# EFFECT OF CLIMATE VARIABILITY ON PEARL MILLET (*PENNISETUM* glaucum) PRODUCTIVITY AND THE APPLICABILITY OF COMBINED DROUGHT INDEX FOR MONITORING DROUGHT IN NAMIBIA

BY

SARAFIA NDAPANDULA ASHIPALA

DEPARTMENT OF METEOLROLOGY

COLLEGE OF BIOLOGICAL AND PHYSICAL SCIENCE

UNIVERSITY OF NAIROBI

P.O. BOX 30197

NAIROBI, KENYA

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN AGRICULTURAL METEOROLOGY

JUNE 2013

# DECLARATION

I declare that this dissertation is my original work and it has not been presented for a degree in any other University.


Signature…………………………………………. Date………………………….

Sarafia Ndapandula Ashipala

Reg. No I56/71911/2011

This dissertation has been submitted for examination with our approval as the University of Nairobi supervisors


Signature…………………………………………. Date………………………….

Dr. Gilbert Ouma

Department of Meteorology

University of Nairobi


Signature…………………………………………. Date………………………….

Dr. Vincent M. Kathumo

 Department of Land Resource Management and Agricultural Technology

University of Nairobi


Signature…………………………………………. Date………………………….

 Mr. Cromwel Lukorito

Department of Meteorology

University of Nairobi

# DEDICATION

I am very pleased to devote this research work to God the Almighty who made it possible by keeping me in good health during the entire period of my study as well as inspiring all the people who contributed with all means for me to achieve the objective of this study, to my lovely children Peter Cherubin, Joseph Junior Ashipala and Rejoice as well as my entire family.

# ACKNOWLEDGEMENT

# ABSTRACT

Climate variability has been one of the most important determinants of crop productivity in the world. Pearl millet farmers in the northern parts of Namibia always encounter poor pearl millet yields due to intra-seasonal characteristics and climate variability. Specifically, the dry spells that always occur across pearl millet growth stages and recurrent droughts adversely affect crop productivity. The overall objective of this study was to assess the effect of climate variability on pearl millet *(Pennisetum glaucum)* productivity and explore the usefulness of the Combined Drought Index for agricultural drought detection in Namibia**.** The specific objectives of the study were to determine the effect of the length of growing period, the length of dry spells that occur during pearl millet growth stages and rainfall anomaly on pearl millet yields. The study also evaluated the possibility of using the Combined Drought Index (CDI) as an indicator for early agricultural drought detection in Namibia.

The study used correlation analysis to determine the degree of association between the study parameters. Instat Statistical Analysis Software was used to perform climatic analysis, whereby soil water balance was used to determine season length and the occurrence of dry spells (dry days) during the pearl millet three major growth stages. Monthly rainfall and temperature for fourteen years (1998- 2012) as well as the Normalized Difference Vegetation Index (NDVI) data were used in the analysis. Estimated daily rainfall for Ondangwa, Outapi and Ongenga were also used in the analysis of this study.

The study revealed that the effect of length of growing period, dry spells and rainfall anomalies on pearl millet yields varies from region to region and also with pearl millet growth stages. There was also significant influence of lengths of dry spells that occur at growth stage one (GS1) in Oshana and Ohangwena, growth stage two (GS2) in Omusati and growth stage three (GS3) in Ohangwena on pearl millet yields.  The Combined Drought Index (CDI) was able to capture the historical drought events experienced in Namibia. The study, therefore recommends the use of the Combined Drought Index as a third agricultural drought monitoring and detection indicator in Namibia.

# TABLE OF CONTENTS

# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AEZ | Agro-ecological Zones |
| CDI | Combined Drought Index |
| DART | Directorate of Agricultural Research and Training |
| DI | Deciles Index |
| ETO | Ekuma Plains and Etosha Pan |
| FAO | Food and Agriculture Organization |
| FAO/UNEP | Food and Agriculture Organization of the United Nations/ United Nations Environment Programme |
| FAO-SWALIM | Food and Agriculture Organization Somalia Water and Land Information Management system |
| FEWSNET | Famine Early Warning System Network |
| GDP | Gross Domestic Product |
| GPZ | Growing period zones |
| GSI | Growth stage one |
| GS2 | Growth stage two |
| GS3 | Growth stage three |
| ICRISAT | International Crop Research Institute for the Semi Arid Tropics |
| IRI | International Research Institute for Climate and Society |
| ITCZ | Inter Tropical Convergence Zone |
| KAL3-2 | Kalahari Sands Plateau |
| KAL3-3 | Kalahari Sands Plateau |
| KAL3-4 | Kalahari Sands Plateau with stabilized sand drift and few pans |
| KAL4 | Kalahari Sands Plateau |
| KAL9-3 | Kalahari Sands Plateau |

| | |
|---|---|
| KALK-4 | Kalkveld |
| KAO1 | Kaokoland mountains and hills |
| KAO4 | Kaokoland, high plateau |
| L.A.C. | Legal Assisstance Centre |
| MAWF | Ministry of Agriculture, Water and Forestry |
| MAWRD | Ministry of Agriculture, Water and Rural Development |
| N.P.C. | National Planning Commision |
| NDVI | Normalized Difference Vegetation Index |
| PDMI | Palmer Drought Severity Index |
| PDI | Precipitation Drought Index |
| R | Undifferentiated rocky hills and Inselberg Mountains |
| RFE | Rainfall estimation |
| SPI | Standardized Precipitation Index |
| SPOT-VGT | Satellite Pour l'Observation de la Terre -Vegetation |
| TDI | Temperature Drought Index |
| UNDP | United Nation Development Programme |
| VGTExtrac | Vegetation extract software program |

## LIST OF FIGURES AND THEIR CAPTIONS

# LIST OF TABLES AND THEIR CAPTIONS

# CHAPTER ONE

## 1.0 INTRODUCTION

### 1.1 Background information

In Namibia, about 60% of the population are subsistence farmers and fully depend on crop production where pearl millet is one of the major crops while at the same time agriculture at large contributes 5-6% towards the GDP of the country (Matanyaire, 1996). However, the country is frequently impacted by climatic extremes such as drought and floods predominantly in the plains. According to United Nations Development Program (UNDP, 2011), for the last forty years the country has experienced recurrent droughts. Namibia is in the category of countries that have experienced six to nine droughts from 1970 – 2004.

Similarly, flooding has inflicted devastating effects on agriculture and people of Namibia who are located in flood prone areas (UNDP, 2011). These extreme climate events lead to reduction of crop yields especially when it occurs at sensitive growth stages such as flowering and grain filling. Although pearl millet can adapt well to growing areas that are characterized by drought, low soil fertility, high temperatures and performs well in soils with high salinity or low pH, climatic variations that result into prolonged drought, water logging, and frost among others can reduce its productivity. Consequently, the nation becomes negatively affected economically by these extreme events (FAO/UNEP, 1999).

Although majority of Namibian subsistence farmers are mainly dependent on rain fed agriculture, the country's precipitation is quite erratic. Climate variability has been the most important determinant of pearl millet production in Asia as well as in most parts of Africa (Hedibi *et al*., 2012). Specifically, inter-annual variability in rainfall and temperature have been the key climatic characteristics that affect the success of agriculture worldwide (Andrew. *et al*., 2009). However, it is difficult to characterize specific intra-seasonal rainfall events such as onset, cessation and length of growing season because of patchy and erratic rainfall in the country.

In Namibia, climate variability and change are already proved by the increase of maximum temperatures which have been getting hotter over the past 40 years, as observed in the increasing frequency of days exceeding 35 $^{\circ}$C (du Pisani, 2004). In the meantime, the frequencies of days with temperatures below 5$^{\circ}$C have been getting less while the frequency and intensity of extreme events are likely to increase (Newton *et al*., 2009). It is predicted that by 2065 Namibia will

undergo an increase in temperatures of 1-3.5$^{o}$C in summer and 1-4$^{o}$C in winter as well as stronger variability in rainfall (Newton *et al*., 2009).

Pearl millet (*Pennisetum glaucum*), locally known as "Mahangu", is grown mainly in the northern parts of Namibia. It is a robust, fast growing, summer cereal with large stems, leaves and panicles  (Jensen, 1996). The crop is well adapted to growing areas characterized by drought, low soil fertility and high temperature and performs well in soils with high salinity and low pH (Ipinge, 2001). The crop is used as the basic staple food for human consumption in various ways including both leavened and unleavened breads, in porridges and can also be boiled or steamed. Apart from grain, its stems are used as animal feed, building materials and also as a source of fuel.

## 1.2 Problem statement

In Namibia, there is lack of documented information concerning intra-seasonal climatic characteristics and the influence of climate variability on crop production, and in particular pearl millet. Although several drought detection/monitoring indices, including the Deciles Index (DI) and Standardized Precipitation Index (SPI) were initially identified to be suitable and recommended for use in Namibia  (du Pisani, 2004), these indicators   fail to adequately capture the extreme climatic events of the country. This is due to the fact that they only consider precipitation, do not consider the persistence of the stress periods and require continuous data observation without gaps (Balint and Mutua, 2011). Other drought indices such as the Combined Drought Index (CDI) have worked satisfactorily elsewhere, especially for Kenya and Somalia for drought detection. As a result, this study undertook to assess the effects of climate variability on pearl millet productivity and explored the possibility of using CDI for agriculture drought detection in Namibia.

## 1.3 Objectives of the study

### 1.3.1 Overall research objective

The overall objective of this study was to assess the effect of climate variability on pearl millet *(Pennisetum glaucum)* productivity and the applicability of the Combined Drought Index (CDI) for monitoring drought in Namibia.

**1.3.2 Specific objectives**

The specific objectives of the study were:

   i.    To determine the effect of length of growing period on pearl millet yields.

  ii.    To determine the effect of the length of dry spells on pearl millet yields.

 iii.    To determine the effect of rainfall anomaly on pearl millet yields.

 iv.    To evaluate the applicability of the Combined Drought Index (CDI) as an indicator for early agricultural drought detection.

**1.4 Hypothesis**

In order to address the overall objective of this study, the following four hypotheses were tested:

   i.    The length of growing period is the key determinant of pearl millet yields in Namibia.

  ii.    Prolonged dry spells are the major cause of the declining productivity of pearl millet in northern Namibia.

 iii.    Rainfall anomalies are the main causes of the declining productivity of pearl millet in northern Namibia.

 iv.    Combined Drought Index is a suitable agricultural drought monitoring indicator for Namibian conditions.

**1.5 Justification**

Pearl millet is a staple food crop to 60% of the northern Namibia population and remains the major rain-fed crop that is proven to be drought tolerant and perceived by the region to be most suitable for the recurrent dry conditions of northern Namibia. However, frequent crop failures and mediocre crop yields characterize the region. In fact, both commercial (61.8% of the agricultural land) and subsistence (31.8% of the agricultural land) farmers in Namibia are always affected by drought.

**1.6 Description of Study area**

**1.6.1 Location and population**

Figure 1 shows the map of the study area. The latitude and longitude of Namibia are 22°00′00″ South, 17°00′00″ East. The neighboring countries include Zambia and Angola in the north, Botswana in the east and South Africa in the south and southeast (Mendelsohn *et al*.,2002).
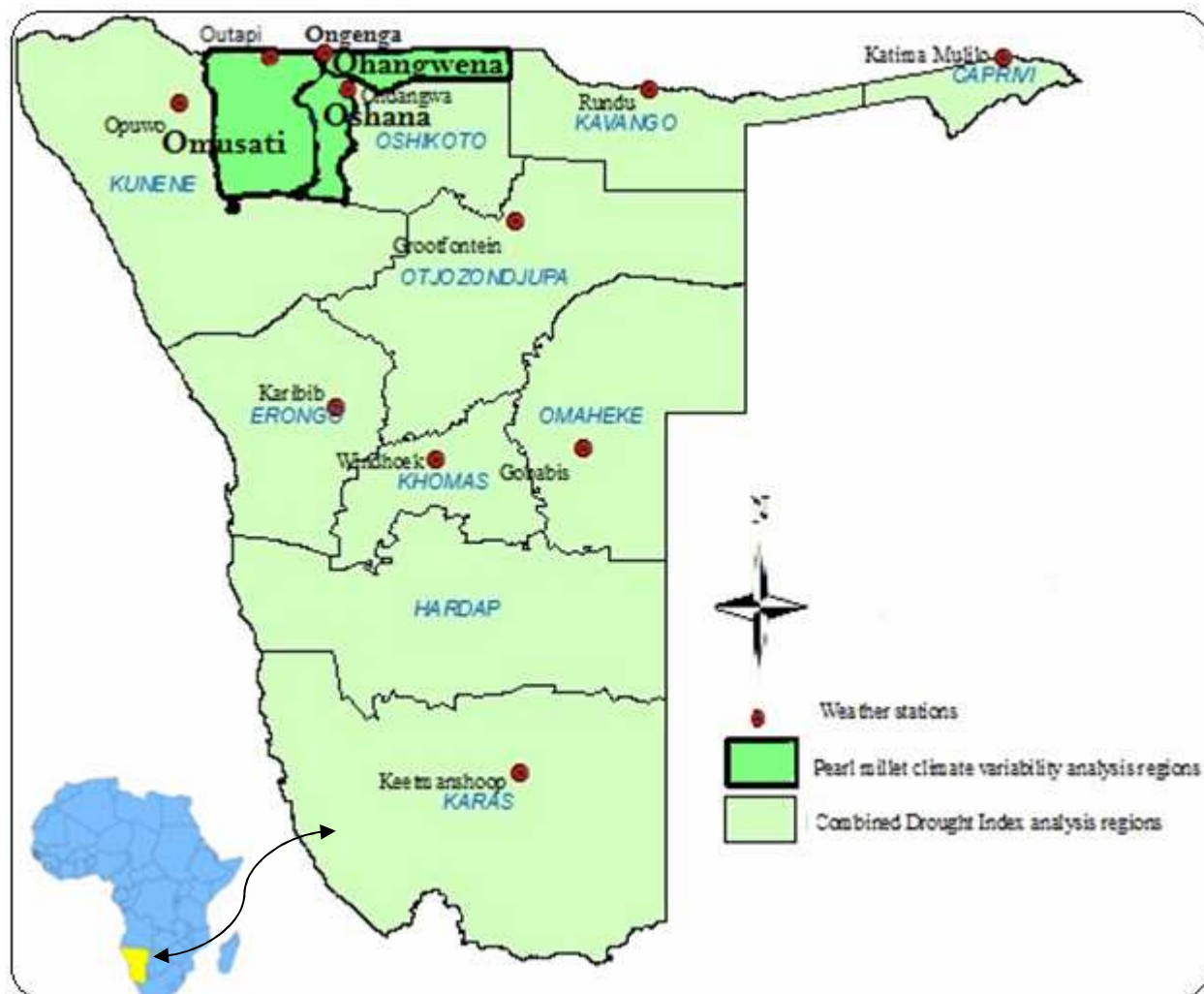
**Figure 1: Map of Namibia showing the study area and geographical location in Africa**

The country has a landmass of approximately 824,000 km², of which 114,500 km² (13.9% of total area) is occupied by national parks, 21, 600 km² (2.5%) comprises restricted 'Diamond area, 469,100 km² (57.0%) represents freehold land with title deeds and 218,300 km² (26.5 %) are non-title deed communal land. The latter two, freehold and communal land, totaling 687,400 km² or 83.5% of the country's landmass, are considered to be available for agricultural land use (L.A.C., 2005). Only 8% of the country can be classified as sub-humid, while 37% is semi-arid, 33% is arid and 22% is desert, whereby an estimation which was done in 1996 indicate that about 25% of the population lived on just 1% of the land in the Cuvelai drainage (Oshana, Oshikoto, Ohangwena and Oshana Regions) area of north-central Namibia (Le Roux, 2011).

The study of the effect of climate variability with respect to length of growing period and the dry spells (in days) that occur during different pearl millet growth stages on pearl millet yields

focused on some regions  (Ohangwena, Omusati and Oshana regions) of the northern part of the country. The geographical locations of these regions are indicated in Figure 1. These are representative regions of the northern part in which 60% of the Namibian population are living and mainly dependent on rain fed agriculture, and in particular on pearl millet as it have been indicated earlier. They are geographically situated in the northern parts of the country whereby Omusati and Ohangwena form the boundary with Angola in the north.

The border of Ohangwena region is Angola in the north, Omusati region in the west, Oshikoto and Oshana regions in the south and Kavango region to the east, covering an area of 10,703 $Km^2$ (N.P.C., 2011). The population is 245,100, with the population density of 23 people per $Km^2$. The border of Omusati region is Angola in the north, Kunene region in the south and to the west, Oshana and Ohangwena in the east, with population of 242,900 (N.P.C.,2011). The Omusati region covers an area of 26,573 $Km^2$ with population density of 9 people $Km^2$.

Oshana region is bordering Omusati region in the west, Ohangwena region in the north, Oshikoto region in the east and Kunene region in the south, with the population of 161,916 (N.P.C., 2011). Oshana region covers an area of 8,653 $Km^2$ with a population density of 19 people per $Km^2$.

**1.6.2 Climate**

The combination of cold water and high pressures in the Atlantic Ocean leads to subsidence of cold dry air over large area of Namibia, which generally suppresses rainfall (du Pisani, 2004). This situation is dominant during most of the year, except in summer when heating of the continent is greatest and the southern position of the Inter-Tropical Convergence Zone (ITCZ) draws moisture from the tropics over northern and eastern Namibia and causes rainfall (du Pisani, 2004). This is the time when the country experiences its single rainfall season (October to April), of which the intensity is dependent on the flow of tropical moisture.

The rainfall in Namibia is highly variable, ranging from less than 50mm per annum in the western Namib and coastal zones to more than 700mm at the eastern end of the Caprivi Strip, with only 5% of the country receiving more than 500mm. The bulk of the rain falls between the months of October and March (Sweet, 1998). Annual rainfall distribution is patchy and erratic with the annual potential evapo-transpiration exceeding annual precipitation by ratios of up to 30:1 (not counting the desert areas), hence drought conditions are a common phenomenon throughout most of the country (Sweet, 2006).

The coastal area of the country is often cooled by the Benguela Current with less than 50 millimeters of rainfall annually while the Central Plateau and the Kalahari have wide diurnal temperature ranges of more than 30° C in summer days and less than 10° C in winter (du Pisani, 2004).

In central plateau, the average temperature for December is 24° C and the average maximum temperature is 31° C. In June and July the average temperature are 13° C and 20° C respectively (du Pisani, 2004; Mendelsohn *et al.*, 2002). Humidity is normally low, and rainfall increases from about 250 millimeters on the southern and western parts of the plateau to about 500 millimeters in the north-central part and 700 millimeters on the Caprivi Strip and Otavi Mountains. The annual temperature of Omusati, Oshana and Ohangwena range between 23 and 34 °C and the average annual rainfall varies between 350 and 600 millimeters. These regions are also prone to floods due to the upper stream of the neighboring country Angola (Shoopala, 2008).

<center>**CHAPTER TWO**</center>

<center>**2.0 LITERATURE REVIEW**</center>

## 2.1 Introduction

This chapter presents reviews of some of the previous studies on how climate variability affects pearl millet productivity during different growth stages on the crop. It also presents reviews of the drought monitoring indices that are used in Namibia.

## 2.2 Climate variability and pearl millet productivity

Climate variability may be defined as the variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events (Burroughs, 2003). It is a term that is often used to denote deviations of climatic statistics over a given period of time (for example a month, season or year) from the long-term statistics relating to the corresponding calendar period being measured by those deviations, which are usually termed anomalies. Climate variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing variability (Burroughs, 2003).

Several methods have been used in order to determine the effect of climate variability on crop yields including crops such as pearl millet. One of the methods is based on a z-distribution chart which was used for different inter-annual climate variability anomalies in response to yield by Ayanlade *et al*., (2009). In this method, crop yield data was transformed into a z-distribution format varying in scale from –3 to +3, whereby, if the resultant z-values are negative (negative anomalies) then the effect is insignificant and positive anomalies represent significant effects on crop yield. With regard to pearl millet, the study by Ayanlade *et al*. (2009) revealed that pearl millet yield was reduced by climate variability measures such as rainfall anomalies.

Despite its high yield potential and drought tolerance, pearl millet production and yield are however faced with numerous constraints. One of the major constraints is the high frequency of dry spells that occur during the growing season and this considerably reduces pearl millet yield as it was also confirmed by Ayanlade *et al*., (2009). Despite the fact that pearl millet *(Pennisetum glaucum)* is one of the most important food crops in the drier semi-arid tropics (Maiti and Bidinger, 1981) that tolerates drought, in Namibia drought was identified as one of

<center>8</center>

the major threats followed by lack of animal draught power (Matanyaire, 1996). The crop biomass production is highly affected by environmental conditions, such as moisture and soil fertility (Newman *et al*., 2010) among others. Climatic variability associated events such as floods and drought among others can cause injury to the crop during the growing period. Studies by Ayanlade *et al*., (2009) and (Burroughs, 2003) revealed and validate that dry spells that occur at the beginning of the growing season affect crop establishment and reduce plant population while dry spells during the flowering period of the pearl millet crop lead to a complete yield failure.

The reduction of yield in pearl millet is determined by several factors including the stages of crop development when these events occur. Among other factors are the duration of floods/drought, air/soil temperatures as well as the presence of auxiliary buds on the damaged plants (Tucker *et al*., 2005 ). Prior to the 6-leaf stage (when the growing point is near or at the soil surface), plants like corn, and millet can survive only 2-4 days of flooded conditions (Le Roux, 2000). In addition, a young crop has a smaller demand for oxygen and may be able to survive better when submerged in water.

Meanwhile, small grain crops that are submerged in water for two days, or longer, have little chance for survival, whereby recovery may be very slow and the yield will be dramatically reduced. Oxygen concentration approaches zero after 24-hours in a flooded soil (Weijun Z. *et al*., 1995). Without oxygen, the plant cannot perform critical life sustaining functions, such as root respiration, nutrient and water uptake due to impaired roots. Even if flooding does not kill plants completely, it may have a long term negative impact on crop performance. Bivariate correlation and multiple correlation analyses were used by Adejuwon, (2005) in order to determine how climate variability affect the cereal crop growth stages.

As it is the case with other crops, each growth stage of pearl millet is affected by climatic variability differently, thereby making different contributions by each growth stage towards the final crop yield. For example, the growth cycle of pearl millet may be divided into three stages. The first stage that ranges from sowing to panicle initiation (GS1) is the vegetative phase. The second stage is the flowering / panicle development stage, that extends from panicle initiation to anthesis and the beginning of grain filling (GS2) and finally the third stage representing grain-

filling stage / physiological maturity (GS3). These stages have different moisture distribution requirements.

Dry spells can cause poor plant growth or no development thereby leading to crop failure or depressed yields. For example dry-spells at germination lead to poor germination or reseeding or optimum planting time being missed (Ayanlade et al., 2009). These authors also looked at the length of dry spells at GS2 that reduce vegetative growth, influence the main stem during the flowering/pollinating of the main stem while at the same time affecting development of new tillers. On the other hand, the dry spells that occur at GS3, affect the grain filling of the main stem, lessening the number of tillers thereby leading to fewer heads per plant and poor seed set/grain filling.

However, because of difficulties due to patchy and erratic rainfall in Namibia, the study found it difficult to point out each and every dry spell that occurs during the entire crop growth cycle and only grouped three major dry spells based on three most important pearl millet growth stages mentioned above. In the event of excess moisture in the early vegetative stages of development, plants may be subject to greater injury during a dry period because root systems at this stage are not sufficiently developed to access available subsoil water.

On the other hand, floods which can occur as a result of way above normal rainfall can be assessed mainly based on variables that define the flood damage to agricultural lands such as the time of year of flood incident, water depth, duration of flooding, flow velocity and the time of occurrence with respect to crop growth stages and critical field operations (Förster *et al*., 2008). Intra-seasonal climate characteristics such as rainfall onset and  cessation, prolonged dry spells and length of growing period can be determined by use of specific climatically driven statistical packages such as Instat among others (Stern *et al*., 2006). To assess how pearl millet can be affected by climate variability, the methods that were used  by Adejuwon ( 2005) and  Stern *et al*., (2006)  for climatic analysis and how climate variability affect crops  were applied.

The assessment included the dates on which the growing season started and ended from which the length of the growing season was determined. The advantage of the "Instant' statistical analysis software is that it allows researchers to manipulate the climatic events such as shifting of season where specific interest period can be applied based on the rainfall season of the region.

On the contrary, there are some aspects that can have an effect on these climatic events. For example, the package can drop the rainfall onset if a parameter date is set and this makes it difficult for determining the onset date for countries with erratic rainfall like Namibia.

## 2.3 Climatic requirement for pearl millet

Generally, pearl millet can be grown where optimum rainfall ranges from 200 to 350 mm. However, it is mostly grown as a rain-fed crop in areas receiving 250 to 500 mm, whereby, relying on sowing early-maturing cultivars is no option (Kamkar *et al* 2006). Despite its drought tolerance, pearl millet requires evenly distributed rainfall during the growing season (Soler *et al*, 2008). Generally, pearl millet development begins at a base temperature around $12^{o}C$ with an optimum temperature between 30 and $35^{o}C$.

Soil temperatures influence all aspects of early vegetative development including, the emergence of seedlings, the initiation, appearance and final number of leaves and tillers (Kamkar *et al.,* 2006). For germination and emergence (GS1), soil temperatures must reach $12^{o}C$ for germination to begin. For the growth and development of GS2, temperature requirements of pearl millet depend on the crop variety, the optimum for plant growth ranging from 22 to $35^{o}C$ (Stigter *et al* 1998). The temperature for root elongation ranges between 22 and $36^{o}C$ with the optimum of $32^{o}C$. For a good photosynthetic response, the optimum temperature ranges from 31 to $35^{o}C$ (Stigter *et al.,* 2002).

## 2.4 Growing period and agro-ecological zones

Agro-ecological zones are basically defined as areas with the same crop suitability ratings, as established through a simplified biomass productivity model while growing period is the time during a growing season when both air temperature and soil moisture permit crop growth (de Pauw *et al*., 1996; Allen *et al*., 1998). Furthermore, the length of growing period is formally defined as the number of days during which precipitation exceeds half the potential evapotranspiration, plus the number of days to evapo-transpire an assumed 100 mm (or less, if not available) of water from excess precipitation (de Pauw *et al.,* 1996).

According to the Namibian agro-ecological and growing period zones, Ohangwena region comprises of Kalahari Sands Plateau (KAL3-2) which is a stabilized sand drift with few pans

comprising of the average growing period of 91-120 days, Kalahari Sands Plateau ( KAL3-3) which is a stabilized sand drift with few pans and average growing period of 61-90 days, dependable growing period of 60 % of average, Kalahari Sands Plateau ( KAL4) which is a stabilized sand drift with common pans and Kalahari Sands Plateau (KAL9-3) 'Oshana' flood system, growing period of 61-90 days, dependable growing period of 60 % of average (de Pauw 1996 *et al.,* 1996).

The agro-ecological zones of Omusati region are characterised by Ekuma Plains and Etosha Pan (ETO), Kalahari Sands Plateau with stabilized sand drift and few pans (KAL3-4). The average growing period ranges from 61 to 90 days with a very short dependable growing period. Some parts are characterised by Kalahari Sands Plateau, 'Oshana' flood system (KAL9-4) with the dependable growing period of 61-90 days and very short dependable growing period. There is also Kalkveld (KALK-4), Kaokoland, high plateaux (KAO4) Kaokoland mountains and hills (KAO1) with median growing period of 61-90 days and very short growing period respectively (de Pauw *et al*, 1996.

Moreover the agro-ecological zones of Oshana region are mainly dominated by Ekuma Plains and Etosha Pan (ETO); Kalahari Sands Plateau (KAL9-4); "Oshana" flood system, Kalkveld (KALK-4) and undifferentiated rocky hills and inselberg mountains (R). The growing period is 61-90 days of very short dependable growing period (de Pauw 1996 *et al*, 1996).

## 2.5 Drought monitoring indices

According to the World Meteorological Organization (WMO), drought index is often defined as a single number characterizing the general drought behavior at a measurement site, whereas a drought event definition is applied to select drought events in a time series including the beginning and end of the droughts (Hisdal and Tallaksen, 2000). Meteorological drought is usually an expression of precipitation's departure from normal (negative) over some period of time. Hydrological drought on the other hand, expresses the deficiencies in surface and subsurface water supplies (du Pisani, 2004). Moreover an agricultural drought is usually expressed in terms of needed soil moisture for a particular crop at a particular time, whereas socio-economic drought is the associated droughts with supply and demand for economic goods (Hisdal and Tallaksen, 2000).

Globally, there are many drought monitoring techniques using various drought indices such Deciles Index (DI) (Gibbs and Maher, 1967), Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDMI) (du Pisani, 2004), among others. Most drought monitoring indices have been widely used in Africa, with users always facing challenges due to insufficient data, and high variations of environment among others. These have led African researchers to develop one drought index that can be easily adapted to various monitoring purposes (Balint, 2011).

Another drought index known as "Combined drought index" is a new statistical drought index that was developed for drought monitoring in the Horn of Africa and it is applicable in data-scarce environments and considers as many drought attributes as possible, which can be easily adapted to various monitoring purposes. The index considers all unfavorable climate conditions that cannot be tolerated by plants for even few months, weeks or days and can also offer the possibility to be extended to annual or even longer periods (Balint and Mutua, 2011) .

In southern Africa, and specifically in Namibia, the drought policy which was developed during the 1990s after independence stipulated that those drought monitoring techniques that have been used in other countries be tested for their applicability (du Pisani, 2004). Deciles Index (DI) and the Standardized Precipitation Index (SPI) were identified to be suitable (du Pisani, 2004). However, these indices are more based on meteorological parameters, need long period data and do not precisely capture "agricultural stress". For example, the SPI can only use the rainfall data and the hardcoded time scale analysis cannot be changed.

Furthermore both of the indices do not consider the persistence of the stress periods and require continuous data observation without gaps (Balint and Mutua, 2011). It is in this context that an additional drought index that incorporates Precipitation Drought Index (PDI), Temperature Drought Index (TDI) and Normalized difference Vegetation Index (NDVI) for soil moisture deficits and persistence of dry soil conditions known as the Combined Drought Index also needs to be tested for Namibia.

Combined drought index considers precipitation component involving rainfall deficits and persistence of dryness, excess temperature and its persistence as well as soil moisture deficits and the persistence of dry soil conditions. Normalized Difference Vegetation Index data can be used due to the limitations of observed soil moisture data (Balint and Mutua, 2011). On the other

hand, Standardized Precipitation Index (SPI) is a probability index which considers only precipitation based on the probability of recording a given amount of precipitation and standardized so that an index of zero indicates the median precipitation amount (half of the historical precipitation amounts are below the median, and half are above the median) according to McKee *et al*., (1993).

Standardized Precipitation Index (SPI) is negative for drought and positive for wet conditions. As the dry or wet conditions become more severe, the index becomes either more negative or positive.  Similarly, Combined Drought Index (CDI) is equal to one (1.0) and if the CDI is greater than 1.0, then it represents wetter than average and if it is below 1.0 then it represents dryer than average conditions. Normalized Difference Vegetation Index (NDVI) values range from +1.0 to -1.0, whereby areas of barren rock, sand, or snow usually show very low values of 0.1 or less. Sparse vegetation such as shrubs and grasslands or senescing plants may result in moderate values (approximately 0.2 to 0.5). High Normalized Difference Vegetation Index (NDVI)  values (approximately 0.6 to 0.9) correspond to dense vegetation such as that found in temperate and tropical forests or crops at their peak growth stage (Bethany *et al*., 2006).

# CHAPTER THREE

## 3.0 MATERIALS AND METHODS

### 3.1 Introduction

This chapter describes the study area and goes on to discuss the data types and sources as well as methodologies that were used to achieve the objectives of this study. It describes the climatic and pearl millet yields as well as satellite Normalized Difference Vegetation Index data.

In addition, the chapter describes methodologies for the assessment of the intra-seasonal climate characteristics such as length of dry spells, rainfall onset and cessation dates that determine the length of growing period which has been related with pearl millet yield. Further, the chapter presents how the Namibian regions (shape files/polygons) were merged together in order to test the suitability of Combined Drought Index for the whole country.

### 3.2 Data types and sources

The study used secondary data for rainfall, temperature, Normalized Difference Vegetation Index (NDVI) and pearl millet yields. The stations whose data were used in this study include Ondangwa, Rundu, Katima Mulilo, Gobabis, Keetmanshoop, Windhoek, Karibib, Opuwo and Grootfontein. The geographical locations of these stations are indicated in section 1.6.1.

### 3.2.1 Pearl millet yield data

Seasonal pearl millet yield data per region were provided by the Ministry of Agriculture, Water and Forestry of Namibia for a period of fourteen years (1998 to 2012). The yield data were expressed in tonnes per hectare.

### 3.2.2 Rainfall data

Monthly and dekadal rainfall data for the period 1998 to 2012 for  Ondangwa, Rundu, Katima Mulilo, Gobabis, Keetmanshoop, Windhoek, Karibib, Opuwo and Grootfontein stations were used to calculate the Combined Drought Index (CDI). However, for stations that were used as regional representatives such as Ondangwa ($17^0$ 91′ 00″ S and $15^0$ 95′ 00″E) in Oshana region, Outapi ($17^0$ 51′ 00″ S and $14^0$ 98′ 00″E) in Omusati region and Ongenga ($17^0$ 45′ 00″ S and $16^0$ 67′ 00″E) in Ohangwena region, estimated daily rainfall data were used due to the unavailability

of observed rainfall data. These data were obtained from International Research Institute for Climate and Society (IRI) website http://portal.iri.columbia.edu.

These data were used to determine the relationship between pearl millet productivity and climate characteristics with respect to dry spells occurrence, rainfall anomalies and length of growing period. In addition, for stations such as Karibib and Opuwo, the estimated rainfall data were also used. These data were obtained from Famine Early Warning System Network (FEWSNET) website http://earlywarning.usgs.gov. FEWSNET is an African Data Portal that provides access to spatial data, satellite imagery, and other data and graphic (Drury, 1990).

### 3.2.3 Temperature data

Daily maximum as well as minimum temperature data of the stations mentioned in section 3.2.2 for the period 1998 to 2012 were obtained from Namibia Meteorological Office. These data were used for computing the Combined Drought Index for drought detection in Namibia.

### 3.2.4 Normalized difference vegetation data

Normalized Difference Vegetation Index data were derived from satellite imagery and used for computing the Combined Drought Index. These data were used as a substitute for soil moisture data which was lacking in the country. Normalized Difference Vegetation Index data was decoded from ten daily syntheses (dekadal) day vegetation synthesis (VGT-S10) product that contains only the NDVI band of "Satellite Pour l'Observation de la Terre (SPOT)" by using a coding formula according to Drury, (1990) given by equation 1 below.

VGT-S10 = (DN * 0.004) - 0.1 ……………………………………..equation 1

*Where,*

*DN, refers to digital number value assigned to a pixel in a digital image.*

*VGT-S10 , refers to a ten daily syntheses (dekadal) day vegetation synthesis product that contains only the NDVI band of "Satellite Pour l'Observation de la Terre (SPOT)".*

The VGT-S10 dekadal data for each month were averaged to get the monthly value. Vegetation (VGT-S10) data were downloaded from the DeVoCast website "http://www.devcocast.eu" a

Satellite Pour l'Observation de la Terre -Vegetation (SPOT-VGT) available at the resolution of 1000 m$^2$ from 1998 to 2012.

## 3.3 Methodology

The methods that were used to achieve the objectives of this study are presented in the subsections that follow.

### 3.3.1 Data quality control

### 3.3.1.1 Data Homogeneity/consistency

To test whether there was consistency in the data sets that were used in this study, single mass curve technique was used. This involved plotting cumulated quantities or values of a study parameter against time. In this study, cumulative monthly totals of rainfall and temperature were plotted against their corresponding years. Data was cumulated backwards in time due to the fact that the current conditions for the minimum and maximum temperature plus rainfall were available. A straight line plot in the single mass curve indicated data homogeneity. Conversely, whenever the straightness of the line was deformed the data sets were considered to be inconsistent.

### 3.3.2 Effect of length of growing season on pearl millet yield

Length of growing season was determined by counting the number of days between the onset and cessation dates of rainfall. The start of the time series was shifted to July as recommended by Stern *et al*., (2006). This was done in order to include the rainfall months which were from October to April. An assumption of sixty (60) millimeters of soil water capacity within the soil horizon where most of the pearl millet feeding roots are concentrated was made based on the findings of Stigter *et al.,* (1998). In this horizon, approximately two-thirds of the root system is in the top 45% of the soil zone. A six (6) millimeter soil evaporation rate per day was adopted for the study regions according to Mendelsohn *et al*.,(2002), who reported that the average evaporation rate in Oshana, Omusati and Ohangwena fall in the range of 2400 - 2600mm per annum.

In defining the onset date of annual rainfall a combination of accumulated rainfall totals (Walter's and Sivakumar's methods) and rainfall or evapotranspiration (Kowal's and Benoit's

methods) was used as criteria (Stigter *et al.,* 1998; Soler *et al*, 2008). Onset dates were classified as days when ten (10) millimeters or more of cumulative rainfall was received on condition that no dry spells of more than seven consecutive days occurred after the date when the initial condition was met.  Seven days were considered in order to take account of germination (GS1) and reproductive stages (GS2) that are more sensitive to short dry periods.

The decision to use  seven days was based on the soil evaporation of the study area which is six (6) millimeters per day, whereby the    average evaporation rate for Oshana, Omusati and Ohangwena fall in the range of 2400 - 2600mm per annum ( Mendelsohn *et al*., 2002) as well as on the soil type which is classified as sandy soils (de Pauw 1996 *et al.*, 1996). Due to the patchy and erratic rainfall of Namibia, the study further used the soil water balance approach as indicator for available soil moisture to determine the dates of rainfall onset, cessation, length of the growing season and dry spells that occur at different growth stages of pearl millet. Instat Statistical Analysis Software was used as a tool for processing the onset and cessation dates.

### 3.3.2.1 Pearson correlation analysis

Correlation analysis was used in this study to determine the degree of relationship between pearl millet yields and length of growing season. Length of growing season (number of days) was correlated with pearl millet yield to determine the Pearson correlation coefficient given in equation 2.

………Equation 2

$$r = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]}}$$

*Where,*

   *r= Pearson Correlation coefficient*

   *n= Total number of observations*

   *x= Length of growing season*

   $y$ *= Pearl millet yields*

In order to analyse the statistical significance of the correlation coefficient between length of growing period and pearl millet yield, the Pearson correlation coefficient was transformed into a test statistic that is distributed as the student t-distribution given in equation 3 below.

$$t_{n-2} = \frac{r\sqrt{\left(\dfrac{n-2}{1-r^2}\right)}}{} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\text{Equation 3}$$

*Where*

*t, is the computed t-statistic*

*n= is the sample size*

*n-2 =degrees of freedom*

*r= is the Pearson correlation coefficient according to equation 2*

The resultant values of the t-statistic were compared with the tabulated values of the student t-distribution at the 5% significance level. The decision rule was crafted as follows:

- If the t-statistic was greater than the tabulated student t-distribution value at n-2 degrees of freedom, then the associated correlation coefficient (r) value was declared statistically significant, implying that pearl millet was strongly influenced by the length of growing season.

- Conversely, the r- value was rendered statistically insignificant if the computed t-statistic was less than the tabulated value of the student t-distribution value, and hence the length of growing season had no significant effect on pearl millet yield**.**

### 3.3.3 Effect of length of dry spells on Pearl millet yield

Dry spells were considered to be the number of consecutive seven or more days after the onset described in section 3.3.2. The effect of consecutive days of dry spells (dry days) on pearl millet yields were identified based on three main pearl millet growth stages according to Maiti and Bidinger (1981). Stage one corresponds to the period from seedling emergence to panicle initiation of the main stem (GS1), stage two from panicle initiation to flowering of the main stem (GS2) and finally stage three which comes after the emergence of panicle of the main stem to physiological maturity (GS3).

The lengths of dry spells corresponding to each pearl millet growth stages GS1, GS2 and GS3 were correlated with the final pearl millet yields to determine the degree of relationship between lengths of dry spells at respective growth stages and the final crop yields. Pearson correlation coefficient as described by equation 2 was used to analyse the statistical significance of the degree of association of the variables. The test of statistical significance of the correlation was done using the same approach as described in section 3.3.2.1.

### 3.3.4 Effect of rainfall anomalies on pearl millet yield

The Weighted Anomaly Standardized Precipitation (WASP) index of Ayanlade *et al.(*2009) was adopted, adjusted and used in this study. The final form of equation that was used to compute the rainfall anomalies is given as equation 4 below.

$$Z = \frac{x - \mu}{\sigma}$$ …………………………Equation 4

Where: $z$ = *Standardized* variate, also called standardized anomaly

> $x$ = *Total seasonal rainfall*
> $\mu$ = *Long term mean seasonal rainfall*
> $\sigma$ = *standard deviation of seasonal rainfall observations*

In order to analyze the effect of rainfall anomalies on pearl millet yield, the yields were also transformed into standardized yield anomalies using Equation 4 above, where the equation parameters now refer to those of pearl millet yields.

The computed rainfall anomalies were correlated with the pearl millet yield anomalies to determine the correlation coefficient using equation 2 in section 3.3.2.1. The statistical significance of the correlation coefficient was performed based on the procedure described in section 3.3.2.1.

### 3.3.5 Evaluation of Combined Drought Index (CDI) as indicator for early agricultural drought detection

Combined Drought Index was determined by using decadal and monthly rainfall data, maximum and minimum temperature as well as Normalized Difference Vegetation Index (NDVI) for the duration of fourteen years (1998 to 2012) in nine (9) representative stations around Namibia. Monthly maximum and minimum temperatures were averaged in order to get a single value per month. Dekadal values for the Normalized Difference Vegetation Index were averaged to get monthly NDVI values for the calculation of monthly CDI.

Vegetation extract software program (VGTExtract) was used as a gateway to ArcGIS 9.3 software for the calculation of the Normalized Difference Vegetation Index values. Namibian stations that were earmarked to be used for extraction of vegetation data to be used for calculation of Combined Drought Index were clipped based on the region shape files of the country. Due to the fact that in some of the regions/areas there were no Meteorological Stations where the extraction of corresponding values of Normalized Difference Vegetation Index could be based on, some of regions shape files were merged / combined together as shown in Table 1 below. ArcGIS 9.3 software was used for merging the regions.

**Table 1: Merged regions and Meteorological stations**

| Region | Station |
|---|---|
| Caprivi | Katima mulilo |
| Erongo | Karibib |
| Karas | Keetmanshoop |
| Kavango | Rundu |
| Khomas & Hardap | Windhoek |
| Kunene | Opuwo |
| Omaheke | Gobabis |
| Omusati, Oshana, Oshikoto & Ohangwena | Ondangwa |
| Otjozondjupa | Grootfontein |

The averaged maximum and minimum temperatures as well as rainfall totals were then inserted into the CDI computer in-built program in order to generate the CDI values. Combined Drought Index was computed using the combination of the weighted average of precipitation, temperature and soil moisture drought indices. The weighted 100% recommended by Balint and Mutua (2011) was distributed amongst precipitation (50%), vegetation (25%) and temperature (25%). In the case where there were no temperature data (Karibib, Gobabis, Ondangwa and Opuwo) stations, 75% was assigned to precipitation while the remaining 25% was assigned to Vegetation. The interest period was considered to be seven months since rainfall in Namibia is received from October to April.

The Combined Drought Index was then calculated using the following three steps according to Balint and Mutua (2011):

a) Step one involved an approach where drought was conceived as a combination of:

• Precipitation component which considers rainfall deficits and persistence of dryness

• Temperature component which considers temperature excesses and persistence of high temperature

• Soil moisture component which considers soil moisture deficits and persistence of dry soil conditions, but because of limitations in soil moisture observations data this was approximated by NDVI deficits and deficit persistence.

b) Step two involved computation of individual drought indices listed below:

• Precipitation Drought Index (PDI)

• Temperature Drought Index (TDI) and

• Vegetation Drought Index (VDI), as a substitute for the Soil Moisture Drought Index

c) Step three involved the integration of the above indices into the computation process of the Combined Drought Index (CDI), using equation 5 below.

$$CDI_{i,m} = W_{PDI} * PDI_{i,m} + W_{TDI} * TDI_{i,m} + W_{VDI} * VDI_{i,m}$$

……Equation 5

*Where:* CDI $=$ *Combined Drought Index*

PDI $=$ *Precipitation Drought Index*

TDI $=$ *Temperature Drought Index*

VDI $=$ *Vegetation Drought Index as a substitute for the Soil Moisture Index*

W $=$ *is the weight of the individual drought index*

In summary, the computation of the desired drought index was simplified using equation 6 below.

$$\text{Combined Drought Index} = \cfrac{\cfrac{\text{Actual average for IP}}{\text{LTM for IP}}}{{}^*\sqrt{\left(\cfrac{\text{Actual length of continous}\frac{\text{deficit}}{\text{excess}}\text{ in the IP}}{\text{LTM length of continous}\frac{\text{deficit}}{\text{excess}}\text{ in the IP}}\right)}}$$

…………Equation 6

*Where: IP, is the interest period,*

*LTM, is the long term average and deficit applies to rainfall and NDVI, and excess applies to temperature*

.
The values of the combined drought index were interpreted according to the criteria set out in Table 2 below in which the smallest value of the index indicated the most severe drought (Balint and Mutua 2011).

**Table 2: Combined Drought Index interpretation**

| CDI value | Drought severity |
|-----------|------------------|
| >1.0 | No drought |
| 1.0 – 0.8 | Mild |
| 0.8 – 0.6 | Moderate |
| 0.6 – 0.4 | Severe |
| <0.4 | Extreme |

Evaluation of the usefulness of the Combined Drought Index in detecting agricultural drought in Namibia was based on how best the index values generated were able to capture historical droughts in the country. The twelve monthly values that were generated during CDI calculation procedure were averaged in order to get a single value per year per season studied over Grootfontein station. This was done due to the fact that long term data were only available per year per season. Grootfontein was specifically selected due to its long term rainfall data (1929-2012). The CDI values were then plotted against the Grootfontein station rainfall time series for 73 years.

A comparison of the Combined Drought Index (CDI) performance and that of the Standardized Precipitation Index (SPI) over Grootfontein station was also undertaken. This was intended to confirm if the CDI could agree with the Standard Precipitation Index in determination of drought years. The interest period was set for seven months (starting from October to April which is the rainfall season in Namibia) for the calculation of the Combined Drought Index.

Standardized Precipitation Index (SPI) yearly values that were used for this comparison were those calculated by du Pisani (2004) for the same period (73 years). A weight of 100% was assigned to precipitation during the calculation of Combined Drought Index. The averaged Combined Drought Index values that were used for the comparison of historical drought years in

the country were then plotted against Standardized Precipitation Index and also correlated using the same approach as described in section 3.3.2.1.

## CHAPTER FOUR

## 4.0 RESULTS AND DISCUSSION

This chapter presents results of the analyses of the study based on the methodology described in Chapter Three as well as a comprehensive discussion of the results thereof.

### 4.1 Data quality control
Figures 2 and 3 below show the single mass curves for rainfall of Grootfontein and Outapi stations.
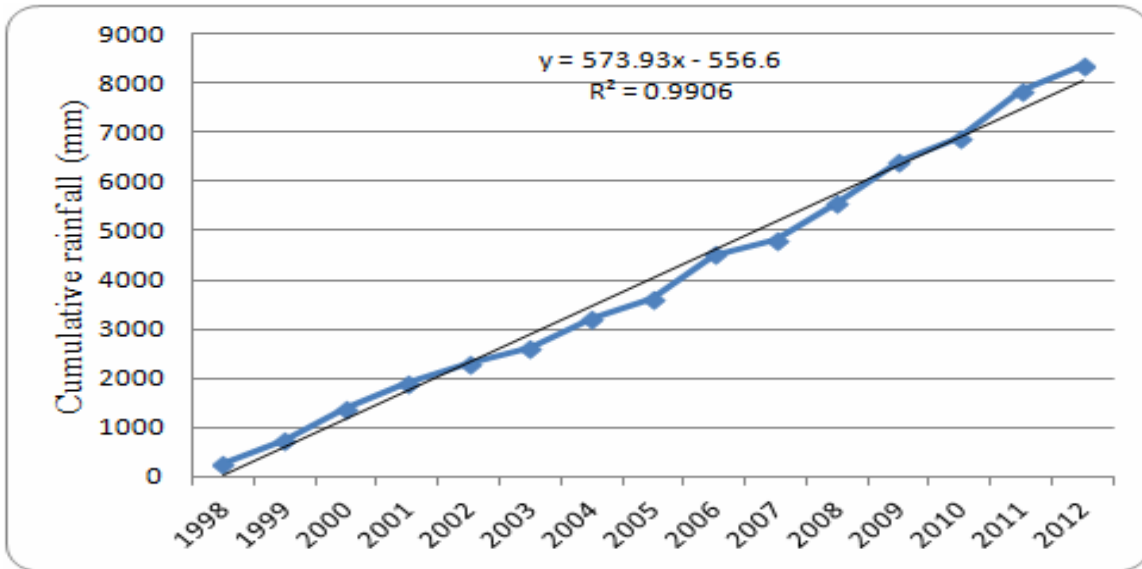
**Figure 2: Single mass curve of Grootfontein rainfall (Observed)**

$y = 573.93x - 556.6$
$R^2 = 0.9906$
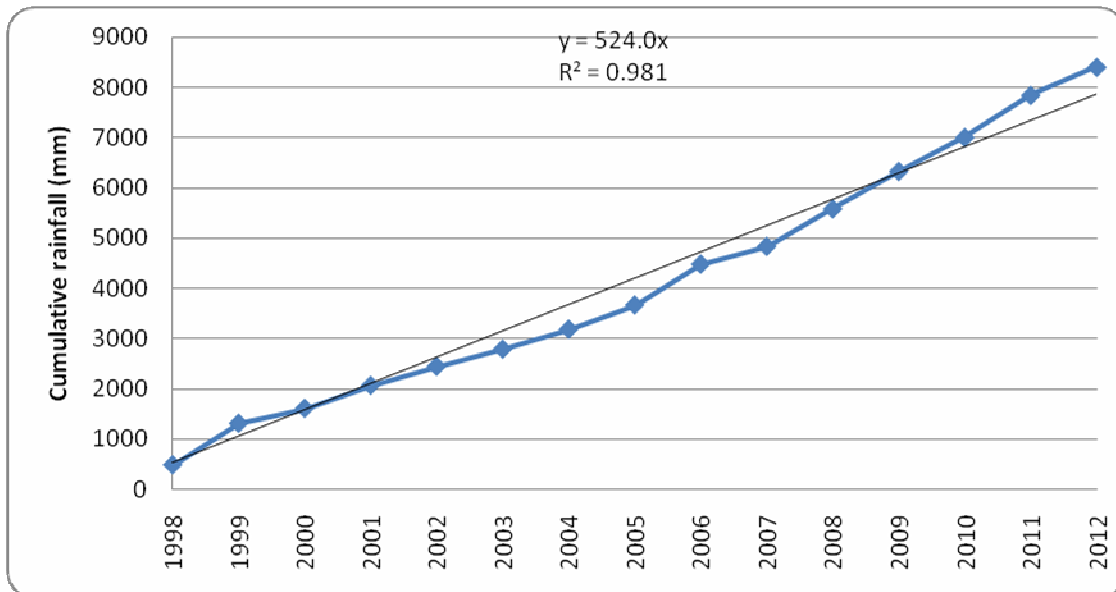


**Figure 3: Single mass curve of Outapi rainfall (estimated (RFE)**

$y = 524.0x$
$R^2 = 0.981$

Despite some minor insignificant deviations from the general linear trend by some data points for rainfall in some years, no adjustments were made to such data because such action could have masked the desired extremes of climate (temperature and rainfall) that this study sought to address.

Figures 4 and 5 below show the single mass curves for vegetation of Grootfontein and Outapi stations while Figure 6 shows the single mass curve for temperature of Grootfontein station.
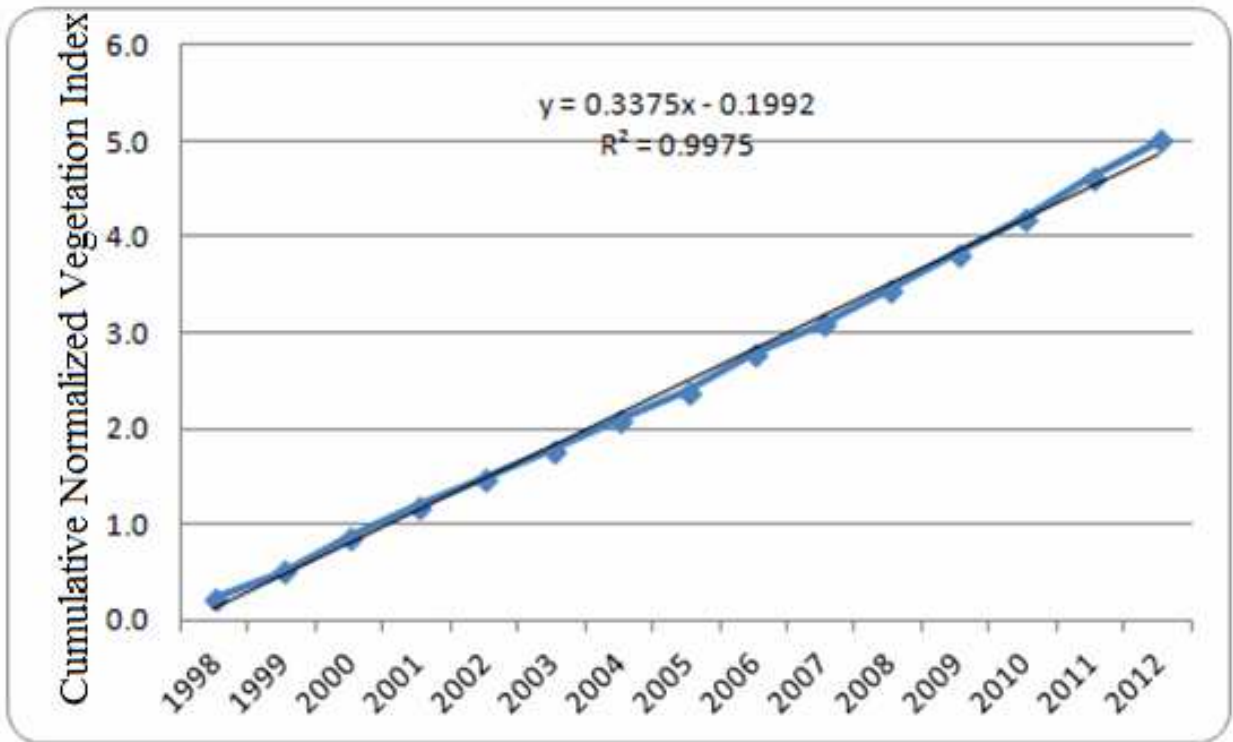
**Figure 4: Single mass curve of Grootfontein vegetation**
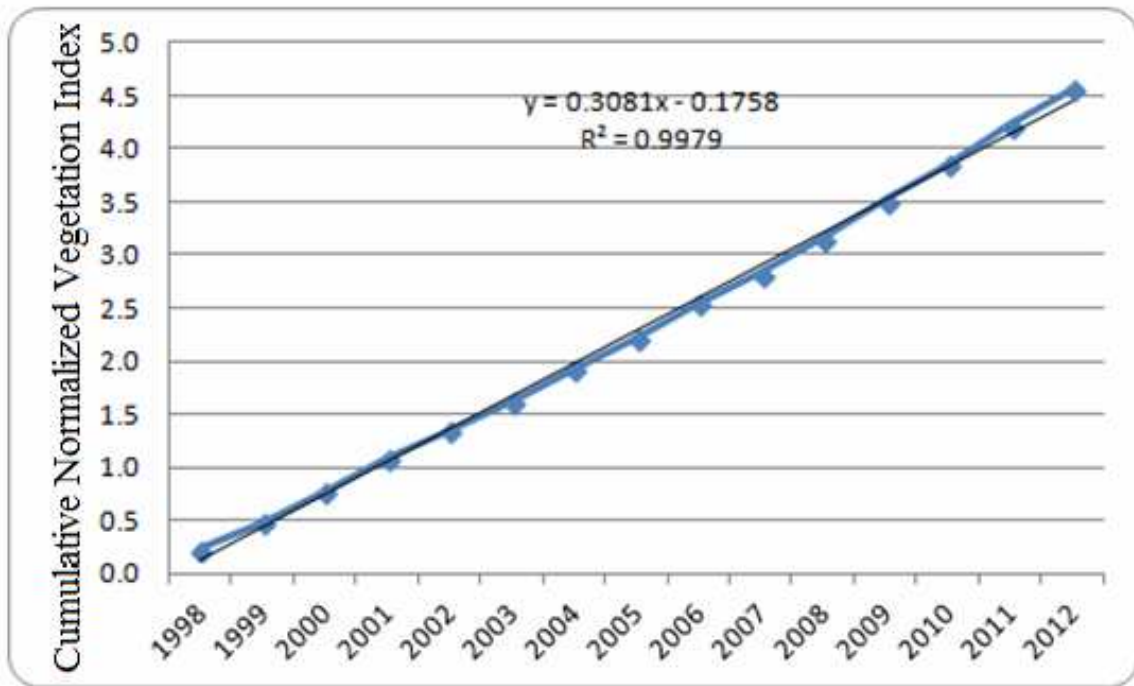


**Figure 5: Single mass curve of Outapi vegetation**
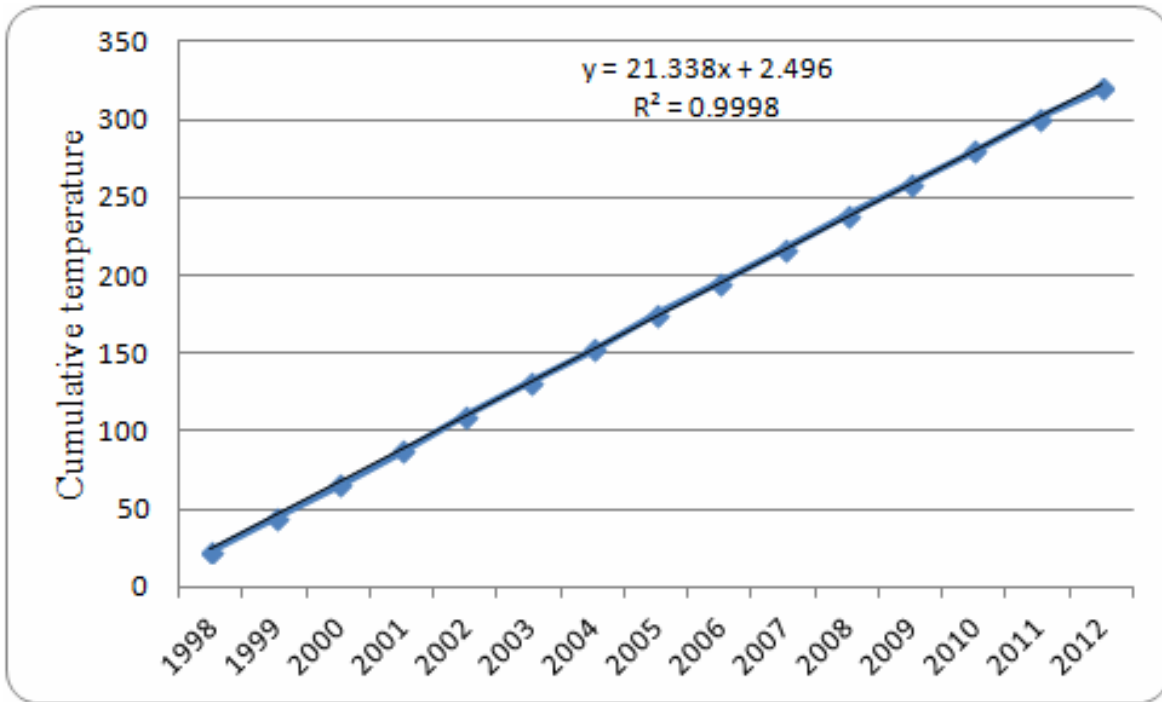
**Figure 6: Single mass curve of Grootfontein temperature**

In most cases, cumulative data plots were approximately straight with statistically significant regression coefficients for the regression lines at the 5% significance level. This confirmed that the data sets used were homogeneous and of acceptable quality for the analyses.

**4.2 Effect of length of growing season on pearl millet yield**

**4.2.1 Length of growing season categories**

Table 3 below shows the percentage of observed length of growing seasons among the three categories (short: 60-90, medium: 91-120 and long: 121-177 days) of length of growing season for Omusati, Oshana and Ohangwena, grouped based on the growing period zones classification of Namibia.

**Table 3: Length of growing season (% of observed)**

| Region | Short | Medium | Long |
|--------|-------|--------|------|
| Omusati | 40% | 20% | 40 % |
| Oshana | 20% | 53% | 27 % |

| Ohangwena | 7% | 80% | 13 % |

Table 3 shows that over the study period, the lengths of growing season varied with regions. Medium level lengths (91-120) of growing season were predominant in Ohangwena (80%)  and Oshana (53%).  There was a balance between the short (60-90 days) and long (121-177) lengths of growing season representing 40% each for Omusati region.

In Ohangwena, the short and long lengths of growing season are quite rare, representing 7% and 13% of the years respectively. A similar pattern was observed for Oshana which experienced short and long lengths of growing season corresponding to 20% and 27% respectively. In Omusati region, medium duration (91-120 days), lengths of growing season are the least (20%) experienced.

**4.2.2 Relationship between pearl millet yield and the length of growing season**

Table 4 below shows the correlation analysis between pearl millet yields and length of growing season for the three study regions (Omusati, Oshana and Ohangwena) together with their respective computed student t-statistics and tabulated t-value.

**Table 4: Correlation coefficients for pearl millet yield and length of growing season**

| Region | correlation coefficient | Computed t-statistic | Tabulated t-value |
|---|---|---|---|
| Omusati | -0.24 | -0.863 | 0.482 |
| Oshana | 0.23 | 0.827 | 0.482 |
| Ohangwena | -0.45 | -1.609 | 0.482 |

Unlike the findings of Ayanlade *et al*., (2009), the results of correlation analysis indicated that length of growing period did not show significant influence on the pearl millet at 95% confidence level in Omusati and Ohangwena regions as it has been shown in Table 4 above.

Possible reasons could be that most of the pearl millet farmers adopted a practice of sowing short duration varieties of pearl millet namely Okashana number one and two as well as Kangara (Ipinge, 2001). These varieties only need ninety days to mature compared to the local varieties that need more than 100 days.

In addition, farmers adopted the practice of reducing risk, by splitting their fields so that one area is dedicated to the long duration varieties if the onset was early and the other one to the short duration varieties if the onset was late which is from January to February (Rohrbach *et al*., 1999). However, the study recognizes other factors that influence pearl millet yield when short season length is experienced. Other major contributing factors include moisture availability which depends on rainfall distribution throughout the growing season (Burroughs, 2003), management practices, soil characteristics, and soil fertility management among others. However, there was a significant influence on the pearl millet at 95% confidence level in Oshana region.

Furthermore, during the 2006/08, 2008/09, 2009/10, 2010/11 and 2011/12 season, the season lengths increased while the pearl millet yield was low. This observation does not agree with that of Ayanlade *et al*., (2009) whose findings indicated that the longer the season the higher the yields of pearl millet. This indicates that there could be other factors that influenced yield in the areas other than season length. Therefore, further investigation is therefore required in order to establish the other factors that could have contributed to pearl millet yields in these areas. The years, except 2006/08 season corresponding to these seasons, were also declared by the Government of the Republic of Namibia as flood disaster years.

Currently, the average yield of pearl millet per hectare in Namibia is estimated at 200Kg/Ha due to moisture unavailability (Matanyaire, 1996), management practices, soil characteristics, and soil fertility management (Burroughs, 2003). Omusati and Oshana experienced high percentage of the pearl millet yield that fell in the category of long season length where the yield was below 200 200Kg/Ha. For example, seasons like 2006/07, 2007/08, 2008/09, 2009/2010 2010/11 and 2011/2012 experienced early onset and long growing period with adequate moisture being available, but the yields were low compared to the 2005/06 season which yielded more than 400 Kg/HA in all three regions, the highest among the seasons.

**4.3 Effect of dry spells on pearl millet yields**

**4.3.1 Occurrence of dry spells in three major pearl millet growth stages**

Table 5 below shows the proportions of dry spell occurrence in Omusati, Oshana and Oshikoto regions distributed in three major pearl millet growth stages (GS1, GS2 and GS3) and three categories of lengths of dry spells (7-10 days, 11-15 days, and over 16 days).

**Table 5: Proportion of dry spells occurrence for Omusati, Oshana and Oshikoto regions**

| Region | No. of consecutive dry spell from seedling to panicle initiation (GS1) | | | No. of consecutive dry spell from panicle initiation (GS2) | | | No. of consecutive dry spell from flowering to physiological maturity (GS3) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 7 -10 days | 11-15 days | 16 days- or more | 7 -10 days | 11-15 days | 16 days- or more | 7 -10 days | 11-15 days | 16 days- or more |
| **Omusati** | 18% | 26% | 40% | 7% | - | - | - | 20% | 27% |
| **Oshana** | 20 % | 33% | 40 % | 40% | 13% | 60% | - | - | 60% |
| **Ohangwena** | 7% | 20% | 60% | 7% | 20% | 20% | - | - | 20% |

Over the entire study period (1998 – 2012), the observed pearl millet yields ranged from 88 to 440 Kg/Ha (Refer to appendices 2 to 4). This range of productivity fell far below the potential pearl millet yields in southern Africa.  The yield of pearl millet in southern Africa region under optimal management ranges from 800 to 920 Kg/Ha (Rohrbach *et al.*, 1999; Ipinge, 2001). Some varieties of Pearl millet at some Namibian agricultural research stations has also recorded 1.5 to 1.75 tonnes per hectare (Rohrbach *et al.*, 1999), (Ipinge, 2001). The results of this study are  in agreement with previous work that indicated that  dry spells that occur during different crop growth stages affect the yields negatively (Ayanlade et al., 2009).

The results indicate that the highest percentage of number of consecutive dry spells occurred during the initiation stage (GS1) whereby 60% of the fifteen years occurred in Ohangwena, and 40% each in Omusati and Oshana of more than sixteen dry days. Oshana region experienced high percentage during the second growth stage (GS2) in all categories of dry spell lengths (40% of 7- 10 and 60% of at least 16 dry days) compared to Omusati which did not experience any dry spell. Although the sensitivity of second growth stage (GS2) cannot be compared with the third

growth stage (GS3) which involves flowering, the crop yield can be adversely affected due to less tillers development. Even if the moisture was adequate to allow the crop to germinate and establish, the performance of the crop will depend on the amount of rainfall accumulated since the onset of rainfall and soil water holding capacity among others.

In addition, in case of dry spell occurrences during the establishment phase, most of the seedlings would not survive due to the fact that the root systems are not yet deep enough to sustain the crop during these dry spells. Even if they survive, the growth and development of the seedlings to the next rain would be affected (Burroughs, 2003). Both Oshana and Omusati regions experienced more than sixteen dry days during the third stage with Oshana region experiencing higher proportion (60%) of dry spells than Omusati (27%). The dry spells that occur immediately after the start of the third stage (GS3) which is the most crucial stage for yield formation play a big role in yield reduction due to the fact that this stage involves flowering, pollination and fertilization of panicle of the main stem.

Previous studies established that pearl millet yield can be reduced if the dry spells occur at the crucial stages such as initiations (GS1) and flowering (GS3) (Ayanlade *et al*., 2009). In this case, the grain filling process, which is the most sensitive to water deficit, is likely to have been adversely affected. In addition, the development or formation of the panicle of the tillers which could have compensated for the yield losses of the main shoot would also have been affected.

### 4.3.2 Relationship between pearl millet yield and lengths of dry spells

Table 6 below indicates the proportions of dry spells across pearl millet growth stages in the three study regions (Omusati, Oshana and Ohangwena).

**Table 6: Proportion of dry spells across growth stages when pearl millet yield fell below 200Kg/Ha**

| Region | % of consecutive dry spell days from seedling to panicle initiation (GS1) | % of consecutive dry spell from panicle initiation GS2 | % of consecutive dry spell from flowering to physiological (GS3) |
|---|---|---|---|
| | | | |

| | | | |
|---|---|---|---|
| **Omusati** | (47%) | (20 %) | (13.3%) |
| **Oshana** | (53.3%) | (33.3%) | (20%) |
| **Ohangwena** | (40 %) | (26.6%) | - |

The study revealed that over the study period, the occurrence of dry spells when the yield fall below average (200Kg/Ha) varies with regions as well as pearl millet growth stages. The highest percentage of years when the pearl millet yield fell below 200Kg/Ha were predominant in growth stage one (GS1) whereby 53% was experienced in Oshana followed by Omusati (47%) and Ohangwena (40%). During stage three (GS3), the percentages are quite less compared to GS1 and GS2, whereby, Ohangwena recorded zero percent, Oshana (20%) and Omusati (13.3%) respectively compared to growth stage (GS2). This corresponds to the growth stage that experienced the highest proportion of consecutive dry spells (Table 5).

According to the pearl millet yield data used for this study, less than 200Kg/Ha were recorded in 1997/98, 1999/00, 2001/02 and 2002/03 in the three regions (Omusati, Oshana and Ohangwena) and these seasons experienced prolonged dry spells that occurred during the crop initiation stage (GS1). In some years, the number of consecutive dry spells went beyond sixteen days. For example in 1997/98 season, the regions experienced dry spells of more than sixteen days. Despite its high drought tolerance, millet yields are however reduced by prolonged dry spells during the growing season and this considerably reduces the yield. This was also confirmed by (Ayanlade *et al*., 2009).

Table 7 below shows the correlation coefficients between pearl millet yields and lengths of dry spells at the three growth stages together with the student t-statistics for the three study regions.

**Table 7: Correlation coefficients between lengths of dry spells and pearl millet yields**

| Region | Correlation coefficient (GS1) | t-statistic | Correlation coefficient (GS2) | t-statistic | Correlation coefficient (GS3) | t-statistic | Tabulated t-statistic |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Omusati** | 0.011 | 0.0388 | -0.195 | 0.701 | 0.077 | 0.276 | 0.482 |
| **Oshana** | 0.302 | 1.0837 | 0.130 | 0.469 | 0.111 | 0.400 | 0.482 |
| **Ohangwena** | 0.302 | 1.0860 | 0.037 | 0.132 | -0.175 | 0.630 | 0.482 |

The results of correlation analysis (Table 7) above indicate that there is a significant relationship between lengths of dry spells that occur at GS1 of pearl millet at 95% confidence level in Oshana and Ohangwena; GS2 for Omusati and GS3 for Ohangwena, whereby the computed t-statistics were greater than the corresponding tabulated student t-distribution values. This finding was also revealed by (Ayanlade *et al*., 2009) although these authors did not distribute the dry spells occurrence according to pearl millet growth stages.

## 4.4 Effect of rainfall anomalies on pearl millet yield

Figures 7 to 9 below show the plots of rainfall and pearl millet yield anomalies over the study period in Omusati, Oshana and Ohangwena regions.



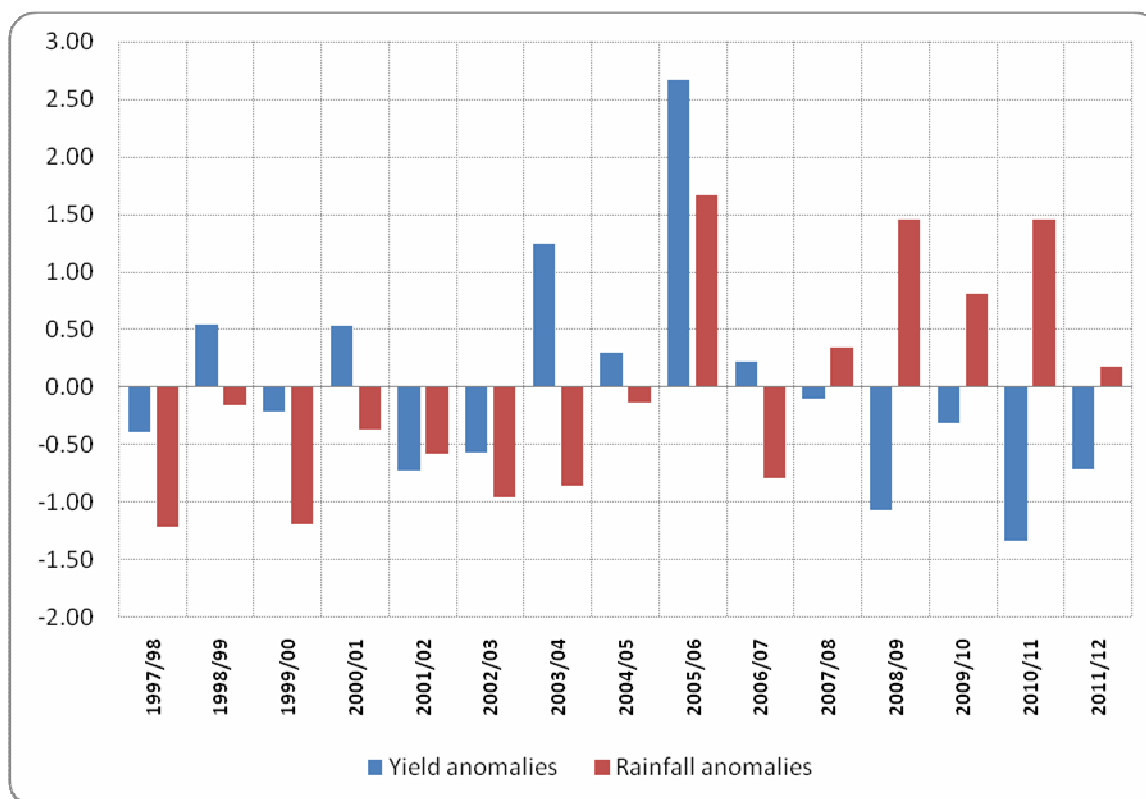**Figure 7: Rainfall and pearl millet yield anomalies in Omusati region**
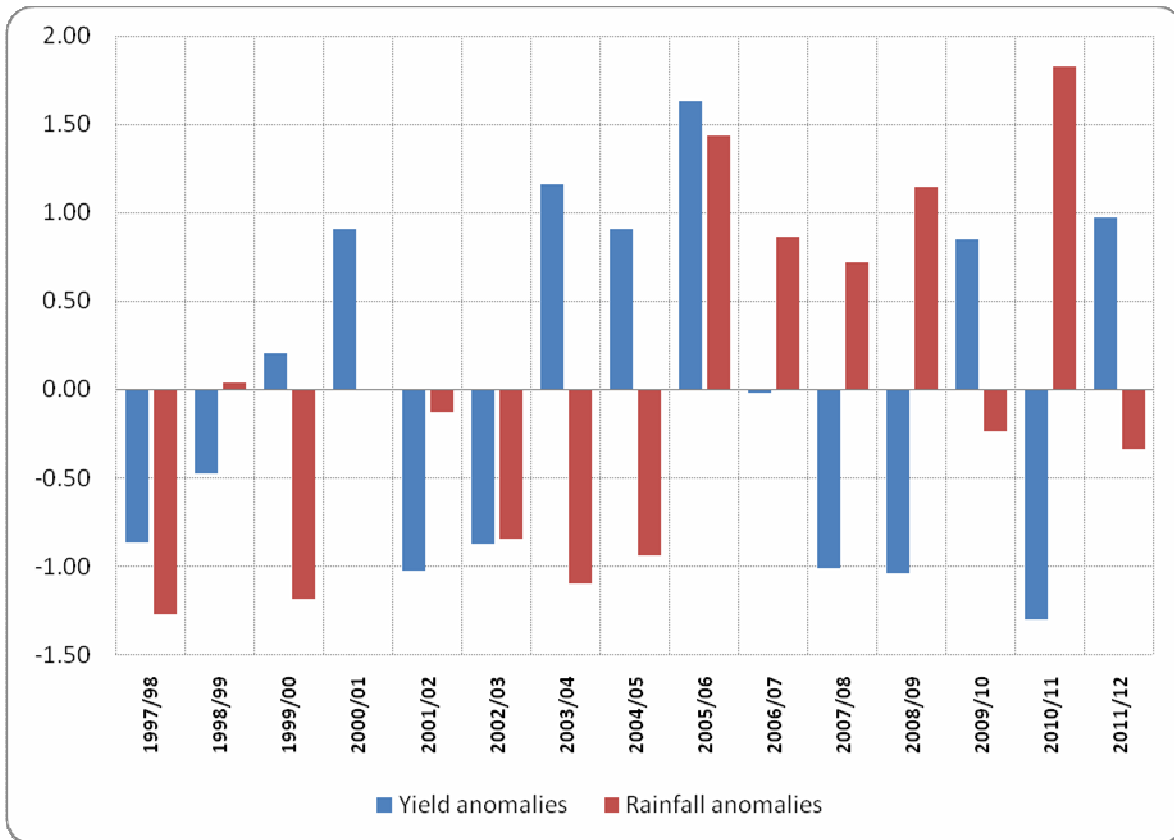
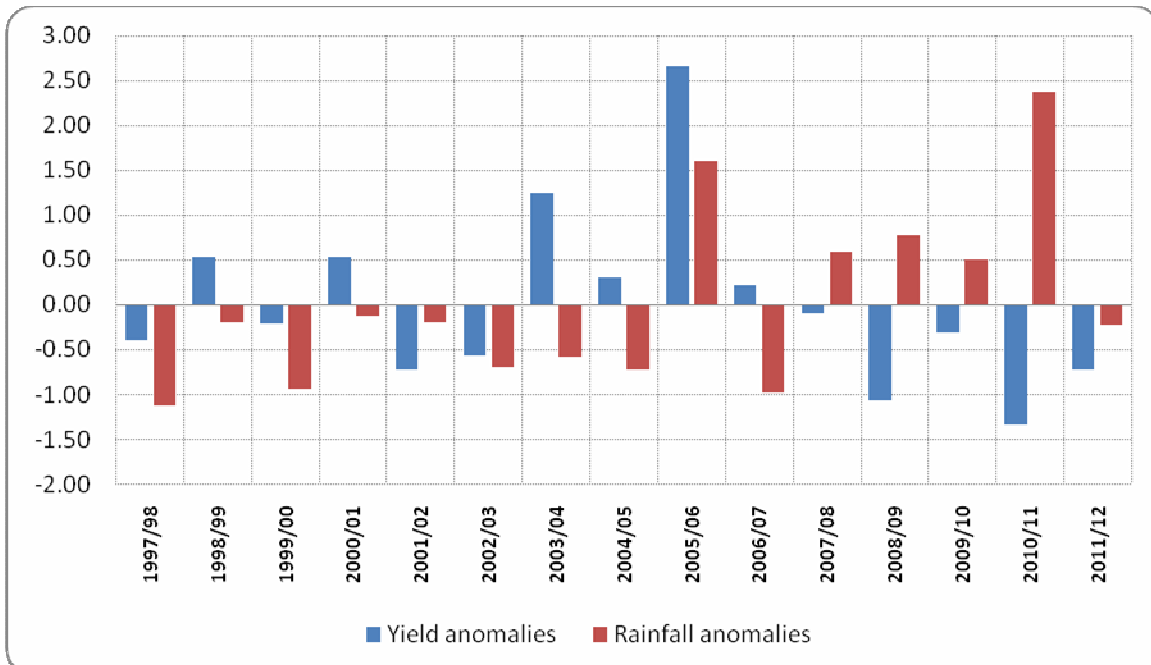**Figure 8: Rainfall and pearl millet yield anomalies in Oshana region**



**Figure 9: Rainfall and pearl millet yield anomalies in Ohangwena region**

Figures 7 to 9 above indicate that 2007/08, 2008/09, 2009/2010 2010/11 and 2011/2012 were wetter than the rest of the study period. However, these seasons experienced the longest growing

period and wet spells; though they recorded the lowest pearl millet yields (Kg/Ha). During 2010/11 crop season, Omusati and Oshana regions recorded 88Kg/Ha. This was also reported by Ayanlade *et al.*, (2009) in some areas of the study regions where pearl millet was adversely affected by too much rainfall.

Too much rainfall during germination period, particularly the first 3 to 4 days, results in poor germination while heavy rain during flowering or ripening reduces seed set/grain filling which leads to reduced yields due to poor grain quality and lodging of plants (Adejuwon, 2005). The highest amounts of annual rainfall that gave rise to pearl millet yields below the average (200Kg/Ha) were received in 2010/11 seasons. These amounted to 853.6mm, 879mm and 1093.2mm for Oshana, Omusati and Ohangwena respectively.

Moreover, Figures 7 to 9 above indicate that there was a relationship between pearl millet yield and the rainfall anomaly. In 2007/08, 2008/09, 2009/2010 2010/11 and 2011/2012, as rainfall anomaly increased, pearl millet yield decreased. As it has been indicated earlier and also confirmed by various studies, too much rainfall results in water logging that reduce the oxygen and nutrient uptake which eventually adversely affect the yield of pearl millet crop. This could also be attributed other factors such as soil moisture distribution which could not allow the crop to establish, or other factors such as flooding, and nutrient leaching among other factors that could have contributed to crop failure.

These findings are in agreement with those by Burroughs (2003) and Ipinge (2001). Some areas within Oshana and Omusati are also known to be in the proximity of salt pans (Namibia agro-ecological zones classification, (de Pauw et *al.*, 1996) whereby if the plant available water mixes with the saline water, the water became unavailable for plant absorption. On the contrary, the decrease in soil moisture during the crop growth stages reduces the potential crop yield, more specifically during stage three (GS2) when the reproductive phase of the crop takes place. Table 8 below shows the correlation coefficients between rainfall anomalies and pearl millet yields.

**Table 8: Correlation coefficients between rainfall anomalies and pearl millet yields**

| Region | Correlation coefficient (GS1) | T-statistic | Correlation coefficient (GS2) | T-statistic | Correlation coefficient (GS3) | T-statistic | Tabulated T- statistic |
|---|---|---|---|---|---|---|---|
| **Omusati** | 0.587 | 2.611 | -0.326 | -1.242 | 0.203 | 0.746 | 0.759 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Oshana** | -0.054 | -0.195 | -0.256 | -0.954 | 0.351 | 1.351 | 0.759 |
| **Ohangwena** | 0.529 | 2.248 | -0.283 | -1.064 | 0.010 | 0.036 | 0.759 |

As shown in Table 8, rainfall anomalies had high significant influence on pearl millet yields that varied from region to region as well as with growth stages of pearl millet. Correlation coefficients between rainfall anomalies representing wet events and pearl millet yields were not statistically significant at 95% confidence level in Oshana during stage one (GS1). However, it was significant at 95% confidence level in Omusati and Ohangwena during the same growth stage. Rainfall anomaly had high significant influence on pearl millet yield in Oshana region during stage three (GS3). The pearl millet yield in Omusati was also statistically significant at 95% confident level during stage three in Omusati while in Ohangwena region, rainfall anomaly had statistically significant influence during the same growth stage.

Other attribution factors could be that the moisture distribution for the entire growing period could not allow the crop to establish well. In addition, persistence of water logging (Weijun Z. *et al*,1995) for a long period in some parts could also kill pearl millet due to lack of oxygen following  submergence of the crops as was experienced during the 2010/11 rain season (Figure 10 below).



**Figure 10: Flooded pearl millet crop during 2010/11 in Oshana region (Source: MAWF)**

Of major interest was the Oshana region, which is predominantly comprised of the "Oshana flood plains" (intersection of shallow water courses locally known as Oshanas which used to be

recharged by flood water from highlands in Angola). These Oshanas used to keep water from heavy rainfall  for a certain period and at the same time they could transport salt which increased salinity in the soil (Mendelsohn *et al*., 2000). This region managed to register pearl millet yields of 330Kg/Ha in 2009/10 while Omusati and Ohangwena which are generally less dominated by flooding systems recorded less than 200 Kg/Ha. The worst season in which pearl millet yield was adversely affected by rainfall anomaly was 2010/11, whereby, Ohangwena recorded 119 Kg/Ha while Omusati and Oshana recorded 88 Kg/Ha each.

## 4.5. Evaluation of Combined Drought Index (CDI) as an indicator for early agricultural drought detection

Combined Drought Index was run for the whole country. However, only the results for selected regions are presented in this dissertation as indicated in sections 4. 5.1 and 4.5.2 below. Results for other regions are presented in appendix 7.

### 4.5.1 Time series of drought indices

Figures 11 to 13 below show a time series of the computed indices including Combined Drought Index (CDI), Precipitation Drought Index (PDI), Temperature Drought Index (TDI) and Vegetation Drought Index (VDI) for Keetmanshoop, Grootfontein and Ondangwa  stations.
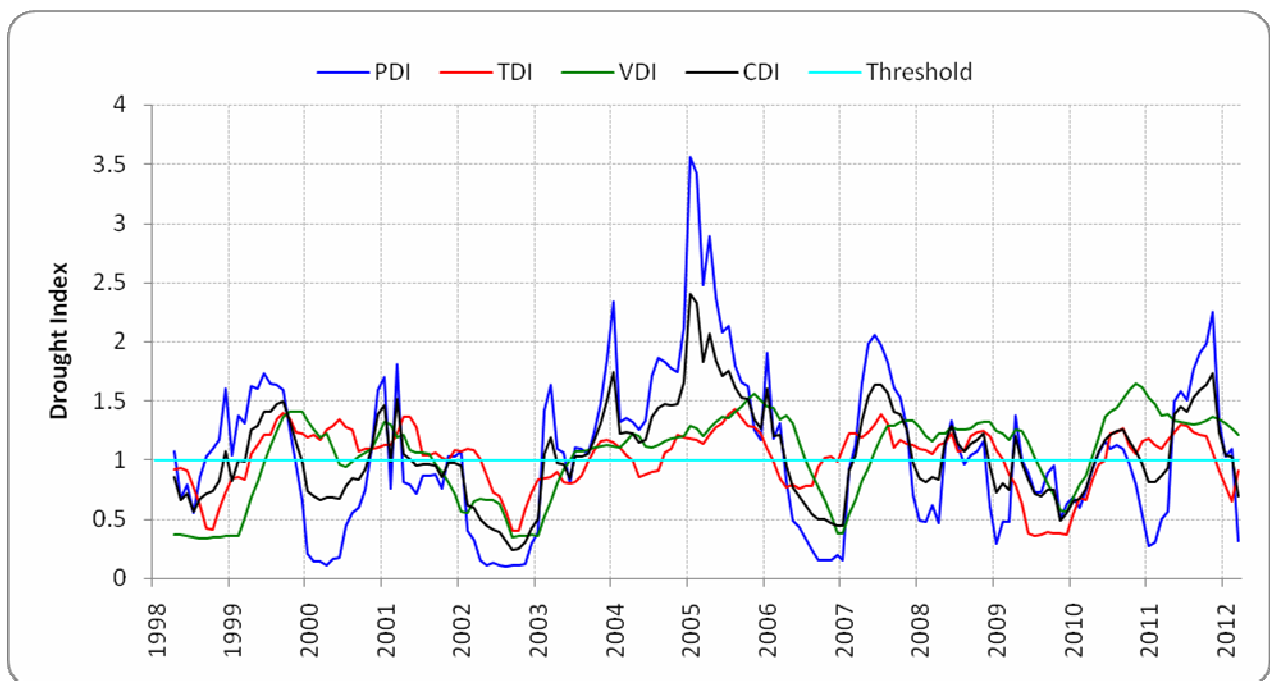


**Figure 11: Time series of drought indices at Keetmanshoop (monthly)**
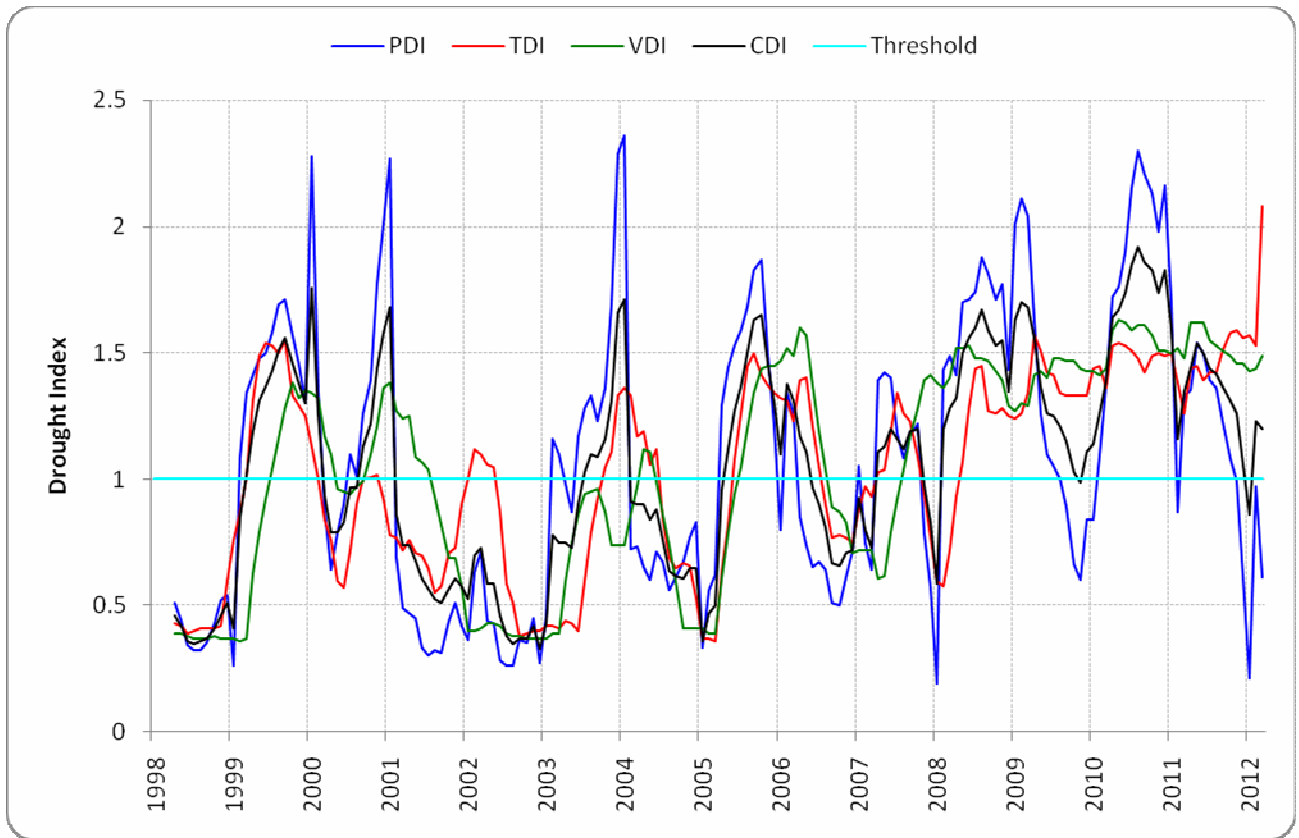
**Figure 12: Time series of drought indices at Grootfontein (monthly)**
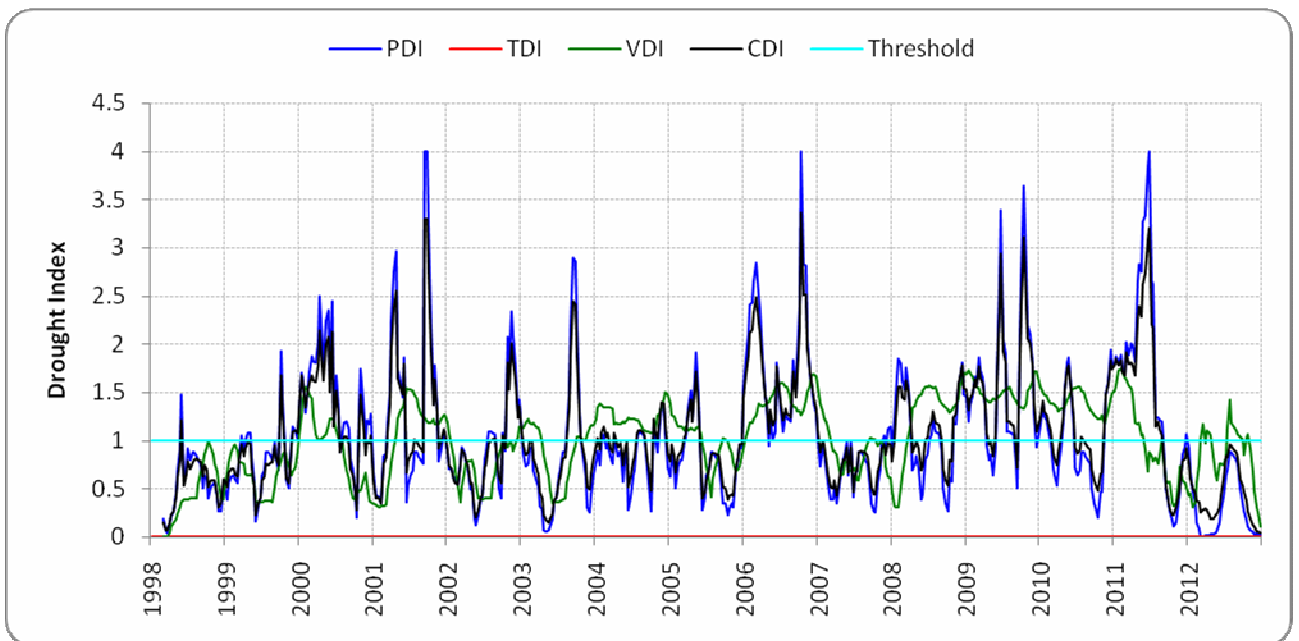


**Figure 13: Time series of drought indices at Ondangwa (dekadal)**

Figure 11 indicates that the Precipitation Drought and Combined Drought indices were below the threshold in 2000, 2008 and 2011 for Keetmanshoop station. Moreover, in 1998, 2002, 2006 and 2009, all three drought indices were below the threshold. Figure 12 indicates that there were similar patterns of all the three drought indices in 1998, 2000, 2003, 2005 and 2007. However, the patterns start to behave differently from 2008 to 2011, whereby the Vegetation Drought and Temperature Drought indices were increasing above the threshold, while Precipitation Drought and Combined Drought indices exhibited same pattern except in year 2009 where the Vegetation Drought Index was below the threshold.

## 4.5.2 Computed Combined Drought Index

Figure 14 to 16 indicate the computed Combined Drought Index (CDI) for the Keetmanshoop (Karas Region), Grootfontein (Otjozondjupa Region) and Ondangwa (Omusati, Oshana Oshikoto and Ohangwena Regions) stations respectively. Figures 14 and 15 were based on the observed monthly temperature, vegetation and precipitation whereas Figure 16 was based on dekadal precipitation and vegetation only.
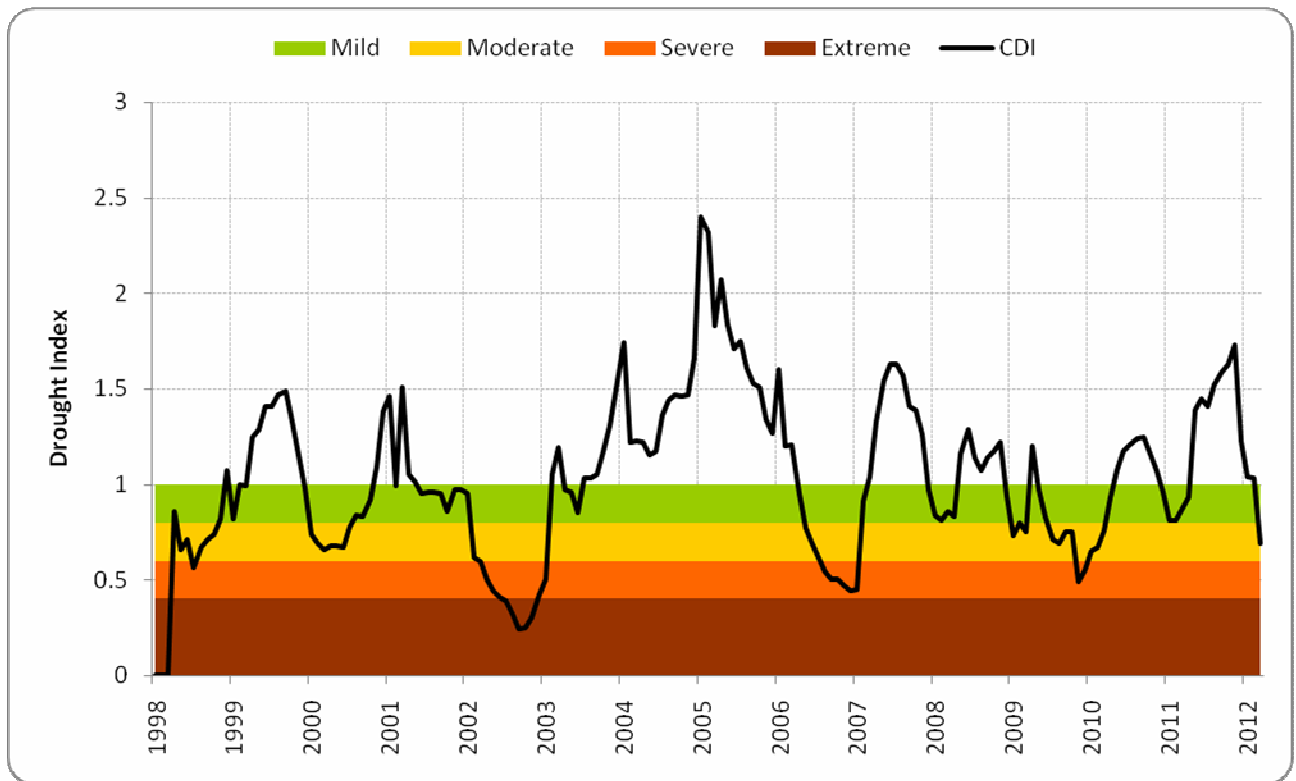
**Figure 14: Keetmanshoop Combined Drought Index (monthly)**
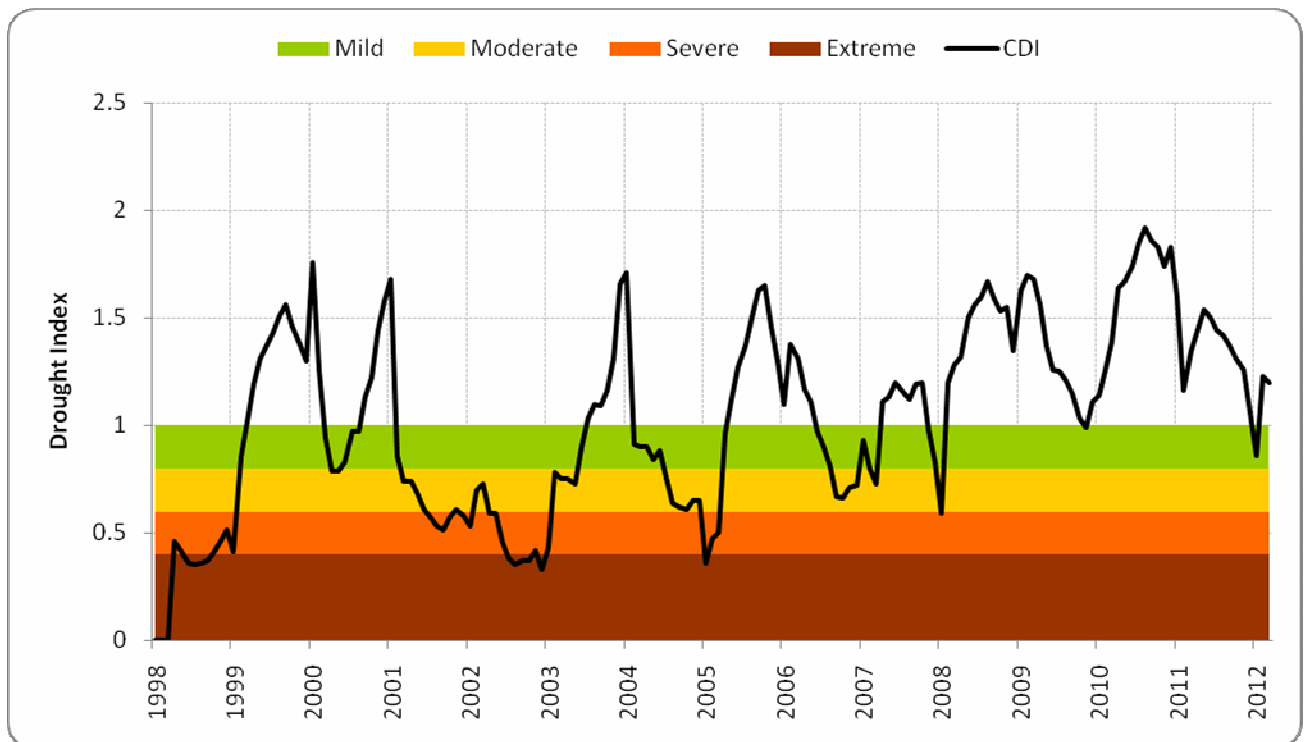


**Figure 15: Grootfontein Combined Drought Index (monthly)**
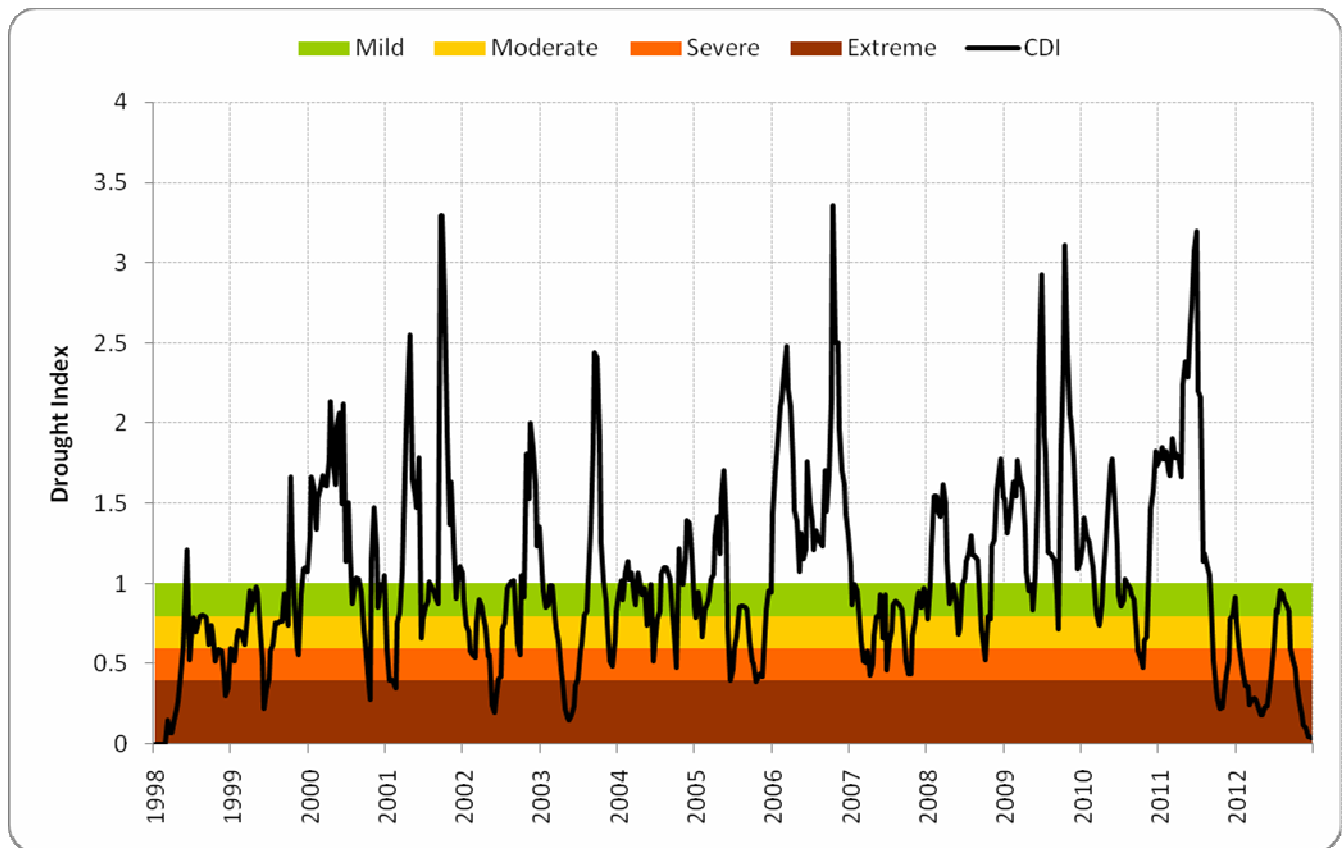
**Figure 16: Ondangwa Combined Drought Index (decadal)**

Figures 14 to 16 indicate that the year 1997/98 was extremely affected by drought (CDI drought severity rating of <0.4). The index behaves in such a way that if all parameters (rainfall, temperature and vegetation) are included in proportions corresponding to 50%, 25% and 25% respectively, it decreases the severity of the drought but if 100% weighted factor is assigned to precipitation only, the drought severity increases. A good example is the case for Grootfontein in 1999, where it reduces the drought severity from extreme to severe. This is one of the advantages of combining these indices into the CDI.

**4.5.3 Comparison of time series Combined Drought Index (CDI) and historical drought years in Namibia**

Time series of rainfall anomaly for the period 1928 to 2000 and the computed Combined Drought Index (CDI) were plotted and presented in Figure 17 below in order to find out if the index captures historical droughts years experienced in Namibia as indicated by historical records of precipitation.

42
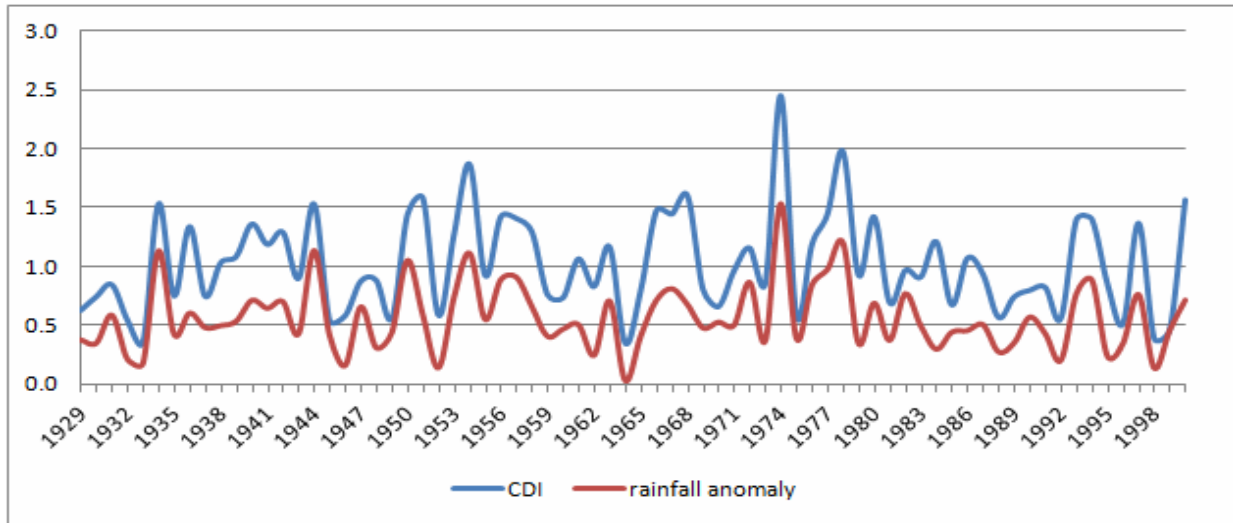
**Figure 17: Time series of Namibia rainfall anomalies and Combined Drought Index (CDI)**

The historical most extreme droughts in Namibia are said to have occurred in the 1930s and for an extended period in the 1960s, and concluded in 1970/71, years which were declared some of the most devastating droughts ever experienced in the region (Sweet, 1998). According to (Sweet 1998) the other " drought disaster " occurred in the period 1982-1984 due to three consecutive years of poor rainfall, and the other one in 1992/93. Sweet, (1998) further stated that another national drought was declared again in 1996 and was considered worse than the 1992/93 but it attracted less publicity and international attention than the one of 1992/93.

The Combined Drought Index (CDI) captured all the above mentioned historical drought years and indicated that extreme droughts were experienced according to CDI drought ranges of <0.4). Furthermore, it also indicates that year 1994/95 and 1997/98 were also extremely affected by drought although they did not appear on the documented list of historical drought years.

### 4.5.4 Comparison of time series of Combined Drought Index (CDI) and Standard Precipitation Index (SPI)

The time series of the Standard Precipitation Index which was earlier calculated by du Pisani (2004) for the same period (73 years) as this study and the Combined Drought Index were plotted on the same axes as shown in Figure 18 below.
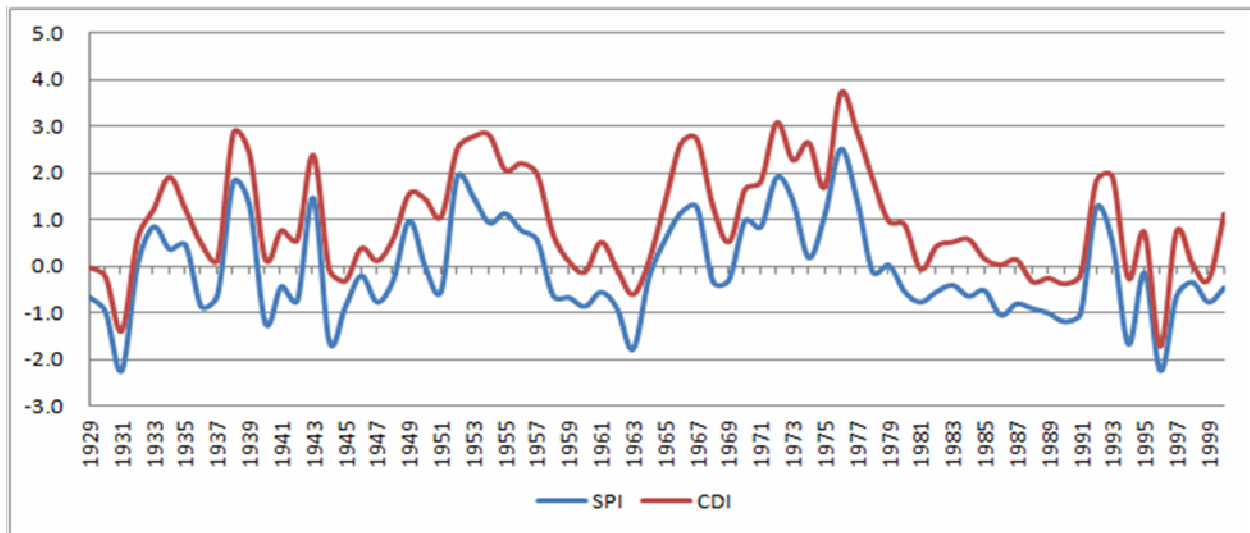
**Figure 18: Grootfontein Combined Drought Index and Standard precipitation indices**

Figure 18 indicates that the two indices were able to capture all the historical drought years in Namibia based on data for Grootfontein station. Although the interpretation of the indices differs, both indices managed to capture all documented historical drought years.

Results from correlation analysis between Combined Drought Index (CDI) and Standard Precipitation index (SPI) for the study period gave a correlation coefficient, r = 0.666 with computed t-statistic 0.288 and tabulated t-value 0.232 respectively indicated that there was a statistically significant relationship between CDI and SPI. The resultant correlation coefficient was statistically significant at 95% level of confidence level. As indicated earlier in this section, the most serious historical drought years identified were 1930/31, 1931/32, 1961/61, 1992/1993 and 1995/96. Both indices agreed in most of the years including 1950's and early 1960s.

# CHAPTER FIVE

# 5.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Introduction

This chapter presents the summary, conclusions and recommendations of the study.

## 5.2 Summary

The study investigated the effect of climate variability on pearl millet productivity and the applicability of a third monitoring agricultural drought index in Namibia. Pearl millet, a staple food for majority of the Namibian population is grown by subsistence farmers at a non-commercial level under rain-fed agriculture. The study was intended to address the problem of undocumented information on how intra-seasonal and climate variability affects pearl millet yield. It was also planned to contribute to the alleviation of the problem of agricultural drought monitoring by exploring the possibility of recommending a third agricultural drought index to be used in Namibia due to the fact that Standard Precipitation and Deciles indices that are currently used in the country require long term data without gaps.

In order to address these challenges, the study determined the effects of the length of growing period, the length of dry spells that occur during pearl millet growth stages and rainfall anomalies on pearl millet yields. It also evaluated the possibility of using the Combined Drought Index (CDI) as an indicator for early agricultural drought detection under Namibia conditions.

Correlation analysis was used to determine the degree of association between the study parameters. Instat statistical analysis software was used to perform climatic analyses, whereas soil water balance was used to determine season length and the occurrence of dry spells (dry days) during the pearl millet three major growth stages. Monthly rainfall and temperature for fourteen years (1998- 2012) as well as the Normalized Difference Vegetation Index (NDVI) data were used in the analysis of the Combined Drought Index (CDI) for the whole country. Due to lack of observed rainfall data, daily rainfall data for Ondangwa, Outapi and Ongenga were estimated and used in the analysis of the effect of climate variability on pearl millet productivity in Omusati, Oshana and Ohangwena regions. The results of the study are summarized in the following subsections.

**5.2.1 The effect of length of growing period on pearl millet yields.**

The results of correlation analysis indicated that length of growing period did not show significant influence on the pearl millet productivity at 95% confidence level in Omusati and Ohangwena regions. However, there was a significant influence on the pearl millet yields at 95% confidence level in Oshana. Furthermore, in certain crop seasons 2007/08, 2008/09, 2009/10, 2010/11 and 2011/12, the growing seasons increased while the pearl millet yields decreased.

**5.2.2 The effect of length of dry spells on pearl millet yields.**

The results of correlation analysis indicated that there is a statistically significant influence at 95% confidence level of lengths of dry spells that occur at growth stage one (GS1) of pearl millet in Oshana and Ohangwena regions; growth stage two (GS2) for Omusati and growth stage three (GS3) for Ohangwena on pearl millet yields.

**5.2.3 The effect of rainfall anomalies on pearl millet yields.**

Rainfall anomaly had statistically significant influence on pearl millet yields that varies from region to region as well as with pearl millet growth stages. Correlation coefficients between rainfall anomalies and pearl millet yields were not statistically significant at 95% confidence level in Oshana during growth stage one (GS1). However, they were statistically significant at 95% confident level in Omusati and Ohangwena during growth stage one. There was a high significant influence of rainfall anomalies on pearl millet yields in Oshana region during growth stage three (GS3). The correlation coefficient between pearl millet yields and rainfall anomaly in Omusati was also statistically significant at 95% confident level during growth stage three (GS3) in Omusati while in Ohangwena region there was no statistically significant influence of rainfall anomalies on pearl millet yields during the same stage (GS3).

**5.2.4 Evaluation of Combined Drought Index (CDI) as an indicator for early agricultural drought detection.**

Combined drought index which was tested for each region in the country based on the representative meteorological stations demonstrated its usefulness as a third agricultural drought monitoring tool which can be used to monitor and detect the occurrence of drought in the country. This was confirmed by the CDI's ability to capture all the documented historical drought years in the country.

In addition, results from correlation analysis between Combined Drought Index (CDI) and Standard Precipitation index (SPI) for the study period indicated that there was a statistically significant relationship between the performance of CDI and SPI at 95% level of confidence.

## 5.3 Limitations of study

Long term historical climatic data such as temperature and rainfall were not available, particularly, in areas that were affected by war conflicts (northern Namibia and southern Angola).

Climatic data for southern Angola are needed for analysis in Namibia since some drainage systems such as Cuvelai Rivers (south of Evale, Angola) among others affect crop production in the northern part of the country. Lack of long term historical agricultural data such as crop yields, soil, hydrological (flood) data and time frame for this study, were the major limitations in this study.

## 5.4 Conclusions

Based on the findings of this study that assessed the effect of climate variability on pearl millet productivity in parts of northern Namibia and the usefulness of the Combined Drought Index (CDI) under the Namibian conditions, the study concluded that:-

i. Length of growing period did not have significant influence on pearl millet yields in Omusati and Ohangwena regions while in Oshana region length of growing period significantly influenced pearl millet yields.

ii. Length of dry spells that occur during three major pearl millet growth stages adversely reduce pearl millet yields in Oshana and Ohangwena during growth stage one (GS1), in Omusati during growth stage two (GS2) and in Ohangwena in growth stage three (GS3).

iii. Rainfall anomalies occurring during growth stage one (GS1) affect pearl millet productivity in Omusati and Ohangwena but don't have significant effect on pearl millet productivity in Oshana region.

iv. Rainfall anomalies occurring during stage three (GS3) highly influence pearl millet yields in Oshana and Omusati regions but not in Ohangwena region.

v. The Combined Drought Index (CDI) can be adopted as a third index for monitoring and detecting the occurrence of agricultural drought in Namibia.

## 5.4 Recommendations

Based on the findings of this study, the following recommendations are made for the Government, researchers, farmers and other stakeholders at large in order to enable them cope with the challenges associated with climate variability on pearl millet productivity and for the efficiency of agricultural drought detection in the country.

While the study acknowledged and appreciated the pearl millet breeders who come up with the short and early maturity varieties of pearl millet in the country, Government, researchers, farmers and other stakeholders at large should consider introducing and intensifying the following policies:

i. The seed multiplication program policy should be amended so that the quantity of pearl millet seeds that is allocated for each farmer be increased in order to alleviate the problem of seed shortage for reseeding in the event of the occurrence of extended dry spells during the initiation stage of pearl millet crop.

ii. Combined Drought Index (CDI) should be adopted as a third agricultural drought monitoring index in Namibia.

iii. The Ministry of Works and Transport which is the sole custodian of meteorological weather stations in the country should expand its observations to measure agro-meteorological data as part of their operations.

## 5.5 Suggestions for future work

This study only looked at the extremes of rainfall but did not go into detail to establish the persistence of water logging during the growing period as well as analyzing the effect of water logging resulting from flooding on pearl millet productivity. The study areas are flood prone which often results into salinity and sodicity of the soil. Therefore, an in depth analysis of the effects of persistent water logging on pearl millet productivity needs to be undertaken. In addition, further studies should be extended to other regions of the country that are growing pearl millet and be supported by ground truth. Future studies should also consider other minor crops such as sorghum, cowpeas and Bambara nuts to establish how these crops are being affected by intra-seasonal climate variability.

## REFRENCES

Adejuwon J.O. 2005. Food crop production in Nigeria Present effects of climate variability Climate Research Clim Res Vol. 30: 53–60, 2005.

Allen R.G., Pereira L.S., Raes D., Smith M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper Rome.

Andrew.C, Ewer. F, Arnold. S, Simelton. E, Fraser E. 2009. Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. Journal of Experimental Botany Vol. 60, No. 10.

Ayanlade A., Odekunle T.O., Orinmogunje O.I., Adeoye N.O. 2009. Inter-annual Climate Variability and Crop Yields Anomalies in Middle Belt of Nigeria. American Eurasian Network for Scientific Information.

Balint Z. 2011: Somali Water and Land Resources.

Balint Z.and Mutua F.M. 2011. Drought Monitoring with the Combined Drought Index- FAO-SWALIM.

Bethany A., Bradley A., Robert W., Jacob, John H. 2006. A curve fitting procedure to derive inter-annual phenologies from time series of noisy satellite NDVI data.

Burroughs W. 2003: Climate: Into the 21st Century.

de Pauw E., Coetzee M. 1996: Production of an Agro-Ecological Zones map of Namibia first approximation:programme, United Nation Development Part 1. Condensed methodology Agricola TCP/NAM/6611.

Drury S.A. 1990. A Guide to Remote Sensing.,Oxford

du Pisani A. 2004. Determining drought indices in Namibia. Ministry of Agriculture Water and Forestry- Agro-ecological Zoning Programme, DART, MAWRD,Namibia.

FAO/UNEP. 1999. United Nation Food and Agriculture organization

Förster S., Kuhlmann B., Lindenschmidt K.E., Bronstert A. 2008. Assessing flood risk for a rural detention area, University of Potsdam, Department of Geo-ecology. Karl-Liebknecht-Str: 24–25.

Gibbs W.J and Maher J.V. 1967. Rainfall deciles as drought indicators. Bureau of Meteorology Bulletin No. 48, .

Hedibi.M, Ananias N. K, Kandawa-Schulz.M. 2012. Effects of storage conditions on viability, germination and sugar content of pearl millet Pennisetum glaucum: grains. Journal of Research in Agriculture 1: 088-092.

Hisdal H., Tallaksen L.M. 2000. Assessment of the Regional Impact of Droughts in Europe Technical Report No. 6.

Ipinge S.A. 2001. The effects of dates of planting on yield and yield components of pearl millet. Agri-cola No.12_11.

Jensen J.R. 1996. Introductory Digital Image Processing- A Remote Sensing Perspective Prentice-Hall New Jersey.

Kamkar B, Koochecki M, Nassiri Mahallati M, Rezevani Moghadam P. 2006. Cardinal Temperture germination in three pearl millet species *Panicum Milliaceum, Pennisetum glaucum* and *Setatlia Italica.*

L.A.C. 2005. An analysis of the Namibian Commercial Agricultural Land Reform Process in: N. Legal Assistance Centre Ed., Windhoek,Namibia.

Le Roux J.L. 2000. Mapping Wildfire in North-Eastern Namibia – A Guide to Basic Remote Sensing & GIS Principles and Techniques, Directorate of Forestry Ministry of Environment & Tourism,Namibia, Windhoek.

Le Roux J.L. 2011. Mapping fire scars and estimating burned area acreage for Namibia, Report for the Atlas of Namibia project, 2000/01, Windhoek.

Maiti R.K., Bidinger F.R. 1981. Growth and Development of the Pearl Millet Plant, International Crops Research Institute for the Semi-Arid Tropics, in: ICRISAT Ed.:, India

Matanyaire C. 1996. Pearl millet production systems in the northern Namibia Ministry of Agriculture Water and Forestry- Agro-ecological Zoning Programme, in: D. MAWRD Ed.:, Windhoek,Namibia.

McKee T.B., Doesken N.J., Kliest J. 1993. The relationship of drought frequency and duration to time scales.

Mendelsohn J., Obeid S., Roberts C., 2000: A profile of Central Northern Namibia, Directorate of Environmental affairs and Gamsberg Macmillen Publishers, Windhoek , Namibia

Mendelsohn J., Jarvis A., Roberts C., Robertson T. 2002. Atlas of Namibia a portrait of the land and its people.

N.P.C. 2011. Namibia Population Statistic, Namibia Ed., Windhoek.

Newman Y., Jennings E., Joae Vendramin J., Blount A. 2010. Pennisetum Glaucum: An overview mananagement.

Newton N., Tuulikki-Parviainen K.M., Zahidul I., Stefan B. 2009. Investigation of the effects of increases in agricultural productivity with regard to food security, employment and rural development in general, Department of Economics and Management, University of Helsinki, Helsinki

Rohrbach D.D., Lechner W.R., Ipinge S.A., Monyo E.S. 1999. Impact from investments in crop breeding: the case of Okashana 1 in Namibia.

Shoopala R. 2008. Assessment using remote sensing and GIS methods: A case study in Skeiðarársandur.

Soler C. M. T., Maman N., Zhang X., Mason S.C., Hoogenboom G. 2008. Determining optimum planting dates for pearl millet for two contrasting environments using a modeling approach

Stern R., Rijks D., Dale I., Knock J. 2006. Instat Climatic Guide.

Stigter C.J, Onyewotu L.O.Z, Olandipo E.O, Owonubi J.J. 1998. Yields of millet between shelterbelts in semi-arid northern Nigeria,

Stigter C.J, Onyewotu L.O.Z, Olandipo E.O, Owonubi J.J. 2002: A comparison of methods to determine the onset of the growing season in northern, Nigeria

Sweet R.J. 1998. Livestock - Coping with Drought: NAMIBIA - A case study, Northern Regions Livestock Development Project

Sweet R.J. 2006. Country Pasture/Forage Resource Profiles, Policy and Support Branch, Office of Knowledge Exchange, Research and Extension, Viale delle Terme di Caracalla,, Rome, Italy.

Tucker C., Tadesse T., Brown J.-F., Hayes M.-J. 2005 . A new approach for predicting drought-related vegetation stress: Integrating satellite, climate, and biophysical data over the US central plains, Remote Sens Environ 82: 127–150

UNDP. 2011. United Nation Development programme, Rome

Weijun Zhou, Linb X. 1995. Effects of waterlogging at different growth stages on physiological
   characteristics and seed yield of winter rape *Brassica napus*

## Appendices 1: Rainfall onset, cessation and length of growing period

| Season | Region | Onset | Cessation | length of growing period | Yield Kilogram/Ha |
|---|---|---|---|---|---|
| 1997/98 | Omusati | 15-Jan | 6-Apr | 82 | 170 |
| | Oshana | 14-Jan | 1-Apr | 78 | 170 |
| | Ohangwena | 15-Jan | 6-Apr | 85 | 162 |
| 1998/99 | Omusati | 23-Dec | 29-Mar | 97 | 253 |
| | Oshana | 25-Dec | 30-Mar | 96 | 253 |
| | Ohangwena | 18-Dec | 2-Apr | 126 | 200 |
| 1999/00 | Omusati | 31-Oct | 11-Mar | 158 | 187 |
| | Oshana | 29-Nov | 5-Apr | 128 | 187 |
| | Ohangwena | 28-Nov | 2-Apr | 126 | 267 |
| 2000/01 | Omusati | 24-Jan | 25-Mar | 107 | 252 |
| | Oshana | 3-Dec | 19-Apr | 137 | 252 |
| | Ohangwena | 3-Dec | 19-Apr | 138 | 336 |
| 2001/02 | Omusati | 15-Jan | 25-Mar | 70 | 141 |
| | Oshana | 15-Jan | 26-Mar | 71 | 141 |
| | Ohangwena | 25-Nov | 21-Mar | 117 | 146 |
| 2002/03 | Omusati | 1-Dec | 5-Mar | 95 | 155 |
| | Oshana | 27-Nov | 3-Mar | 97 | 155 |
| | Ohangwena | 2-Dec | 18-Apr | 138 | 161 |
| 2003/04 | Omusati | 30-Dec | 11-Mar | 103 | 315 |
| | Oshana | 16-Dec | 11-Mar | 86 | 315 |
| | Ohangwena | 14-Dec | 12-Mar | 89 | 361 |
| 2004/05 | Omusati | 12-Nov | 25-Mar | 134 | 231 |
| | Oshana | 14-Nov | 23-Mar | 130 | 231 |
| | Ohangwena | 13-Nov | 5-Apr | 144 | 336 |
| 2005/06 | Omusati | 3-Jan | 23-Apr | 111 | 440 |
| | Oshana | 4-Jan | 28-Apr | 115 | 440 |
| | Ohangwena | 2-Jan | 22-Apr | 111 | 407 |
| 2006/07 | Omusati | 19-Oct | 29-Mar | 162 | 225 |
| | Oshana | 20-Oct | 10-Mar | 143 | 225 |
| | Ohangwena | 24-Nov | 31-Mar | 128 | 245 |
| 2007/08 | Omusati | 3-Nov | 31-Mar | 149 | 196 |
| | Oshana | 31-Oct | 17-Mar | 138 | 196 |
| | Ohangwena | 17-Nov | 26-Mar | 130 | 147 |
| 2008/09 | Omusati | 9-Nov | 14-Mar | 150 | 111 |
| | Oshana | 10-Nov | 13-Mar | 124 | 111 |
| | Ohangwena | 8-Nov | 16-Mar | 130 | 145 |
| 2009/10 | Omusati | 18-Nov | 9-Apr | 147 | 178 |

| | | | | | |
|---|---|---|---|---|---|
| | Oshana | 19-Nov | 5-Apr | 138 | 178 |
| | Ohangwena | 18-Nov | 6-Apr | 140 | 330 |
| 2010/11 | Omusati | 16-Nov | 29-Apr | 165 | 88 |
| | Oshana | 19-Nov | 29-Apr | 165 | 88 |
| | Ohangwena | 16-Nov | 5-May | 171 | 119 |
| 2011/12 | Omusati | 18-Nov | 30-Mar | 132 | 142 |
| | Oshana | 16-Nov | 30-Mar | 166 | 142 |
| | Ohangwena | 16-Nov | 30-Mar | 135 | 343 |

## Appendices 2: Dry spells occurrence during pearl millet growth stage of Omusati

| | No. of consecutive dry spell days from seedling to panicle initiation (GS1) | No. of consecutive dry spell from panicle initiation GS2 | No. of consecutive dry spell from flowering to physiological (GS3) | Yield Kilogram/Ha |
|---|---|---|---|---|
| 1997/98 | 16 | | 34 | 170 |
| 1998/99 | 11 | | | 253 |
| 1999/00 | 12 | 31 | 64 | 187 |
| 2000/01 | | | | 252 |
| 2001/02 | 6 | | | 141 |
| 2002/03 | 12 | | 15 | 155 |
| 2003/04 | 29 | | 17 | 315 |
| 2004/05 | 40 | | | 231 |
| 2005/06 | | | 12 | 440 |
| 2006/07 | 21 | | 14 | 225 |
| 2007/08 | 10 | | 22 | 196 |
| 2008/09 | 18 | | | 111 |
| 2009/10 | 25 | | 11 | 178 |
| 2010/11 | | | | 88 |
| 2011/12 | 11 | | | 142 |

## Appendices 3: Dry spells occurrence during pearl millet growth stage of Oshana

| | No. of consecutive dry spell days from seedling to panicle initiation (GS1) | No. of consecutive dry spell from panicle initiation GS2 | No. of consecutive dry spell from flowering to physiological (GS3) | Yield Kilogram/Ha |
|---|---|---|---|---|
| 1997/98 | 18 | 23 | | 170 |
| 1998/99 | 20 | | | 253 |
| 1999/00 | 11 | | 31 | 187 |
| 2000/01 | 13 | 26 | | 252 |
| 2001/02 | 13 | 18 | | 141 |
| 2002/03 | 10 | | 14 | 155 |
| 2003/04 | 9 | 23 | | 315 |

| | | | | |
|---|---|---|---|---|
| 2004/05 | 51 | 19 | 16 | 231 |
| 2005/06 | 13 | | | 440 |
| 2006/07 | 28 | 23 | 16 | 225 |
| 2007/08 | | 8 | | 196 |
| 2008/09 | 8 | 8 | 22 | 111 |
| 2009/10 | 16 | | 24 | 178 |
| 2010/11 | 9 | | | 88 |
| 2011/12 | 12 | | | 142 |

**Appendices: 4 Dry spells occurrence during pearl millet growth stage of Ohangwena region**

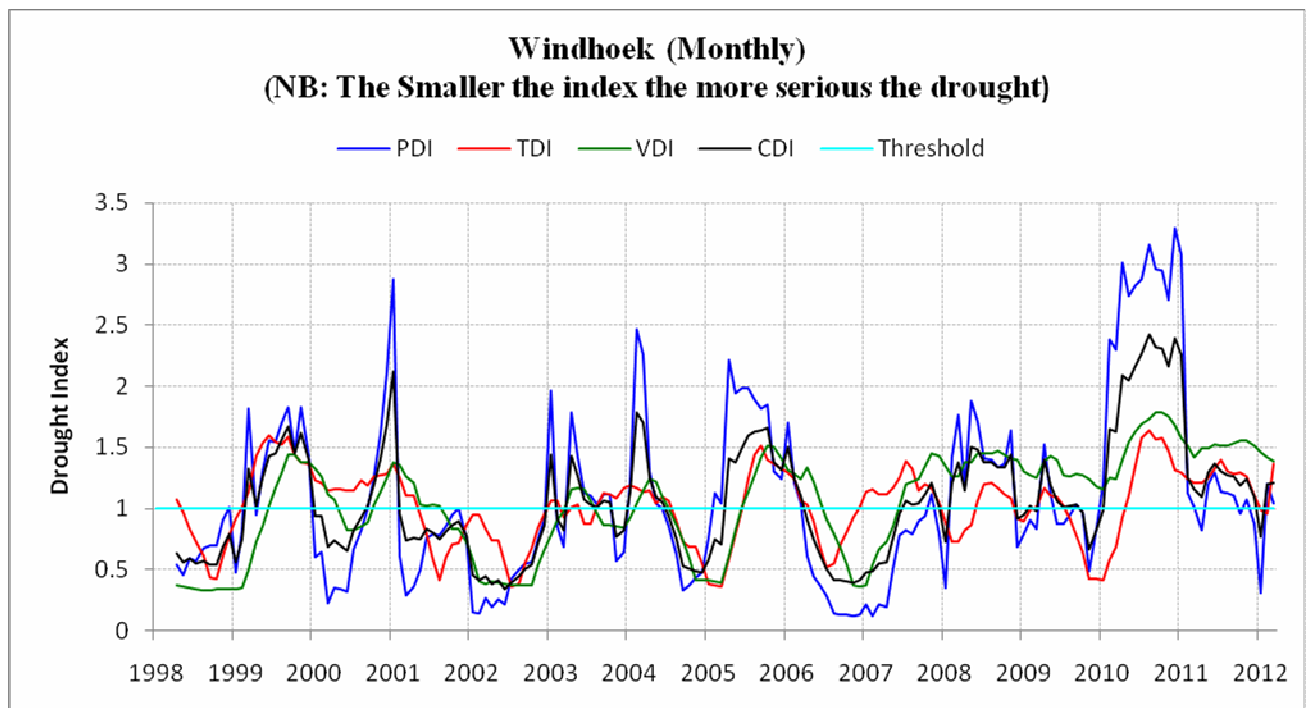| | No. of consecutive dry spell days from seedling to panicle initiation (GS1) | No. of consecutive dry spell from panicle initiation GS2 | No. of consecutive dry spell from flowering to physiological (GS3) | Yield Kilogram/Ha |
|---|---|---|---|---|
| 1997/98 | 16 | | 34 | 162 |
| 1998/99 | 8 | 8 | 18 | 200 |
| 1999/00 | 21 | | 21 | 267 |
| 2000/01 | 11 | 21 | | 336 |
| 2001/02 | 22 | | | 146 |
| 2002/03 | 21 | 49 | | 161 |
| 2003/04 | 18 | 11 | | 361 |
| 2004/05 | 33 | 13 | | 336 |
| 2005/06 | 18 | | | 407 |
| 2006/07 | 14 | 16 | | 245 |
| 2007/08 | 26 | 13 | | 147 |
| 2008/09 | | | | 145 |
| 2009/10 | 16 | | | 330 |
| 2010/11 | | | | 119 |
| 2011/12 | 12 | | | 343 |

**Appendices 5: Rainfall anomalies against pearl millet yield**

| | Annual rainfall anomalies | Omusati yield/HA | Oshana rainfall anomalies | yield/HA | Ohangwena rainfall anomalies | yield/HA |
|---|---|---|---|---|---|---|
| 1997/98 | -1.22 | -0.40 | -1.27 | -0.87 | -1.13 | -0.40 |
| 1998/99 | -0.16 | 0.53 | 0.04 | -0.48 | -0.20 | 0.53 |
| 1999/00 | -1.20 | -0.21 | -1.19 | 0.20 | -0.94 | -0.21 |
| 2000/01 | -0.38 | 0.53 | 0.00 | 0.91 | -0.13 | 0.53 |
| 2001/02 | -0.59 | -0.74 | -0.13 | -1.03 | -0.20 | -0.74 |
| 2002/03 | -0.96 | -0.58 | -0.85 | -0.88 | -0.70 | -0.58 |
| 2003/04 | -0.86 | 1.24 | -1.10 | 1.16 | -0.58 | 1.24 |
| 2004/05 | -0.14 | 0.29 | -0.94 | 0.91 | -0.73 | 0.29 |
| 2005/06 | 1.66 | 2.66 | 1.43 | 1.63 | 1.60 | 2.66 |
| 2006/07 | -0.80 | 0.22 | 0.86 | -0.02 | -0.98 | 0.22 |
| 2007/08 | 0.33 | -0.10 | 0.72 | -1.02 | 0.58 | -0.10 |
| 2008/09 | 1.45 | -1.08 | 1.14 | -1.04 | 0.77 | -1.08 |
| 2009/10 | 0.80 | -0.32 | -0.24 | 0.85 | 0.50 | -0.32 |
| 2010/11 | 1.45 | -1.34 | 1.82 | -1.30 | 2.37 | -1.34 |
| 2011/12 | 0.17 | -0.72 | -0.34 | 0.97 | -0.23 | -0.72 |
| **mean** | **522** | **206** | **510** | **247** | **598** | **206** |
| **stdev** | **229** | **88** | **203** | **98** | **209** | **88** |

**Appendices 6: Length of growing season anomalies against pearl millet yield**

| | Omusati | | Oshana | | Ohangwena | |
|---|---|---|---|---|---|---|
| | **Season length days:** | **yield/HA** | **Season length days:** | **yield/HA** | **Season length days:** | **yield/HA** |
| 1997/98 | -1.36 | -0.40 | -1.48 | -0.87 | -1.48 | -0.40 |
| 1998/99 | -0.88 | 0.53 | -0.84 | -0.48 | -0.84 | 0.53 |
| 1999/00 | 1.09 | -0.21 | 0.28 | 0.20 | 0.28 | -0.21 |
| 2000/01 | -0.55 | 0.53 | 0.59 | 0.91 | 0.59 | 0.53 |
| 2001/02 | -1.75 | -0.74 | -1.72 | -1.03 | -1.72 | -0.74 |
| 2002/03 | -0.94 | -0.58 | -0.81 | -0.88 | -0.81 | -0.58 |
| 2003/04 | -0.68 | 1.24 | -1.20 | 1.16 | -1.20 | 1.24 |
| 2004/05 | 0.32 | 0.29 | 0.35 | 0.91 | 0.35 | 0.29 |
| 2005/06 | -0.42 | 2.66 | -0.18 | 1.63 | -0.18 | 2.66 |
| 2006/07 | 1.22 | 0.22 | 0.80 | -0.02 | 0.80 | 0.22 |
| 2007/08 | 0.80 | -0.10 | 0.63 | -1.02 | 0.63 | -0.10 |
| 2008/09 | 0.21 | -1.08 | 0.14 | -1.04 | 0.14 | -1.08 |
| 2009/10 | 0.74 | -0.32 | 0.63 | 0.85 | 0.63 | -0.32 |
| 2010/11 | 1.32 | -1.34 | 1.19 | -1.30 | 1.19 | -1.34 |
| 2011/12 | 0.25 | -0.72 | 1.61 | 0.97 | 1.61 | -0.72 |
| **mean** | **124** | **206** | **120** | **247** | **127** | **206** |
| **stdev** | **31** | **88** | **28** | **98** | **21** | **88** |

**Appendices 7: Time series of Combined Drought Index at different stations across Namibia**



Windhoek (Monthly)
(NB: The Smaller the index the more serious the drought)

**Windhoek CDI (Monthly)**
**(NB: The Smaller the index the more serious the drought)**

Legend: Mild, Moderate, Severe, Extreme, CDI



**Windhoek Precipitation only(Monthly)**
**(NB: The Smaller the index the more serious the drought)**

Legend: Mild, Moderate, Severe, Extreme, CDI
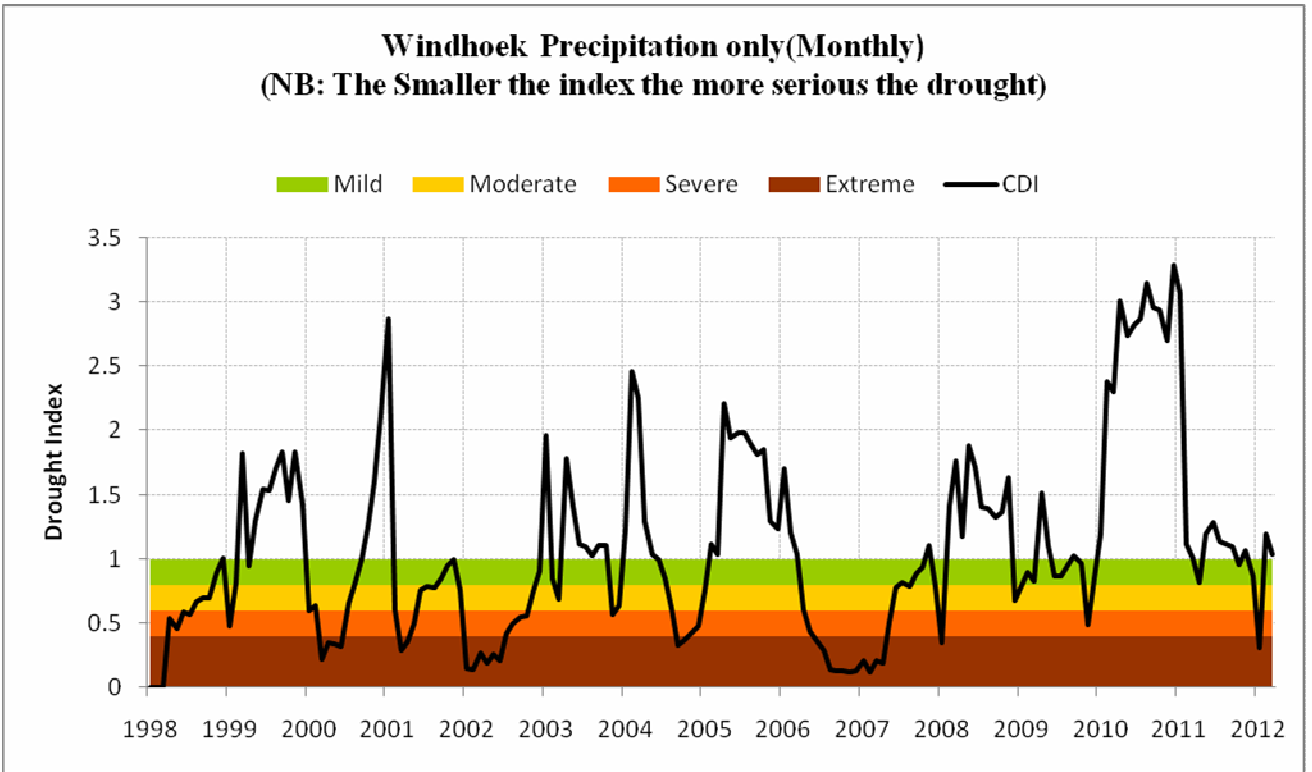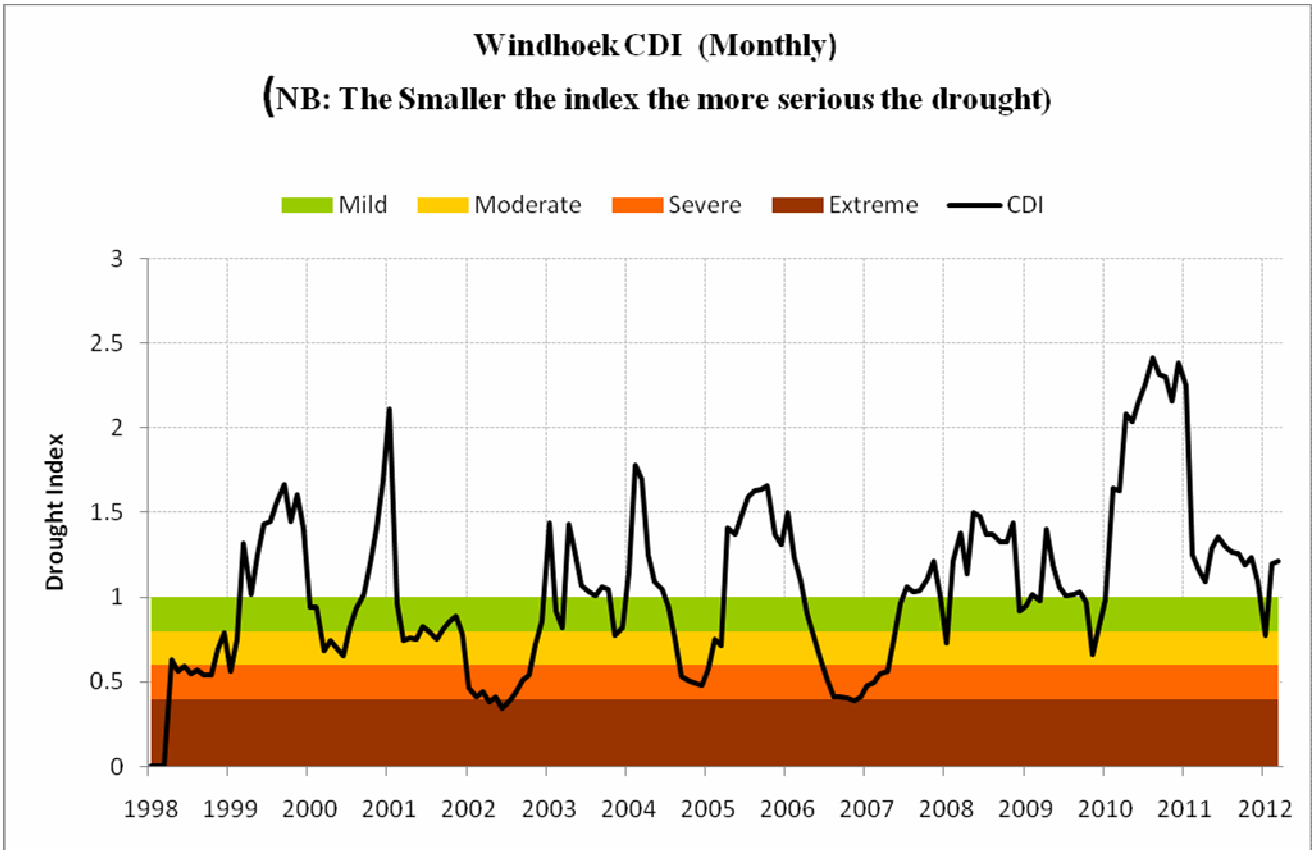
Keetmanshoop (Monthly)
(NB: The Smaller the index the more serious the drought)
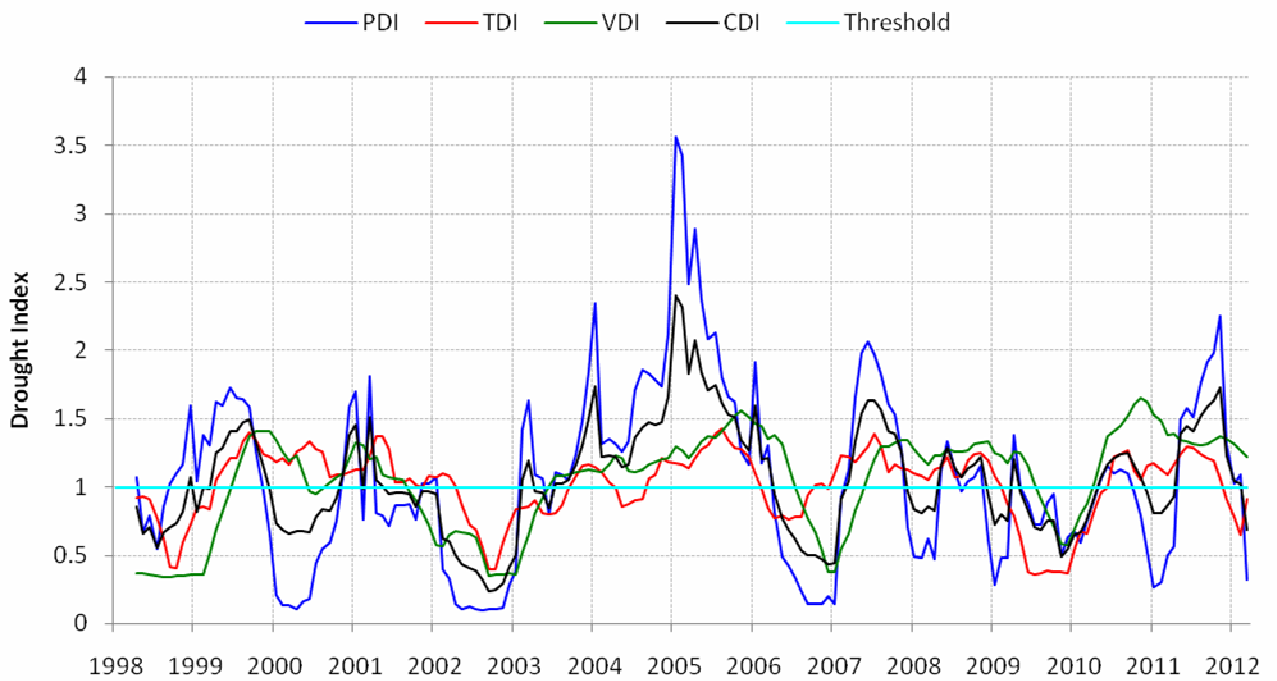


Keetmanshoop CDI (Monthly)

Keetmanshoop precipitation only (Monthly)



Rundu (Monthly)
(NB: The Smaller the index the more serious the drought)



Rundu CDI (Monthly)

Rundu Precipitation only (Monthly)



Katima_mulilo (Monthly)
(NB: The Smaller the index the more serious the drought)

Katima_mulilo CDI (Monthly)



Katima_mulilo precipitation only (Monthly)

Grootfontein (Monthly)
(NB: The Smaller the index the more serious the drought)



Grootfontein CDI (Monthly)



Grootfontein preciptation only (Monthly)