16.0	3.0
90	28.1	41.0	16.0	5.0	2.0	1.0	41.0	41.0	9.0	4.0	2.0	41.0	41.0	41.0	6.0	2.0	41.0	41.0	41.0	11.0	4.0	41.0	41.0	41.0	41.0	6.0
100	21.2	41.0	41.0	29.0	4.0	2.0	41.0	41.0	41.0	5.0	2.0	41.0	41.0	41.0	41.0	4.0	41.0	41.0	41.0	41.0	5.0	41.0	41.0	41.0	41.0	41.0
110	8.2	41.0	41.0	41.0	41.0	8.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
120	1.6	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
130	0.2	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
140	0.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
150	0.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0

Table 4.12f: Indications of Probable Length of Growing Season in Potiskum (days)

		5mm					10mm					15mm					20mm					25mm				
	Dry Spell Threshold (days)	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%
1	5	30	90	110	120	120	20	90	90	120	120	20	20	90	100	120	20	20	60	100	120	20	20	20	90	100
2	10	90	100	110	120	130	70	90	110	120	120	20	90	90	110	120	20	70	90	100	120	20	20	80	90	110
3	15	90	100	110	120	130	90	90	110	120	120	80	90	100	110	120	50	80	90	110	120	20	70	90	90	110
4	20	100	110	110	120	130	90	100	110	120	120	80	90	100	110	120	70	90	90	110	120	20	70	90	100	110
5	25	100	110	110	120	130	90	100	110	120	120	90	90	100	110	120	70	90	100	110	120	60	70	90	100	110

Table 4.11g: Maximum length of Dry Spell (Days) at Five probability levels for different DAS at Sokoto.
Data are presented under each of the four rainfall thresholds used for dry-spell computations. (Optimum Sowing Day:176th day)

DAS	Rainfall Depth (mm)	5mm					10mm					15mm					20mm					25mm				
		90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10	90	75	50	25	10
10	48.4	5.0	3.3	2.0	1.0	0.0	8.0	6.0	2.0	1.0	0.0	13.9	8.0	3.5	1.0	0.0	20.0	12.0	6.0	2.0	1.0	21.0	13.3	8.0	2.8	1.0
20	59.9	6.0	4.0	3.0	1.0	0.0	10.0	6.3	3.0	1.0	0.1	10.9	8.0	4.0	2.0	1.0	14.0	10.0	5.0	2.0	1.0	18.8	13.3	8.0	3.0	1.0
30	63.7	7.8	4.0	1.0	1.0	0.0	9.0	5.0	2.5	1.0	0.0	9.0	7.3	4.0	1.0	0.1	11.7	8.0	4.0	2.0	1.0	22.5	11.3	5.5	3.0	1.0
40	74.2	4.9	3.0	2.0	1.0	0.0	6.0	4.3	3.0	1.0	0.0	8.0	5.3	3.0	1.0	0.0	15.9	8.0	3.0	1.0	0.0	24.7	14.3	4.5	1.0	0.1
50	80.1	7.0	4.0	2.0	1.0	0.0	7.0	5.3	2.5	1.0	0.0	9.9	7.0	4.0	1.0	0.1	15.9	10.3	6.0	2.8	1.0	40.3	15.0	7.0	4.0	2.0
60	73.0	5.9	3.0	1.0	0.0	0.0	6.9	5.0	2.0	1.0	0.0	9.0	6.0	3.0	1.0	0.0	23.9	11.3	4.5	2.0	0.1	41.0	19.3	6.0	2.0	0.1
70	67.3	5.9	3.0	1.0	0.8	0.0	9.8	5.3	2.0	1.0	0.0	17.5	9.0	4.0	1.0	0.0	41.0	19.3	8.0	1.8	1.0	41.0	41.0	9.5	5.0	1.0
80	60.9	10.0	5.3	3.0	1.0	0.0	39.4	9.0	4.0	1.0	0.0	41.0	15.0	4.0	1.0	0.0	41.0	41.0	9.5	2.0	0.0	41.0	41.0	14.0	3.8	0.0
90	41.2	41.0	33.5	4.0	2.0	0.0	41.0	41.0	13.0	3.0	0.0	41.0	41.0	41.0	4.0	0.0	41.0	41.0	41.0	8.0	1.2	41.0	41.0	41.0	12.8	3.0
100	19.8	41.0	41.0	41.0	5.0	2.0	41.0	41.0	41.0	7.8	4.0	41.0	41.0	41.0	35.8	5.0	41.0	41.0	41.0	41.0	5.2	41.0	41.0	41.0	41.0	7.0
110	8.1	41.0	41.0	41.0	41.0	8.0	41.0	41.0	41.0	41.0	10.1	41.0	41.0	41.0	41.0	13.1	41.0	41.0	41.0	41.0	13.1	41.0	41.0	41.0	41.0	41.0
120	4.4	41.0	41.0	41.0	41.0	14.9	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
130	1.1	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
140	0.2	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0	41.0
150	0.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0

Table 4.12g: Indications of Probable Length of Growing Season in Sokoto (days)

	Dry Spell Threshold (days)	5mm					10mm					15mm					20mm					25mm				
		90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%	90%	75%	50%	25%	10%
1	5	30	90	110	120	120	20	20	100	110	120	20	20	100	110	120	20	20	50	100	110	20	20	20	100	110
2	10	100	100	110	120	130	90	100	100	120	120	20	90	100	110	120	20	50	100	110	120	20	20	90	100	120
3	15	100	100	110	120	140	90	100	110	120	130	80	100	100	110	130	40	80	100	110	130	20	70	100	110	120
4	20	100	100	110	120	140	90	100	110	120	130	90	100	100	110	130	70	90	100	110	130	30	80	100	110	120
5	25	100	100	110	120	140	90	100	110	120	130	90	100	100	110	130	80	90	100	110	130	60	80	100	110	120

With the analysis based on the most probable ONSET dates defined according to Stern et. al (1982) for 30mm rainfall depth threshold., the results provides a good idea of the average rainfall pattern during the crop cycle at each station under study. For Gusau, assuming that a pearl millet variety of a 90-day maturity duration comes to panicle initiation stage within 20days after sowing (DAS) and to the flowering stage by 50-60 DAS, mean rainfall from sowing to panicle initiation stays around 59 mm per decade and increases to 86 mm per decade by the time of flowering.

The interpretation of the data under the 90% probability columns is that, using a given 10-day period after sowing, 90% of the dry spell will end within the number of days given. Using the earlier example given above, at 50 DAS, for the 10-mm rainfall threshold, 90% of the dry spells will end in 7 days or less, while 75% of the dry spells will end in about 4 days or less.

The frequencies of dry spells have also been computed at five rainfall threshold of 1, 5, 10, 15 and 20mm for dry spell of < 5, 5-10, 10-15, 15-20,20-25,25-30 and > 30 days. The percentage frequency of dry spells at Gusau, Kano and Katsina, Maiduguri, Nguru, Potiskum and Sokoto are shown in Table 4.13 a –g below. The data show that at the lower rainfall threshold of 1mm, the frequency of dry spells of > 5 days is by far much higher in comparison to other dry-spell ranges. As the rainfall threshold is increased from 1 to 20mm, the percentage frequency of dry spells of< 5 days decreases and the frequency for the other ranges increases.

Table 4.13a: Percentage frequency of dry spells for indicated rainfall thresholds at Gusau

DAS	Rainfall Threshold (mm)	Dry Spell for Indicated Rainfall Threshold (Days)						
		< 5	5 - 7	7 -10	10-15	15 -20	20-25	> 30
10	1	96.4	3.6	0	0	0	0	0
	10	72.7	20	3.6	1.8	1.8	0	0
	20	50.9	18.2	10.9	7.3	7.3	3.6	1.8
20	1	98.2	1.8	0	0	0	0	0
	10	80	12.7	5.5	1.8	0	0	0
	20	54.5	14.5	14.5	9.1	1.8	1.8	3.6
30	1	89.1	10.9	0	0	0	0	0
	10	76.4	18.2	3.6	1.8	0	0	0
	20	52.7	25.5	10.9	5.5	5.5	0	0
40	1	96.4	3.6	0	0	0	0	0
	10	78.2	20	1.8	0	0	0	0
	20	61.8	23.6	10.9	1.8	0	0	1.8
50	1	94.5	3.6	1.8	0	0	0	0
	10	78.2	18.2	3.6	0	0	0	0
	20	52.7	30.9	10.9	3.6	1.8	0	0
60	1	96.4	3.6	0	0	0	0	0
	10	76.4	23.6	0	0	0	0	0
	20	60	27.3	12.7	0	0	0	0
70	1	100	0	0	0	0	0	0
	10	94.5	3.6	0	1.8	0	0	0
	20	78.2	9.1	7.3	5.5	0	0	0
80	1	100	0	0	0	0	0	0
	10	81.8	18.2	0	0	0	0	0
	20	60	25.5	9.1	0	1.8	0	3.6
90	1	96.4	3.6	0	0	0	0	0
	10	78.2	10.9	7.3	1.8	0	0	1.8
	20	54.5	18.2	9.1	5.5	0	0	12.7
100	1	89.1	5.5	1.8	0	0	0	3.6
	10	65.5	10.9	7.3	1.8	0	1.8	12.7
	20	45.5	9.1	7.3	1.8	0	0	36.4
110	1	60	10.9	3.6	0	1.8	1.8	21.8
	10	32.7	10.9	1.8	3.6	1.8	0	49.1
	20	20	7.3	3.6	0	0	0	69.1
120	1	23.6	14.5	5.5	5.5	0	0	50.9
	10	10.9	10.9	1.8	1.8	0	0	74.5
	20	7.3	5.5	0	3.6	0	0	83.6
130	1	10.9	14.5	0	1.8	0	1.8	70.9
	10	5.5	5.5	0	0	0	1.8	87.3
	20	1.8	5.5	0	0	0	0	92.7
140	1	3.6	1.8	0	1.8	0	0	92.7
	10	0	0	0	1.8	0	0	98.2
	20	0	0	0	0	0	0	100

Table 4.13b: Percentage frequency of dry spells for indicated rainfall thresholds at Kano

DAS	Rainfall Threshold (mm)	Dry Spell for Indicated Rainfall Threshold (Days)						
		< 5	5 - 7	7 -10	10-15	15 -20	20-25	> 30
10	1	85.2	13.6	1.1	0.0	0.0	0.0	0.0
	10	65.9	25.0	6.8	2.3	0.0	0.0	0.0
	20	42.0	26.1	12.5	10.2	3.4	1.1	4.5
20	1	90.9	9.1	0.0	0.0	0.0	0.0	0.0
	10	71.6	20.5	5.7	1.1	0.0	1.1	0.0
	20	50.0	25.0	12.5	4.5	2.3	3.4	2.3
30	1	94.3	5.7	0.0	0.0	0.0	0.0	0.0
	10	78.4	18.2	1.1	1.1	1.1	0.0	0.0
	20	55.7	22.7	9.1	6.8	4.5	1.1	0.0
40	1	97.7	2.3	0.0	0.0	0.0	0.0	0.0
	10	76.1	15.9	5.7	1.1	1.1	0.0	0.0
	20	52.3	27.3	12.5	5.7	2.3	0.0	0.0
50	1	97.7	2.3	0.0	0.0	0.0	0.0	0.0
	10	83.0	14.8	2.3	0.0	0.0	0.0	0.0
	20	69.3	17.0	12.5	1.1	0.0	0.0	0.0
60	1	93.2	6.8	0.0	0.0	0.0	0.0	0.0
	10	81.8	17.0	0.0	0.0	1.1	0.0	0.0
	20	63.6	25.0	3.4	3.4	1.1	1.1	2.3
70	1	96.6	3.4	0.0	0.0	0.0	0.0	0.0
	10	80.7	13.6	3.4	0.0	0.0	1.1	1.1
	20	58.0	19.3	9.1	5.7	1.1	0.0	6.8
80	1	95.5	2.3	1.1	0.0	0.0	0.0	1.1
	10	76.1	14.8	4.5	1.1	0.0	0.0	3.4
	20	40.9	20.5	5.7	3.4	4.5	1.1	23.9
90	1	81.8	12.5	2.3	1.1	0.0	0.0	2.3
	10	47.7	18.2	10.2	4.5	0.0	0.0	19.3
	20	26.1	11.4	8.0	6.8	1.1	0.0	46.6
100	1	52.3	18.2	3.4	2.3	0.0	1.1	22.7
	10	31.8	17.0	1.1	0.0	1.1	0.0	48.9
	20	15.9	13.6	2.3	0.0	0.0	1.1	67.0
110	1	29.5	9.1	0.0	1.1	2.3	3.4	54.5
	10	11.4	3.4	2.3	0.0	0.0	2.3	80.7
	20	4.5	0.0	1.1	1.1	0.0	1.1	92.0
120	1	4.5	1.1	4.5	3.4	0.0	0.0	86.4
	10	2.3	0.0	1.1	2.3	0.0	0.0	94.3
	20	1.1	1.1	0.0	1.1	0.0	0.0	96.6
130	1	6.8	3.4	0.0	0.0	0.0	0.0	89.8
	10	1.1	2.3	0.0	0.0	0.0	0.0	96.6
	20	0.0	1.1	0.0	0.0	0.0	0.0	98.9
140	1	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0

Table 4.13c: Percentage frequency of dry spells for indicated rainfall thresholds at Katsina

DAS	Rainfall Threshold (mm)	Dry Spell for Indicated Rainfall Threshold (Days)						
		< 5	5 - 7	7 -10	10-15	15 -20	20-25	> 30
10	1	95.7	4.3	0	0	0	0	0
	10	71	23.2	4.3	1.4	0	0	0
	20	47.8	23.2	14.5	4.3	4.3	0	5.8
20	1	88.4	11.6	0	0	0	0	0
	10	71	15.9	13	0	0	0	0
	20	46.4	27.5	11.6	2.9	5.8	2.9	2.9
30	1	97.1	2.9	0	0	0	0	0
	10	82.6	14.5	1.4	1.4	0	0	0
	20	56.5	20.3	11.6	4.3	4.3	1.4	1.4
40	1	94.2	5.8	0	0	0	0	0
	10	76.8	14.5	7.2	0	1.4	0	0
	20	62.3	18.8	7.2	4.3	2.9	2.9	1.4
50	1	97.1	1.4	1.4	0	0	0	0
	10	73.9	15.9	10.1	0	0	0	0
	20	47.8	18.8	10.1	10.1	0	0	13
60	1	89.9	7.2	1.4	1.4	0	0	0
	10	69.6	21.7	4.3	2.9	0	0	1.4
	20	36.2	21.7	8.7	8.7	1.4	1.4	21.7
70	1	78.3	11.6	2.9	1.4	1.4	0	4.3
	10	50.7	15.9	11.6	5.8	1.4	0	14.5
	20	34.8	13	7.2	2.9	1.4	1.4	39.1
80	1	68.1	11.6	5.8	1.4	0	0	13
	10	34.8	14.5	2.9	2.9	1.4	0	43.5
	20	18.8	7.2	2.9	1.4	1.4	0	68.1
90	1	27.5	7.2	2.9	7.2	0	0	55.1
	10	8.7	4.3	4.3	1.4	1.4	0	79.7
	20	7.2	1.4	1.4	0	1.4	0	88.4
100	1	11.6	8.7	2.9	0	1.4	0	75.4
	10	4.3	2.9	2.9	0	0	0	89.9
	20	1.4	1.4	1.4	0	0	0	95.7
110	1	2.9	0	2.9	0	0	1.4	92.8
	10	2.9	0	0	0	0	0	97.1
	20	1.4	0	0	0	0	0	98.6
120	1	2.9	0	0	1.4	0	0	95.7
	10	0	0	0	0	0	0	100
	20	0	0	0	0	0	0	100
130	1	0	1.4	0	0	0	0	98.6
	10	0	0	0	0	0	0	100
	20	0	0	0	0	0	0	100
140	1	0	0	0	0	0	0	100
	10	0	0	0	0	0	0	100
	20	0	0	0	0	0	0	100

Table 4.13d: Percentage frequency of dry spells for indicated rainfall thresholds at Maiduguri

DAS	Rainfall Threshold (mm)	Dry Spell for Indicated Rainfall Threshold (Days)						
		< 5	5 - 7	7 -10	10-15	15 -20	20-25	> 30
10	1	92.7	7.3	0.0	0.0	0.0	0.0	0.0
	10	65.5	25.5	5.5	1.8	0.0	0.0	1.8
	20	45.5	29.1	14.5	7.3	0.0	0.0	3.6
20	1	96.4	3.6	0.0	0.0	0.0	0.0	0.0
	10	80.0	12.7	5.5	0.0	1.8	0.0	0.0
	20	58.2	25.5	1.8	3.6	3.6	3.6	3.6
30	1	90.9	7.3	1.8	0.0	0.0	0.0	0.0
	10	74.5	10.9	12.7	0.0	1.8	0.0	0.0
	20	50.9	23.6	12.7	7.3	3.6	0.0	1.8
40	1	94.5	5.5	0.0	0.0	0.0	0.0	0.0
	10	76.4	16.4	7.3	0.0	0.0	0.0	0.0
	20	45.5	30.9	10.9	1.8	3.6	0.0	7.3
50	1	92.7	3.6	3.6	0.0	0.0	0.0	0.0
	10	63.6	25.5	7.3	0.0	1.8	0.0	1.8
	20	40.0	21.8	14.5	3.6	3.6	0.0	16.4
60	1	89.1	5.5	3.6	0.0	0.0	1.8	0.0
	10	69.1	16.4	5.5	0.0	1.8	1.8	5.5
	20	41.8	18.2	5.5	1.8	1.8	1.8	29.1
70	1	81.8	16.4	0.0	1.8	0.0	0.0	0.0
	10	45.5	14.5	9.1	5.5	3.6	3.6	18.2
	20	21.8	3.6	7.3	5.5	7.3	1.8	52.7
80	1	52.7	20.0	3.6	3.6	3.6	1.8	14.5
	10	25.5	10.9	7.3	3.6	3.6	0.0	49.1
	20	14.5	7.3	7.3	1.8	0.0	0.0	69.1
90	1	27.3	12.7	7.3	3.6	0.0	1.8	47.3
	10	16.4	7.3	3.6	0.0	0.0	0.0	72.7
	20	9.1	3.6	0.0	0.0	0.0	0.0	87.3
100	1	16.4	5.5	1.8	1.8	1.8	0.0	72.7
	10	7.3	0.0	0.0	0.0	0.0	0.0	92.7
	20	3.6	0.0	0.0	0.0	0.0	0.0	96.4
110	1	7.3	1.8	1.8	0.0	0.0	0.0	89.1
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0
120	1	1.8	0.0	0.0	0.0	0.0	0.0	98.2
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0
130	1	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0
140	1	0.0	0.0	0.0	0.0	1.8	0.0	98.2
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0

Table 4.13e: Percentage frequency of dry spells for indicated rainfall thresholds at Nguru

DAS	Rainfall Threshold (mm)	Dry Spell for Indicated Rainfall Threshold (Days)						
		< 5	5 - 7	7 -10	10-15	15 -20	20-25	> 30
10	1	89.1	9.1	1.8	0.0	0.0	0.0	0.0
	10	65.5	18.2	10.9	3.6	1.8	0.0	0.0
	20	36.4	18.2	18.2	14.5	5.5	0.0	7.3
20	1	87.3	10.9	1.8	0.0	0.0	0.0	0.0
	10	67.3	23.6	7.3	1.8	0.0	0.0	0.0
	20	41.8	29.1	18.2	3.6	3.6	1.8	1.8
30	1	92.7	7.3	0.0	0.0	0.0	0.0	0.0
	10	70.9	20.0	7.3	1.8	0.0	0.0	0.0
	20	50.9	21.8	14.5	7.3	0.0	1.8	3.6
40	1	89.1	3.6	5.5	1.8	0.0	0.0	0.0
	10	67.3	23.6	1.8	5.5	1.8	0.0	0.0
	20	43.6	25.5	7.3	10.9	5.5	0.0	7.3
50	1	85.5	9.1	5.5	0.0	0.0	0.0	0.0
	10	58.2	23.6	10.9	0.0	0.0	1.8	5.5
	20	23.6	25.5	10.9	5.5	7.3	7.3	20.0
60	1	72.7	20.0	0.0	1.8	0.0	0.0	5.5
	10	40.0	23.6	9.1	5.5	1.8	0.0	20.0
	20	16.4	21.8	12.7	7.3	0.0	0.0	41.8
70	1	60.0	12.7	3.6	1.8	3.6	0.0	18.2
	10	30.9	10.9	9.1	3.6	1.8	0.0	43.6
	20	20.0	10.9	1.8	0.0	0.0	0.0	67.3
80	1	38.2	14.5	3.6	3.6	1.8	0.0	38.2
	10	12.7	10.9	3.6	1.8	0.0	0.0	70.9
	20	3.6	3.6	1.8	0.0	0.0	1.8	89.1
90	1	20.0	10.9	1.8	1.8	0.0	1.8	63.6
	10	5.5	1.8	0.0	0.0	0.0	0.0	92.7
	20	1.8	0.0	0.0	1.8	0.0	0.0	96.4
100	1	3.6	1.8	0.0	1.8	0.0	1.8	90.9
	10	1.8	0.0	0.0	0.0	0.0	1.8	96.4
	20	0.0	1.8	0.0	0.0	0.0	1.8	96.4
110	1	0.0	1.8	0.0	1.8	0.0	0.0	96.4
	10	0.0	0.0	0.0	1.8	0.0	0.0	98.2
	20	0.0	0.0	0.0	1.8	0.0	0.0	98.2
120	1	0.0	1.8	0.0	0.0	0.0	0.0	98.2
	10	0.0	1.8	0.0	0.0	0.0	0.0	98.2
	20	0.0	1.8	0.0	0.0	0.0	0.0	98.2
130	1	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0
140	1	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0

Table 4.13f: Percentage frequency of dry spells for indicated rainfall thresholds at Potiskum

DAS	Rainfall Threshold (mm)	Dry Spell for Indicated Rainfall Threshold (Days)						
		< 5	5 - 7	7 -10	10-15	15 -20	20-25	> 30
10	1	95.0	5.0	0.0	0.0	0.0	0.0	0.0
	10	70.0	25.0	3.3	1.7	0.0	0.0	0.0
	20	46.7	26.7	18.3	5.0	0.0	1.7	1.7
20	1	93.3	6.7	0.0	0.0	0.0	0.0	0.0
	10	73.3	21.7	5.0	0.0	0.0	0.0	0.0
	20	51.7	23.3	15.0	5.0	3.3	0.0	1.7
30	1	93.3	5.0	1.7	0.0	0.0	0.0	0.0
	10	70.0	21.7	6.7	1.7	0.0	0.0	0.0
	20	56.7	23.3	11.7	5.0	3.3	0.0	0.0
40	1	98.3	1.7	0.0	0.0	0.0	0.0	0.0
	10	86.7	10.0	3.3	0.0	0.0	0.0	0.0
	20	66.7	15.0	6.7	3.3	3.3	1.7	3.3
50	1	93.3	5.0	1.7	0.0	0.0	0.0	0.0
	10	76.7	11.7	5.0	6.7	0.0	0.0	0.0
	20	56.7	15.0	8.3	10.0	1.7	1.7	6.7
60	1	90.0	8.3	1.7	0.0	0.0	0.0	0.0
	10	71.7	15.0	10.0	1.7	0.0	1.7	0.0
	20	41.7	21.7	11.7	11.7	1.7	3.3	8.3
70	1	80.0	13.3	5.0	1.7	0.0	0.0	0.0
	10	65.0	21.7	5.0	1.7	0.0	0.0	6.7
	20	35.0	28.3	8.3	3.3	3.3	1.7	20.0
80	1	80.0	13.3	6.7	0.0	0.0	0.0	0.0
	10	48.3	13.3	8.3	10.0	6.7	3.3	10.0
	20	25.0	5.0	5.0	11.7	3.3	0.0	50.0
90	1	63.3	15.0	1.7	1.7	1.7	1.7	15.0
	10	28.3	21.7	8.3	6.7	1.7	0.0	33.3
	20	10.0	13.3	3.3	1.7	0.0	0.0	71.7
100	1	40.0	15.0	6.7	3.3	1.7	1.7	31.7
	10	23.3	8.3	3.3	0.0	0.0	0.0	65.0
	20	8.3	5.0	0.0	0.0	0.0	0.0	86.7
110	1	16.7	3.3	1.7	1.7	0.0	0.0	76.7
	10	3.3	0.0	0.0	0.0	0.0	0.0	96.7
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0
120	1	1.7	1.7	0.0	0.0	0.0	0.0	96.7
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0
130	1	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0
140	1	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0

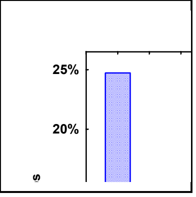


Table 4.13g: Percentage frequency of dry spells for indicated rainfall thresholds at Sokoto

DAS	Rainfall Threshold (mm)	Dry Spell for Indicated Rainfall Threshold (Days)						
		< 5	5 - 7	7 -10	10-15	15 -20	20-25	> 30
10	1	88.2	9.8	2.0	0.0	0.0	0.0	0.0
	10	60.8	33.3	3.9	2.0	0.0	0.0	0.0
	20	43.1	23.5	19.6	0.0	11.8	2.0	0.0
20	1	82.4	15.7	2.0	0.0	0.0	0.0	0.0
	10	62.7	23.5	11.8	2.0	0.0	0.0	0.0
	20	47.1	25.5	17.6	7.8	2.0	0.0	0.0
30	1	90.2	9.8	0.0	0.0	0.0	0.0	0.0
	10	70.6	21.6	5.9	2.0	0.0	0.0	0.0
	20	52.9	35.3	7.8	2.0	0.0	0.0	2.0
40	1	94.1	3.9	0.0	2.0	0.0	0.0	0.0
	10	74.5	19.6	2.0	3.9	0.0	0.0	0.0
	20	62.7	15.7	5.9	7.8	3.9	2.0	2.0
50	1	92.2	7.8	0.0	0.0	0.0	0.0	0.0
	10	68.6	25.5	5.9	0.0	0.0	0.0	0.0
	20	39.2	33.3	11.8	5.9	2.0	0.0	7.8
60	1	88.2	9.8	2.0	0.0	0.0	0.0	0.0
	10	72.5	25.5	2.0	0.0	0.0	0.0	0.0
	20	49.0	21.6	9.8	2.0	7.8	0.0	9.8
70	1	88.2	7.8	2.0	0.0	2.0	0.0	0.0
	10	70.6	17.6	7.8	0.0	2.0	0.0	2.0
	20	35.3	25.5	11.8	2.0	5.9	2.0	17.6
80	1	78.4	19.6	2.0	0.0	0.0	0.0	0.0
	10	58.8	17.6	5.9	2.0	2.0	2.0	11.8
	20	35.3	13.7	11.8	3.9	2.0	0.0	33.3
90	1	60.8	15.7	2.0	2.0	2.0	2.0	15.7
	10	35.3	7.8	7.8	5.9	0.0	0.0	43.1
	20	21.6	3.9	7.8	2.0	0.0	2.0	62.7
100	1	23.5	19.6	3.9	2.0	2.0	0.0	49.0
	10	11.8	15.7	0.0	0.0	3.9	0.0	68.6
	20	7.8	5.9	0.0	2.0	2.0	0.0	82.4
110	1	15.7	9.8	5.9	0.0	2.0	0.0	66.7
	10	0.0	7.8	3.9	0.0	0.0	0.0	88.2
	20	0.0	7.8	2.0	0.0	0.0	0.0	90.2
120	1	7.8	2.0	2.0	0.0	0.0	0.0	88.2
	10	3.9	0.0	0.0	0.0	0.0	0.0	96.1
	20	2.0	0.0	0.0	0.0	0.0	0.0	98.0
130	1	2.0	0.0	0.0	0.0	0.0	0.0	98.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0
140	1	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	20	0.0	0.0	0.0	0.0	0.0	0.0	100.0

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This study has applied drought inference technique and drought indexing method to characterize and quantify the drought conditions and occurrences in the Sudano-Sahelian region of Nigeria.

The conceptual viewpoint of the research work is that a clear understanding and meaningful interpretations of the characteristics of precipitation, being a major drought-causing element, can be adequately used to describe or infer the occurrence or conditions leading to drought in an area. The study therefore defined and utilized some precipitation effectiveness variables to infer and describe the drought conditions in the SSRN.

Multiple measures of rainfall deficiency, variability and precipitation effectiveness used for indicating or inferring the occurrence of drought over a place have been employed in the development of standardized rainfall index (SRI), normalized rain-days index (NRI) and a conjunctive precipitation-effectiveness index (CPEI). The first two indices have been used to show the potentials of some PEVs in drought indexing.

Using a historical daily rainfall records from 1916-2003 for seven (7) stations in the SSRN, CPEI for these stations were estimated and compared with (4) other emerging drought indices, namely the Standard Precipitation Index (SPI), Rainfall Anomaly Index (RAI), Bhalmey-Mooley Drought Index (BMDI) and Palmer Drought

Severity Index (PDSI). By comparing the results obtained from the derived CPEI various combinations of the 10 PEVs, and that for the SPI, RAI and BMDI, the study showed that a maximum combination of six (6) PEVs gave an average correlation (r) value above 0.8. This furthered showed the potentials of each of the ten (10) identified PEVs in indexing drought.

Through a further analysis, the ultimate number of PEVs that can be effectively combined to get the optimum CPEI values for each station was evaluated. The results shows that an ultimate three (3) PEVs were most effective in indexing the drought in Gusau and Kano, five (5) PEVs in Sokoto and Maiduguri and the rest stations had four (4) PEVs for obtaining its optimum CPEI.

A review of the droughts in the Sudano-Sahel regions of Nigeria using a multiple of drought indices (i.e the Optimum CPEI, RAI, SPI, PDSI and BMDI) and drought inference techniques has been carried out with the following as its outcomes:

(i) The high temporal variability in the amount and distribution of rainfall and the low level reliability of the amount of seasonal rainfall observed within the region has to a large extent contributed to the persistent and exemplified post 1967 drought occurrences in the region.

(ii) The persistently high drought index values observed up till the 1990s within the region also indicate that the drought condition since the late sixties might not have ended.

(iii) The performance of the newly developed conjunctive precipitation index ranks fairly when compared with the results from SPI, RAI, BMDI and PDSI. It is however worth nothing that the use of the newly developed index has the advantage of being simple in its data usage and in mode of analysis. It can be comfortably adopted and possibly developed further as a national drought index since there is yet a national accepted drought index in the country.

(iv) Drought in the SSRN can be indexed with not just the conventional mean season rainfall depth (MAR) but also with other precipitation effectiveness variables such as length of the rainy season (LRS), total no of wet days (TWD), total no of dry days within a year (TDY), maximum dry spell length within a wet season (MDL), and onset of rainy season (ORS),

The study also characterized the occurrence and distribution of dry spells within the wet seasons in the Sudano-Sahelian region of Nigeria. The study confirmed the results of Sawa (2002) that dry spells have over 80% probability of occurring in the entire Sudano-Sahelian region. This worrisome situation prompted the strong yearning to seek to understand the true nature of these spells, and to try to find a scientific base of coping with the spells. So the premise of the dry spell analysis was to provide information that can guide farmers in the selection of drought resistant crops, adopting effective cropping patterns, and the development of suitable crop breeds etc. Using the results from EADS, the study has sufficiently provided adequate information to enable farmers and other stakeholders involved in planning and management of drought to come to terms with the menace.

As rightly observed by Otun et. al. (2004), Nigeria has the managerial and technological skills to reduce the hydrological scourges of drought to its barest minimum. This study has logically provided basic tools for characterizing (quantifying) and coping with the conditions and occurrences of drought in the most-drought prone zone in Nigeria.

Without any doubt, the era of the fire brigade approach to drought occurrences might soon be over. Drought occurrences can now be identified and quantified using minimum available rainfall data. Insurance companies can also rely on the findings of this study to estimate the risk involved within a dry spell period and possibly use the drought severity measure (CPEI) derived in this study to estimate compensations for drought victims.

The study provided useful information for deciding the appropriate measures for alleviating the effects of dry spells often noticed during the growing periods in the Sudano-Sahelian region. It will help to effectively plan for rain-fed agriculture within the Sudano-Sahel region of Nigeria.

This study as expected has been able to achieve the following in line with its objectives:

(i) Fill information gap on the state of drought conditions in the Sudano Sahelian areas of Nigeria within the past half century (1950-2000).

(ii) Conceptualize the use of some PEVs, other than rainfall amounts, to develop an operational drought index for quantifying the drought conditions of a place.

(iii) Provide empirical basis or tool for effective management of the drought in the Sudano Sahelian areas of Nigeria.

(iv) Acts as a drought management support tool for proposed Regional/National Drought Monitoring policy.

5.2 RECOMMENDATIONS

It is believed that the application of the methodology presented in this study will provide a basis for characterizing the drought conditions in the Sudano-Sahelian region of Nigeria. However, since drought is a continuous climate phenomenon, further research is necessary in order to keep abreast of and increase the understanding of drought phenomena. The following recommendations are made to enhance the quality of future drought research works in the Sudano-Sahelian region of Nigeria and the entire country.

(i) Only the deterministic features of the precipitation effectiveness variables have been identified and used in developing the CPEI. The random aspect of the precipitation variables can be further studied and integrated into CPEI for future probabilistic predictions.

(ii) Similarly, the deterministic trend in the PEVs can also be extended to future time periods by any known classical mathematical methods such as time series techniques i.e. moving average (MA), Auto-regressive integrated moving average (ARIMA) etc. for drought predictions.

(iii) The primary data often needed for drought assessment and management are, to a great extent, difficult to gather. At present, the ground-based hydro meteorological data provided by NIMET and the River Basin Authorities are inadequate and poorly kept. The number of stations managed by these agencies is decreasing. There is therefore the need for these statutory organizations involved in handling and managing hydro-meteorological data to strengthen their capacities to collect, process and effectively store these data for effective drought studies.

(iv) As drought awareness is generally low in the entire country, there is the challenge to build an awareness of drought as a normal part of the climate of the Sudano-Sahelian region of Nigeria. At present, there is no single private or public organization in the country that is charged with the responsibility of relaying drought information to the general public. This has led to the present poor level of preparedness and lack of mitigation plans. The newly created department of drought and desertification in the Federal Ministry of Environment (DDFME) should rise up to this challenge. They should develop and implement an effective extension services for relaying drought information to relevant stakeholders within SSRN. Regular jingles on all electronic media should be produced to communicate regular drought information within SSRN. Similarly, a regular bulletin posted in the news media and possibly on a defined web site of DDFME will also help to achieve the purpose of improving the drought awareness in the country.

(v) The proposed bulletin and extension services should among other things, provide an improved understanding of the different types of drought, using some of the multiple drought indices on a multiple-time scale as presented as guide in this study.

The present institutional arrangement and support for effective drought monitoring and mitigation is poorly structured and arranged. There is the need to build linkages within and outside the country, refocus some of the government agencies like North-east arid zone research center, in Maiduguri (NEAZRC), National Water Resources Institute, Kaduna and NIMET with related mandates on droughts.

The North-east arid zone research center, in Maiduguri, should be further helped to improve its capacity –building and possibly challenged to take up the responsibility of effectively carrying out the national drought mitigation plan. This challenge can only be made operational and effective by high level of commitment and involvement from both government and the private sector in terms of high investments in drought quantification and dissemination.

There is therefore the need to expedite action on the proposed National drought policy for the country. It is strongly believed that the policy can make use of the drought quantification techniques presented in this study.

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Appendix: I Statistical Parameters

The objective of statistics is to extract the essential information from a set of data, reducing a large set of numbers. The summary of some statistical parameters are given as follows:

(i) Midpoint Parameters

(a) Arithmetic mean $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ (a.1)

(b) Median 50th-percentile value of data

(a.2)

(ii) Variability Parameters

(a) Variance $s^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2$ (a.3)

(b) Standard Deviation $s = \left[\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2\right]^{\frac{1}{2}}$ (a.4)

(c) Coefficient of variation (CV) $CV = \frac{s}{\bar{x}}$

(a.5)

(iii) Symmetry Parameters

(a) Coefficient of Skewness (C_S) $C_s = \frac{n\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^3}{(n-1)(n-2)s^3}$

(a.6)

Appendix: II Computer Programs and Algorithms

```
$debug
      PROGRAM BMDI
*     Computes Bhalme and Mooley Drought Severity Index (BMDI)
*     Using the output of daily rainfall data from BSR1.FOR
*     for different rainfall period (i.e.month and year interval)
*     A Season refers to Rainfall Totals of 1,5,7,10,15,30 & 365 Days
*     Since BMD programs uses the output of BSR1.FOR
*     Please always RUN BBSR1.for before running DDA programs.
      parameter (nq=500,ir=20,iu=100,ix=200,iy=400)
      real  q(366),qq(6500),qt(90,75),ti(75),tm(75)
      integer icl(7),idl(7),ifl(7),cod,mdy(12),lyr(90)
      character name2*16,cn6*7,name1(24)*6, name3*4, name5*27
      data name1/'katsin','kachia','maidug','samaru','mokwa1',
     +'ibadan','enugu1','calaba','kafanc','kad-so','kad-ap',
     +'minna1','gusau1','jos-ap','bida11','siroro','lokoja',
     +'lagos1','sokoto','vom-vt','kanoap','potisk','nguru1','ogstom'/
      data icl/1,12,24,36,52,73,365/
      data idl/365,30,15,10,7,5,1/
*     data icl/365,73,52,36,24,12,1/
*     data idl/1,5,7,10,15,30,365/
      data ifl/13,21,1,3,23,22,19/
      data mdy/31,28,31,30,31,30,31,31,30,31,30,31/
1     thv = 0.01
      do 600, ia=1,7
      thv = 0.01
      cod = ifl (ia)
      call ccls
      print*, 'Processing Data For :- ',name1(cod)
      ls=12
      lt=13
      lu=14
      lv=15
      lw=16
      lx=17
      ly=18
      lz=19
      name2 = 'C:\jay\for\rata\'
      name3 = '.bs3'
      cn6= name1(cod)
      name5 = name2 // name1(cod) // name3
      open(ls,file=name5,err=618, status= 'old')
```

```
      name2 = 'c:\jay\for\fand\'
      name3 = '.bm1'
      name5 = name2 // name1(cod) // '.bm1'
      open(lt,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.bm2'
      open(lu,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.bm3'
      open(lv,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.bm4'
      open(lw,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.bm5'
      open(lx,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.bm6'
      open(ly,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.bm7'
      open(lz,file=name5,status= 'unknown')
      icd=0
15     nst = iu
      do 550 ib = 1, 6
      kz = ls + ib
      write(kz,*)' BMDI Drought Computation'
      write(kz,*)' Analysis of Rainfall Total of', idl(ib), 'day(s)'
      read(ls,20,err=618) idll,itp,iyyt,iyy,iydf
20     format(2x,5(i5,2x))
      write(kz,20) idll,itp,iyyt,iyy,iydf
      ipp = itp
      itt = 0
      do 80 iq=1,iyy
      iip = iq
      read(ls, 25) iq1,mzz,ipp
      lyr(iq)=mzz
      read(ls, 30) (q(mth), mth=1,ipp)
25     format(2x,3(i5,2x))
30     format(1x,12(2x,f7.2))
      itp = ipp
      lpi = 0
      iyr = mzz
      ayr =float(iyr)
      iyct = 365
      idl(1) = 365
      if ((iyr/4) .eq. (int(ayr/4. + 0.75))) then
      lpi = 1
      iyct = 366
      idl(1) = 366
```

```
      end if
      if (lpi .eq. 1) mdy(2) = 29
      if (lpi .ne. 1) mdy(2) = 28
      n = ipp
*      Obtaining the basic statistics for BHMI analysis
       im1 = 0
       im2 = 0
       im3 = idl(ib)-1
       iwk = 0
       do 50, im=1,icl(ib)
       iwk = iwk + 1
       im1 = im2 + 1
       im2 = im1 + im3
       ttt= 0.0
       if (im .eq. icl(ib))im2 = iyct
       do 45, ij=im1,im2
       ttt = ttt + q(ij)
45      continue
       qt(iip,iwk)=ttt
       itt = itt + 1
       qq(itt) = ttt
50      continue
80      continue
       call stasd (itt,qq,avg,std)
       cc = -0.57
       dd = 38.84
       do 90, ij=1, iyy
       ttt = 0.0
       do 85, il=1, iwk
       tt1 = 100*(qt(ij,il) - avg)/std
       ttt  = ttt + tt1
*       tm(il)=  ttt
       tm(il)=  tt1
85      continue
       ti(1) = tm(1)/dd
       if (iwk .gt. 1) then
       do 88, il=2, iwk-1
       ti(il)=  (tm(il)/dd) + ((1+cc)*ti(il-1))
88      continue
       end if
       write(kz,330)ij,lyr(ij),(ti(il), il=1,iwk)
90      continue

320    format(i4,2x,i4,2x,5(i4,1x))
```

```
325   format(i4,2x,i4,2x,11(i4,1x),2x,f7.2)
330   format(i4,2x,i4,2x,75(f7.3,1x))
340   format(i4,2x,i4,2x,65(i4,2x))
345   format(i4,2x,i4,2x,65(i4,2x))
348   format(i4,2x,i4,2x,65(i4,2x))

525   icp=0
      rewind (ls)
      close(kz)
550   continue
600   continue
      close(ls)
      goto 625
618   write(*,*)'Some File Error Discovered'
      goto 624
619   write(*,*)'No of Data is less than 1'
      goto 624
620   write(*,*)'Some Reading Error Discovered'
624   Pause
      close (ls)
      go to 1
625   dummy = 1
      stop
      end

       subroutine ccls
       do 1 jhz= 1, 23
1       write(*,*)
       print*, 'Processing'
       return
       end

       subroutine stasd (nav,ssx,avg,std)
c      Subroutine for computing the mean and standard deviation only
       integer i,nav
       real sum,arn,brn,avg,var,std,dif,sup2
       real ssx(nav)
       sum = 0.0
       avg = 0.0
       std = 0.0
       var = 0.0
       if (nav .le. 1) goto 210
       do 100 i = 1, nav
       sum = sum + ssx(i)
```

```
 100   continue
       arn = float(nav)
       avg = sum/arn
       brn = arn -1.
       std = 0.0
       sup2 = 0.0
       do 200 i=1,nav
       dif = ssx(i) - avg
       sup2 = sup2 + (dif**2)
200    continue
       if (brn .ne. 0) var = sup2 / brn
       if (var .gt. 0) std = sqrt(var)
210    dum = 0.
       return
       end
```

☐

```
$debug
      PROGRAM RAI
*     Computes Rainfall Anomally Drought Index (RADI)
*     Using the output of daily rainfall data from BSR1.FOR
*     for different rainfall period (i.e.month and year interval)
*     A Season refers to Rainfall Totals of 1,5,7,10,15,30 & 365 Days
*     Since BMD programs uses the output of BSR1.FOR
*     Please always RUN BBSR1.for before running DDA programs.
      parameter (nq=500,ir=20,iu=100,ix=200,iy=400)
      real  q(366),qq(6500),qt(90,75),t1(75),t2(75)
      integer icl(7),idl(7),ifl(7),cod,mdy(12),lyr(90)
      character name2*16,cn6*7,name1(24)*6, name3*4, name5*27
      data name1/'katsin','kachia','maidug','samaru','mokwa1',
     +'ibadan','enugu1','calaba','kafanc','kad-so','kad-ap',
     +'minna1','gusau1','jos-ap','bida11','siroro','lokoja',
     +'lagos1','sokoto','vom-vt','kanoap','potisk','nguru1','ogstom'/
      data icl/1,12,24,36,52,73,365/
      data idl/365,30,15,10,7,5,1/
*     data icl/365,73,52,36,24,12,1/
*     data idl/1,5,7,10,15,30,365/
      data ifl/13,21,1,3,23,22,19/
      data mdy/31,28,31,30,31,30,31,31,30,31,30,31/
1     thv = 0.01
      do 600, ia=1,7
      thv = 0.01
      cod = ifl (ia)
      call ccls
      print*, 'Processing Data For :- ',name1(cod)
      ls=12
      lt=13
      lu=14
      lv=15
      lw=16
      lx=17
      ly=18
      lz=19
      name2 = 'D:\jay\for\rata\'
      name3 = '.bs3'
      cn6= name1(cod)
      name5 = name2 // name1(cod) // name3
      open(ls,file=name5,err=618, status= 'old')
      name2 = 'D:\jay\for\fand\'
      name3 = '.ra1'
      name5 = name2 // name1(cod) // '.ra1'
```

```
      open(lt,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.ra2'
      open(lu,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.ra3'
      open(lv,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.ra4'
      open(lw,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.ra5'
      open(lx,file=name5,status= 'unknown')
      name5 = name2 // name1(cod) // '.ra6'
      open(ly,file=name5,status= 'unknown')
      icd=0
15     nst = iu
      do 550 ib = 1, 6
      kz = ls + ib
      write(kz,*)' BMDI Drought Computation'
      write(kz,*)' Analysis of Rainfall Total of', idl(ib), 'day(s)'
      read(ls,20,err=618) idll,itp,iyyt,iyy,iydf
20     format(2x,5(i5,2x))
      write(kz,20) idll,itp,iyyt,iyy,iydf
      ipp = itp
      itt = 0
      do 60 iq=1,iyy
      iip = iq
      read(ls, 25) iq1,mzz,ipp
      lyr(iq)=mzz
      read(ls, 30) (q(mth), mth=1,ipp)
25     format(2x,3(i5,2x))
30     format(1x,12(2x,f7.2))
      itp = ipp
      lpi = 0
      iyr = mzz
      ayr =float(iyr)
      iyct = 365
      idl(1) = 365
      if ((iyr/4) .eq. (int(ayr/4. + 0.75))) then
      lpi = 1
      iyct = 366
      idl(1) = 366
      end if
      if (lpi .eq. 1) mdy(2) = 29
      if (lpi .ne. 1) mdy(2) = 28
      n = ipp
*      Obtaining the basic statistics for BHMI analysis
```

```
      im1 = 0
      im2 = 0
      im3 = idl(ib)-1
      iwk = 0
      do 50, im=1,icl(ib)
      iwk = iwk + 1
      im1 = im2 + 1
      im2 = im1 + im3
      ttt= 0.0
      if (im .eq. icl(ib))im2 = iyct
      do 45, ij=im1,im2
      ttt = ttt + q(ij)
45     continue
      qt(iip,iwk)=ttt
      itt = itt + 1
      qq(itt) = ttt
50     continue
60     continue
      call stasd (itt,qq,avg,std)
      ii = itt
      goto 64
      ii = 0
      do 62, ij=1,itt
      if (qq(ij) .gt. 0.) then
      ii = ii+ 1
      qq(ii)=qq(ij)
      end if
62     continue
64     dum = 0
      call sortx(ii,qq)
      ttt = 0.0
      do 65, ij=1, 10
      ttt = ttt + qq(ij)
65     continue
      sum1 = ttt/10.0
      ttt = 0.0
      ikk = ii
      do 70, ij=1, 10
      ttt = ttt + qq(ikk)
      ikk = ikk -1
70     continue
      sum2 = ttt/10.0

      do 90, ij=1, iyy
```

```
      do 88, il=1, iwk
      t1(il)= 3.0*(qt(ij,il)-avg) / (sum2-avg)
      t2(il)= -3.0*(qt(ij,il)-avg) / (sum1-avg)
88     continue
      write(kz,330)ij,lyr(ij),(t2(il), il=1,iwk)
      write(kz,330)ij,lyr(ij),(t1(il), il=1,iwk)
90     continue

320   format(i4,2x,i4,2x,5(i4,1x))
325   format(i4,2x,i4,2x,11(i4,1x),2x,f7.2)
330   format(i4,2x,i4,2x,75(f7.3,1x))
340   format(i4,2x,i4,2x,65(i4,2x))
345   format(i4,2x,i4,2x,65(i4,2x))
348   format(i4,2x,i4,2x,65(i4,2x))

525   icp=0
     rewind (ls)
     close(kz)
550   continue
600   continue
     close(ls)
     goto 625
618   write(*,*)'Some File Error Discovered'
     goto 624
619   write(*,*)'No of Data is less than 1'
     goto 624
620   write(*,*)'Some Reading Error Discovered'
624   Pause
     close (ls)
     go to 1
625   dummy = 1
     stop
     end

      subroutine ccls
      do 1 jhz= 1, 23
1      write(*,*)
      print*, 'Processing'
      return
      end

      subroutine stasd (nav,ssx,avg,std)
c      Subroutine for computing the mean and standard deviation only
      integer i,nav
```

```
      real sum,arn,brn,avg,var,std,dif,sup2
      real ssx(nav)
      sum = 0.0
      avg = 0.0
      std = 0.0
      var = 0.0
      if (nav .le. 1) goto 210
      do 100 i = 1, nav
      sum = sum + ssx(i)
 100  continue
      arn = float(nav)
      avg = sum/arn
      brn = arn -1.
      std = 0.0
      sup2 = 0.0
      do 200 i=1,nav
      dif = ssx(i) - avg
      sup2 = sup2 + (dif**2)
200   continue
      if (brn .ne. 0) var = sup2 / brn
      if (var .gt. 0) std = sqrt(var)
210   dum = 0.
      return
      end

      subroutine sortx(n,x)
*      Sorts in an ascending way (a.....z.)
      dimension x(n)
      do 801 i=1,n-1
      imin=I
      xmin=x(imin)
      do 800 j=i+1,n
      if (x(j).lt.xmin) then
      xmin=x(j)
      imin=j
      endif
800   continue
      x(imin)=x(i)
      x(i)=xmin
801   continue
      return
      end
```
□

Program Listing for PDSI

```
#include <stdlib.h>
#include <math.h>
#include <cstring>
#include <stdio.h>
#include <ctype.h>
#include <direct.h>

//============================================================================
====
//pdsi.cpp              University of Nebraska - Lincoln            May 21
2002
//============================================================================
====
//
//Self-calibrating, multiple time scale version.  Based upon
weekly_pdsi.cpp
//which is a self-calibrating, weekly PDSI program developed by Nathan
Wells.
//This version is capable of calculating a self-calibrating weekly PDSI,
//a self-calibrating monthly PDSI, and the original monthly PDSI.
//
//Calculates the Palmer Drought Severity Index for a given station.
//
//Most recently translated to C++ from FORTRAN by Rob Reed and Nate Wells,
//University of Nebraska - Lincoln, advised by Dr. Steve Goddard - July
2001.
//
//Methodology based on Research Paper No. 45; Meteorological Drought; by
//Wayne C. Palmer for the U.S. Weather Bureau, February 1965.
//
//Based mostly on the source code of pdsi.f, a FORTRAN program that
calculates
//monthly PDSI values.  The source code came from NCDC, originally written
by
//Tom Karl, and revised by Roger Winchell, Alan McNab, and Richard Heim.
//
//Slight modifications in the algorithm were made based on the source of
//palmcode.f, a FORTRAN program that calculates weekly PDSI values,
received
//from Tom Heddinghaus at NCEP, who is also the original author of that
//particular code.
//
//Additional modifications were made to adapt the algorithm to a weekly
time
//scale based on recalculations of several constants as described in
Palmer's
//paper.
//
//Additional modifications were made to attempt to make this program
//completely independent of emperically derived formulas.  This will allow
the
//program to perform accurately in any enviroment.  Most changes came in
the
//addition of the CalcConstants() function.  The program was also modified
to
//automatically adjust the output values to the scale of -4 to 4 in order
to
//make comparisions between stations more accurate.  --August 2001
//
```

```
//The incorporation of a self-calibrating monthly and the oringal monthly
PDSI
// -- May 2002
//-----------------------------------------------------------------------
----
//
// 4 input files:
//
//weekly_T and weekly_P:
//  Weekly temperature and precipitation files; each line starts with the
year
//  and is followed by 52 data entries.  It is important to note that only
52
//  weeks are on each line, even though 52 weeks is only 364 days.  The
years
//    starting each line must increase sequentially.  This means that after
a
//    certain period of time, the first week of the line will no longer
//    correspond to the year that begins the line.
//
//T_normal:
//    The average weekly temperature for each week of the year.  One line,
52
//    data entries.
//
//parameter:
//    contains two numbers specific to each station: the underlying soil
water
//    capacity - Su (in inches), and the negative of the tangent of the
latitude
//    of the station - TLA.
//
//-----------------------------------------------------------------------
----
//
//------ Output Files:
//
//There are two formats of output, table and column, which are selected by
//command line options.  The table output files end with .tbl and the
column
//output files end with .clm.  The table files list a whole year's worth of
//resultsing values on each line while the column files list the year and
week
//followed by the resulting value on each line.
//
//PDSI.tbl and/or PDSI.clm:
//    The Palmer Drought Severity Index values
//
//PHDI.tbl and/or PHDI.clm:
//    The Palmer Hydrological Drought Index values.
//
//WPLM.tbl and/or WPLM.clm:
//    The "Weighted" Palmer Index.  An average of either X1 and X3, or X1
and X2
//    weighted by the probability of the current spell ending.  For more
//    information, see how the WPLM is calculated in the pdsi::write()
function.
//
//ZIND.tbl and/or ZIND.clm:
//    The Z Index, or the moisture anomaly
//
```

```
//------ Other possible output files, depending on certain flags:
//
//WB.tbl
//      The water ballance coefficients (Alpha, Beta, Gamma, & Delta) for
each
//      week
//
//bigTable.tbl
//      Z, % Prob(end), X1, X2, and X3 for every week.
//
//potentials
//      P, PE, PR, PRO, PL, and P - PE for every week.
//
//============================================================================
====
//                            end of introductory comments
//============================================================================
====

// This defines the type number as a double.  This is used to easily change
// the PDSI's variable types.
typedef double number;
typedef int flag;
#define min(a,b) ((a) < (b) ? (a) : (b));

//----------------------------------------------------------------------------
----
//**********   START OF STRUCTURE DEFINITION FOR STRUCT:  node
*********
//----------------------------------------------------------------------------
----
// The node struct is used specifically in the linked list class and is not
// relevant to the actual PDSI.
//----------------------------------------------------------------------------
----
struct node {            // A structure for a node
public:
  number key;            // Where the data is stored
  struct node *next;     // Where the next node is
  struct node *previous; // Where the previous node is
};
//----------------------------------------------------------------------------
----
//**********   CLOSE OF STRUCTURE DEFINITION FOR STRUCT:  node
*********
//----------------------------------------------------------------------------
----

//----------------------------------------------------------------------------
----
//**********   START OF CLASS DEFINITIONS FOR THE CLASS:  llist
*********
//----------------------------------------------------------------------------
----
// The llist class is a dynamic storage class.  It is used in the PDSI to
// eliminate problems with filling static arrays.
//----------------------------------------------------------------------------
----
class llist {            // A linked list class
private:
  node *head;            // A pointer to the head of the linked-list
```

```
public:
  llist();               // The constructor
  ~llist();              // The destructor
  // The insert function takes an argument of type number and places it on
  // the head of the linked list.
  void insert(number x);
  // The remove functions remove from either the head (head_remove) or the
  // tail (tail_remove) of the linked list.
  number head_remove();  // remove the first node and returns its key
  number tail_remove();  // remove the last node and returns its key
  // These are other useful functions used in dealing with linked lists
  int is_empty(); // Returns 1 if the llist is empty 0 otherwise
  friend void copy(llist &L1,const llist &L2); // Copies L2 to L1
  number sumlist();  // Sums the items in list
  void sumlist(number &prev_sum, int sign);//sums items in list into
prev_sum
  number maxlist();
  number minlist();
  // The set_node function sets the key of the node pointed to by set.  It
  // checks the linked list to make sure set is in the node to prevent
  // runtime errors from occuring.
  node *set_node(node *set=NULL, number x=0);
};
//---------------------------------------------------------------------------
----
//**********   CLOSE OF CLASS DEFINITIONS FOR THE CLASS:  llist
*********

//---------------------------------------------------------------------------
----

//---------------------------------------------------------------------------
----
//**********   START OF CLASS DEFINITIONS FOR THE CLASS:  pdsi
*********
//---------------------------------------------------------------------------
----
// The pdsi class contains and deals with all necessary pdsi variables and
// calculations.  The paramater values and starting/ending years are set
upon
// creation, but the actual pdsi values are not calculated until Calcpdsi
is
// called.
//---------------------------------------------------------------------------
----
class pdsi {
public:
  // The pdsi constructor takes in an array of arguments (argv[]) and an
  // integer number of arguments (argc).  These arguments should contain
  // the various flags desired to custimize the performance of the pdsi
  pdsi();
  ~pdsi();

  // The set_flags function takes in an array of flags/arguments (flags[])
  // and an integer number of flags/arguments (num_flags).  It then sets
  // the various pdsi options accordingly.  If incorrect or invalid flags
  // are input, the set_flags function terminates the program.
  void set_flags(int num_flags, char *flags[]);

  // These functions are work horse of the pdsi class.  They calls all
  // functions necessary to calculate all aspects of the pdsi from the
```

```
  // temperature and precipitation files.
  // WeeklyPDSI() calculates a self-calibrating weekly PDSI
  // MonthlyPDSI() calculates the original PDSI
  // SCMonthlyPDSI() calculates a self-calibrating monthly PDSI
  void WeeklyPDSI();
  void WeeklyPDSI(int length);
  void MonthlyPDSI();
  void SCMonthlyPDSI();

  // These write function creates output files based on the flags sent
  void Write();
  void Write(char* directory);

private:
  //these variables keep track of what type of PDSI is being calculated.
  bool Weekly;
  bool Monthly;
  bool SCMonthly;

  // The variables for storing the starting year of calculation and the
  // total number of years to calculate
  int startyear;
  int endyear;
  int totalyears;

  int period_length;        //number of weeks in the time scale
  int num_of_periods;       //number of periods of period_length in a year.

  // The variables used as flags to the pdsi class
  flag bug;
  flag output_mode;
  flag verbose;
  flag s_year;
  flag e_year;
  flag extra;

  // Various constants used in calculations
  number TLA; // The negative tangent of latitude is used in calculating PE
  number AWC; // The soils water capacity
  number I;   // Thornthwaites heat index
  number A;   // Thornthwaites exponent
  number tolerance; // The tolerance for various comparisons

  // The arrays used to read in the normal temp data, a years worth of
  // actual temp data, and a years worth of precipitation data
  number TNorm[52];
  number T[52];
  number P[52];

  // These variables are used in calculation to store the current weeks
  // potential and actual water balance variables as well as the soil
  // moisture levels
  number ET;            // Actual evapotranspiration
  number R;             // Actual soil recharge
  number L;             // Actual loss
  number RO;            // Actual runoff
  number PE;            // Potential evapotranspiration
  number PR;            // Potential soil recharge
  number PL;            // Potential Loss
  number PRO;           // Potential runoff
  number Su;            // Underlying soil moisture
```

```
number Ss;            // Surface soil moisture

// These arrays are used to store the weekly sums of the 8 key
// water balance variables and the precipitation
number ETSum[52];
number RSum[52];
number LSum[52];
number ROSum[52];
number PESum[52];
number PRSum[52];
number PLSum[52];
number PROSum[52];
number PSum[52];

// These arrays store the weekly water balance coefficeints
number Alpha[52];
number Beta[52];
number Gamma[52];
number Delta[52];

// The CAFEC percipitation
number Phat;

// These variables are used in calculating the z index
number d;     // Departure from normal for a period
number D[52]; // Sum of the absolute value of all d values by period
number k[52]; // Palmer's k' constant by period
number K;     // The final K value for a period
number Z;     // The z index for a week (Z=K*d)

// These variables are used in calculating the PDSI from the Z
// index.  They determine how much of an effect the z value has on
// the PDSI based on the climate of the region.
// They are calculated using CalcConstants()
number drym;
number dryb;
number wetm;
number wetb;


// The X variables are used in book keeping for the computation of
// the pdsi
number X1;    // Wet index for a week
number X2;    // Dry index for a week
number X3;    // Index for an established wet or dry spell
number X;     // Current weeks pdsi value before backtracking

// These variables are used in calculating the probability of a wet
// or dry spell ending
number Prob;  // Prob=V/Q*100
number V;     // Sumation of effective wetness/dryness
number Q;     // Z needed for an end plus last weeks V

// These variables are statistical variables computed and output in
// verbose mode
number DSSqr[52];
number DEPSum[52];
number DKSum;
number SD;
number SD2;
```

```
  // linked lists to store X values for backtracking when computing X
  llist Xlist;          //final list of PDSI values
  llist altX1;          //list of X1 values
  llist altX2;          //list of X2 values

  // These linked lists store the Z, Prob, and 3 X values for
  // outputing the Z index, Hydro Palmer, and Weighted Palmer
  llist XL1;
  llist XL2;
  llist XL3;
  llist ProbL;
  llist ZIND;
  llist PeriodList;
  llist YearList;

  // Class Functions

  // This function initializes some variables before the pdsi is calculated
  void initialize();

  // These functions read in the input files
  int GetTemp(FILE * In, number *A); // Gets the Weekly Temp
  int GetPrecip(FILE *In, number *A); // Gets the Weekly Precip
  int GetMonInput(FILE *In, number *A); //gets monthly precip or temp
  void GetParam(FILE * Param);          // Gets Paramaters Su and TLA

  // These functions calculate the Potentials needed
  // Calculates Potential Evapotranspiration from Thornthwaite
  void CalcWkPE(int period, int year);
  void CalcMonPE(int month, int year);
  void CalcPR();  // Calculates Potential Recharge
  void CalcPL();  // Calculates Potential Loss
  void CalcPRO(); // Calculates Potential Runoff

  // This function calculates the actual values from the potentials
  void CalcActual(int per);   // Calculates Actual values

  // These functions do calculations on a yearly basis
  void SumAll(); // Creates sums of Actual and Potential values
  void Calcd();        // Finds the values for d, phat and then finds D
  void CalcK();        // Calculates k
  void CalcOrigK();  // Calculates oringal K, and then calc original PDSI
  void CalcZ();          // Calculates Z and calls CalcX()
  void CalcX(int week_number, int year);       // Calculates Z and all X

  void Calibrate();      // Calibrates the PDSI

  // This function backtracks through the X values
  // and replaces them with the appropriate value of X1 or X2
  // when necessary
  void Backtrack(number X1, number X2);
  void ChooseX(number& newX, number& newX1, number& newX2, number& newX3,
int bug);

  // These functions calculate Thornthwaite coefficients
  number CalcWkThornI();      // Calculates Thornthwaite Heat Index
  number CalcMonThornI();
  number CalcThornA(number I);      // Calculates Thornthwaite Exponent

  // This function calculates the coefficients for the Water Balance
Equation
```

```
  void CalcWBCoef();

  // This function calculates the constants used in calculating the PDSI
value
  // from the Z index.  These constants affect how much influence the Z
index
  // has on the PDSI value.
  void CalcConstants(number &slope, number &intercept, int sign);

  // This function will move any extra files to the appropriate directory
  void MoveFiles(char* dir);

  // This function
  void FinalWrite(char* prefix);

  // These are simple functions to determine if the characters of a string
  // form an integer or a floating point number.
  inline int is_int(char *string,int length);
  inline int is_flt(char *string,int length);
};
//---------------------------------------------------------------------------
----
//**********   CLOSE OF CLASS DEFINITIONS FOR THE CLASS:  pdsi
*********
//---------------------------------------------------------------------------
----

//---------------------------------------------------------------------------
----
//**********                    MAIN PROGRAM
*********
//---------------------------------------------------------------------------
----
// The main program takes in command line arguments and passes them to the
// constructor of a pdsi variable tester.  It then calls Calcpdsi to
calculate
// the pdsi values.  Finally it calls write to output these values to file.
//---------------------------------------------------------------------------
----
void main(int argc,char *argv[]) {
  pdsi PDSI;                 // Creates a pdsi named PDSI
  PDSI.set_flags(argc,argv); // Sets the flags of PDSI
  PDSI.WeeklyPDSI();         // Calculates the weekly pdsi values for PDSI
  PDSI.Write("weekly");
  PDSI.WeeklyPDSI(2);
  PDSI.Write("weekly/2");
  PDSI.WeeklyPDSI(4);
  PDSI.Write("weekly/4");
  PDSI.WeeklyPDSI(13);
  PDSI.Write("weekly/13");
  PDSI.MonthlyPDSI();
  PDSI.Write("monthly");
  PDSI.SCMonthlyPDSI();
  PDSI.Write("sc_monthly");
}
//---------------------------------------------------------------------------
----
//**********                    PROGRAMS END
*********
//---------------------------------------------------------------------------
----
```

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c        Standardized Precipitation Index. (SPI)
c
c
c       Usage: spi length [length ...] [<infile] [>outfile]
c
c       Where:
c          run_length - integer > 0; running sum length for SPI
c          infile - optional input file; if omitted, spi reads
c                   from standard input.
c          outfile - optional output file; if omitted, spi writes
c                   to standard output.
c
c
c       Notes on the ForTran version:
c
c       1) Lengths are hard coded to be 3, 6, 12, and 24 months.  This is
c       necessasry since ForTran has no standard way of passing command
c       line arguments.
c
c       2) System dependent code is bracketed with 'c*****'s
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

      program spiprg
      parameter (nlen=4, maxyrs=120, amssng=-99.0,
     1          ibegyr=1880, iendyr=ibegyr+maxyrs)
      character header*80
      dimension len(nlen)
      real prec(maxyrs*12), beta(12), gamm(12), pzero(12),
     1     spi(maxyrs*12,nlen)
      data len / 3, 6, 12, 24/
c*****
c
c  Open files.  These are defaults under most unix f77's
c
c       open(unit=0, file='stderr')
c       open(unit=5, file='stdin')
c       open(unit=6, file='stdout')
c
c*****
      call rdprec(header, prec, 5)
      write(6, 1000) header

c  Compute SPI's
      do 10 i = 1, nlen
         call spigam (len(i), prec, beta, gamm, pzero, spi(1,i))
 10   continue


c  Skip leading missings
      ifirst = 0
 20   continue
      ifirst = ifirst + 1
      if (spi(ifirst,1) .eq. amssng) goto 20

c  Skip trailing missngs
      last = maxyrs*12 + 1
 30   continue
      last = last - 1
```

```
      if (spi(last,1) .eq. amssng) goto 30

c  Ouput SPI's
      do 40 i = ifirst, last
c         if (spi(i,1) .eq. amssng) goto 50
         iy = (i-1)/12 + ibegyr
         im = mod (i-1,12)+1
         write(6, 1001) iy, im, (spi(i,j), j=1,nlen)
 40   continue
 50   continue
      stop
 1000 format(a80)
 1001 format(i4,i3,4f7.2)
      end
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c  Read monthly prec data.
c
c   Format:
c        Header
c        Data- yyyy mm prec
c
c        Where:
c            yyyy - year; values > ENDYR and < BEGYR will be skipped.
c            mm   - month [1-12]
c            prec - precipitation (in 0.01's)
c
c        Special codes:
c            -9900 = Missing
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      subroutine rdprec(header, prec, inprec)
      parameter (nlen=4, maxyrs=120, amssng=-99.0,
     1          ibegyr=1880, iendyr=ibegyr+maxyrs)
      character header*80
      real prec(maxyrs*12)
c   Set prec array to MISSING
      do 10 i = 1, maxyrs*12
         prec(i) = amssng
 10   continue
c   Read header
      read(inprec, 1000, err=40) header
c   Read data
 20   continue
         read(inprec, *, end=30, err=40) iy, im, iprc
         iy = iy - ibegyr
         if(iy .lt. 0) goto 20
         if(iy .gt. maxyrs) goto 30
         prec(iy*12+im) = iprc/100.0
c         write(6, *) iy, im, prec(iy*12+im)
      goto 20
 30   continue
      return
 40   continue
      write(0, *) 'Error reading input file.'
      stop
 1000 format(a80)
      end
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c     These functions compute the Standardized Precipitation Index
```

```
c     using an incomplete gamma distribution function to estimate
c     probabilities.
c
c     Useful references are:
c
c     _Numerical Recipes in C_ by Flannery, Teukolsky and Vetterling
c     Cambridge University Press, ISBN 0-521-35465-x
c
c     _Handbook of Mathematical Functions_ by Abramowitz and Stegun
c     Dover, Standard Book Number 486-61272-4
c
c     Notes for ForTran users:
c     - There is a companion _Numerical Recipes in Fortran.  The
c     following code was translated from the c code.
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c   Calculate indices assuming incomplete gamma distribution.
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      subroutine spigam (nrun, pp, beta, gamm, pzero, index)
      parameter (nlen=4, maxyrs=120, amssng=-99.0,
     1     ibegyr=1880, iendyr=ibegyr+maxyrs)
      real pp(maxyrs*12), index(maxyrs*12),tmparr(maxyrs+1),
     1     beta(12), gamm(12), pzero(12)
c
c   The first nrun-1 index values will be missing.
c
      do 10 j = 1, nrun-1
         index(j) = amssng
 10   continue
c
c     Sum nrun precip. values;
c     store them in the appropriate index location.
c
c     If any value is missing; set the sum to missing.
c
      do 30 j = nrun, maxyrs*12
         index(j) = 0.0
         do 20 i = 0, nrun-1
            if(pp(j - i) .ne. amssng) then
               index(j) = index(j) + pp(j - i)
            else
               index(j) = amssng
               goto 30
            endif
 20      continue
 30   continue
c
c   For nrun<12, the monthly distributions will be substantially
c   different.  So we need to compute gamma parameters for
c   each month starting with the (nrun-1)th.
c
      do 50 i = 0,11
         n = 0
         do 40 j = nrun+i, maxyrs*12, 12
            if(index(j) .ne. amssng) then
               n = n + 1
               tmparr(n) = index(j)
```

```
            endif
 40      continue
         im = mod (nrun+i-1, 12) + 1
c
c     Here's where we do the fitting.
c
         call gamfit (tmparr, n, alpha, beta(im), gamm(im), pzero(im))
 50   continue
c
c     Replace precip. sums stored in index with SPI's
c
      do 60 j = nrun, maxyrs*12
         im = mod (j-1,12) + 1
         if(index(j) .ne. amssng) then
c
c     Get the probability
c
          index(j) = gamcdf(beta(im), gamm(im), pzero(im), index(j))
c
c     Convert prob. to z value.
c
          index(j) = anvnrm(index(j))
         endif
 60   continue
      return
      end

ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cc
c
c   input prob; return z.
c
c   See Abromowitz and Stegun _Handbook of Mathematical Functions_, p. 933
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cc
      function anvnrm (prob)
      data c0, c1, c2 /2.515517, 0.802853, 0.010328/
      data d1, d2, d3 /1.432788, 0.189269, 0.001308/

      if (prob .gt. 0.5) then
         sign = 1.0
         prob = 1.0 - prob
      else
         sign = -1.0
      endif

      if (prob .lt. 0.0) then
         write(0, *) 'Error in anvnrm(). Prob. not in [0,1.0]'
         anvnrm = 0.0
         return
      endif

      if (prob .eq. 0.0) then
         anvnrm = 1.0e37 * sign
         return
      endif

      t = sqrt(alog (1.0 / (prob * prob)))
      anvnrm = (sign * (t - ((((c2 * t) + c1) * t) + c0) /
     1     ((((((d3 * t) + d2) * t) + d1) * t) + 1.0)))
```

```
      return
      end
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c  Estimate incomplete gamma parameters.
c
c  Input:
c     datarr - data array
c     n - size of datarr
c
c Output:
c     alpha, beta, gamma - gamma paarameters
c     pzero - probability of zero.
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      subroutine gamfit (datarr, n, alpha, beta, gamm, pzero)
      real datarr(*)
      if (n .le. 0) then
         write(0, *) 'Error in gamfit - empty data array'
         stop
      endif

      sum = 0.0
      sumlog = 0.0
      pzero = 0.0
      nact = 0

c     compute sums
      do 10 i = 1, n
         if (datarr(i) .gt. 0.0) then
            sum = sum + datarr(i)
            sumlog = sumlog + alog (datarr(i))
            nact = nact + 1
         else
            pzero = pzero + 1
         endif
 10   continue
      pzero = pzero / n
      if(nact .ne. 0.0) av = sum / nact

c     Bogus data array but do something reasonable
      if(nact .eq. 1) then
         alpha = 0.0
         gamm = 1.0
         beta = av
         return
      endif

c     They were all zeroes.
      if(pzero .eq. 1.0) then
         alpha = 0.0
         gamm = 1.0
         beta = av
         return
      endif

c     Use MLE
      alpha = alog (av) - sumlog / nact
      gamm = (1.0 + sqrt (1.0 + 4.0 * alpha / 3.0)) / (4.0 * alpha)
      beta = av / gamm
```

```
      return
      end


cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c  Compute probability of a<=x using incomplete gamma parameters.
c
c  Input:
c      beta, gamma - gamma parameters
c      pzero - probability of zero.
c      x - value.
c
c  Return:
c      Probability  a<=x.
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc


      function  gamcdf (beta, gamm, pzero, x)
      if(x .le. 0.0) then
         gamcdf = pzero
      else
         gamcdf = pzero + (1.0 - pzero) * gammap (gamm, x / beta)
      endif
      return
      end

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c  Compute inverse gamma function i.e. return x given p where CDF(x) = p.
c
c  Input:
c      beta, gamma - gamma parameters
c      pzero - probability of zero.
c      prob - probability.
c
c  Return:
c      x as above.
c
c  Method:
c      We use a simple binary search to first bracket out initial
c      guess and then to refine our guesses until two guesses are within
c      tolerance (eps).  Is there a better way to do this?
c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc


      function gaminv (beta, gamm, pzero, prob)
      data  eps /1.0e-7/

c     Check if prob < prob of zero
      if (prob .le. pzero) then
         gaminv = 0.0
         return
      endif

c     Otherwise adjust prob
      prob = (prob - pzero) / (1.0 - pzero)

c     Make initial guess. Keep doubling estimate until prob is
```

```
c     bracketed.
      thigh = 2.0*eps
 10   continue
      phigh = gamcdf (beta, gamm, pzero, thigh)
      if(phigh .ge. prob) goto 20
      thigh = thigh*2.0
      goto 10
 20   continue
      tlow = thigh / 2.0

c     Iterate to find root.
      niter = 0
 30   continue
      if((thigh - tlow) .le. eps) goto 40
      niter = niter + 1
      t = (tlow + thigh) / 2.0
      p = gamcdf (beta, gamm, pzero, t)

      if (p .lt. prob) then
         tlow = t
      else
         thigh = t
      endif
      goto 30
 40   continue
      gaminv = (tlow + thigh) / 2.0
      return
      end
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c  Functions for the incomplete gamma functions P and Q
c
c                  1     /x  -t a-1
c   P (a, x) = -------- |   e  t    dt,  a > 0
c              Gamma(x)/ 0
c
c   Q (a, x) = 1 - P (a, x)
c
c Reference: Press, Flannery, Teukolsky, and Vetterling,
c       _Numerical Recipes_, pp. 160-163
c
c Thanks to kenny@cs.uiuc.edu
c
ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c Evaluate P(a,x) by its series representation.
c
      function gamser (a, x)
c     Maximum number of iterations, and bound on error.
      parameter (maxitr=100, eps=3.0e-7)
      data iwarn /0/
      gln = gammln (a)
      if (x .eq. 0.0) then
         gamser = 0.0
         return
      endif
      ap = a
      sum = 1.0 / a
      del = sum
      do 10 n = 1, maxitr
         ap = ap + 1.0
```

```
         del = del * (x / ap)
         sum = sum + del
         if (abs (del) .lt. eps * abs (sum)) goto 20
 10   continue
      iwarn = iwarn + 1
      if (iwarn .lt. 20) then
         write (0, *) 'gamser(',a,x,'): not converging.'
         write (0, *) 'Approximate value of ',sum,'  + /-',del,' used.'
      endif
 20   continue
      gamser =  sum * exp (-x + a * alog (x) - gln)
      return
      end
c
c     Evaluate P(a,x) in its continued fraction representation.
      function gammcf (a, x)
      parameter (maxitr=100, eps=3.0e-7)
      data nwarn / 0 /, g / 0.0 /
      gln = gammln (a)
      gold = 0.0
      a0 = 1.0
      a1 = x
      b0 = 0.0
      b1 = 1.0
      fac = 1.0
      do 10 n = 1, maxitr
         an = n
         ana = an - a
         a0 = (a1 + a0 * ana) * fac
         b0 = (b1 + b0 * ana) * fac
         anf = an * fac
         a1 = x * a0 + anf * a1
         b1 = x * b0 + anf * b1
         if (a1 .ne. 0.0) then
            fac = 1.0 / a1
            g = b1 * fac
            if (abs((g - gold) / g) .lt. eps) goto 20
            gold = g
         endif
 10   continue
      nwarn = nwarn + 1
      if (nwarn .lt. 20) then
         write (0, *) 'gammcf(',a,x,'): not converging.'
         write (0, *) 'Inaccurate value of ', g, ' +/- ',
     1                abs(g - gold), ' used.'
      endif
 20   continue
      gammcf =  g * exp (-x + a * alog (x) - gln)
      return
      end
c     Evaluate the incomplete gamma function P(a,x), choosing the most
c     appropriate representation.
      function gammap (a, x)
      if (x .lt. a + 1.0) then
         gammap = gamser (a, x)
      else
         gammap = 1.0 - gammcf (a, x)
      endif
      return
      end
c     Evaluate the incomplete gamma function Q(a,x), choosing the most
```

```
c   appropriate representation.
      function gammaq (a, x)
      if (x .lt. a + 1.0) then
         gammaq = 1.0 - gamser (a, x)
      else
         gammaq = gammcf (a, x)
      endif
      return
      end
c     For those who don't have a ln(gamma) function.
      function gammln(xx)
      dimension cof(6)
      data cof /76.18009173, -86.50532033, 24.01409822, -1.231739516,
     1     0.120858003e-2, -0.536382e-5/
      x = xx - 1.0
      tmp = x + 5.5
      tmp = tmp - (x+0.5) * alog (tmp)
      ser = 1.0
      do 10 j = 1, 5
         x = x + 1.0
         ser = ser + cof(j) / x
 10   continue
      gammln = -tmp + alog (2.50662827465 * ser)
      return
      end
```